IMPACTS OF NATURAL ADDITIVES ON THE PROPERTIES OF EARTH PLASTERS

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submitted by **MATTHIEU JOSEPH PEDERGNANA** in partial fulfillment of the requirements for the degree of **Doctor of Philosophy** i**n Building Science in Architecture, Middle East Technical University** by,

Prof. Dr. Halil Kalıpçılar
Dean, Graduate School of **Natural and Applied Sciences** ________________

Prof. Dr. F. Cânâ Bilsel
Head of the Department, **Dept. of Architecture** ________________

Prof. Dr. Soofia Tahira Elias-Ozkan
Supervisor, **Dept. of Architecture, METU** ________________

Examining Committee Members:

Prof. Dr. Sinan Turhan Erdoğan
Dept. of Civil Engineering, METU ________________

Prof. Dr. Soofia Tahira Elias-Ozkan
Dept. of Architecture, METU ________________

Prof. Dr. Gilles Foret
Dept. of Civil Engineering, ENPC-Laboratoire Navier ________________

Assoc. Prof. Dr. Ayşe Tavukçuoğlu
Dept. of Architecture, METU ________________

Prof. Dr. Gülser Çelebi
Department of Interior Architecture, Çankaya University ________________

Date: 15.12.2022

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name Last Name: Matthieu Joseph Pedergnana

Signature :

ABSTRACT

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Matthieu Joseph Pedergnana
Doctor of Philosophy, Building Science in Architecture
Supervisor : Prof. Dr. Soofia Tahira Elias -Özkan

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Traditional earth plasters and renders have a long history of usage adapted to the climate history and culture of the population. They procure aesthetics, protection and comfort in the building they are applied on and they are made of local materials and with local workmanship reducing the environmental footprint of the construction and enhancing the social responsibility of the owner. However, earth plasters need to be upgraded to the standard of the construction industry and they need to fulfil the expectations of the users by becoming a strong and long-lasting material while retaining its ease to use, low environmental impact and comfort procuring properties. Thus, the improvement of plasters should be made with materials which will allow the former properties to be conserved while dealing with the issues of strength improvement, water resistance and cohesion enhancement.

This research explores the traditional knowledge on earth plaster and investigates the state-of-art of earth mortar stabilization through the usage of natural and local materials and their adaptation to modern construction standards. Accordingly, a type of soil, known to be used for the production of traditional earth mortar was selected and ten types of sands, eleven types of fibres and thirteen types of biopolymers were chosen amongst the diversity of the material available according to their known or expected beneficial impacts on earth mortars. A reference mortar corresponding to the minimum requirements of the existing standards on earth plaster was produced and after that, the traditionally used sand and fibre were substituted with alternative ones in similar quantities or biopolymers such as molasses, linseed oil or egg white were added in different quantities to the earth mortar. Once fully dried, all specimens were tested for their physical, mechanical, durability, hydric and hygric properties to determine the impact of the changes in the mix on the plaster properties and the possibility to use the selected additives for the production of up-to-standard plasters. Mechanical properties obtained from flexural and compressive tests, water resistance properties obtained from erosion and immersion tests and cohesion properties obtained from abrasion tests were improved by the substitution of sands and fibres with alternative ones but even better results were obtained by the addition of biopolymers such as linseed oil, flour paste, cow dung or casein. Such improvements were obtained without impacting the hygric, properties found from the vapour permeability and vapour sorption tests for flour paste or liquid from the decomposition of hay or casein.

In conclusion, it was determined that it is possible to improve the properties of earth plasters and increase their resistance and strength without decreasing their high vapour sorption property. It should be noted that, the results obtained here are only valid for the specific soil chosen with the specific additives tested and more work is necessary to understand the principles behind the improvement of the properties in order to generalize the conclusions of this study for all kinds of earthen materials.

Keywords: Earth Plaster, Earth Construction, Natural materials, Natural Additives, Natural Fibres

ÖZ

DOĞAL KATKI MADDELERİNİN TOPRAK SIVALAR ÜZERİNDEKİ ETKİLERİ

Matthieu Joseph Pedergnana
Doktora, Yapı Bilimleri, Mimarlık
Tez Yöneticisi: Prof. Dr. Soofia Tahira Elias-Özkan

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Geleneksel toprak sıva yapımı, insanların kültür ve iklim tarihlerine uyarlanmış şekilde uzun bir geçmişe sahiptir. Toprak sıvalar uygulandıkları binalarda güzel görünüm, koruyuculuk ve rahatlık sağlar ve aynı zamanda yerel malzemeler kullanılarak yerel işçilikle yapıldıkları için binanın çevresel ayakizini azaltır ve sahibinin sosyal sorumluluğuna katkı sağlar. Bununla birlikte, toprak sıvalar inşaat sanayiinin standartlarına yükseltilmeye muhtaçtır ve bir yandan kullanım kolaylığı, düşük çevresel etki ve rahatlık sağlayıcı özellikleri karşılarken diğer yandan kullanıcıların, kuvvetli ve uzun ömürlü malzeme beklentilerini karşılamak durumundadır. Bu şekilde, sıvaların geliştirilmesi, daha önceki özellikleri muhafaza eden malzemelerin kullanılması yanında dayanıklılığın geliştirilmesi, su direnci ve kohezyonun artırılması gibi konularla da ilgilenmelidir. Bu araştırma, bir taraftan toprak sıvanın korunması konusundaki geleneksel bilgileri ortaya koyarken aynı zamanda doğal ve yerel malzemelerin kullanımı vasıtasıyla toprak harç stabilizasyonu ve onun çağdaş inşaat standartlarına uyarlanması konusunda en son teknolojileri araştırmaktadır. Bu kapsamda, geleneksel toprak harcı yapımında kullanıldığı bilinen bir toprak türü ele alındı ve toprak harcı üzerinde yararlı etkileri olduğu bilinen veya söylenen çeşitli kum, lif ve biyopolimerler, bu özelliklerine binaen mevcut malzeme çeşitliliği içinden seçildi. Toprak sıva konusunda mevcut standartların minimum koşullarını sağlayan bir referans harç üretildi ve bundan sonra, geleneksel olarak kullanılan kum ve liflerin yerine benzer miktarlardaki alternatifleri uygulandı veya melas, bezir yağı, yumurta akı gibi biyopolimerler toprak harcına farklı miktarlarda ilave edildi. Karışımdaki değişikliklerin sıva özellikleri üzerindeki etkilerini ve standarta uygun sıvaların üretimi için seçilen katkı maddelerinin kullanım ihtimalini tespit etmek amacıyla, bütün nümuneler tamamen kurutulduktan sonra fiziksel, mekanik, dayanıklılık, su ve nemle ilgili özellikleri için testlerden geçirildi. Eğilme ve basınç testlerinden elde edilen mekanik özellikler, aşınma ve daldırma testlerinden elde edilen su direnci özellikleri, sürtünme ve aşındırma testlerinden elde edilen kohezyon özellikleri, alternatif kum ve lif kullanımının geliştirici etki yarattığını, hatta bezir yağı, un lapası, inek dışkısı veya kazein gibi biyopolimerlerin eklenmesinin çok daha geliştirici sonuçlar yarattığını ortaya koymuştur. Bütün bu geliştirmeler, un lapasının, kazeinin ve samanın dekompozisyonu sonucu oluşan sıvının katkı maddesi olarak kullanıldığı numunelerde, buhar geçirgenliği ve buhar emilimi testleri sonucunda elde edilen nem özelliklerinde olumsuz bir etki oluşturmadan elde edilmiştir. Sonuç olarak, şurası görülmüştür ki, yüksek buhar emilimini düşürmeksizin toprak sıvaların kuvvet ve direncini yükseltmek ve böylece toprak sıvaların özelliklerini geliştirmek mümkündür. Ancak, burada elde edilen sonuçlar, sadece seçilen özel toprak ve test edilen özel katkı maddeleri için geçerlidir. Bu çalışmada elde edilen sonuçları toprak malzemelerinin tüm çeşitlerine genelleştirebilmek amacıyla özelliklerin geliştirilmesinin arkasındaki prensipleri anlayabilmek için daha fazla çalışma yapmak gereklidir.

Anahtar Kelimeler: Toprak sıva, Toprak yapı, Doğal malzeme, Doğal kaktı maddeleri, Doğal lifler.

To our Planet Earth

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CHAPTER 1

INTRODUCTION

In occidental countries, earth construction and more generally construction techniques with natural materials except for timber has been long disused for its lack of standardization and the difficulty to achieve the fast construction of large buildings, which are not depending on the presence of local and suitable materials of construction. However, due to the growing concern for climate change and lack of resources worldwide; as well as the search for more affordable and appropriate construction techniques in the so-called “developing countries”, the usage of earth in construction has been rediscovered by architects and engineers. The Bayalpata Hospital in Nepal, the Great Wall of Western Australia, the Alnatura Campus in Germany, the “Village de Terre” de l’Isle d’Abeau and the projects by Diébédo Francis Kéré that led to his being awarded the Pritzker Prize in 2020 are worldwide famous examples or the earthen construction revival. Some researchers around the world are working on finding new construction techniques with earth such as poured earth or earth concrete, 3D printed earth, etc. to adapt it to contemporary and futurist building techniques; whereas others are trying to improve the traditional material by using diverse mixes to increase its strength, its durability or to improve its already widely used water vapour absorbing properties for interior climate regulation.

Earth plasters consist in a large part of the implementation of earthen materials in contemporary architecture as they combined an ease of application and production and a direct improvement of the comfort and safety of interior spaces. Research has shown that the usage of earth plaster contributes to the reduction of interior air pollution (Darling et al., 2012; Darling & Corsi, 2016), to the reduction of electricity consumption by reducing the need for mechanical ventilation (Klinge et al., 2016, 2019), to the improvement of the humidity level in buildings (Maddison et al., 2009;

Randazzo et al., 2016; Thomson et al., 2015), to the fire safety of buildings (Liblik et al., 2020; Liblik & Just, 2016). But the most important benefit of earth plasters for construction is their low carbon footprint (Montana et al., 2013) and the usage of local materials characterized by the diversity of material sources tested by researchers and the adaptation of the construction regulation to non-standardized materials by on-site test (*Guide de bonnes pratiques des enduits en terre*, 2016; NZS 4297 (1998): Engineering design of earth buildings, 1998).

However, earth plasters also suffer from draw-backs that have led to their disuse especially for exterior usage. Earth plasters if not stabilized have usually a low resistance to erosion, to abrasion, to water absorption by capillarity or a low mechanical strength. As explained by Eires et al. (2013, 2014), different strategies have been implemented to reduce the exposure of earthen materials to water or to stabilize the material, i.e. improve its durability. These strategies are aimed at either to protect the building with a large roof and high basement (as most traditional earth buildings were built), or in considering the plaster as a sacrificial coat that need to be renewed regularly (the most famous example being the mosque of Djenné in Mali). A third strategy is the usage of traditional plant or animal based additives (Anger et al., 2012; Beas, 1991; Vissac et al., 2013) or the usage of mineral binders or synthetic additives which increase the environmental impact and sometimes also impact the comfort related properties without high gain in durability (Van Damme & Houben, 2018).

As underlined by Vissac et al. (2016), the main interest of the usage of natural additives is that they usually preserve the water vapour permeability of the earthen plaster while improving the cohesion in dry conditions (abrasion, mechanical strength, etc.) or conserving it in humid conditions (erosion, water absorption, etc.).

Moreover, by similarity, other additives can also be discovered and tested (Barbeta Solà et al., 2014) while other materials which were never deemed usable found themselves having a positive impact on earth materials (Achenza & Fenu, 2007; Clausell & Solà, 2017)

Earth plasters may not only consist of earth and sometimes an additive, but because of the properties of the earth used, it might need to be improved and transformed by the addition of sand – to lower the proportion of clay – or fibres to reduce the impact of the clay on the material. Traditionally, locally found sand and fibres such as chaff have been used to reinforce the plasters, however, contemporary research on earthen material have found that the properties of the sand – e.g. dimension, particle size distribution and sharpness – and the properties of the fibres – e.g. length/diameter ratio, tensile strength, water absorption, roughness – have also an impact on the properties of the plaster, in addition to their amount in the earth mix.

1.1 Research Problem

Although, natural additives are numerous and usually easy to find in close vicinity of the working area (Paul & Changali, 2020; Vissac et al., 2013), most of them have not been tested with scientific methods, which leads to a lack of trust in their efficacy and, therefore, lowers the interest for their usage, outside the traditional community (Vissac et al., 2016).

1.2 Objectives

The main objective of this research is to explore the respective impact of different materials on the properties of earthen plasters made with one specific type of earth. This dissertation focuses on the usage of natural materials only and specifically on materials that are easily available in Central Anatolia where the research was conducted. The aim is to determine a mix of earth, sand and fibres which satisfy the requirements of existing standards (DIN18947, 2013) and then modify this mix to determine the impact of different types of sand and fibres. Additives which have not being widely studied yet but recognized for improving the properties of earth mortars will also be used.

1.3 Disposition

This, the first chapter introduces the background of the study and presents the research problem and objectives, and the disposition of the dissertation.

The second chapter of this dissertation consists of an exhaustive literature review on the impact of sand, fibres and additives on the properties of earth mortars. The selected corpus only deals with earth mortars called "plastic paste" – which comprises mortars for plasters, mud-bricks or wattle and daub – and therefore have similar properties, whereas the works made with dryer or more liquid mortars will be used only as background reference.

The third chapter presents the methodology and the materials used for this research as well as the development of the work from using a raw material to an engineered one with specific amount of materials and additives. The different type of materials used – earth, sand, fibres and additives – will be presented and the specific experimental set-up will be described together with the source used to determine the specific properties - e.g. physical properties, mechanical properties, durability properties, water and water vapour absorption and desorption properties – of the mortars.

The chapters 4, 5 and 6 will present the results and discuss these results, respectively. Chapter 4 will describe the results of the test made to identify the type of earth and sand used while the Chapter 5 will present the results of tests on non-modified and non-stabilized earth mortars and report the properties of earth mortars made with one type of earth, sand and fibre. In this chapter, the physical properties of the unmodified earth will be presented first, then the properties of the earthen mortars and finally the properties of the reinforced earth mortars will be given. The Chapter 6 will focus on presenting the properties of modified earth mortars – i.e. usage of alternative sands and fibres instead of using traditional sand and fibres. Finally, the addition of plant and animal based stabilizers and the discussion on the impacts of these materials on the properties of plasters will be exposed in Chapter 7.

In the last chapter, a general conclusion will summarize the findings of this research and open the field for new possible research based on the findings and the limitations and delimitations of this work.

CHAPTER 2

LITERATURE REVIEW

This chapter presents an extensive review of the literature on earth mortars that might be used for plastering and rendering as they are defined in CHAPTER 1. In the literature these mortars might have been qualified as mortars, renders, or plasters, but also as cast bricks, adobe or mud-bricks as these materials have a similar fresh composition (Schroeder, 2016; Van Damme & Houben, 2018). Therefore, from this point, the term earth mortar has been used for all mixes which have enough plasticity to be used for plastering and/or rendering a wall; even if the authors intended it for a different production. Their composition, their experimental testing set-ups and their properties were identified and the impacts of their composition were determined, summarized and compared in this chapter.

An extensive review of one hundred thirty-five articles and academic work dating from 1987 to 2022 presenting detailed information on the mortar composition and the results have been made and articles have been selected to create a corpus for more detailed analysis. Articles in the corpus have been selected according to the reliability and clarity of the information given. Papers which exclusively present earth mortars stabilized with more than 15% of mineral, chemical or organic binder have been omitted as it is usually the amount of clay necessary to produce earth mortars for plasters. Some papers with repeating information as the results might have been partially published in two different journals or conferences have been found. In this case, both of them were selected for the corpus but were grouped for analysis. This corpus is presented in Table A 1 to Table A 3 in APPENDIX A and has been used to gain a deeper knowledge of the materials and the impact of these materials on the properties of plastic earth mortars. Of course, other publications are also used to explain and gain additional knowledge which is not available in the corpus.

In the first section of this chapter, the composition of earth mortars included in the corpus has been studied and the diversity of materials used and their specific properties have been shown. In the second section, the impact of the different materials on the properties of mortars has been discussed. In the third part, the methods of production and methods of testing used in the literature have been reviewed and their impact on the properties of mortars has been shown.

2.1 Composition of earth mortars for plastering and rendering

Earth mortars are made of earth – clay, silt, sand and gravel – mixed with water. Depending on the type of earth, additional materials are used – such as aggregates, pellets (plant aggregates), fibres and stabilizers – to enhance one or several properties of the fresh or dry mortar and allow its usage for construction. In the studied corpus, earth mortars have been found using several types of clay and earth; several types, amounts and sizes of fibres; several types, amounts and particle size distribution of sands; and several types and amounts of additives. These findings from 110 articles are presented in APPENDIX A.

2.1.1 Earth type and clay content

The type of earth used for mortar is usually the less documented material and authors refer to it as local soil, local earth, or clayey earth; without more information on it. However, according to different sources, the type of earth used and its clay content, as well as the type of clay, is very important and it has an impact on the properties of the mortar.

2.1.1.1 Type of earth

The type of earth used can be defined in different ways which involve different methodologies and equipment. The easiest and more commonly done are the textural classification and the Atterberg limits. In French-speaking countries, another easy-to-do identification is often used which is the Methylene Blue Index. A few recent papers also used the Cation Exchange Capacity as a novel indicator of the activity of the clay. Several papers have also undergone more specific research on the earth type by making different mineralogical analyses. A summary of the relevant information on the 102 different earth or clay-sand mixes used in the corpus is given in Table A 4 in APPENDIX A.

2.1.1.1.1 Textural classification

The earth used is mostly qualified by its particle size distribution (Table 2-1) – clay (<0.2 μm), silt (0.2 μm to 63 μm), sand (63 μm to 2 mm) and gravel (> 2 mm) amount – despite this classification not being fully representative of the physicochemical properties of the earth, i.e. the real amount of clay particles, as their size might vary out of the limit defined by the standards; and smaller fraction of quartz or mica can be counted as clay (Meimaroglou & Mouzakis, 2019; Schroeder, 2016) or the different properties of each type of clay. However, most authors and standards used this textural classification to prescribe the type of earth to be used (Houben & Guillaud, 2008; Jiménez Delgado & Guerrero, 2007).

Table 2-1: Particle size distribution and classification of earth according to different standards. Table from Schroeder *(2016, p. 69)*

No.	Soil type	DIN 18196		USCS	
		Letter symbol[a]	Grain sizes d [mm]	Letter symbol	Grain sizes d [mm]
1	Cobbles or boulders	X (Bo/Co)	≥63	B	≥76.2
2	Gravel	G (Gr)	$2.0 \leq d < 63$	G	$4.75 \leq d < 76.2$
3	Sand	S (Sa)	$0.063 \leq d < 2.0$	S	$0.075 \leq d < 4.75$
4	Silt	U (Si)	$0.002 \leq d < 0.063$	M	$0.002 \leq d < 0.075$
5	Clay	T (Cl)	<0.002	C	<0.002
6	Organic loose rock	O		O	

[a]Letter symbols according to DIN EN ISO 14688-1

In the corpus of selected papers, most of the earths used have been qualified by their texture. However, the texture given is the texture of the natural soil, only a few papers give the texture of the used soil when it has been modified with the addition of sand or gravel (Corrêa, Mendes, et al., 2015; Corrêa, Protásio, et al., 2015; Rescic et al., 2021; Tavares et al., 2019).

Another drawback is the difficulty to determine exactly the amount of silt and clay inside the amount of fines (particles passing the 0.75 mm or 0.63 mm sieve) which implies the usage of more complicated set-ups which are not always available. Therefore, often only the amount of fine is available. In the corpus of selected papers, the amount of clay-sized particles varies from 100% for some research using pure clay (Clausell et al., 2020; Pinto et al., 2014) to 0.5% or 5% for silty soil with almost no clay (Achenza & Fenu, 2007; Aymerich et al., 2012).

2.1.1.1.2 Atterberg limits

Atterberg limits – Liquid Limit (LL) and Plastic Limit (PL) – are an indication of the plasticity of the fine particles of the soils by determining standardized levels of moisture content in the soil. The Plastic Index (PI) is the difference between these limits and determines the range of plasticity of the soil as shown in Table 2-2. However, according to Lagouin et al. (2021), the determination of the Pl is dependent on the ability of the apparatus operator so the risk of error due to the interpretation of the test is high.

Table 2-2: Correlation between the Plasticity Index (PI) and soil's plasticity from Lagouin et al. *(2021)*

PI (%)	Level of plasticity
0-3	non-plastic
3-15	slightly plastic
15-30	medium plastic
>30	highly plastic

Other information related to the Atterberg limits is the quantity of water needed to make a plastic mortar for construction. It has been determined by Lagouin et al. (2021) that the amount of water needed to reach the proper consistency of the mortar is closely related to the liquid limit. Moreover, in several papers (Mellaikhafi et al., 2021), the amount of water added to the mortar has been determined either by the plastic limit or by the formula linking the plastic limit and liquid limit as shown in Eq. (1).

$$W(\%) = \frac{WL\ + WP}{2} \quad (1)$$

Most of the authors have provided information on the Atterberg limits, and the soil they have used falls between the limits of slightly plastic and medium plastic, except for a few exceptions of non-plastic soil (Achenza & Fenu, 2007) or highly plastic soils (Bouhicha et al., 2005; Corrêa, Protásio, et al., 2015; Laborel-Préneron, Aubert, et al., 2017; Mellaikhafi et al., 2021) when soils with a high amount of fines have been used.

2.1.1.1.3 Earth classification

Soil has been classified according to different national and international standards for agricultural or construction purposes. 3 different systems are found in the literature i.e. USCS, AASHTO and ISSS; and the most used is the USCS system which is based on the size of particles and liquid and plastic limits of the fine soil. In this classification system, most of the soils used in the corpus, are classified as Lean Clay (CL) and some of them as silt (ML, Elastic Silt (MH) or Silty Sand (SM). However, most authors don't give any reference as this classification is not done for building construction purposes. Some resources, using the *Handbook for Earth Construction* (Houben & Guillaud, 2008) as a reference, advise the usage of Lean Clay soils. However, most authors don't give any reference as this classification is not done for building construction purposes. The classification of soils used by authors can be found in Table A 4 in APPENDIX A. x

2.1.1.1.4 Mineralogical and chemical analysis

Other analyses commonly done are the mineralogical analysis to determine the minerals present in the earth and sometimes the type and amount of clay present in the earth. However, despite the knowledge that "*plasticity, water-holding capacity, soil strength, as well as volume change behaviour of soil greatly depend on clay mineralogy*" (Meimaroglou & Mouzakis, 2019) no direct relationship has been found between the amount and type of clay and their properties. It is only known and determined by some authors that non-swelling clays such as illite or kaolin should be used and that illite will have better behaviour than kaolin.

A majority of authors haven't given any information on the mineralogical and chemical analysis of clay or only partial data such as the type of minerals encountered. The type of clay present in the soil and more often, the amount of this clay is mostly not specified, and therefore the previous tests that are only making correlations between a property and the type of clay are used.

In the set of natural soils used to produce mortar, a few authors have given the mineralogical composition Table A 4 in APPENDIX A. In these soils, most of them are constituted of non-swelling clays – kaolinite and illite – either alone but most of the time combined and with other clays. Some authors report the presence of smectite or montmorillonite which are swelling clays but always in a very low quantity (Atzeni et al., 2007; Zak et al., 2016).

2.1.1.2 Summary of the type of earth used

According to Table A 4 in APPENDIX A, it can be seen that most of the earths used are natural earths, and according to most authors, taken from a local area with a soil known to be clayish or known to have been used to produce earthen materials. However, a few authors used a commercial type of earth, either a ready-made product for earth construction (Lima et al., 2020, 2019) – plaster, adobe, fired brick – or a refined product made almost uniquely of clay (Alhaik et al., 2017; Clausell et al., 2020; García-Vera & Lanzón, 2018; Peetsalu et al., 2010). Some authors also used a very different product, which is composed of quarry fines that are a by-product of the aggregate production in the form of powdered sludge obtained from washing the aggregates (Laborel-Préneron, Aubert, et al., 2017; Lagouin, Aubert, et al., 2021).

According to Table 2-2 and Table A 4 in APPENDIX A, most of these earths will fall within the limit of plastic earth with a PI comprised between 3% and 30% and a large majority of it between 10% and 20%. Their natural texture is one of clayey earth with about 10% to 30% clay-sized particles and 50% to 70% of sand. Moreover, this range is the same as the natural earths before any transformation due to the addition of aggregates.

2.1.2 Aggregates used for earth mortars

According to European Standards, aggregates are "*granular material used in construction" (EN12620: 2002.).* Different types of aggregates are used in earth construction mostly mineral aggregates from different sources but sometimes also plant aggregates. In some publications, the term aggregates is also used for fibres (Schroeder 2016 for example) however, here the usage of long and thin materials (fibres) and granular materials (aggregate) will be separated.

2.1.2.1 Type and properties of aggregates

The aggregates used in the studied corpus are given in Figure 2-1 (aggregates) and Figure 2-2 (pellets) and a detailed summary of the properties of the aggregates and pellets used in the selected corpus is presented in Table A 5 and Table A 6 in APPENDIX A. From Figure 2-1, it can be seen that most of the aggregates used are mineral sands coming from natural sources. Other used aggregates are wooden chips in different sizes and crushed plants. Finally, a few authors have used specifically developed aggregates (PCM) or recycled wastes (shredded tires).

2.1.2.1.1 Mineral aggregates (sand and gravel)

Mineral aggregate types are determined by their size or more exactly by the size of the sieve they pass through. This allows a classification of aggregates as sand – between 0.063 mm and 2 mm according to ISO 14688 – where fine sands are from 0.063 to 0.2 mm, medium sands from 0.2 mm to 0.63 mm and coarse sands from 0.63 mm to 2 mm. Particles larger than 2 mm are usually considered as gravels but some studies determine the sand as being particles passing through the 0.075 mm sieve and the 4.75 mm sieve (Lanzón et al., 2017; Vargas Neumann et al., 1987) and this acceptance will be used throughout this dissertation. In the corpus of selected articles, most of the authors used only aggregates of sand size or smaller, however, a high diversity of sand is being used according to their particle size distribution (PSD):

- Different types of PSD might be used; with some authors using uniquely coarse sand (Atzeni et al., 2006; Gomes et al., 2018; Peetsalu et al., 2010) or fine sand (Lima, Correia, et al., 2016; Perrot et al., 2018; Rasa et al., 2008, 2009)

- Some of the authors used washed sand, meaning that the filler – particles smaller than 0.063 mm – have been removed almost entirely (García-Vera & Lanzón, 2018; Lagouin, Laborel-Préneron, et al., 2021) whereas others might use particles with a large amount of filler.

The provenance of the aggregates can be different with authors using river sand, masonry/plaster sand (Stazi et al., 2015), quarry sand (Liuzzi et al., 2018; Perrot et al., 2018) or quarry dust (Maheri et al., 2011).

Sands can also be classified according to their mineral composition, either as siliceous sand or quartz sand, used by the large majority of the authors but others might use alternative sands such as calcareous sand coming from the stone quarry (García-Vera & Lanzón, 2018) or basaltic sand (Scalisi, 2014). Some authors use other types of aggregates because of their specific properties such as pumice (Binici et al., 2007) or PCM (Brzyski & Suchorab, 2018; Faria & Santos, 2014; Santos, Faria, et al., 2020) for thermal properties or diatomic, tuff or brick dust for their possible pozzolanic reaction with clay (Schicker & Gier, 2009)

Moreover, environmental concerns about the availability of aggregates have led some researchers to use recycled materials (Maheri et al., 2011; Niroumand & Kassim, 2010). Özmen and Bayülke (1987) use the aggregates that they sieved from the earth they were producing bricks with to reduce the proportion of soil. Other authors propose the usage of crushed demolition wastes as aggregates replacement (Joshi et al., 2019; Rojas-Valencia & Aquino Bolaños, 2016).

In addition to the provenance, the type and the PSD of the aggregates, some authors are also giving test results for such important properties as their density or their water absorption.

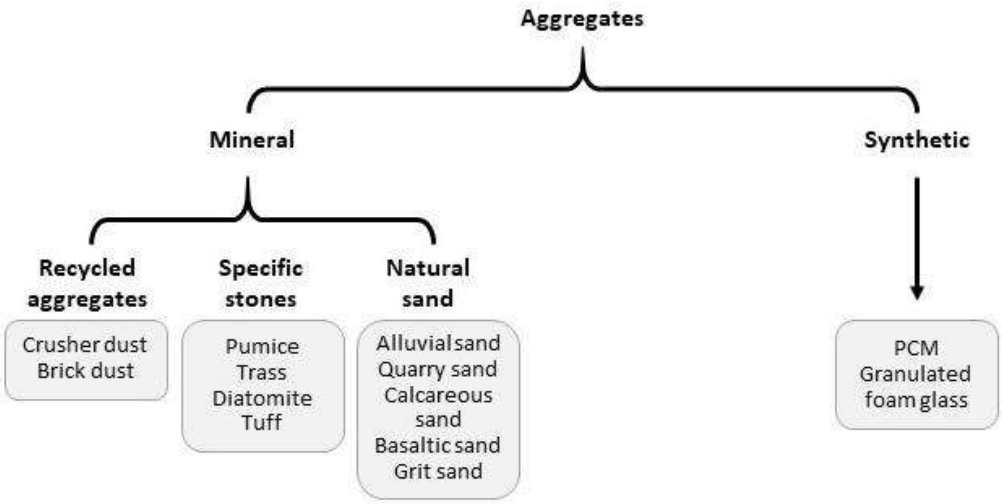

Figure 2-1: Source and type of aggregates used for earth mortars

2.1.2.1.2 Pellets

Pellets are plant aggregates that "are coming from the stem of plants cultivated either for their fibres (hemp, flax, etc.) or for their seeds (oleaginous flax, sunflower, etc.)"(Amziane & Sonebi, 2016, p. 2) and as mineral aggregates, they present a bulky shape. Since coming from a fibrous material, there are usually elongated in 1 or 2 dimensions, malleable, lightweight and highly porous with a low apparent density (Picandet, 2013). Most authors do not differentiate pellets from fibres and use them in the same conditions (Ashour & Wu, 2010); but Laborel-Préneron et al. (2016) have presented a way to differentiate plant fibres/straw from aggregates, by using the inverse of the aspect ratio (1/AR), which is the ratio of the length to the diameter, versus the diameter. According to these authors, the 1/AR of pellets is higher than 0.10.

The large range of plant aggregates that are being used in earth construction in substitution of the mineral aggregates in the studied corpus is presented below. The review from Laborel-Preneron et al. (2016) further presents some of these aggregates as well as others.

The pellets and their provenance and properties used in the selected corpus are presented in Table A 6 in APPENDIX A. It can be seen that most of the pellets used in this corpus are coming from timber processing waste such as saw-dust or wood shaving (Ashour & Derbala, 2010; Costi De Castrillo et al., 2017; Schicker & Gier, 2009; Vatani Oskouei et al., 2017; Vilane, 2010) or from the stem of plants (Ba et al., 2021; Hamard et al., 2013; Laborel-Préneron, Magniont, et al., 2017); which will give them an elongated and flat shape different from bulky pellets such as corn-cob (Laborel-Préneron, Magniont, et al., 2017) or ground corn pith (Palumbo et al., 2016). The main difference between woody and non-woody plant pellets is in their structure and the amount of lignin and cellulose which gives them hardness and brittleness compared to other plant pellets. Niroumand and Kassim (2010) and Serrano et al. (2016) propose the usage of shredded wastes – namely tire, rubber crumbs and polyurethane insulation.

The size of the pellets is also an important difference between them with very fine materials such as ground olive pits (Serrano et al., 2016) or very large ones such as the olive tree prunings used by Liuzi et al. (Liuzzi et al., 2018) with a length of 20 mm and a diameter of 5 mm.

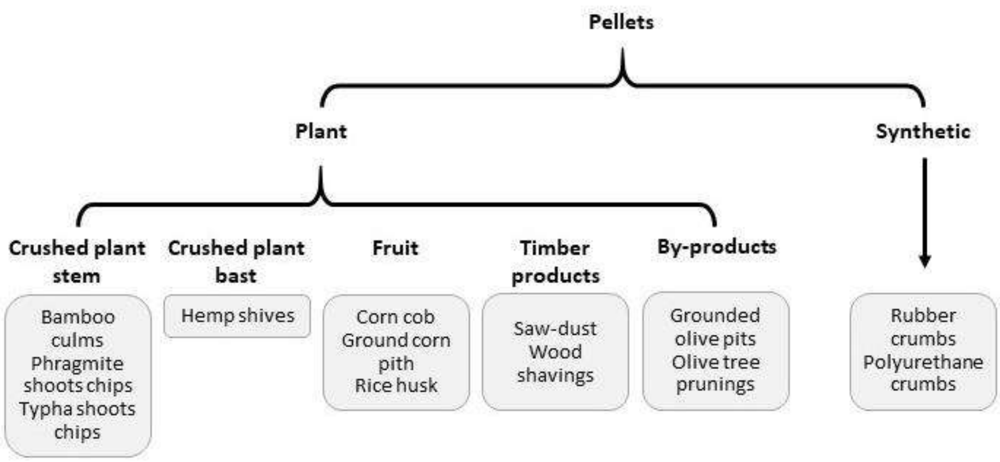

Figure 2-2: Source and type of pellets used for earth mortars

2.1.2.2 Functions of aggregates in the mortar

In earth construction, aggregates (added or naturally present) form the most important part of the material, in plastic earth construction they might weigh up to 60% of the dry materials. Their function is to give structure and strength to the mix as well as stability as an inert material. Moreover, as a filler, they are used to reduce shrinkage. Specific features such as thermal insulation or water vapour absorption can also be changed by the usage of aggregates.

Especially in plasters, "*specific textured finishes can be obtained by careful selection of the type and composition of sands*" (Reichel et al., 2004, p. 38) so their colours, aspect and workability are also important.

2.1.2.2.1 Functions of mineral aggregates

The principal function of mineral aggregates is to change the grain size distribution of the mix both to reduce the proportion of clay and to create a more homogenous distribution of particles. For different types of earth construction, optimum distributions have been produced by Houben and Guillaud (2008) or others as summarized by Jimenez Delgado and Guerrero (2007). Despite these recommendations, reality shows that earth construction can be done with a large variety of soils as the studies on existing construction (Champiré et al., 2016; Duarte et al., 2017; Montana et al., 2013; Pagliolico et al., 2010) or alternative construction (Lin et al., 2017; Rezende et al., 2017) show.

For plastic earth mortars, no particular trend in the amount of added aggregates can be observed from the corpus of selected works, however, some authors propose to follow

- the ideal distribution according to Fuller Formula as modified by Houben and Guillaud (Montana et al., 2013) or

- the optimization method for the best density by Dreux and Gorisse (Perrot et al., 2018).

However, most usage of sand in earth plaster is to reduce the clay amount to a maximum of 15% to 20% for plasters (Minke, 2012; Weismann & Bryce, 2008) or 15% to 30% of clay for mud-bricks (Barbosa 2010, cited by Tavares et al., 2019)

In the few works which are using an engineered mix – with the amount of each particle chosen for the PSD to fit a specific curve – or in the corrected mixes – which are the mix after the addition of aggregates – the total amount of sand is comprised between 43% (Rogiros Illampas et al., 2017) and 72% (Rescic et al., 2021). Some authors (Guihéneuf et al., 2019a, 2020; Menasria et al., 2017; Perrot et al., 2018) working on a specific mix of clay and sand have even used 80% of sand because their mix doesn't contain any silt.

Some aggregates have been chosen for their specific properties such as low density or high porosity (Binici et al., 2007) or their thermal properties (Sevilla Avila et al., 2015). In this case, the aim is to produce a thermal-resistant material with the help of aggregates as the main constituent of the material.

2.1.2.2.2 Functions of plant pellets

The role of pellets is usually intended to reinforce the material as a secondary structure as would work fibres (Serrano et al., 2016). Because of their provenance and shape, they are often used instead of fibres (Ashour, Wieland, et al., 2010; Maddison et al., 2009) but some authors recognized that their behaviour is different from that of fibres (Vatani Oskouei et al., 2017) and therefore should be used for a different reason.

2.1.3 Fibres used for earth mortars

“Fibre” or “plant fibre” is the usual name given to all plant-based elements added to the mortar independently of their shape and physical properties. Some authors, following Schroeder (2016) and the standards on earth construction, even used the word plant aggregates (Laborel-Préneron et al., 2016) or bio-aggregate (Brás et al., 2019). However, as explained in Section 2.1.2.1, the classification of Laborel-Préneron et al. (2016) based on the aspect ratio (AR) and description of these aggregates will be followed here for better comprehension. Plant aggregates with 1/AR higher than 10 will be classified as pellets whereas others will be classified as fibres, straws or hairs depending on their 1/AR, their shape, their provenance – tube or not, broken part of the stem or real fibre – but under the generic name of fibre.

Fibres are traditionally used to prevent shrinkage and formation of cracks in mud bricks, earth mortars or plasters during the drying process (Piattoni et al., 2011). According to (Costi De Castrillo et al., 2017), traditional adobe might contain 17% to 37% of fibre by volume, which is usually straw or other agricultural by-products while several authors propose an optimal amount between 0.5% and 1% by weight of dry mix (Călătan et al., 2016; Danso et al., 2014; Galán-Marín et al., 2010b; Lima & Faria, 2016) depending on the selected fibres and desired properties, while traditional plasters contain a lower amount of shorter fibres (straw or animal hair). In the selected corpus, 36 papers-reported the results of experiments on earth mortars containing 48 different kinds of fibres; such as cereal straws, alternative fibres from plants or animals (e.g. palm fibres, typha fibre, seagrass, plantain pseudo-stem fibres or pig bristles), or recycled or waste products like PET or glass fibres. The properties (shape, physical, mechanical…) of the fibres are different depending on their type and provenance.

2.1.3.1 Types and origin of plant fibres used for earth mortars

Archaeological records (Costi De Castrillo et al., 2017; Quagliarini & Lenci, 2010) and research on traditional mud bricks (Coroado et al., 2010; Costi de Castrillo et al., 2021; R. Illampas et al., 2011) have shown that often local straw or hay have been added in different proportions. Other authors have tested commercial products and have found a large variety of organic content in the mix of mud bricks and plasters which were considered as fibres and were coming from different plants in the same mix (Li Piani et al., 2018; Montana et al., 2013).

In the literature, fibres used for earth mortar are divided into two main categories according to their origin, natural fibres and synthetic fibres. Natural fibres can also be separated between fibres of animal origin and fibres of plant origin. The plant fibres used in the corpus have been further classified according to their provenance – type of plant and part from where the fibres are taken – and their origin and transformation are described in the following pages. Figure 2-3 gives the types of natural fibres used for the composition of earth mortar, whereas Table A 7 in APPENDIX A gives the amount of fibres used and their main properties when known. From this review, it can be understood that most of the research on earth mortar is concentrated on the usage of straw (cereal stems) and other natural fibres from different plants. The review of Laborel-Préneron et al. (2016) provides a large amount of additional information about the provenance and properties of fibres.

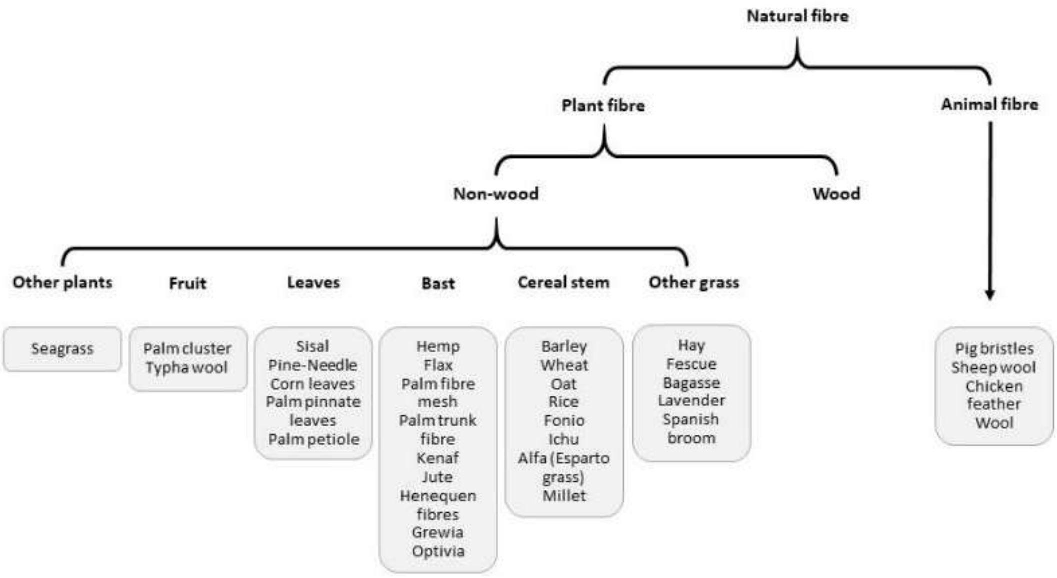

Figure 2-3: Source and types of natural fibres used for earth mortars

In the following description, the numbers between parenthesis indicate the number of articles/number of types of fibre used as authors might have published several articles relating the same research or used the same materials in different research; e.g. “(14/10)” means in 14 articles 10 types of straw fibres have been used.

(i) Cereal stems (straws)

Cereal stems (straws) are the traditional fibres used in mud bricks and plasters in most regions. Cereal stems have a tubular shape and are breakable or easily flattened. In this review, they are considered fibres, despite their shape and AR being between pellets and fibres (Laborel-Préneron et al., 2016). They have been used in a large majority of studies that used fibres, thanks to their wide availability in any region as an agricultural by-product; as described by Giroudon et al (2019) for France or Ashour (Ashour, 2003) in Egypt. In several articles (14/10), the type of straw used is not defined and fibres are only characterized by the name “straw”. In other cases, the articles gave the type of cereal used which is usually coming from the most cultivated crops – i.e. barley (18/9), wheat (11/6), oat (6/2), rice (1/1), fonio (1/1) –

and from other grasses from the same family with tubular shape – Ichu (1/1), Alfa grass (1/1) and hay (1/1).

Other grasses and plant fibres have been used directly without being processed or lightly processed. These plants' parts can be the stem of the plant directly cut when the grass is thin and flexible enough such as hay (1/1), fescue (1/1) or Spanish broom (1/1) or the broken stem of the plant such as lavender stems (1). Three authors (6/3) have been dealing with the usage of sugarcane bagasse which is the left-over material after extraction of the juice. It is composed of crushed stem fibres and pith fibres and can be used washed or unwashed.

(ii) Bast fibres

Bast fibres are usually long and thin fibres extracted from the stem of the plant. According to Laborel-Préneron et al. (2017), they have good tensile strength and good thermal insulation properties. Some of these fibres can be taken directly from the surface of the stem such as palm mesh fibres (1/1) but most of them need an extraction process. The extraction of these fibres is usually a mechanical process involving water-retting and/or breaking down the bast to separate the fibres from the woody part. Hemp (6/3), flax (3), jute (2), date palm trunk fibres (1), kenaf fibres (1), henequen fibres (1), *Grewia Optiva* fibres (1) have been used in the selected articles.

(iii) Leaves, pine needles and leaf fibres

Leaves are the part of the plant usually responsible for photosynthesis and therefore they have a flat and elongated surface. Four different species of pine trees have been used by 2 different authors (Jové-Sandoval et al., 2018; Sharma et al., 2015) for their elongated and non-tubular shape and their rough surface, which helps to bind with the mortar. Some leaves have been used as such for earth mortars when they are thin and flexible enough such as corn leaves (1/1) but often fibres are processed from the thick body of the leaves. Fibres with different properties and compositions have been taken from two different parts of the palm tree trunk and from the fruit-holding branch (Mellaikhafi et al., 2021). Fibres called sisal have also been extracted from the leave of the agave plant (2/2).

(iv) Fruits envelope

The protection envelope of the seed might be also rich in fibre and the envelope of palm date (1/1) has been used in one occurrence as well as the fibre to which is attached the typha seed (5/3).

(v) Seaweed

Seaweed (2/2) based fibres have been used by two authors who used different types of seaweed but all were washed and cut and not processed further.

(vi) Cellulose-based fibres

Three authors have also used almost only cellulose-based fibres – which are a microscopic chain of cellulose molecules – either in liquid or viscous way – paper pulp residues (1) or methylcellulose (1) or integrated as a solid but water-degradable material – Isofloc (1) and shredded paper (1). However, as these fibres and especially methylcellulose are also working at a microscopic level the later is described in section 2.1.5 on additives for earth mortars.

2.1.3.2 Types and origin of animal fibres used for earth mortars

Animal fibres have not been widely studied despite some evidence of their use for archaeological plasters. Two studies dealt with the usage of agricultural waste – pig bristles (1) and chicken feathers (3/2) - to produce earth mortar and two other authors used sheep wool produced for the textile industry either cleaned (1) or processed (1).

2.1.3.3 Types and origin of synthetic fibres used for earth mortars

Synthetic fibres have also been used to replace traditional straws and natural fibres. Synthetic fibres consist of fibres developed for the concrete industry (1) or of by-products and plastic waste (4), however, most of them are not fully described and only qualified as plastic fibres (2) or polystyrene fibres (2). Steel fibres have also been used in one occurrence.

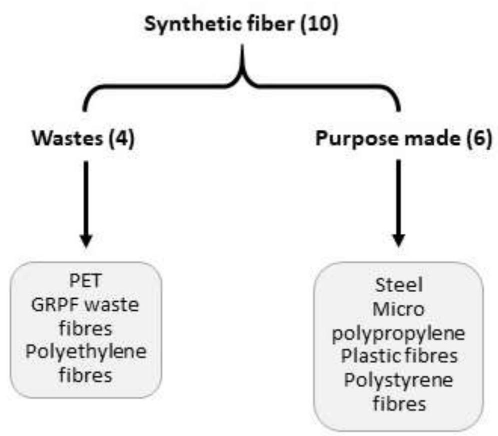

Figure 2-4: Types of synthetic fibres used for earth mortars in the literature on earth mortars

2.1.3.4 Composition of natural fibres used for earth mortars

The composition of natural fibres used has been studied by some authors or references of previous work have been given to characterise these fibres. However, in most cases, the composition is not given. Table 2-3 gives the composition of the natural fibres used for earth mortar for plastic paste. The fibres described in the literature are all plant-based and therefore are composed of the same materials in different quantities. These materials are lignin, cellulose, hemicellulose, extractives and ashes. According to Laborel et al. (2017), each of these materials has a specific function and might affect the property of the mortar. Cellulose content affects the mechanical properties of the fibres, hemicellulose affects its water absorption and lignin its durability and resistance to biodegradation as it is the main component of the exterior skin of the plant (Laborel-Préneron, Magniont, et al., 2017).

Table 2-3: Information and data from 7 studies on the composition of the natural fibres and plant pellets used for earth mortars

Fibre type	Amount of lignin (%)	Amount of Cellulose (%)	Amount of hemicellulose (%)	Amount of extractives (%)	Amount of ashes (%)	Reference
Barley straw	5.5	37.7	26.7	14.4	12.3	(Brás et al., 2019)
Barley straw	5.5	37.7	26.7			(Laborel-Préneron et al., 2015)
Alfa stem	24	45	24			(Elhamdouni et al., 2015)
Bagasse	21.2	51.4	29.1	6.3/3.7	3.3	(Corrêa, Protásio, et al., 2015)
Agave fibres	10.7	40.1	28.3			(Caballero-Caballero et al., 2017)
Kenaf fibres	4	71	20			(M. Ouedraogo et al., 2017)
Hemp shives	17.2	50.3	17.9	5.9	2.1	(Brás et al., 2019)
Hemp shives	17.2	50.3	17.9			(Laborel-Préneron et al., 2015)
Palm mesh fibre	39.9	47.5	12.7			(Mellaikhafi et al., 2021)
Palm trunk fibres	30.3	39.4	23.3	25.2		(Mellaikhafi et al., 2021)
Palm petiole fibres	26.1	43.1	31.3	24.9		(Mellaikhafi et al., 2021)
Palm pinnate leaves	36.7	47.1	16.1	32.9		(Mellaikhafi et al., 2021)
Palm cluster mesh	29.5	43.1	29.5	9.8		(Mellaikhafi et al., 2021)
Rice husk	33	30	20	3	14	(Brás et al., 2019)

2.1.3.5 Studied properties of fibres used for earth mortars

The main properties of fibres that are explored in the literature are the length which is determined by the author of the research and the diameter which depend on the fibres. These properties are given in Table 2-4 to Table 2-6. Some authors also exceptionally studied the water absorption, porosity, tensile strength and elongation at break as well as the surface aspect (roughness), which all directly depend on the fibre's type. These properties are summarized in Table 2-5. It can be seen that the density, the water absorption and the tensile strength of the different fibre types are very different and therefore it might impact the properties of the mortars.

As underlined by Jove-Sandoval et al. (2018) and Ghavami et al, (1999) the most important properties are the swelling and shrinkage behaviour of fibres full of water and their lack of adhesion to the matrix after drying. However, only Rivera-Gomez et al. (2014) quantified this shrinkage and showed it through microscopic imagery. Jove-Sandoval et al. (2018) also showed that the shape of pine needles visually changed under microscopic observations. The latter also determine the difference in the behaviour of the fibres when dried and saturated as it can help to understand the behaviour of the mortar under specific conditions.

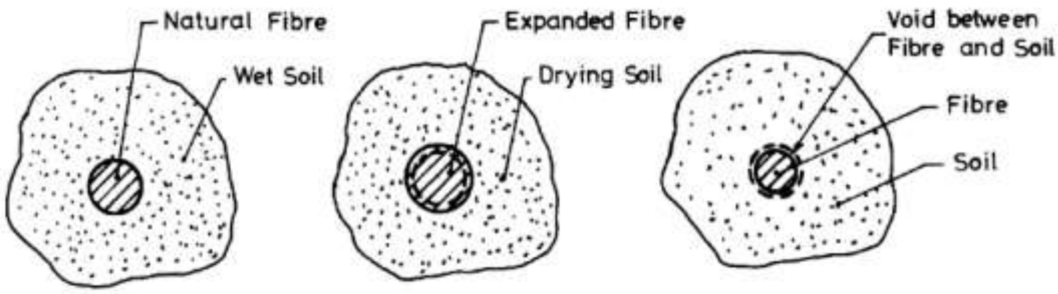

Figure 2-5: Interaction of natural reinforcing fibre and drying soil. (Ghavami et al., 1999)

Authors also take into account the surface and the texture of the fibres and several authors underline the importance of having a rough surface to improve the bond between the fibre and the matrix (Araya-Letelier et al., 2020; Bouasker et al., 2014; Jové-Sandoval et al., 2018; M. Ouedraogo et al., 2017; Salih et al., 2020b) and therefore improving the tensile strength of the material even for similar fibres (Bouasker et al., 2014). Fibres' surface has been quantified by only one author according to the DIN4766 (Araya-Letelier et al., 2017). Some authors have studies the fibres under microscope and detected the presence of nodes or rugosity which would be important to increase the bond between fibres and matrix (Gandia et al., 2019; Jové-Sandoval et al., 2018; M. Ouedraogo et al., 2017; Rivera-Gómez et al., 2014; Salih et al., 2020a). Other authors (Araya-Letelier et al., 2021; Laborel-Préneron, Magniont, et al., 2017; M. Ouedraogo et al., 2019) use the Scanning Electron Microscope images to determine the internal structure of the fibres and especially the size of nodes and pores, which could help understand the hygro-thermal and mechanical properties of the fibres.

Table 2-4: Information and data from 3 studies on the physical and mechanical properties of animal fibres

Fibre type	**Apparent density (kg/m3)**	**Water absorption at 1 min (%)**	**Tensile strength (MPa)**	**Elongation at break (%)**	**Thermal conductivity (kWh/m²K)**	**Surface roughness**	**Reference**
Chicken feather	89	85	187				(Araya-Letelier et al., 2020)
Chicken feather	70	68					(Salih et al., 2020a)
Pig bristles		95	99.2			0.104	(Araya-Letelier et al., 2018)

Table 2-5: Information and data from 14 studies on the physical and mechanical properties of plant fibres

Fibre type	Apparent density (kg/m3)	Water absorption at 1 min (%)	Tensile strength (MPa)	Elongation at break (%)	Thermal conductivity (kWh/m²K)	Reference
Straw	*0.312*	365	128			(Olacia et al., 2020)
Straw	1224	348	38 -50			(Vatani Oskouei et al., 2017)
Barley straw	1223	500-600				(Bouhicha et al., 2005)
Barley straw	574	414			0.044	(Brás et al., 2019; Laborel-Préneron, Magniont, et al., 2017)
Wheat straw			17.25	3.42		(Meena et al., 2019)
Wheat straw			21.7			(Jové-Sandoval et al., 2018)
Pine needles			8.9 - 20.5			(Jové-Sandoval et al., 2018)
Pine needles			11.15	10.7		(Sharma et al., 2015)
Seagrass	*0.721*	23	56			(Olacia et al., 2020)
Alfa fibres	890					(Elhamdouni et al., 2015)
Millet waste	380	28.6				(Babé et al., 2020)
Grewia Optiva			15.35	10.3		(Sharma et al., 2015)
Palm mesh fibres		230	65.1	0.037		(Vatani Oskouei et al., 2017)
Hemp fibres	121.2	130				(Alhaik et al., 2018)
Flax	105.8	130				(Alhaik et al., 2018)
Kenaf	1050	230	900			(M. Ouedraogo et al., 2017)
Sisal	106.5		15			(Caballero-Caballero et al., 2017)
Jute			350	1.5-1.9		(Concha-Riedel et al., 2019)
Jute	1.1 -1.5	12	400 800	10		(Araya-Letelier et al., 2021)

Table 2-6: Information and data from 2 studies on the physical and mechanical properties of synthetic fibres

Fibre type	Apparent density (kg/m3)	Water absorption at 1 min (%)	Tensile strength (MPa)	Elongation at break (%)	Thermal conductivity (kWh/m²K)	Reference
Micro propylene	116	0	310	60-140		(Araya-Letelier et al., 2019)
Polyethylene	95		420			(Bertelsen et al., 2019)

2.1.4 Additives used for earth mortars

Additives used for earth mortars are numerous and authors have tried several different ways to enhance the properties of fresh and dry mortars. Additives have been classified by their provenance into three main categories. These categories are mineral binders (cement and lime mostly), chemical additives (often coming from the cement industry) and natural biopolymers (traditional additives or processed biopolymers) and the classification of additives is shown in Figure 2-6. Other authors (Kebao & Kagi, 2012) also classify the additives according to their intended usage or primary usage; i.e. they are developed for other purposes but are also tested for earth construction.

As the experimental work described in this dissertation focuses on the impact of natural additives (biopolymers) for earth plasters, in the following section (section 2.1.5) on biopolymers, their origin, usage and interactions with clay are reviewed whereas this section will discuss the type and origin of mineral additives and chemical additives (organic synthetic additives in Figure 2-6). Table A 4 in APPENDIX A and Figure 2-7 lists the additives used in the corpus, the amount used and their intended use or primary use when defined.

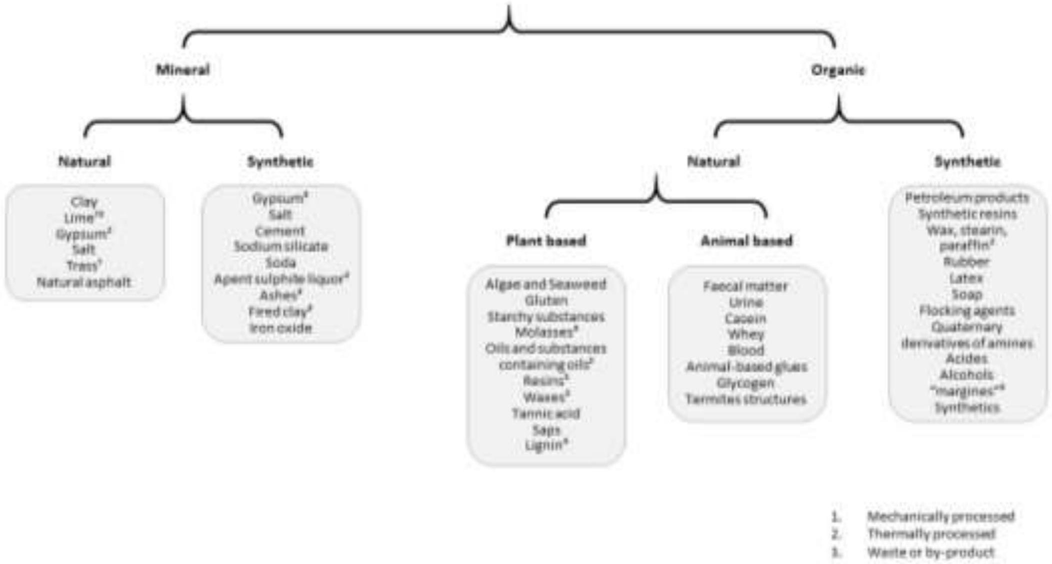

Figure 2-6: Classification of additives and examples of some of them used in earth construction by Thurm C (2001). Source: Schroeder (2016, p.151)

Hydraulic binders such as lime and cement and non-hydraulic binders such as air-lime or asphalt and more recently gypsum have been used widely as they provide reasonable performance in terms of water protection and mechanical performances (Gallipoli et al., 2017; Van Damme & Houben, 2018). In some cases, other binders inducing pozzolanic reactions such as industrial by-products or ashes have been used to reduce costs (Schroeder, 2016). As all these binders are often not preventing water absorption – and even favour it – their usage has been replaced by chemical water-repelling admixtures (Gallipoli et al., 2017; Kebao & Kagi, 2012). The main disadvantage of these both types of additives is that they imply a non-reversible chemical reaction with the clay particles, which hinders future re-use of the material (Gallipoli et al., 2017; Schroeder, 2016).

2.1.4.1.1 Mineral additives and binders

The addition of mineral binders is the most used stabilization technique in earth construction (Medvey & Dobszay, 2020), especially for rammed-earth (RE) and compressed earth blocks (CEB) but also for wet paste mortars. In the corpus surveyed, mineral additives have been used 73 times and the type of binders used is shown in Figure 2-7; while the amount used by the different authors is shown in Table A 8 and Table A 9 in APPENDIX A. Mineral additives have been classified into binders and non-binding materials. Binders have been further classified according to the type of reaction that occurs inside the mix and which allows them to harden.

2.1.4.1.1.1 Hydraulic binders

The most common of these binders is Portland cement which has been used as such or under its different form (CEM I, CEM II or CEM III). Hydraulic lime and natural cement have also been used in one study as a comparison between different hydraulic and air-entrained binders (Gomes et al., 2012). In addition to these common binders, several industrial byproducts have been used as hydraulic binders such as fly ashes (Degirmenci, 2005), blast furnace slag (Schicker & Gier, 2009) or cement kiln dust (Rescic et al., 2021). Ashes have also been used by two authors for their high content in non-crystalline silica which might induce a cementation process (Bahobail, 2012; Sanou et al., 2019). Another hydraulic binder used consists of a geoplymeric solution intended to create cementation and pozzolanic reactions (Rescic et al., 2021).

The usage of hydraulic binders contributes to create different chemical reactions between the water and the clay of the earth and the components of the binders. These reactions can happen within minutes or days – cation exchange (clay particles create links with calcium ions from the binder instead of metals ions from the soil which leads to a stronger link between clay layers) flocculation (after the cation exchange, the particles of clay gets closer and then the Van de Waals forces create a stronger bond between them), hydratation which allowed the two precedent phases by releasing ions and allowed the cementation and pozzolanic reaction by releasing C-S-H and calcium hydrates (CH) – or during months to a year for pozzolanic reaction and carbonation process. The pozzolanic reaction will happen in presence of hydraulic binders that will bring calcium silicates/aluminates (Sargent, 2015)

2.1.4.1.1.2 Non-hydraulic binders

Non-hydraulic binders are a large family that comprises binders that will be set through different chemical reactions such as carbonatation, crystallisation or oxidation.

The main non-hydraulic binder used was air-lime either used in powder (hydrated lime) or putty. Air-lime is carbonating – becoming limestone – in presence of CO2 and the process happens over a long-time (years) in presence of air.

Other widely used binders are gypsum (Degirmenci, 2008; Rasa et al., 2009; Rescic et al., 2021) and bitumen (Al-Ajmi et al., 2016; Braun, 2017a; Heredia Zavoni et al., 1988). Gypsum is setting through crystallisation and creates a crystalline network in the mortar while the setting expands slightly which compensates for the shrinkage of the earth (Rescic et al., 2021). Natural gypsum which is a calcinated and powdered stone and phosphogypsum – an industrial byproduct – might be used.

2.1.4.1.1.3 Other mineral additives

Several other mineral-based additives have been used water glass (Braun, 2017a), soda (Braun, 2017a; Călătan et al., 2015) and salt (Călătan et al., 2015). Laponite nanoparticles are a synthetic layered silicate composed of identical disk shape crystals (Scalisi, 2014)

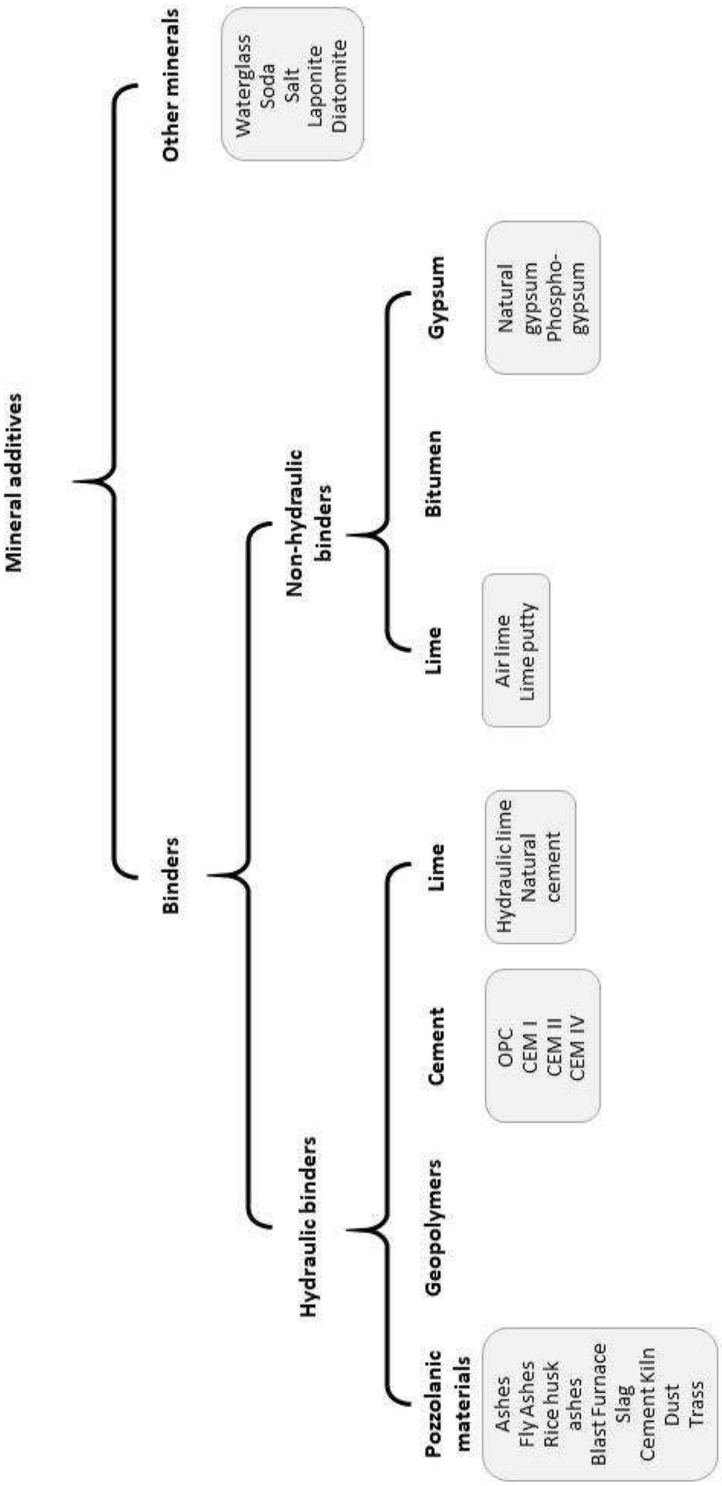

Figure 2-7: Classification of mineral additives used in the corpus surveyed

2.1.4.1.2 Synthetic additives

Under the name of synthetic additives, all additives that are a product of a chemical reaction and transformation of existing material are classified. These additives are often materials used in the concrete industry for specific purposes such as plastifiers that prevent a too high usage of water or hydrophobic mixture to make the material waterproof. Some of these materials are specially developed for earth construction to improve their strength or their durability.

(i) Plastifiers:

Plastifiers are used to reduce the amount of water in the earth mix while creating a consistency that allows the mix to be worked. They transform the properties of the mix – pH or electric charges - and while doing so allow the clay particles to separate and reorganized without the addition of water. Only a few plastifiers have been used in the study and always in addition to another additive, some of them only given as plastifier (Alhaik et al., 2018; Atzeni et al., 2007; Lagouin, Laborel-Préneron, et al., 2021) or naphthalenesulfonate (Atzeni et al., 2007) but a specific additive to clay – sodium hexametaphosphate – which is used as a deflocculant in the ceramic industry has been also used by other authors to reduce the amount of water used.

(ii) Hydrophobic additives

Hydrophobic additives are numerous and have been presented extensively by Kebao and Kagi (2012) who underline that even a very small amount of these additives would be enough to create water-repellent materials. They have classified these additives under two categories, which are "*Oil- or fat-based water-repellent admixtures"* or "*Silicone water-repellent admixtures*". From the corpus, it can also be seen that some additives usually used as surface coating have also been used as bulk additives such as acrylic-based coatings. These hydrophobic additives are usually based on acrylic solutions, silicon solutions, silane solutions or oil solutions.

These hydrophobic additives are usually a solution of a complex molecule available as a commercial product, however, some of them are complex mixes and are known only by their commercial names such as Funcosil (Braun, 2017a, 2017b) or Acronal S (Braun, 2017a, 2017b; Pineda-Piñón et al., 2007). They might also be complex mixes involving several different products such as “silane-coated amorphous silica” or “combination of zinc-soap sodium oleate” used by Lišková et al. (2016)

(iii) Specific additives to earth construction

Several authors have used specific additives for earth construction. Synthetic termite saliva is a commercial material that is developed for stabilizing earth in earthwork and by mimicking the behaviour of termite saliva it creates a more durable substrate for road construction (Corrêa, Mendes, et al., 2015; Corrêa, Protásio, et al., 2015). Cationic dodecylamine and anionic fatty acid have been used by Pineda-Piñón et al (2007) in order to determine if changing the electrical charge of the fresh mortar will impact the properties of the dry mortar, especially by reorganizing the clay particles.

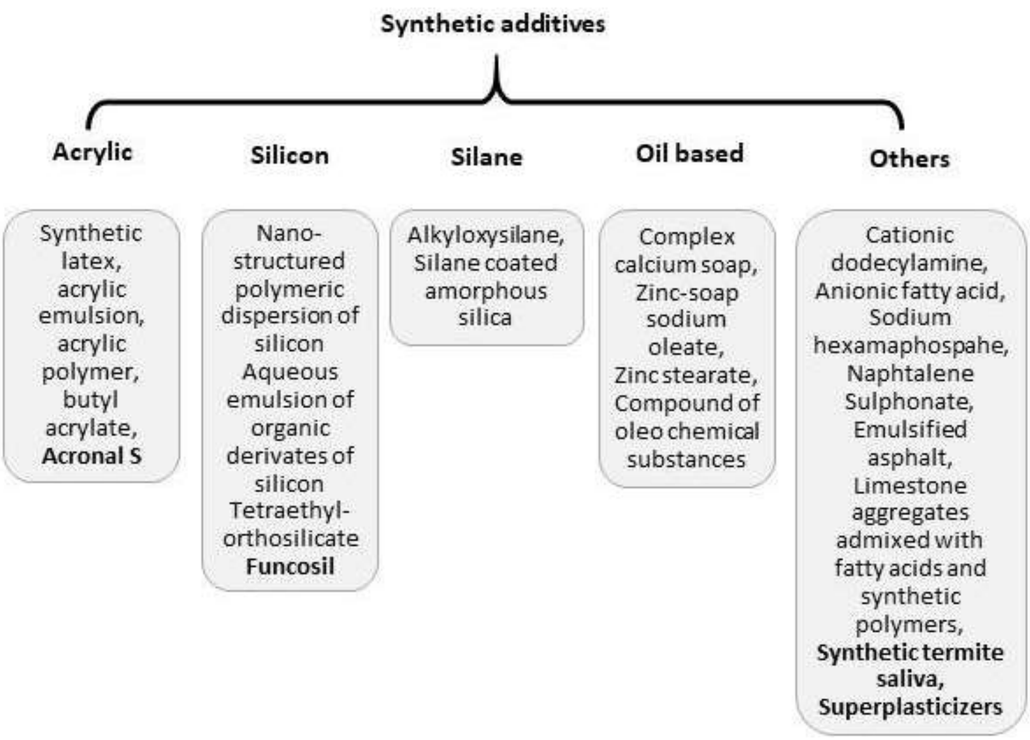

Figure 2-8: Classification of synthetic additives by composition

2.1.5 Biopolymers

Biopolymers are polymers extracted from plants or animals. They have been used traditionally in the production of mortars for earth construction and several works (Anger et al., 2012; Paul & Changali, 2020; Vissac et al., 2013) have shown their importance and the large number of biopolymers used around the world. Actual research on earth construction also focuses on finding and using new polymers or testing traditional ones to determine their real impact (Losini et al., 2021) as there is a concern about the lack of sustainability of earth construction stabilized with binders and the difficulty of reusing it (Schroeder, 2016) whereas addition of biopolymers is not considerably changing the chemical composition of the earth and therefore allow its reuse (Călătan et al., 2017). These biopolymers are used to stabilize earthen material and improve their strength and especially their water resistance as it was traditionally the main concern for buildings (Eires et al., 2013).

According to Vissac et al. (2016) and other works, biopolymers can be divided into four different main categories: polysaccharides, lipids, proteins and complex molecules. To this classification, a fifth category can be added, which is a biopolymer mix, as some additives are made with biopolymers that can’t be separated (mostly animal excrement).

This review of biopolymers shows all types of biopolymers used as stabilizers for earth mortars in the reviewed literature. However, emphasis is given to the polymers that are used in the work done for this dissertation and the review of their impacts will be presented in section 2.2.5.

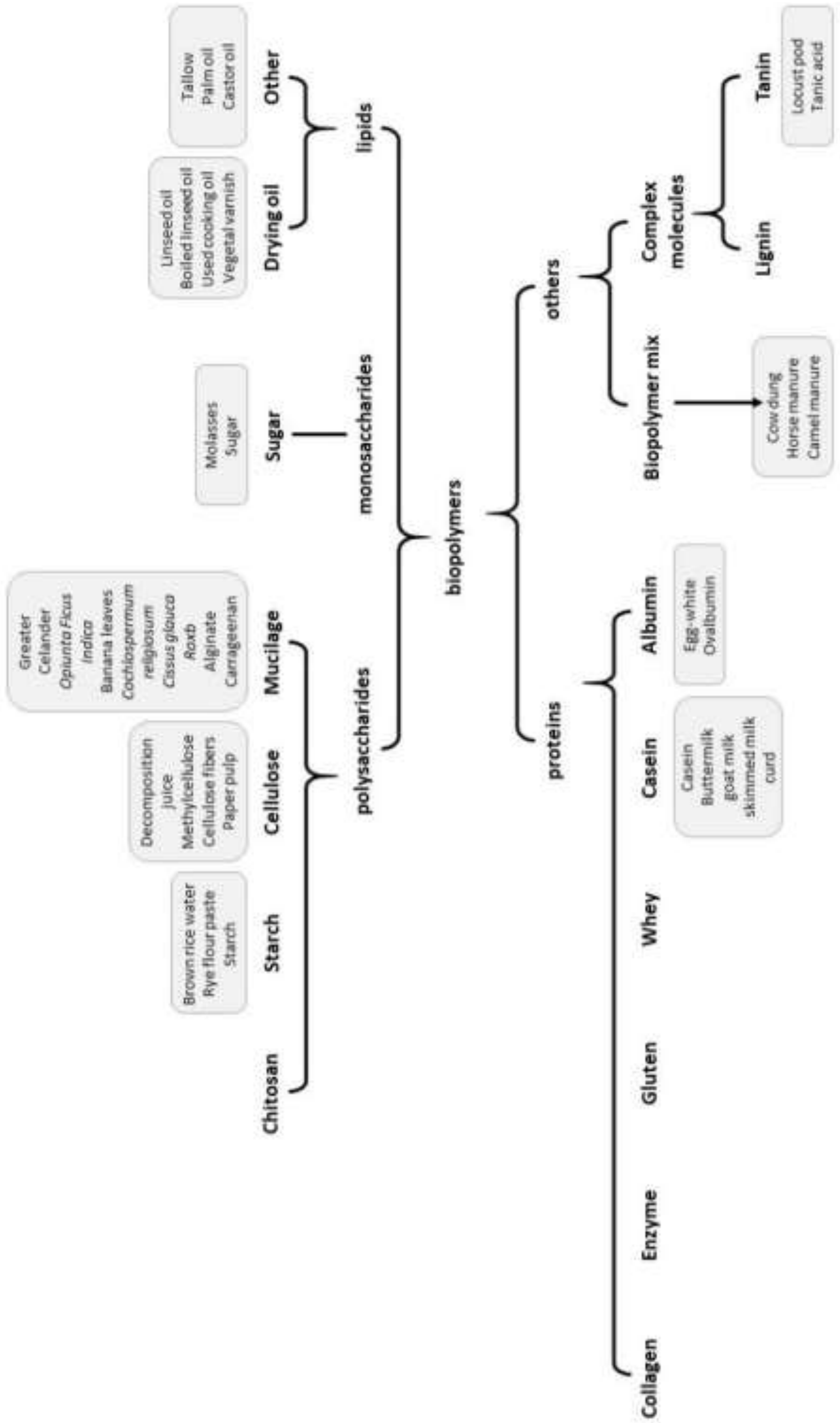

Figure 2-9: Classification of the different biopolymers used in earth mortars

2.1.5.1 Polysaccharides

Polysaccharides are long chains of sugar molecules and are present in nature in both animal and vegetal products, either as a structural material (cellulose, chitin) or to store energy (starch) (Vissac et al., 2016). However, because of their very organized structure and their length, they might not be directly usable and a preliminary process might be required to “activate” – i.e. reduce the size of the molecules and free them from each other. This step might be a fermentation process as in the case of cellulose fibres or a heating up as in the case of starch. Commercial products of refined polysaccharides are also available. (Anger et al., 2012)

These polymers will interact with water and form a gel which changes the consistency of the fresh mortars. While drying they help create microscopic bonds which link several minerals together. (Vissac et al., 2013)

Stabilizing earthen construction with polysaccharides is the most developed of the traditional stabilization techniques and several recipes have been reported by Vissac and others (2013, 2016) Beas (1991) and Eires (2013). In the studied literature, 20 different types of stabilizers have been used as shown in Table A10 in APPENDIX A, however, most of the work of the different authors focuses on the same molecules, namely cellulose either as fermented fibres – animal dung, fermented fibres, cellulosic commercial products – or starch – flour paste, commercial starch. Only a few work experiments on the plant mucilage (Barbeta Solà et al., 2014; Heredia Zavoni et al., 1988) or refined materials such as gums (Guihéneuf et al., 2019a, 2020) or seaweed extracts (Dove, 2014; Dove et al., 2016; Galán-Marín et al., 2010b; Guihéneuf et al., 2019a, 2020; Lagouin et al., 2019; Navarro et al., 2015; Tourtelot et al., 2021).

2.1.5.1.1 Cellulose-based additives

Cellulose-based additives can come from different raw resources and be commercially produced.

(i) Fermented fibres

Fermented fibres are a traditional way of using fibres in several countries. The decomposition of fibres by bacteria separates the cellulose into microscopic fibres (Vissac et al., 2016). The products of fibre fermentation depend on the type of fibre used, (especially their softness, i.e. their lignin content) and the length of the decomposition. The longer the decomposition, the smaller will be the cellulose molecules (Vissac et al., 2013). For these reasons, builders tend to prefer soft plants such as seaweed, hay or rice husk (Vissac et al., 2016). The same authors have reported the usage of rice husk in Mali or fine paper pulp in Japan. Guiheneuf et al. (2019a) used the water made by the fermentation of 500 grams of fibres in 10 litres of water for 1 month.

(ii) Paper pulp and cellulose fibres

Paper pulp (Muñoz et al., 2020) or similar products (Braun, 2017a, 2017b) have been used in the production of earth mortar for adobe. However, as there was no time settling time before applying to start an alteration process (decomposition), most probably the cellulose fibres were used as microscopic fibres more than an additive. Other works with cellulose include the addition of several types of cellulose – α-cellulose, μ-cellulose and cotton cellulose from commercial provenance (Tourtelot et al., 2021). Despite the very small size of the fibres, they were also used as a fibre more than as an additive.

(iii) Methylcellulose

Methylcellulose is a product obtained by chemically transforming cellulose. It forms a gel when placed in cold water and is used as a thickener in the food industry. (Vissac et al., 2013) as well as for increasing plasticity in the concrete industry (Ivanov & Stabnikov, 2016). It has been used in low amounts to increase the workability of earth mortars (Thomson et al., 2015) or the binding properties of grouts (Simon et al., 2011).

Glues made from methylcellulose have been used in the reviewed work (Braun, 2017a, 2017b; Guihéneuf et al., 2019a).

2.1.5.1.2 Starches

The use of starch for improving plasters is traditional in different regions (Vissac et al., 2013; Zheng et al., 2016). Sources of starch (cereals, such as corn, rice or wheat, potatoes or other roots) depend on their availability. Some studies comparing the impact of different starches have found that maize starch is more efficient at ambient temperature (Alhaik et al., 2017) but wheat starch has a stronger impact when heated above 70°C.

During the process of gelatinization, particles of starch lose their semi-crystalline structure, then they change their viscosity according to their vegetable origin as well as their per- centage of amylose and amylopectin. This process is irreversible and gives a soluble starch (about 98%) in water at ambient temperature. (Alhaik et al., 2018)

Flour paste is the main traditional source of starch (Anger et al., 2012; Braun, 2017a; Guelberth & Chiras, 2003) as flour is mainly composed of starch. Mixing hot water and flour activate the starch molecules that expand and create a sticky gel. (Alhaik et al., 2017; Vissac et al., 2016) Recipes for the preparation of flour pastes are given by Vissac et al. (2016), Minke (2006), Guelberth and Chiras (2003) or Lerner (2011) and all include heating the flour above 70°C, often boiling it. There is also a wide range of recipes available on the web with different types of flour, temperature and concentration. Some authors have also tested directly pure commercial starches (Alhaik et al., 2017; Lagouin, Laborel-Préneron, et al., 2021; Tourtelot et al., 2021). Starch from cooking water of rice which is a traditional Indian additive to earth plasters has been used by Paul and Changali (2020).

2.1.5.1.3 Sugar

Sugar coming from a by-product of sugar processing has been sometimes traditionally used as an additive for earth construction in India (Prakash Joshi, 2008) and China (Lv et al., 2017) and is recommended by some international organizations as stabilizer (BASIN & Ruskulis, 2008). Studies on bird nests show an important amount of glucose in the composition of the nest walls (Silva et al., 2010).

(i) Domestic sugar (saccharose)

One study (Pinto et al., 2014) used domestic sugar in the production of earth mortar to verify the conclusion of a previous study on bird nests (Silva et al., 2010). Saccharose forms strong hydrogen bonds with each other and with water and might lead to transform the water dynamics in the earth's mortar.

(ii) Molasses

Molasses are a by-product of sugar production either sugarcane or beetroot. They contain a high amount of polysaccharides and glucose. According to Vilane (2010), *"the calcium content of the ash fraction"* might be responsible for enhancing the binding properties of clay. Very few studies (Rodriguez Cuervo, 2020; Vilane, 2010) have used molasses for plastic paste mortar but it has been used as a plasticizer by the concrete industry (Vilane, 2010).

2.1.5.1.4 Mucilage

Mucilage is the juicy and sticky part of the plants. Depending on the plant, it can be directly available or a process of soaking and/or boiling might be necessary to extract it. It usually contains a high amount of pectin. Several authors have tested the mucilage of plants.

(i) Pectin

Pectin is a polysaccharide which has impacts on the mechanical strength of plants. It is present in the cells, surrounding the cellulose (Tourtelot et al., 2021). Under specific conditions of heat, pH or the presence of cations (especially calcium and sodium), the molecules of pectin create some gels which are used in the production of earth mortar (Vissac et al., 2016). Industrially produced pectin coming from apple seeds has been used by the mentioned authors.

(ii) Prickle pear cactus (*Opuntia*)

Prickle pear cacti have been used by Heredia Zavoni et al. (1988) for testing the durability of mortar. They determine the conditions on how to extract and use this mucilage. Other authors also have used this juice which is a traditional additive in Latin America (Barbeta Solà et al., 2014; Beas, 1991)

(iii) Sticky juice of plants

Traditionally, the mucilage of plants has been used in several regions of the world to change the properties of earth mortars (Vissac et al., 2013, 2016). Depending on the type of plants a maceration or heating process can be required to create a gluey juice or a gel. Several recipes, especially using prickle pear cactus are easily available but few authors have been researching the usage of mucilage for earth mortar in the studied literature. Chelidonia Major (Barbeta Solà et al., 2014), carob pod (*Ceretonia Siliqua*) (Clausell & Solà, 2017) and prickle pear cactus (Heredia Zavoni et al., 1988) have been successfully tested whereas other plants tested by the later authors have been discarded. A study by Paul and Changali (2020) also references several plants used as a traditional source of mucilage in India. The authors also tested two of these plants, namely the fruit of *Cochlospermum Religiosum* and the stem which releases a gel when crushed and immersed in water. According to the authors, this gel is a polysaccharide based gel.

(iv) Seaweed gel

Vissac et al. (2013) report the usage of red seaweed to produce a gluey juice used in traditional plasters in Japan. Carrageenan is the main active polysaccharide extracted from this seaweed (Vissac et al., 2016) whereas alginate is extracted from brown macro-seaweed (*Phaeophyceae*) (Dove et al., 2016). Both polymers have been used by the concrete industry (Nakamatsu et al., 2017; Petric-Gray et al., 2009) to increase strength and improve curing however, alginate has the advantage of not requiring any heating before usage (Dove et al., 2016)

In the studied literature, carrageenan usage has been reported by Nakamatsu et al. (2017) which uses commercial carrageenan made from Peruvian *Chondracanthus Chamissoi.* Several articles researched the usage of alginate either as a commercial anonymous product (Galán-Marín et al., 2010b; Guihéneuf et al., 2019a; Lagouin et al., 2019; Menasria et al., 2017; Navarro et al., 2015; Tourtelot et al., 2021) whereas Dove et al. (Dove, 2014; Dove et al., 2016) studied different alginate coming from different type and parts of brown seaweed which have different M/G ratio, pH and flow curves when diluted.

2.1.5.1.5 Chitosan

Chitosan is a polysaccharide which is hydrophobic and insoluble in water and is produced from chitin – the material of the shell of insects and crustacean shells – and is widely used by the food industry (Losini et al., 2021). It has been used by Aguilar et al. (2016) for its reaction in presence of water.

2.1.5.2 Lipids

Lipids are the molecules of fat either vegetal oil or animal fat. They are mostly hydrophobic molecules (Vissac et al., 2012) but the presence of a hydrophilic end in the molecule is possible for characterizing how they will react in presence of water

(Vissac et al., 2016). Therefore, depending on the type of lipid, the action of the additives on the plaster will be different. Moreover, in contact with air, some oil will harden through oxidation (siccativation) and create a non-reversible protective film (Guihéneuf et al., 2020). During the preparation process, the addition of oils might also change the consistency of the mortar acting as a lubricant (Vissac et al., 2016).

In the studied literature, few works include lipids – and most of them are using linseed oil – whereas the traditional recipes collected by Vissac et al. (2013, 2016) show the usage of several other lipids of vegetal origin.

(i) Linseed oil

Linseed oil is an oil extracted from the flax seed. It is mainly composed of polyunsaturated fatty acid which makes it a drying oil (Vissac et al., 2016). The polymerization process through heat and sun creates a protective 3D structure in the mortar (Tourtelot et al., 2021).

In the surveyed literature, authors have used either raw linseed oil (Braun, 2017a, 2017b; Guihéneuf et al., 2019a, 2020; Lima, Silva, et al., 2016; Navarro et al., 2015; Tourtelot et al., 2021) or boiled linseed oil (Braun, 2017a, 2017b; Morton & Little, 2015; Straube, 2003) as recommended by Minke (2012). Some authors used also linseed oil-based varnish in which some admixtures have been used to accelerate the polymerization of the oil (Brzyski & Grudzińska, 2020; Brzyski & Suchorab, 2018). A similar varnish consisting of a vegetal oil emulsion has also been used (Guihéneuf et al., 2020)

(ii) Used cooking oil

Olive oil is composed of mono-unsaturated fatty acid, which means that it would not go through the siccativation process and will not get harder. However, the high-temperature heating of cooking oil creates a high amount of unsaturated fatty acids which are subject to siccativation and therefore these used oils have been used by Karozou and Stefanidou (2018) for surface impregnation of earth mortars. In the surveyed literature, Battistelle et al. (2020) tested used cooking oil coming from a mix of several oils into their earth mortar mixes.

(iii) Non-drying oils

Non-drying oils – which are not subject to natural polymerization – have also been used for their hydrophobic properties. Battistelle et al. (2020) used castor oil produced from the fruits of *Ricinus communis L.* whereas Bahobail (2012) used palm oil.

(iv) Tallow

Tallow is the transformed fat of animals and is mostly constituted of triglycerides. It has been reported to be used in earth construction (Houben & Guillaud, 2008) and as an additive to lime (Eires et al., 2013; Minke, 2012). Morton (Morton & Little, 2015) used liquid tallow as an additive to earth mortar

2.1.5.3 Proteins

Proteins are natural polymers composed of several amino acids. They are usually grouped together either under the shape of fibre or balls. Their shape gives their surface properties and the possibility to interact with their environment. (Vissac et al., 2016). According to the authors, amino acids have a hydrophobic part and a hydrophilic part allowing them to interact easily with the clay particles and protect them from water. According to Anger et al. (2012)"*In earth, the hydrophilic parts are adsorbed on the clay particles which are coated with thin water molecule layers, while the hydrophobic parts remain around the outside and therefore in contact with air, forming a sort of surface membrane which repels water*."

Proteins have been used traditionally for reinforcing earth construction using non-transformed materials such as whey, animal blood or egg whites (Anger et al., 2012; Beas, 1991). Research papers reviewed and listed in Table A 10 in APPENDIX A mostly focus on commercially produced casein (Brzyski & Suchorab, 2018;

Guihéneuf et al., 2019a, 2020; Lagouin et al., 2019; Navarro et al., 2015; Tourtelot et al., 2021) and albumin.

2.1.5.3.1 Globular proteins

Globular proteins are molecules which have a spherical shape due to the arrangement of their atoms and the interaction with their environment.

(i) Albumin

Albumin is a family of animal globular proteins. Albumin can be found in blood (serum albumin), in egg-white (ovalbumin) and in whey (Anger et al., 2008). They are amphiphilic proteins and soluble in water. Ovalbumin has been used traditionally as a varnish for paints and in some cases for earth plasters (Vissac et al., 2013). Despite interesting properties underlined by Colas and Bourges (2013) on earth mortars stabilized with egg white and Ouedraogo et al. (2021) and Krauss (2015) on CEB very few works have been dealing with albumin. In the corpus surveyed, Lagouin (2019; 2021) used commercial ovalbumin as an additive.

According to Ouedraogo et al. (2021) and others, albumin acts by creating a strong bond between the different clay particles, preventing their separation due to its hydrophobic properties but also after drying, as albumin gel, formed by its dissolution in water, dries and seals the cracks in the material.

It is important to underline that albumin is not the only protein of egg white which interacts with clays. Ovotransferrin also has metallic binding properties and "*almost all the egg white proteins have some tensioactive ability*" (K. A. J. Ouedraogo et al., 2021)

(ii) Whey

Whey is a protein mix extracted from milk and consists of a large part of proteins of the albumin family. It is usually used as an additive to lime plasters (Minke, 2012;

Morton & Little, 2015) forming calcium albuminate, which is hard and not soluble in water but it has been used as an additive in earth mortar by Braun (2017a, 2017b).

(iii) Casein

Casein is the most prevalent protein contained in milk together with whey. It is formed by precipitating milk with an acidic reaction (Vissac et al., 2013). In natural milk, several types of casein are existing in different proportions and they form micelles of large size (Plank, 2005). To be able to use casein micelles should be decomposed by the addition of products such as ammonia which allows the release of free micelles. These micelles are amphiphile, i.e. they have a hydrophobic part and a hydrophilic part (Vissac et al., 2016). Casein is used as a superplasticizer in self-levelling concrete and natural water-based paints (Plank, 2005).

According to Vissac et al. (2013), casein is working as a glue between clay particles and since it retains partly its hydrophobic properties it prevents water to penetrate the material. However, as underlined by Ouedraogo et al. (2019), casein needs to be "activated", i.e. used in an alkali environment to prevent the formation of casein balls and allow the micelles to interact with the clay.

Casein has been used in several forms and activated by different products in the article surveyed. Braun (2017a, 2017b) have used buttermilk, goat milk, skimmed milk and curd as casein source. In the case of curd, it has been used together with shell lime, to create an alkali environment. Brzyski and Suchorab (2018) used casein activated by a high ratio of lime whereas Laguoin et al. (2019) used lime in very low quantity together with casein. Navarro et al. (2015) used acetic acid and sodium bicarbonate in equal parts as an activator for commercial casein. Tourtelot et al. (2021) used commercial powdered casein activated with sodium hexametaphosphate (NaHMP). Guiheneuf et al. (2019a, 2020) used commercially powdered casein without any activation.

(iv) Gluten

Gluten is a plant protein extracted from cereals. It might constitute 80% of wheat proteins (K. A. J. Ouedraogo, 2019). In the corpus reviewed, it has been used by Lagouin et al. (2019; 2021).

(v) Enzyme

Enzymes are large proteins used as a catalyser for chemical solutions. They are used to change the physicochemical conditions – pH or ionic strength – of the clay solution (Anger, 2011; Pinel et al., 2017) and therefore transform it into a hard paste.

Rescic et al. (2021) propose the usage of commercial enzymes and determine that besides changing the pH and ionic strength they might also act as a shield, binding organic molecules around clay particles.

2.1.5.3.2 Fibrous protein

Fibrous proteins are long chains of amino acids in a shape of a filament. Fibrous proteins absorb water but are not soluble (Vissac et al., 2013).

(i) Collagen

Collagen is a long protein present in connective tissue (bones, tendons, cartilage…) and the skin of mammals and it has been used traditionally as a glue. Like all fibrous proteins, it is not soluble in cold water but it expands (Plank, 2005; Vissac et al., 2013). Traditionally, collagen from different sources has been used as a reinforcement for plasters (Anger et al., 2012; Paul & Changali, 2020)

Collagen has been used by Calatan et al. (2015, 2016; 2014) in its commercial shape (bone glue) whereas Paul and Changali (2020) used traditional Indian additives with collagen coming from fish mucus.

2.1.5.4 Complex biopolymer

Complex biopolymers are very large molecules which are not based on the repetition of the same part but on several repetitions.

(i) Lignin

With cellulose and hemicellulose, lignin is one of the constituents of plants which gives its strength. It also protects the plant from biological attacks. (Laborel-Préneron, Magniont, et al., 2017). It is a complex and hydrophobic biopolymer (Tourtelot et al., 2021) and it has been used in a powdered industrial form by the latter.

(ii) Tannin

Tannins are complex molecules present in plants. It is a soluble molecule which can bring a negative charge in the solution and therefore act as a dispersant depending on the pH of the clay solution. Tannins also form iron tannate while reacting with iron ions and freeing some iron ions which will stick to clays and create a non-soluble paste (Anger, 2011; Losini et al., 2021; Vissac et al., 2016). Traditional recipes use nuts and shells of fruits boiled in water to release tannins (Vissac et al., 2013) whereas some recent works on CEB underline the need for iron-rich soil to be used in combinations with tannins (Banakinao et al., 2015; Keita et al., 2014; Sorgho et al., 2013).

In the corpus retained for analysis, four research focuses on different types of tannin obtained from different tree species. Clausell et al. (2020) worked on tannin extracted from *Ceratonia Siliqua L.* (carob tree pods), Guiheneuf et al. (2019a, 2020) tested earth mortar mixed with chestnut tannin solution intended for winemaking and oak seed extract commercialized as a dispersant for bentonite. Finally, Laguoin et al. (2019; 2021) and Tourtelot et al. (2021) used tannic acid as a dispersant.

2.1.5.5 Biopolymer mix

Biopolymer mixes can be naturally produced mix such as cow-dung studies by several authors or human-produced mixes designed to take advantage of some biopolymer's specific properties.

(i) Cow dung

According to Vissac et al. (2013), the same phenomenon of fermentation is happening in the stomachs of cows. After digestion, hard fibres of non-decomposed and mixed lignin and cellulose are excreted. Cow dung can be used fresh or dried. Fresh cow dung mostly contains water and urea (Millogo et al., 2016) whereas dry/cured cow dung is then composed of lignin and cellulose, together with organic amine compounds from the drying of ammonia (Pachamama et al., 2020) and intestinal microbes. Minke (2012) and Kulshreshtha et al. (2022) underline the fact that cow dung should be used fresh and left to ferment for several days. According to Vissac et al. (2016), cow-dung is working as a skeleton at different levels according to the size of the fibres left in the cow dung. Microscopic cellulose fibres are particularly interesting as they can link several clay pellets. Moreover, the presence of cow dung in earth render influences its mineralogy through the formation of insoluble amine silicate (Si(OH)4. 4NH3) (Bamogo et al., 2020). Another active element used for the stabilization of earth mortars is the small-sized microbial agents which constitute one-third of the mass of the fresh cow dung and are mostly hydrophobic fatty acids (Kulshreshtha et al., 2022).

In the studied literature, several authors have used the excrements of ruminants, mostly air-dried cow dung (Bahobail, 2012; Bamogo et al., 2020; Braun, 2017a, 2017b; Pachamama et al., 2020) but also horse and camel dung (Braun, 2017a, 2017b).

(ii) Soap

Cleaning soaps are made of two different biopolymers – glycerin and fatty acids from vegetal or animal oils – linked by a chemical reaction as an alkali solution (Bahobail, 2012). The same author used soap as an additive for earth mortars.

(iii) Tomatoes and sugar beet residues

One team of authors (Achenza & Fenu, 2007) has been using a mix of several agricultural by-products (tomatoes and sugar beet residue) as an additive in the production of earth mortars. According to them, this mix contains in addition to cellulose a high amount of sugar, starch, gum and pectin as well as different acids and proteins in low amounts.

2.1.5.6 Biopolymers preparation and dosage

Most biopolymers used for stabilizing earth mortars are either non-processed and unconventional products or commercial products aimed at a different usage. For these reasons, several studies have explained the way the additives were prepared and used as well as their dosage. Moreover several of them need some specific environment (pH, heat, etc.) to be activated. Heredia Zavoni et al. (1988) state the different possibilities of preparing opuntia mucilage and its impact on the water resistance of mortars. Guiheneuf et al. (2019a) determined the optimum amount of casein to use in their work according to its compressive strength. Other authors determined how the additives should be activated, i.e. by heating and or boiling for starch (Alhaik et al., 2017, 2015) or by adding some alkali products for casein or alginate (Lagouin et al., 2019; Navarro et al., 2015) These preparations are summarized (when known) in Table A 10 in APPENDIX A.

2.2 Properties of earth mortars

In this section, the properties of earth mortars will be checked and the contribution of the different additions (fibres, aggregates, additives) to the different properties of mortars will be explained. In the first part, the general properties of earth mortars will be explained, then the impact of each different type of stabilizer – aggregate, pellets, fibres and additive – and finally the expected and normative properties of earth plasters will be given.

2.2.1 General properties of earth mortars

The properties of earth mortars are very different and depend on the type of earth (Bouhicha et al., 2005; Emiroğlu et al., 2015; Guihéneuf et al., 2020, 2019b; Lagouin, Aubert, et al., 2021), the casting method (Guihéneuf et al., 2019b) and drying method as well as other variables such as the amount of water in the fresh mix (Guihéneuf et al., 2019b). Such a large amount of parameters which need control lead to a large distribution of the properties of earth mortars. However, in general, it can be said that non-stabilized earth mortars – from a plastic fresh mix – have a high shrinkage, low mechanical strength, low durability – water resistance, erosion resistance, and abrasion resistance – especially when measured with tests developed for industrial materials, low thermal resistance and high thermal capacity, high water vapour sorption and diffusion capacity and low environmental impact (Van Damme & Houben, 2018). Therefore there is a need of stabilizing these mortars either by the addition of sands to increase the compaction and density of the mix (Hamard et al., 2013) or fibres to reduce or shrinkage, either by the usage of stabilizers that will impact the material at a microscopic level.

2.2.1.1 Impact of clay type and content

The main material determining the properties of earth mortars is the type of clay used as their composition and therefore their reaction with water and their binding strength is depending on their chemical composition (Anger, 2011). This view is also supported by Lagouin et al. (2021) who state that "*analysing the properties of earthen materials by equating clayey fraction to size fraction below 2 μm is not sufficient. The mineralogical composition of the soil appears to be a key parameter and will be explored in further work*." Deliniere et al. (2014), Gomes et al. (2018) and Lima et al. (2020) worked with natural excavated earth – modified or not with the same amount of sand or with an amount of sand designed to obtain a similar Particle Size Distribution (PSD) of the final mix (Delinière et al., 2014; Gomes et al., 2018) – and found that the properties of mortar differ with the type of clay used for similar PSD and amount of clay. Perrot et al. (2018) demonstrated it by working with both natural earth and processed kaolin and the authors showed that modifying both materials to obtain similar PSD, results in an increase in density but a decrease in strength for the natural earth with high compressive strength and an increase in strength for low strength kaolin. Similar results are also achieved by Guiheneuf et al (2019b) comparing 2 types of natural earth and the same kaolin mix used in the former research.

However. as underlined by Meimaroglou & Mouzakis (2019) who worked mostly on non-swelling clays. the amount of clay in the chosen earth gives still a good indication of the shrinkage, density and strength of the mortar.

The clay content and clay type not only have an impact on the mechanical properties of earth mortars but also seem to have an impact on the water vapour absorption, thermal conductivity and water absorption of mortars as suggested by Gomes et al. (2018) and Lima et al. (2020).

2.2.1.2 Impact of casting method and sample dimensions

Few authors have worked on the impact of the production method and sample dimension except for the changes in the strength given by the usage of different sizes of samples (Aubert et al., 2013).

Kouakou and Morel (2009) compared the strength of Pressed Adobe Bricks (PAB) and traditionally cast mud bricks and found similar strength for both materials with a similar amount of water and density. Similar results are found in some recent studies comparing four different casting methods (Guihéneuf et al., 2019b; Perrot et al., 2018) showing that for the same type of soil, the density of the sample impacts more than the casting and densification method (compaction or vibro-compaction or extrusion).

2.2.1.3 Impact of water content

The impact of water content on the properties of plaster despite being widely explained as important because of the formation and cracks, the reduction of density and therefore the reduction of the strength of plaster have been studied by only a few authors.

Meimaroglou and Mouzakis (2019) tested a large number of different types of earths with 35% of water and then the required amount to comply with the consistency proposed by the German Standard on earth plasters (DIN18947, 2013). The results of this large testing campaign show that reducing the amount of water generally reduces the shrinkage and increases the density and the compressive strength, however, the type of earth used impacts strongly the amount of changes.

Emiroğlu et al. (2015) also tested the impact of the water amount on the compressive strength of earth mortars by increasing the mixing water of the mortar with the highest strength. The strength of the samples decreased by 50% while adding 70% of water to the mix instead of 30%. Similar conclusions were drawn by Pinto et al.

(2017) who underlined that reducing the water content also reduces the workability of the mortar.

Perrot et al. (2018) and Kouakou and Morel (2009) underlined that there is an optimum water content necessary to obtain a maximum density but this optimum amount of water depends on the production method. The first authors found that for the type of earth they used, a 14% of addition of water was necessary to obtain an optimum density whereas the second found an optimum between 18% and 20% of water showing the impact of the type of earth on this optimum content. Moreover, the latter shows that a reduced amount of water changes the porosity of the material, creating a predominance of micropores instead of macropores in the dry material.

The impact of the type of earth and especially the amount of clay on the necessary amount of water to reach a minimum shrinkage and maximum strength while having sufficient workability is underlined by Bouhicha et al. (2005) who also stress that the amount of fine and not only clay is an indicator of the necessary amount of water.

2.2.1.4 Impact of the physical properties of earth mortars on the other properties of mortars.

The impact of physical properties of earth mortars (shrinkage, density and porosity) have often been related to mechanical strength as density is often found as a good indicator of compressive strength (Kouakou & Morel, 2009; Lagouin, Aubert, et al., 2021; Perrot et al., 2018) but less work has been done to relate them with other properties such as hygric properties, hydric properties, thermal properties or cohesion despite the indication that porosity and hygric properties (Ba et al., 2021) or porosity and water absorption or thermal conductivity (Gomes et al., 2018) are closely linked.

The impact of the density of earth mortars on compressive strength has been related by several authors working on one type of earth (Kouakou & Morel, 2009; Perrot et al., 2018) however, Meimaroglou & Mouzakis (2019) and Abhilash et al. (2022) that the density of materials made with different earths should not be compared to determine the compressive strength. However, the formers propose the usage of shrinkage as an indicator of strength.

2.2.2 Impact of aggregates on earth mortars

The addition of sand is common in the traditional (Houben & Guillaud, 2008; Kouakou & Morel, 2009) or commercial production of plasters or adobe mix (Costa et al., 2019; Delinière et al., 2014; Montana et al., 2013; Santos & Faria, 2018; Schroeder, 2016; Thomson et al., 2015) especially to decrease the proportion of clay in the mix. Adding sand to earth mortars lowers the proportion of clay in the mix and modifies the particle size distribution and, thus, its properties (Hamard et al., 2013; Reman, 2004).

The impact of aggregates on earth mortar has been discussed only by a few authors even if more have used at least some sand without determining either the aim or the changes due to this usage. According to the literature, the impact of adding aggregate will depend on the type of aggregate. Using sand and other mineral aggregates will impact physical, mechanical and durability properties whereas using lightweight aggregates will mostly impact its physical properties and hygrothermal properties.

2.2.2.1 Impact of the addition of sand on the fresh properties

The impact of the addition of sand on fresh properties has been shown by Lagouin et al. (2019; 2021) who tested different soils with different amounts of sand. To ensure a similar texture of the mortar, the optimum amount of water was determined by the flow test and a flow table value of 17.5 mm, as recommended by the German Standard DIN 18947. This lead to adding a lower amount of water for an increasing amount of sand, independently of the type of earth used. Another study compared the necessary amount of water to achieve similar fresh mortar consistency for 23 different types of soil and show that soil with less sand needed more water

(Meimaroglou & Mouzakis, 2019). However, the study by Lima et al. (2016) shows the opposite with mortars with more sand needing more water to obtain the same consistency.

Emiroğlu et al. (2015) tested several mixes with the same amount of earth and water but different amounts of sand and determined with the ball-drop test that the addition of sand improves the workability until an optimum level. The same conclusion was given by Hamard et al. (2013) who states that plasters with high content of sand "*were very sandy, making them more difficult to work with and relatively powdery after drying*" (Hamard et al., 2013)

Santos et al. (2020) compared the fresh density and consistency of mortars made with fine sand and coarse sand on the flow table. It appeared that similar density and similar consistency are determined for mortar using fine sand and mixes of coarse and fine sand whereas mortar with coarse sand has a similar density but a much lower flow test result to obtain the same workability. Lima et al (2016) also compared different types of sand with the same earth and found that the addition of fine or coarse and washed sand increases the demand for water and decreases the fresh density for the same consistency. The same authors, in another article (Lima, Faria, et al., 2016) show that the fresh density seems to decrease with the addition of sand.

2.2.2.2 Impact of the addition of aggregates on the physical properties of the dry mortar

The addition of aggregates is mostly aimed to reduce the shrinkage by reducing the ratio clay/sand ratio or to increase the density and reduce the open porosity through a better distribution of particles.

2.2.2.2.1 Shrinkage

The first impact of the addition of sand on the physical properties of mortar is the reduction of shrinkage. A larger amount of sand means a lower shrinkage, regardless of the sand, clay type and testing method (Emiroğlu et al., 2015; Hamard et al., 2013; Lagouin et al., 2019; Lagouin, Aubert, et al., 2021; Lima, Faria, et al., 2016; Santos et al., 2018; Stazi et al., 2015). Meimaroglou and Mouzakis (2019) state that depending on the water content, there is a maximum amount of clay, and therefore a minimum amount of sand necessary to prevent over-shrinkage. However, not only the amount of sand is important but also the type of sand as demonstrated by Lima et al. (2016). The authors show that using washed fine sand or washed coarse sand instead of well-graded sand will further reduce shrinkage.

2.2.2.2.2 Porosity

Atzeni et al. (2007) underline that the addition of washed and calibrated mortar sand (1-2mm quartz sand) creates larger pores and higher total porosity. In the same way, the study of Brzyski & Suchorab (2018) with foam glass as an aggregate shows that the usage of larger aggregate decreases the density. The same results are given by Lima et al. (2016) however, the reduction is smaller and according to the authors using fine sand would decrease the density even more.

2.2.2.2.3 Crack formation

Lagouin et al. (2021) show that not only the shrinkage on the prism is important but the development of cracks and the length of the cracks, especially while preparing mortars for plasters and that mortars with less than 5% of volumetric shrinkage might still develop cracks. Emiroğlu et al. (2015) also show that cracks development is important with plaster with a very high amount of sand still developing cracks while applied on bricks; whereas Hamard et al. (2013) show that plasters with less than

12% of clay were not presenting any crack or deformations for the two types of earth tested. However, as underlined by Stazi et al. (2015), Deliniere et al. (2014) and Santos et al. (Santos et al., 2018) -who agree with the previous authors – in their studies of earth plaster, not only the mix and the amount of sand is important in the development of cracks and the amount of shrinkage but also the support on which the material is applied.

2.2.2.3 Impact of the addition of aggregates on the mechanical properties

The impacts of the addition of sand on the mechanical properties of earth mortars can be grouped according to the type of aggregates used:

- Using a well-distributed aggregate to change the proportion of sand and clay in the mix;
- Using sand with specific granulometry to change the particle size distribution;
- Using an aggregate with specific properties to impact the mortar in a specific manner.

2.2.2.3.1 Impact of the amount of sand

According to several authors, regardless of the type of earth, compressive strength and flexural strength are related to the amount of fine particles and particularly clay particles. However, as underlined by Meimaroglu and Mouzakis (2019), it is a low correlation and it can be dependent on the type of clay.

2.2.2.3.1.1 Compressive and flexural strength

Several authors have tested the impact of an increasing amount of sand on the compressive and/or flexural strength of earth mortar (Călătan, Hegyi, & Mircea, 2014; Emiroğlu et al., 2015; Hamard et al., 2013; Lagouin, Laborel-Préneron, et al., 2021; Piattoni et al., 2011; Taylor et al., 2006) . As a result, there is a general conclusion that the increase of sand decreases the strength of mortar. However, when the results are looked at more closely, it can be seen that most studies show that there might be an optimum amount of sand added that might slightly increase the strength of mortar for some type of earth (Emiroğlu et al., 2015; Lagouin, Aubert, et al., 2021; Lima, Faria, et al., 2016; Reman, 2004; B. Wu et al., 2017). This is also shown by Santos et al. (2020) who found that adding 75% of sand very slightly increases the compressive strength but still reduces flexural strength. This impact is studied by Perrot et al. (2018) who show that the addition of sand and especially well-graded sand on pure clay will increase both its density and strength whereas the addition of sand on an already sandy material is reducing the strength.

2.2.2.3.1.2 Shear Strength/Adhesive Strength

Shear strength or adhesive strength has been studied for earth plasters by a few authors either following the French regulations (Hamard et al., 2013; Lagouin, Aubert, et al., 2021; Stazi et al., 2015) or the DIN 18947 (DIN18947, 2013). The impact of strength on adhesive strength determined by the DIN 18947 is difficult to determine as the procedure is problematic (Delinière et al., 2014; Santos et al., 2018) but Lima et al. (2016) show that the amount of sand does not impact the strength. On the contrary, tests made according to the procedure adopted by the French regulations show that there is an optimum amount of clay – and therefore an optimum amount of sand – which increases the shear strength and this amount depends on the type of earth but not on the support (Hamard et al., 2013; Stazi et al., 2015). This amount of clay can be as high as 16% (Stazi et al., 2015) or as low as 2% (Lagouin, Aubert, et al., 2021)

2.2.2.3.2 Impact of the type of sand and its granulometry

The effect of the type of aggregates in the mortar has been demonstrated by Shicker (2009), who added small quantities of different types of aggregates to test their impacts on the strength of earth mortar and concluded that mostly aggregates that induce a pozzolanic reaction have a significant outcome and therefore at this amount of sand addition, the type and granulometry is not important.

Lima et al. (2016) state that using washed fine or coarse sand – which therefore reduces the quantity of fines – produces unfavourable results compared to using well-graded sand and this is confirmed by Stazi (2015) who tested the same mortar with fine-sieved sand (<1mm) and well-graded sand and found a decrease of compressive strength. These results are in agreement that sands contribute to the densification of the mortar and that the granular arrangement of the fine particles is important to increase strength. However, Santos et al. (2020) argue that using the same type of earth with fine sand can reduce porosity and thus increase the mechanical strength of the mortar.

2.2.2.4 Impact of aggregates on durability

The impact of aggregates on durability has only be checked by a little number of researchers mostly working on earth plasters and therefore looking up on the abrasion resistance, water resistance surface cohesion.

2.2.2.4.1 Abrasion resistance

Lima et al. (2016) have tested several mixes with different amounts of sand and they found that increasing the amount of sand decreases the abrasion resistance. The same results are shown by Santos et al. (2018). The same authors have also tested mortars made with a mix of fine and coarse earth as aggregate. According to their study, it seems that the usage of fine sand only reduces their abrasion resistance. On the other hand, Santos et al. (2020) show the opposite using fine sand reduces the weight of material loss during the abrasion test, but the authors state that it might be due to the lower density of the material. This is corroborated by the fact that in the same study, mortar made with PCM instead of sand has an even lower mass loss. Moreover, increasing the amount of sand also reduces the cohesion and resistance to abrasion. The same conclusion is given by Lima et al. (2016).

In the same study (Santos et al., 2018), the surface hardness of mortars has been checked and it is seen that clay content at the tested levels (between 6% and 12% of the total mass) or the type of sand used has only a limited impact.

2.2.2.4.2 Surface cohesion

Santos et al. (2018) tested the surface cohesion on 6 samples made with different amounts of fine and coarse washed sands and found that using only fine sand reduces the surface cohesion. The same authors state that increasing the amount of sand also reduces surface cohesion. Lima et al. (2016) also show that using fine sand or coarse sand instead of well-graded sand reduces surface cohesion.

2.2.2.4.3 Water resistance

Stazi et al. (2015) have tested earth mortars made with 2 types of sand for wettability and resistance to erosion. The authors found that there is no impact of using fine sand on the wettability and very low improvement in erosion resistance. On the contrary, using fine sand will lead to water capillarity and will increase the absorption rate of the mortar when compared to coarser sand. Lerner and Donahue (2003) point out that plaster with a high amount of sand will erode very fast.

2.2.2.5 Impact of aggregates on the hygric properties

Lima et al. (2016) have studied the addition of sand between 70.7% and 82.3% by weight and have shown that increasing the amount of sand decreases water vapour adsorption and desorption. Another study (Lima, Correia, et al., 2016) using similar earth material also show that using fine sand increase the adsorption and desorption rate of mortar whereas using coarse sand has no relevant impact.

2.2.2.6 Impact of aggregates on the thermal conductivity

Brzyski & Suchorab (2018) studied the impact of the particle size distribution of lightweight aggregates in the earth mortar and show that thermal conductivity is directly linked to density and therefore the usage of larger aggregates leads to lower thermal conductivity. This property is also underlined by Santos et al. (2018) which shows that using coarse aggregates reduces the thermal conductivity, probably because of higher porosity. However, the study of Lima et al. (2016), using similar testing methods, contradicts this fact with mortars made with coarser sands presenting a higher thermal conductivity and mortar with finer sand having a lower thermal conductivity.

From the study of Santos et al. (2018), it also seems that a higher amount of sand leads to a higher thermal conductivity but the results of the study of Lima et al. (2016) show the opposite.

2.2.2.7 Summary of the impact of aggregates on the properties of earth mortars

Table 2-7: below summarises the impact of “normal” sand on the different properties of earth mortars

Table 2-7: Impact of sand on the properties of earth mortars

	Strength	Adhesion	Abrasion	Erosion	Thermal conductivity	Water vapour adsorption
Increasing amount	↓	↑↓	↓			↓
Using coarse sand	↓	=			↓	=
Using fine sand	↑	=		↓	↑	↑

2.2.3 Impact of PCM on the properties of earth mortars

Sevilla Avila et al. (2015) and Faria and Santos (2014) used PCM as a sand replacement to determine the impact of PCM on the hygrothermal properties of plasters. Faria and Santos (2014) found that the usage of PCM reduces the thermal conductivity by 50% with 20% of PCM addition whereas Sevilla Avila et al. (2015) state that the addition of PCM has no impact on the thermal conductivity and even increases it with the addition of 5% of PCM. However, according to the same author, it also increases the amount of energy stored in the mortar. Both authors agree on the fact that the usage of PCM reduces the water vapour absorption and increases the water vapour resistance factor, but only slightly compared to the reference mortar.

In addition to the hygro-thermal properties which are the properties that are desired to be enhanced by the addition of PCM, these authors have also quantified the impact of PCM on the mechanical properties and hydric properties. According to Faria and Santos (2014), water absorption is increased by the addition of even a low amount of PCM but its drying rate is also increased, which might compensate for the increase in absorption. Sevilla Avila et al. (2015) and Santos et al. (2020) show that the addition of PCM greatly reduces the strength of mortar and its durability (Santos et al., 2017) as well as increasing its shrinkage (Santos, Faria, et al., 2020) and its susceptibility to biological growth (Santos et al., 2017). Therefore, the usage of PCM should be carefully considered.

2.2.4 Impact of fibres on earth mortars

The impact of fibres on the properties of earth mortars has been discussed by a large number of authors as it is the reinforcement method most used for plastic paste. The impact of fibres on the properties of earth mortars can be divided into 3 categories:

- Properties impacted by the addition of fibres – fresh properties, shrinkage, porosity, density, thermal, properties, durability,
- Properties not impacted – or very few impacted – hygric properties (water vapour diffusion and sorption)
- Properties for which the impact of fibres is discussed – mechanical properties

However, it is important to underline here that the impact of fibres can be very different according to the type of fibres used and their properties (Ashour & Derbala, 2010; Laborel-Préneron et al., 2018; Laborel-Préneron, Aubert, et al., 2017; Sharma et al., 2015)

2.2.4.1 Impact of fibres on the fresh properties of earth mortars

The addition of fibres, especially of small dimensions, increases the necessary amount of water to obtain the same texture (Alhaik et al., 2018; Gomes et al., 2012). The necessary additional amount of water depends on the water absorption of the fibres (Brás et al., 2019). However, this additional water is lost during the drying period and the diameter of the fibres reduces due to the loss of water creating a gap and a loss of adherence between the fibres and the mortar as underlined by several authors and shown in the SEM images from Rivera-Gómez et al. (2014)

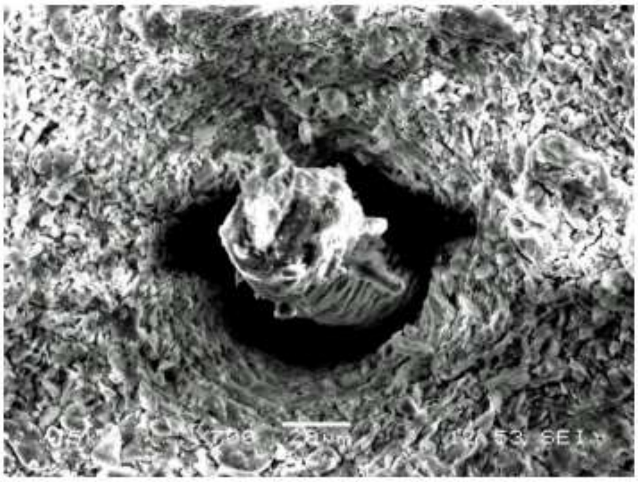

Figure 2-10: Wool fibre in a dry earth mix. Image from Rivera-Gómez et al. (2014)

2.2.4.2 Impact of fibres on the shrinkage and density of earth mortars

The impact of fibres on the shrinkage and density of earth mortar is the less discussed and most stated impact.

Almost all researches including fibres - even in a quantity as low as 0.5% - in which the shrinkage and the density have been measured show that adding fibres reduces the shrinkage independently of the type of fibres and their length or the testing method (Araya-Letelier et al., 2021; Brás et al., 2019; Caballero-Caballero et al., 2017; Rogiros Illampas et al., 2017; Lima & Faria, 2016). However, to reach a sufficient reduction of shrinkage – which should be as low as 2% or 3% according to codes (Schroeder, 2016)– a larger amount of fibre is often necessary. Only one article underlines that depending on the type of soil and the additional amount of water needed, the addition of fibres might lead to a higher volumetric shrinkage (Lagouin, Laborel-Préneron, et al., 2021).

2.2.4.3 Impact of fibres on the water resistance of earth mortar

The impact of fibres on the water resistance and water absorption of mortars has not been widely researched, however, some authors found that the addition of fibres and the increase of fibres amount reduces the water absorption (Bock-Hyeng et al., 2016; M. Ouedraogo et al., 2019; Sharma et al., 2016) whereas other authors working on different types of fibres found opposite results (Gonzalez-Calderon et al., 2020). This difference might come from the size and amount of the fibres as Ouedraogo et al. (2017) have shown for kenaf fibres of 1.5 cm and 3 cm long which showed an increase in the water absorption before a decrease for different amounts of fibres depending on the size. Similarly, Costi de Castrillo et al. (2021) found an increase in water absorption for mortars stabilized with sawdust and a decrease for mortars stabilized with straw.

Another impact of the increase in fibres amount is the control of water-related damages either by preventing erosion or loss of cohesion during immersion (Bock-Hyeng et al., 2016; Costi de Castrillo et al., 2021) or during erosion test (Ashour & Wu, 2010; Lerner & Donahue, 2003; M. Ouedraogo et al., 2019)

2.2.4.4 Impact of fibres on hygric properties of mortars

Laborel-Preneron et al (2018) have studied the impact of three different plants – namely corn cob, hemp shives and barley straw – on the hygrothermal properties of earth mortars. Despite these plants having different amounts of lignin and different moisture absorption capacity, their impact on the vapour sorption capacity and moisture buffering of the earth mix is low and all mixes with a similar weight of fibres have similar properties. Similar results have been found by Lima & Faria (2016) on different fibres.

2.2.4.5 Impact of fibres on the mechanical properties of earth mortars

The mechanical strength of earth mortar is the most researched property as most of the standards for adobe or plaster require a minimum compressive and flexural strength. According to Salih (2020b), the minimum allowable compressive strength for adobe bricks ranges from 1.20 MPa to 2.10 MPa depending on the national standard, whereas the minimum strength of earth plasters is 2.0 MPa (DIN18947, 2013). The impact of fibres on the mechanical properties of fibres is widely discussed and the subject has been reviewed in several articles (Danso et al., 2014; Laborel-Préneron et al., 2016; Salih et al., 2020b) which include plastic paste. According to these authors and the review of the literature, the main properties of fibres affecting the strength are;

- the type of fibres and specifically
    - their physical properties (roughness or shape of the stem) (Giroudon et al., 2019; Jové-Sandoval et al., 2018);
    - the mechanical properties (Zak et al., 2016);
    - the water absorption and swelling/shrinkage behaviour (Danso et al., 2017; Ghavami et al., 1999; Ige & Danso, 2021),
    - the length or aspect ratio (Danso et al., 2017; Ghavami et al., 1999; Ige & Danso, 2021);
- the amount of fibres.

However, according to some of the latest studies, despite the addition of fibres having sometimes a beneficial and sometimes a detrimental impact, the main purpose of the addition of fibres is to enhance the post-breaking behaviour and decrease the shrinkage and cracking of mortar during drying as well as increasing its durability. (Araya-Letelier et al., 2021). A reason for the lack of agreement between the different researchers might be that for different types of earth, the same amount of same fibres will have a different impact (Galán-Marín et al., 2010a)

2.2.4.5.1 Impact of the fibre type

The impact of the type of fibres on the mechanical properties of earth mortar has been assessed by several authors that made comparisons between two or more types of fibres in the same research. In most cases, a type of straw (barley, wheat or oat) is used as a reference fibre and the impact of other fibres is compared to it.

2.2.4.5.1.1 Impact of fibre size, diameter or aspect ratio

According to Millogo et al. (2014) and further analysis from Danso et al. (2014) and Laborel-Préneron et al (2016), the aspect ratio (AR) of the fibre, i.e. the diameter divided by its length is the most critical feature to enhance the strength of samples. The smaller the AR, the stronger would the mortar be for the same amount and type of fibres. Andres et al. (2016b) Caballero-Caballero et al. (2017), Ouedraogo et al. (2017), Concha-Riedel et al. (2019) and Olacia et al. (2019) and others have studied different types of fibres straw, agave, kenaf, jute and seagrass respectively and used different lengths of fibres of it. These studies conclude that using longer fibres will increase both compressive and flexural strength regardless of the type of fibres.

This conclusion is contradicted by Laborel-Préneron et al (2017), who show that because of the non-homogeneous distribution of fibres the mortar’s flexural strength might be reduced by the usage of long fibres and by the studies of Araya-Letelier et al. (Araya-Letelier et al., 2018, 2020, 2021) on pig bristles and jute fibres suggest the opposite, i.e. a decreasing compressive and flexural strength with the usage of longer fibres. According to the same authors (2018), one of the reasons for this decrease while increasing the length of fibres is the “*tortuosity*” which is expected with longer fibres and the formation of bundles of fibres which prevents direct adhesion between the fibres and the soil (Ba et al., 2021). This conclusion is supported by Olacia et al. (2019, 2020) which shows that for a small amount of fibre (0.5%), the strength will be increased by the usage of long fibres, whereas for a higher amount of fibre the strength will decrease for long fibres and increase for short fibres. For the same amount of flax fibres Peetsalu et al. (2010) show that there is an optimum length of fibres to improve the compressive strength, however, the longer the fibres, the less crack development will happen and the longer the strength is retained after deformation. Again, according to previous authors, longer fibres are not distributed homogeneously and create bundles which prevent the development of the strength of the samples.

Instead of fibre length, Navarro et al. (2015) have used the fibre diameter to differentiate between the fibre size. However, their results could not indicate a preference for using fibres with a larger or smaller diameter probably because of the method used for segregating the fibres.

2.2.4.5.1.2 Impact of water absorption of fibres

Jové-Sandoval et al. (2018) compared the swelling of fibres in water and suggest, together with previous research (Ghavami et al., 1999) that fibres with lower swelling will have a better strength because they will develop a better adhesion to the matrix while drying.

2.2.4.5.1.3 Impact of physical properties of fibre

Sharma et al (2016) indicate that the shape of the fibres is important in addition to their AR. Triangular-shaped pine needles are not able to develop enough bonds between fibres whereas finer *Grewia Optiva* fibres could develop this bond and also a better soil/fibres bond. Jové-Sandoval et al. (2018) also suggest that the double curvature of pine needles increases their bond with the soil compared to hollow straws and that using thin pine needles also provides a better bond. The same conclusion is given by Vatani-Oskouei (2017) who compared the impact of hollow straws and solid palm fibres. According to the authors, the solid structure of the palm fibres prevents them from crushing under load and their lower diameter allows a better distribution through the sample. Other authors (Araya-Letelier et al., 2017; Ba et al., 2021; Caballero-Caballero et al., 2017; Elhamdouni et al., 2015; Laborel-Préneron, Magniont, et al., 2017; M. Ouedraogo et al., 2017) have characterized numerically or by SEM photographs the surface roughness of fibres and proposed that the roughness will provide better adhesion to the soil.

2.2.4.5.1.4 Impact of mechanical properties of fibre

A few authors have researched the mechanical properties of fibres and some more have given numbers for the tensile strength and elongation at break taken from the literature. One of the outcomes is that the usage of a fibre with a lower flexural strength than the original earth mix will reduce its strength "… *not only by replacing the stronger material but also by inducing stress peaks around the fibres, which can lead to earlier failure."* (Zak et al., 2016, p. 181). Olacia et al. (2019) achieved a similar conclusion based on the comparison of straw and seagrass-reinforced mortars. Araya-Letelier et al. (2017) prefer to explain the loss of mechanical strength by the low modulus of elasticity of the materials used instead of the strength itself.

Calatan et al. (2014) state that the lower compressive strength of tubular fibres, such as straws, might be explained by their propensity to crush under heavy loads. By comparing the surface characteristics of barley straw and lavender straw, Giroudon et al. (2019) point out that the compressibility of the fibres, in addition to their water absorption, might impact the strength of the earth mortar. However, Laborel-Préneron et al. (2017) disagree and state that it is this capacity of straw to be compressed that allows for the consolidation of the material under higher loads.

2.2.4.5.2 Impact of the amount of fibres

The impact of the amount of fibres on the strength of mortars has been widely researched – 56 articles from the studied corpus deal with either the compressive or the flexural strength of earth mortars – and reviewed by several authors (Danso et al., 2014). There seems to be an agreement between authors that the optimum fibre amount for reinforcing earth mortars is between 0.2% and 1% by weight and that the mechanical strength of fibre-reinforced mortars is lower than the strength of non-reinforced mortars. However, there is no consensus on the impact of increasing the quantity of fibres on the strength of mortars as tested. Some authors found that there is no impact due to the low amount of fibres tested (Binici, 2017) whereas some found a decrease in strength (Muhammad et al., 2018) while others will find an increase (Bock-Hyeng et al., 2016) or an optimum (Corrêa, Protásio, et al., 2015; Vega et al., 2011).

This lack of converging data might come from the testing procedures such as the dimension of the specimen tested (Aubert et al., 2013, 2015; Pkla et al., 2003) or if the final strength or the strength after a certain allowable deformation is considered (Giroudon et al., 2019; Laborel-Préneron, Aubert, et al., 2017). According to these authors, considering the strength after 1.5% deformation will reduce the strength of mortars and increase the strength difference between the different amounts of fibres.

2.2.4.6 Impact of fibres on the thermal conductivity of earth mortars

The study of Alhaik et al. (2018) shows that the thermal conductivity and the thermal capacity of earth mortar decrease with an increasing amount of fibres but for fibres with similar thermal properties (flax and hemp particles) the type of fibres is not impacting the results.

Binici et al. (2007) show that the type of fibre doesn't have a large impact on thermal conductivity, although the usage of straw leads to lower conductivity. However, Bràs et al. (2019) show that the size of fibres is important with larger fibres leading to a lower thermal conductivity, especially stating that "*the bigger the fibres, the lower the bulk density, leading to lower thermal conductivity of the composite*"

2.2.4.7 Impact of fibres on the abrasion of earth mortars

The addition of fibres reduces the material loss of earth mortars during abrasion tests as shown by Gonzalez-Calderon et al. (2020) or Araya-Letelier et al. (2017), however, the mechanisms behind this reduction are not clear yet as a low amount of fibres seem to have a higher impact than a higher amount, probably through maintaining a better surface cohesion of the mortar (Araya-Letelier et al., 2017) however, depending on the size of the fibres, a minimum amount is necessary to observe an improvement (Gonzalez-Calderon et al., 2020)

2.2.5 Impact of biopolymers on earth mortars

Biopolymers are a specific type of additives extracted and produced from organic natural resources. According to the literature and the outcomes of the articles selected for the corpus, additives are usually used for 3 main reasons (Lagouin, Laborel-Préneron, et al., 2021):

- increasing the mechanical strength of earth mortars,
- increasing their durability, especially their water resistance by protecting the bond between clay particles (preserving cohesion) and
- acting as a dispersant and changing the workability and reducing the initial amount of water and therefore the final porosity, allowing a higher strength (Guihéneuf et al., 2019a).

However, they also have side impacts on physical properties such as shrinkage and especially on changing the hygrothermal properties of the mortars.

The impact of the different biopolymers used in the studied corpus will be explained in two manners:

- Table A 10 in APPENDIX A shows the detailed impact of additives similar to the one used in the experimental work.

- Sections 2.2.5.1 to 2.2.5.6 summarize the impacts of the different biopolymers according to the properties tested and their actions on the clays when described. Impact of additives on the fresh properties of earth mortars

2.2.5.1 Impact of additives on the fresh properties of earth mortars

Researchers have checked how the additives could contribute to reducing the amount of mixing water needed for mortar by using additives as a dispersant or as pH-changing materials. The different additives tested for improving the fresh properties of mortars and their impacts are presented in Table 2-8.

Alhaik et al. (2017, 2018) tested the addition of starches and showed that the addition of starch increases the need for water to achieve similar consistency measured on the flow table and VEBE consistometer, although drying time is similar with or without the addition of starches. However, Lagouin et al. (2021) found that using a smaller amount of similar starches on similar earth will decrease the need for mixing water. Alhaik et al. (2017, 2018) also determined that the transformation process undergone by the starch is more important for the thixotropy of the mix than the type of clay or the provenance of the starch.

Clausell et al. (2020) worked on the impact of tannins of carob pods on the mixing water amount of mortar made with a different type of clay. With the optimum addition of tannin in an acidic environment, the clays are dispersed naturally and therefore the need of mixing water is reduced. The impact of tannins has also been tested by Guihéneuf et al. (2019a) and Lagouin et al. (2021) on different types of earth and both authors state that adding tannins reduces the need of mixing water by checking the Atterberg limits

Guihéneuf et al. (2019a) also determined the Atterberg limits (liquid limit and plastic limit) for other additives and they state that regardless of the type of earth, Sodium-Hexametaphosphate (HMP), tannins, citric acid and oak seed extract act as dispersant whereas casein, cellulosic glue, alginate and linseed oil worked as a colloidal agent, which means that there will be a higher need of water to achieve similar consistency.

Lagouin et al. (2021) determined that the usage of gluten and ovalbumin increases the need for water independently of the type of earth used, only the proportions changed from a very low increase (<5%) with some earth and ovalbumin to a high increase with gluten (>35%)

Table 2-8: Impact of biopolymer on the fresh properties and workability of the mortar

Additive	Amount (%of binder)	W/B ratio	pH	LL	
Starch	1	↑			(Alhaik et al., 2017, 2018)
Starch	0.25	↓		↑	(Lagouin, Laborel-Préneron, et al., 2021)
Casein	5	↑		↓	(Guihéneuf et al., 2019a)
Cellulosic glue	n.a.	↑		↑	(Guihéneuf et al., 2019a)
Linseed oil	n.a.	↑		↑	(Guihéneuf et al., 2019a)
Ovalbumin	0.25	= ↑			(Lagouin, Laborel-Préneron, et al., 2021)

n.a. means that the amount of additives is not given as a percentage of the binder but with other units and relationships.

2.2.5.2 Impact of additives on the physical properties of earth mortars

The use of additives to reduce the amount of mixing water is aimed to reduce the shrinkage and increase the dry density. However, Lagouin et al. (2021) show that despite the reduction of the volumetric shrinkage, the action is not sufficient to prevent the apparition of cracks in constrained shrinkage test and that their action will depend also on the type of earth. A summary of the action of the different biopolymers is presented in Table 2-9.

2.2.5.2.1 Shrinkage

According to the studies of Laguoin et al. (2019; 2021), most of the additives increased shrinkage and crack development. However, some authors have found some contradictory outcomes, especially while testing similar additives in similar conditions. Colas and Bourges (2013) using egg whites directly found a decrease in shrinkage whereas Laguoin et al. (2019; 2021) found an increase in shrinkage while using powdered ovalbumin. The same opposition on the impact of drying oils is seen between the work of Lima et al. (2016) for one part, Colas and Bourges (2013), Brzyski et al. (2020) and Gomes-Batitstelle et al. (2020) for another part who found that the addition of drying oils reduces the shrinkage. The only additive that has a clear and high impact on the shrinkage is cow-dung with a reduction of 30% of shrinkage for 6% by weight of cow dung (Bamogo et al., 2020) and 70% for 20% of cow dung (Pachamama et al., 2020). This impact is probably due to the amount of fibres present in the additive. The addition of carrageenan also clearly decrease the shrinkage as the usage of a 2% solution instead of mixing water decreased the shrinkage by almost 50% (Nakamatsu et al., 2017). For the same type of additive, results might be different. Dove et al. (2014; 2016) used several types of alginate coming from different seaweed and parts of the same seaweed and tested them on different earth and found that the shrinkage might be either highly decreased or highly increased.

2.2.5.2.2 Density

The impact of the biopolymers on the density is dependent on the biopolymer and the type of earth as well as on the amount of additives. Generally, except for fibrous additives such as cow dung (Bamogo et al., 2020; Pachamama et al., 2020) or tomatoes and beetroot residues (Achenza & Fenu, 2007), which show a clear decrease in density, especially for a high amount of additives (until 40% decrease), other additives only have a low positive or negative impact, if any, except for the addition of tannin that also decreased the density by 10%. These results are confirmed by the ones of Tourtelot et al. (2021) who tested 10 different additives. In their study, all tested additives lead to a decrease in density, very slight for pectin and μ-cellulose but significant for others and especially for casein and lignin. Conversely, alginate as tested by Dove et al. (2014; 2016) lead to a significant increase in density, independently of the type of earth and alginate but this is probably due to the low amount of additive tested since Perrot et al. (2018) found opposite results for a higher amount of alginate.

2.2.5.2.3 Porosity

Porosities have only been calculated in three studies. While the study of Bamogo et al. (2020) and Achenza and Fenu (2007) deal with lightweight and fibrous additives which increase the porosity as if it would be for fibres, the study of Brzyski et al. (2020) shows that the addition of linseed oil, even if only having a very low impact on density closes the pores of the materials which might impact both hydric and hygric related properties.

Table 2-9: Summary of the impacts of some additives on the physical properties of earth mortar

Additive	Amount (% of binder)	Shrinkage	Density	Porosity	Reference
Cellulose (s)	10		= ↓		(Tourtelot et al., 2021)
Starch	0.25 / 1	↑	=		(Lagouin, Laborel-Préneron, et al., 2021; Tourtelot et al., 2021)
Sugar	0; 5; 10	=	=		(Pinto et al., 2014)
Linseed oil	0; 1.2; 3.1	↑	=		(Lima, Silva, et al., 2016)
Linseed oil	0 - 6	↓	=	↓	(Brzyski & Grudzińska, 2020; Colas & Bourgès, 2013)
Linseed oil	1		↓		(Tourtelot et al., 2021)
Castor oil	0; 2; 4	↓ ↑			(Gomes Battistelle et al., 2020)
Used cooking oil	0; 2	↓			(Gomes Battistelle et al., 2020)
Ovalbumin	0.25				(Lagouin, Laborel-Préneron, et al., 2021)
Ovalbumin					(Colas & Bourgès, 2013)
Cow-dung	0 - 20	↓	↓	↑	(Bamogo et al., 2020; Pachamama et al., 2020)

2.2.5.3 Impact of the additives on the mechanical properties of earth mortars

Strength and especially compressive strength is the most researched property of earth mortar. Several authors have checked the impact of the additive on the strength, and most of the additives have led to an increase in strength even if minimal. However, as is detailed in the paragraphs below, the impact of additives is not fixed and might be depending on several factors such as the type of clay (Galán-Marín et al., 2010b; Lagouin, Laborel-Préneron, et al., 2021) or the amount of clay/fines in the earth. Moreover, the amount of additives might also determine its impact with an optimum amount of additives for a given mix (Corrêa, Mendes, et al., 2015; Corrêa, Protásio, et al., 2015; Pachamama et al., 2020; Rodriguez Cuervo, 2020). Table 2-10 summarizes all the papers used in the corpus dealing with mechanical strength.

(i) Cellulose

Tourtelot et al. (2021) have tested 3 types of cellulose among other additives and have found that all of them increase significantly the compressive strength and the Modulus of elasticity. According to the authors, the strengthening impact is coming from both physical and chemical bonds between the microscopic fibres, and the minerals and the hydroxyl groups present on the surface of cellulose forming additional hydrogen bonds with the clay particles.

(ii) Starches

Alhaik et al. (2017, 2018) tested several starches with a different type of earth (Alhaik et al., 2017) and in combination with fibres and superplasticizer and/or lime (Alhaik et al., 2018). They showed that the addition of starches generally increased both the compressive strength and flexural strength but the amount of increase depended on the type of starch and the casting conditions. Maize and waxy maize starches seemed to be the most efficient of natural starches at 20°C (Alhaik et al., 2017). The increase of compressive strength by the addition of starch is also underlined by Tourtelot et al. (2021) who explained that the release of amylopectin by heating the starch allows these long and highly branched molecules to create a network between the clay particles and create hydrogen bonds with it. However, Lagouin et al. (2021) tested one type of starch on several types of earth and found that compressive strength is in the margins of error with earths and the flexural strength is worsened by the addition of starch. The same author also tested mortars reinforced with starch for shear strength and found no improvement or deterioration due to the large margin of error and dispersion of results. The difference in results might be because of the usage of different types of earth and especially different concentrations of starch which is 4 to 5 times lower in the work of Lagouin et al. (2021).

(iii) Molasses

The usage of molasses is reported by 2 authors who obtained very different results. While Rodriguez Cuervo (2020) reported a loss of compressive strength for any amount of molasses, while Vilane (2010) reported an increase of strength for an increasing amount of molasses both in dry and water-saturated conditions. The difference might be due because of the amount of clay in the studied earth, as it was reported higher than 50% of clay in the earth tested by Rodriguez Cuervo (2020)

(iv) Drying oils

Linseed oil (LO) and other oils have been tested by several authors for different results. Lima et al. (2016) and Guiheneuf et al. and others (2019a; 2018) have found a large increase in compressive strength for an increasing amount of LO. Lima et al. (2016) also note that the flexural and adhesive strength is increased with an increasing amount of LO. However, these results are in opposition with the ones of Brzyski et al. (2020) and Tourtelot et al. (2021) who found a decrease in compressive strength. The latter also found a decrease in the modulus of elasticity as was also found by Colas and Bourges (2013). The humid strength of LO-stabilized samples has been researched by Guiheneuf et al. (2020). According to the authors, LO doesn’t prevent a loss of strength for the same amount of humidity absorbed compared to the reference sample, but as it prevents humidity absorption, consequently, it prevents the decrease of strength for similar conditions.

Castor oil and used frying oils have also been tested for compressive and flexural strength and the authors have found a large decrease in strength (Gomes Battistelle et al., 2020).

(v) Ovalbumin

The usage of ovalbumin as an additive increases the compressive and flexural strength of all tested earth mortar, except for the earth containing a high amount of swelling clay (Lagouin, Laborel-Préneron, et al., 2021). Colas and Bourges (2013) also reported a decrease in the modulus of elasticity while using egg whites. Ouedraogo et al. (2021) report that the increase in strength for mortar stabilized with ovalbumin powder is due to the length of the ovalbumin polymeric chains that bind several particles together and also to the creation of a sulfur gel that fills the material cracks while drying and bind all particles together. Moreover, as Minke (2012) has also underlined, in egg white, not only ovalbumin has an active impact, but also other molecules such as ovotransferrin.

(vi) Casein

Casein has been tested by 2 authors for compressive strength. Results are the opposite as Tourtelot et al. (2021) found a large decrease in strength and Guiheneuf et al (2019a) found a large increase. These differences might be due to the type of casein used or the type of earth or due to the amount of casein used was the same - 5% of earth – but the earth/sand ratio was different and therefore the total amount of casein was lower in the case of Tourtelot et al. (2021).

(vii) Cow dung

Cow dung has been used in three occurrences on different materials. All articles reported the usage of air-dried cow dung at similar concentrations (5% to 20%) however, the outcomes are very different with an increase in compressive and flexural strength for Millogo et al. (2016), Bamogo et al. (2020) and Pachamama et al. (2020) at low concentration of cow-dung but no impact at all for dry or saturated compressive strength according to Vilane (2010). The main difference might be the usage of different earth with Millogo et al. (2016), Bamogo et al. (2020) and Pachamama et al. (2020) using a kaolinitic earth with a high amount of clay – over 35% - and Vilane (2010) using a soil with a low amount of clay – less than 10%. Therefore, it is possible that the silicate anime created by the reaction between amine organic compounds contained in cow dung and kaolinite is not happening properly, preventing the mortar to develop additional strength (Millogo et al., 2016).

Table 2-10: Summary of the impact of additives on the mechanical strength of earth mortars

additive	Amount (% of binder)	CStr	FStr	MoE	AStr SStr	Reference
Cellulose (s)	10	↑	↑	↑		(Tourtelot et al., 2021)
Starch	0.25	=	↓		=	(Lagouin, Laborel-Préneron, et al., 2021)
Starch	1	↑	↑	↑		(Alhaik et al., 2017; Tourtelot et al., 2021)
Sugar	0; 5; 10	↓				(Pinto et al., 2014)
Molasses	5; 10; 15	↓				(Rodriguez Cuervo, 2020)
Molasses	5 - 20	↑				(Vilane, 2010)
Linseed oil	0; 1.2; 3.1	↑	↑		↑	(Guihéneuf et al., 2019a; Lima, Silva, et al., 2016)
Linseed oil	/0 - 6	↓	↑	↓		(Brzyski & Grudzińska, 2020; Colas & Bourgès, 2013; Tourtelot et al., 2021)
Castor oil	0; 2; 4	↓				(Gomes Battistelle et al., 2020)
Used oil	0; 2	↓				(Gomes Battistelle et al., 2020)
Ovalbumin	0.25	↑	↑		↓	(Colas & Bourgès, 2013; Lagouin, Aubert, et al., 2021)
Casein	5	↓				(Tourtelot et al., 2021)
Cow-dung	0 - 20	↑	↑		↑	(Bamogo et al., 2020; Pachamama et al., 2020)
Cow-dung		↓				(Vilane, 2010)

CStr = Compressive Strength, FStr = Flexural Strength, MoE = Modulus of Elasticity, AStr = Adhesive Strength, SStr = Shear Strength

2.2.5.4 Impact of additives on the durability

The durability properties of earth mortars are linked to their capacity to endure weather conditions and usage in construction. After increasing strength, this is often the main criterion of the choice of an additive (Nakamatsu et al., 2017), to determine its impact on durability and more importantly on the resistance to water destruction as the loss of bond between clay particles in a humid environment is a real drawback in its usage. However, other important properties of mortars about durability are given here.

2.2.5.4.1 Surface cohesion

Surface cohesion, which determines how much the surface particles will tend to detach was determined only on two types of additives. The addition of linseed oil increases surface cohesion (Colas & Bourgès, 2013; Lima, Silva, et al., 2016) as well as the addition of flour paste (Colas & Bourgès, 2013).

2.2.5.4.2 Abrasion

Abrasion has been tested on a few additives and the results differ according to the type of biopolymers. According to the available results, it seems that additives working as a gel or glue – either mucus from plants or gel at a microscopic level – will have a lower impact than additives that are working on the deflocculation of clay particles e.g. tannin (Clausell et al., 2020) – or on the creation of new and more resistant materials e.g. cow dung (Bamogo et al., 2020). However, as the testing methods are different in every article it is difficult to determine precisely. The study of Paul (2020) on four different natural and traditional additives from India shows that rice starch and the mucilage of *Cochlospermum religiosum* have a highly beneficial impact on abrasion resistance whereas others are decreasing it. Linseed oil (Lima, Silva, et al., 2016) and alginate (Dove et al., 2016) reinforced mortar also show similar improvements probably thanks to the creation of a biopolymer film protecting the particles. Cow dung (Bamogo et al., 2020) reinforced mortars are experiencing less material loss during the abrasion test due to the creation of strong links by anime silicate, whereas the better particle organization due to tannins prevents the separation of loose particles (Clausell et al., 2020).

2.2.5.4.3 Erosion

The main campaigns of tests on the behaviour of stabilized earth mortars have been carried out by Braun (2017a) on adobe tested by spray test and Morton and Little (2015) on plasters exposed to real environmental conditions. As these campaigns cover more or less the whole field of natural additives, it makes it easier to do comparisons. According to Braun (2017a), all biopolymers tested increased the resistance of the mortars, from 14% less loss of material for wallpaper paste (methylcellulose + starch) to 98% less loss of material for buttermilk (whey), goat milk (whey + casein), skimmed milk (casein) or rye flour paste (starch). Other additives such as linseed oil, animal dung or pure whey also performed well with about 92% to 95% less loss of material than the reference mortar. Similar results are given by Morton and Little (2015) who report that plasters stabilized with linseed oil or tallow suffer less after 4 years of exposure whereas plasters made with fresh animal dung performed not too bad but with more loss of material and the development of seaweed. Other authors have also tested several biopolymers under different conditions, and expect alginate tested by Navarro et al. (2015) and *E. coli* tested by Rescic et al. (2021), it seems that all tested additives increase the resistance to erosion compared to the reference mortar independently of the type of test. Results and tested additives are summarized in Table 2-11.

2.2.5.4.4 Water permeability (sessile test)

This test is intended to determine the property of the surface towards water permeability. On a repellent surface, a drop will be formed and will not be absorbed or only slowly. The angle made between the surface of the sample and the drop at the contact interface determines the water permeability. Guiheneuf et al. (2020) also tested the mortars stabilized with xanthan and linseed oil and reported that xanthan – in the two tested concentrations – has no impact on the absorption of the water whereas linseed oil prevents it. Colas and Bourges (2013) have also tested linseed oil and compared it with flour paste. For these authors, as both additives prevent the absorption of water, it seems that the linseed oil creates a more water-repellent surface.

2.2.5.4.5 Capillary water absorption

The behaviour of stabilized earth mortar in contact with water can be very different depending on the type and amount of additives but also depending on the type of earth used. Most of the tested additives will reduce the capillarity absorption rate of mortars but depending on the time spent in contact with water they might still have the same total absorption. It can be argued, however, if a total absorption obtained after 10 days is an important factor for earth construction.

As in other tests, comparison between data from different articles is not relevant as experimental set-ups and earth types are completely different. However, trends can be compared thanks to the work of some authors who tested several additives or earth with the same experimental setups. Guineheuf et al. (2020) tested several additives with three different types of earth and found that in most cases, the behaviour was the same independent of the earth tested, only the additives “responded” better or worst to the earth used. However, as can be seen in Table 2-11, alginate and casein will have different behaviour with different soils. This is also underlined by the work of Navarro et al. (2015) who found different outcomes with the same additives and

Dove et al. (2016) who tested different earths with alginate and also found different behaviours.

Conversely, some additives are not impacted by the type of earth probably because their reaction to water and the conditions of their actions are different. This is the case of linseed oil as tested by several authors (Table 2-11) but also as given as reference by others (Minke, 2012) and also the case of xanthan gum (Guihéneuf et al., 2020) or tannins (Clausell et al., 2020; Guihéneuf et al., 2020)

This difference in behaviour is mostly related to the way the additives are stabilizing the mortars. According to Guiheneuf et al.(2019a, 2020) and Nakamatsu et al. (2017), xanthan gum and carrageenan are working in the same way, creating a non-soluble link between the clay particles and therefore preventing their separation and the water absorption. Linseed oil will work differently by creating a hydrophobic surface on and in between the clay particles, preventing any water to enter and keeping the cohesion of the mortar (Guihéneuf et al., 2019a). However, due to the viscosity of the oil, it might be difficult to mix with the mortar and therefore disparities can happen (Brzyski & Grudzińska, 2020).

On the other hand, additives like casein, alginate or cow dung react with the clay to create new components and therefore their action is dependent on the type of clay. This is demonstrated by Bamogo et al. (2020) who state that the addition of cow dung led to the creation of insoluble amine silicate which is a hydrophobic molecule that isolates clay particles and therefore prevents capillary absorption. The authors also add that the presence of fibres also reduces capillary absorption as presented in section 2.2.4.3

The third way of action that is less efficient is the change of the water into a more viscous solution by the dissolution of the additive. This is presented by Pinto et al. (2014) in their work on saccharose as an additive.

2.2.5.4.6 Slake test (immersion)

The results of slake tests are very similar to the one of capillary absorption, however, there the destruction of the samples by water is recorded. In the cases described here and summarized in Table 2-11, the water resistance is increased in the same way that the samples are absorbing less water.

Table 2-11: Impact of the biopolymers on the durability of earth mortars

Additive	Surface cohesion	Abrasion	Surface permeability	Erosion resistance	Capillarity water absorption		Water resistance	Reference
					rate	total		
Rye flour paste				↑	↓			(Braun, 2017a)
Flour paste			↓		↓			(Colas and Bourgès 2013)
Brown rice starch		↑		↑	=			(Paul and Changali 2020)
Saccharose				↑	↑			(Pinto et al. 2014)
Molasses					↓			(Vilane, 2010)
Linseed oil	↑	↑	↓	↑	↓	↓	↑	(Morton and Little 2015; Guihéneuf et al. 2020; Colas and Bourgès 2013; Brzyski and Suchorab, 2018; Brzyski and Grudzińska, 2020; Lima et al. 2016b)
Linseed oil				↑	=			(Navarro et al. 2015)
Linseed oil				↑	↓			(Braun, 2017a)
Casein				↑	=	=	↑	(Navarro et al. 2015; Guihéneuf et al. 2020 ; Brzyski and Suchorab, 2018)
Casein					↓	↓		(Guihéneuf et al. 2020, "soil K" and "soil R")
Casein					↑	↑		(Guihéneuf et al. 2020, "soil S")
Oavlbumin	↑	=			↓			(Colas and Bourgès 2013)
Cow dung		↑		↑	↓			(Bamogo et al. 2020; Braun 2017a; Morton and Little 2015)
Cow dung					=			(Vilane, 2010)
Horse dung				↑				(Braun, 2017a)
Horse dung				↓				(Morton and Little 2015)
Camel dung				↑	↓			(Braun, 2017a)

2.2.5.5 Impact of additives on the hygric properties

Guiheneuf et al. (2019a, 2020) also studied the impact of linseed oil and xanthan gum on the water vapour absorption of samples and shows that xanthan gum has no impact on the permeability of samples whereas linseed oil decreased the water vapour permeability and the sorption rate. The same behaviour of the addition of linseed oil is observed by Lima and Faria (2017), Colas and Bourges (2013) and Navarro et al. (2015) who studied the water vapour diffusion resistance. The latter also reports similar behaviour of mortar for the addition of casein and alginate but both additives have a lower impact than linseed oil. Conversely, Dove et al. (2016) tested the water vapour absorption and found that alginate has almost no impact on the sorption isotherm of the mortar, in accordance with previous studies "*which argue that the hygroscopic behaviour is linked primarily to the properties of the soil such as the particle size distribution and type of clay minerals present"* (Dove et al., 2016). In addition to linseed oil, Colas and Bourges (2013) also tested the addition of egg whites and found that it also impacts the water vapour resistance but in a lesser way. Rescic et al. (2021) show that the addition of enzymes has no impact on the vapour diffusion resistance. From these results, it seems that only oils and probably additives that will create a hydrophobic layer around the clay particles as well as reducing the porosity will increase the water vapour resistance whereas others will have only a limited impact.

In addition, Guiheneuf et al. (2020) also demonstrate that the water vapour resistance factor is highly dependent on the density of the material. For the same additive or even different additives, there is a trend towards an increase in resistance with an increase in density.

2.2.5.6 Impact of additives on the thermal properties of earth mortars

As the main aim of the addition of additives is on increasing the strength and water resistance of earth mortars, only a few studies have checked their impact on the thermal properties and when it has been done it might be mostly to acknowledge the fact that there is no impact (Alhaik et al., 2018). Other authors have determined the thermal conductivity for mortars stabilized with casein (Navarro et al., 2015), alginate (Navarro et al., 2015), linseed oil (Lima, Silva, et al., 2016; Navarro et al., 2015), palm oil (Bahobail, 2012) and cow dung (Bahobail, 2012; Bamogo et al., 2020). Because of the lack of research, it is difficult to determine any trend especially because results are contradictory for the same additives. In fact, according to Lima et al. (2016), 5% of linseed oil increases the thermal conductivity by 15%, which is in line with the study of Bahobail (2012) who reports an increase of 15% in thermal conductivity with the addition of 5% of palm oil. However, in the opposite, Navarro et al. (2015) reports a decrease of 7% with 2% of linseed oil. According to the same author, alginate also decreases thermal conductivity while casein has no impact on it. Also according to Navarro et al. (2015), the thermal diffusivity is not affected by any of the tested additives.

2.3 Experimental methods used for the testing of earth mortars

Despite or because earth construction being used for thousands of years, the research on earth construction is very new and the standardization of the research and experimental set-ups is not been achieved yet (Jiménez Delgado & Guerrero, 2007), each country or group of researchers using its methods – i.e. the adhesion test/shear strength tests for plasters according to German Standards (DIN18947, 2013) or according to the method developed by Hamard (2013) – most of the time taken and adapted from other fields (adaptation of methods for testing cement mortars or stones). Moreover, even inside the existing standards, uncertainties regarding the experimental procedures and materials are existing (Faria et al., 2016) which makes the comparison between the different papers very difficult. More research is needed to correlate the relationship between the different properties and different testing methods (Santos & Faria, 2020), In the following paragraph, the different methods used to prepare samples and determine their properties are explained.

2.3.1 Samples preparation

The sample preparation is an important step in the determination of the mortar properties which can be defined by the earth preparation process (drying sieving grinding etc.), the mixing process and water addition process, the casting/moulding process and the drying process. According to German standards (DIN18947, 2013), methods used for the preparation of earth mortars are based on the EN 1015 (Delinière et al., 2014)

2.3.1.1 Earth preparation

Natural earth (plain earth) for construction is a material which is directly extracted from the ground at a depth that prevents the presence of a large amount of organic matter (Houben & Guillaud, 2008; Schroeder, 2016). Often plain earth needs to be transformed into construction soil through grinding and sieving and the addition of non-active particles to reduce the amount of clays (Houben & Guillaud, 2008; Schroeder, 2016). According to several authors, the suggested amount of clay varies between 10% and 20% by weight (Călătan et al., 2016; Kouakou & Morel, 2009; Quagliarini & Lenci, 2010) and authors have determined some limits for particle distribution according to their size which determines how plain earth should be transformed for a specific usage (Houben & Guillaud, 2008). The preparation is often made by the addition of sand to obtain an engineered mix (Bertelsen et al., 2021; Corrêa, Protásio, et al., 2015; Rescic et al., 2021) but some authors reports mixing two types of soil with different properties to get a new one (Özmen & Bayülke, 1987; Tavares et al., 2019)

2.3.1.2 Mortar mixing

The mixing of the mortar is described by German standards (DIN18947, 2013) but the procedure differs for each author which sometimes prefers manual mixing (Simons et al., 2015) to mechanical mixing. The standardized procedure for mortars (DIN18947, 2013) suggests the homogenization of dry materials, then the addition of water followed by a short mixing period, a resting period and then again a short mixing period (Emiroğlu et al., 2015; Santos & Faria, 2020). The procedure of mixing is rarely described by the authors despite its utmost importance on the properties of the mortars as clearly described by (Costi de Castrillo et al., 2021).

After mixing the fresh mortar can be cast directly as is often the case in laboratory experiments (Delinière et al., 2014) but as the tradition suggests, it can be left to mature for a certain period (Costi de Castrillo et al., 2021; Laborel-Préneron et al., 2021; Simons et al., 2015).

The drying of the mortar is usually done in laboratory conditions (Atzeni et al., 2007) or in a controlled environment with constant temperature and humidity (Pinto et al., 2014) especially if the mortar contains some hydraulic binders (Rasa et al., 2009; Stathopoulos et al., 2021; Taylor et al., 2006). However, some authors tested the mortars in different conditions of temperature and humidity (Ashour, Bahnasawy, et al., 2010) or oven-dried above 60°C (Ba et al., 2021; Laborel-Préneron et al., 2018; Muñoz et al., 2020) to accelerate the process or study the differences of properties.

The steps involved in the preparation of mortars are summarized below:

- sieving and/or crushing of the earth dried at 105°C
- removing all organic matters such as roots (Ashour & Wu, 2010)
- homogenization of the dry materials (addition of fibres and/or aggregates)
- addition of stabilizers if any (Stazi et al., 2015)
- mixing with water according to the need (Atzeni et al., 2007; Liuzzi et al., 2013)
- settling (not always)
- casting filling
- Drying/curing time

2.3.1.3 Determining the water content

The determination of the water content and the consistency is important as it impacts several properties such as the implementation or the density and shrinkage and therefore the strength, hygric and thermal properties. Several methods are used to determine the optimum water content to be used for the mortar but the most used ones are the proctor test – which determines the water amount according to the optimum density of the mortar – and the flow table test which determines the amount of water according to the desired consistency whereas other authors used relation between plastic limit and liquid limit (Guihéneuf et al., 2019b) and described section 2.1.1.1.2 – or a fixed ratio of water to earth (Bertelsen et al., 2021; Costi de Castrillo et al., 2021).

2.3.1.3.1 Proctor

The Proctor test determines the optimal water amount in a mix to obtain a maximum dry density under a specific compaction (Mesbah et al., 1999). Several authors have used the normal or modified proctor test – especially authors working on mortars for mud bricks and Pressed Adobe Bricks (PAB) (Brás et al., 2019; Laborel-Préneron, Aubert, et al., 2017) to determine the optimum amount of water despite the knowledge that this test is not suitable for earth construction -except rammed earth – as it doesn't represent the compaction method used (Kouakou & Morel, 2009)

2.3.1.3.2 Flow table test

Most authors determined the amount of water according to the consistency of the mix using the flow table technique as described by Lagouin et al. (2019) or Deliniere et al. (2014) which consists in shaking at regular intervals during one minute of a certain amount of mortar placed with a truncated conical mould and measuring the diameter of the resulting circle. The German Standards for earth mortars and plasters propose a diameter of 17.5 cm under 15 vertical impacts for plasters (Delinière et al., 2014; Lagouin et al., 2019) or 14 cm for earth mortars (Schroeder, 2016).

2.3.1.4 Casting and moulding

Moulds – often as a frame without a bottom to ease the removal – can be made of different materials such as timber or aluminium. When the frames have no bottom, the type of surface where it is applied has an impact on the drying shrinkage. A flat surface should be used and to prevent restrained shrinkage and the formation of cracks, it is possible to use a plastic tarp on the hard surface to disconnect the mortar from its support (Rojat et al., 2014). For timber frames, before usage, mould should be wetted to prevent the earth to stick and the timber to absorb the water from the mix (Costi de Castrillo et al., 2021). For metallic frames, oil might be used to ease the removal of the frame.

Researchers used several ways of casting according to the size of the sample or the purpose of the mortar. However, as explained by Deliniere et al. (2014), standards describe a casting process that involves pouring material in a small-size mould in two or several layers and tamping it with a given pressure or a given number of shocks. Thus, particles and especially the fibres tend to be organized in layers parallel to the surface of the specimens which might not represent the reality of the material and might impact its properties due to the fibres' arrangement (Brás et al., 2019) or the size of the specimens (Aubert et al., 2013). Therefore several authors have worked on specimens which might better represent reality, either by using real dimensions blocks (Costi de Castrillo et al., 2021; Quagliarini & Lenci, 2010) as proposed by Aubert et al. (2015) or by using similar production processes such as presses reproducing the pressure and movement for PAB (Giroudon et al., 2019) or casting large samples using similar movements with plastering methods for plaster mortars as prisms (Rojat et al., 2015) or on a wall (Hamard et al., 2013; Lagouin et al., 2019; Stazi et al., 2015). The casting methods are summarized when known in Table A 1 to Table A 3 in APPENDIX A

2.3.2 Sample sizes

The size of the samples and the type of mould differs according to the procedures used for the testing of specimens. The DIN 18947 and the EN 1015 suggest the usage of 40x40x160 mm^3 for mechanical strength and shrinkage or Ø 90 mm samples for vapour permeability and 200x500mm^2 for sorption desorption behaviour. However, other authors used their national standards to produce samples according to their needs especially cubic samples of 5x5x5 cm^3 or 10x10x10 cm^3 for compressive strength (Alam et al., 2015; Araya-Letelier et al., 2021; Ashour, Bahnasawey, et al., 2010; Maheri et al., 2011; Tourtelot et al., 2021).

In the absence of international references on the subject and the non-adequacy of a standardized method for some properties of the plaster (Delinière et al., 2014), some authors such as Faria, et al (2016) propose a wider range of sizes of test samples (Figure 2-11) adapted to different tests in their proposal of an experimental procedure to characterize earth plasters. Similar specific sets of specimens are proposed by Araya-Letelier et al. (2019, 2021), or Stazi et al. (2015) for the testing of properties of earth mortars (Figure 2-12). Table A 12 and Table A 13 in APPENDIX A shows the different types of samples used for the different types of tests.

Moreover, as underlined by Hamard et al. (2013) or Faria, dos Santos and Silva (2014), the support wall and the application method are important to determine some properties of samples and the usage of small samples is not representative especially in the case of fibrous samples due to side and corner effect which should be removed. (Minke, 2012; Rojat et al., 2014).

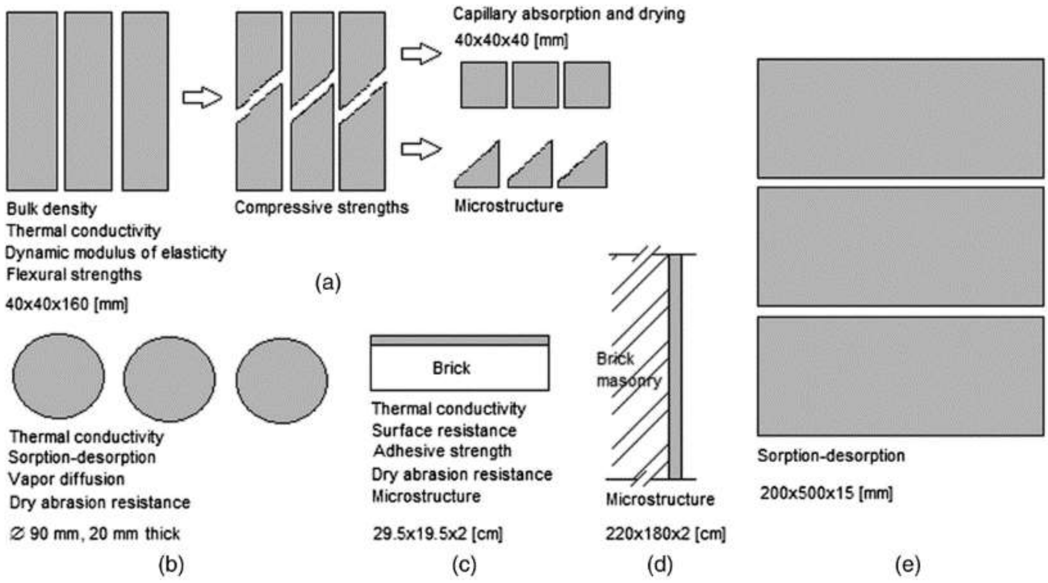

Figure 2-11: Sizes of samples for characterization of earth plasters (Faria et al., 2016)

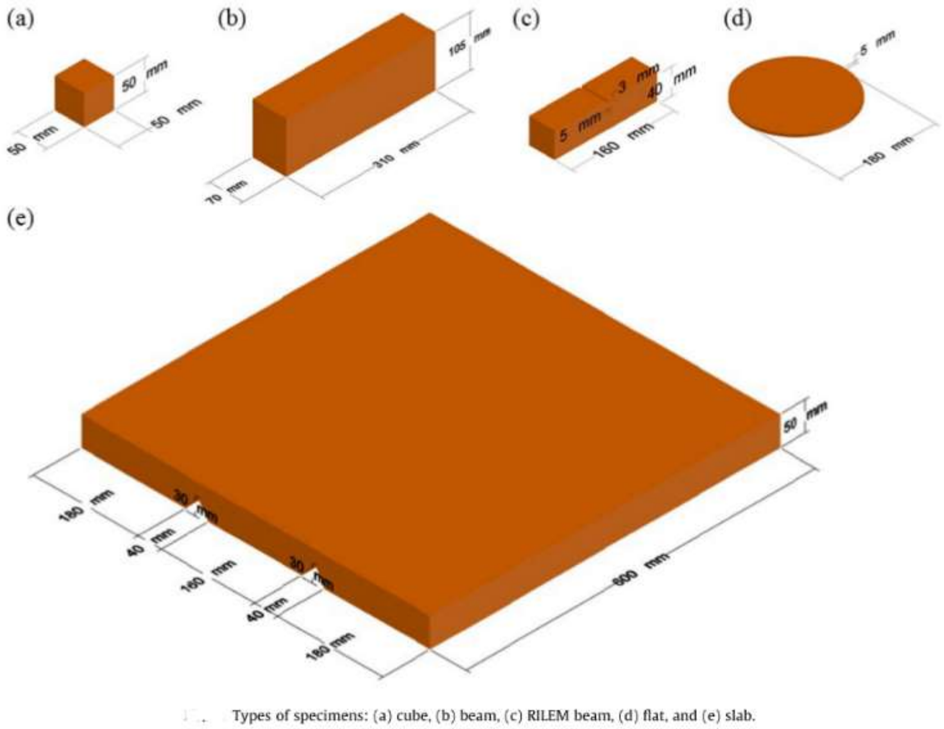

Figure 2-12: Sizes of samples for characterization of earth mortars (Araya-Letelier et al., 2019)

2.3.3 Physical Properties

Most of the authors used the samples produced for their test campaign to determine the shrinkage and bulk density of the hardened mortars. The DIN 18947 recommends the usage of 4x4x16cm³ moulds (DIN18947, 2013) for both shrinkage and bulk density.

2.3.3.1 Shrinkage

According to Lagouin et al. (2021), two different types of shrinkage should be evaluated which have a different natüre. On prismatic specimens, there is no restriction to shrinkage whereas, on walls, the surface of the wall and the interconnection of a large area prevents the size contraction due to shrinkage, thus possibly creating cracks.

A few authors (Ashour & Derbala, 2010; Tamošiūnas et al., 2016) specifically produced samples for shrinkage testing despite the literature on earth construction recommending linear shrinkage measurement (or Alcock test) on 4x4x60 cm³ samples (Avrami et al., 2008; Houben & Guillaud, 2008; Norton, 1986) or 2x2x20 cm³ samples (Minke, 2012) but most of the shrinkage measurement is done on 4x4x16 cm³ specimens.

Other authors prefer to determine the shrinkage either on wall surfaces (Hamard et al., 2013; Stazi et al., 2015; Vargas Neumann et al., 1987) or on wall elements such as bricks (Cardoso et al., 2013; Emiroğlu et al., 2015; Minke, 2011). The comparison of these different types of shrinkage (surface and prisms) have been made by Lagouin et al. (2021; 2021) but no exact relation is existing as the behaviour differs widely.

Similarly, shrinkage has been evaluated in terms of cracks development by Araya-Letelier et al. (2019, 2021) on some specifically developed samples as it has been also shown by Rojet et al. (2014) on very large samples – who additionally tested different types of the bottom to understand the impact of preventing free movement of the mortar – or Lagouin et al. (2021; 2021) on wall samples using software specifically developed for it.

Faria, dos Santos and Aubert (2016) show that the size of the sample is influencing its shrinkage as well as the shape and the support material (Rojat et al., 2014) or the drying temperature (Ashour & Derbala, 2010).

2.3.3.2 Density

The density is usually calculated on the same samples used for mechanical testing at room temperature or on oven-dried samples. Despite Minke (2012) showing that the corners of uncut specimens might have a different density than the cut samples, no authors calculated density on samples of reduced dimensions.

2.3.4 Mechanical Properties

Mechanical testing procedures of earth plasters differ according to the authors. Most of the authors only determine the compressive strength or both compressive and flexural strength of plasters on samples of different sizes and with different loading protocols.

2.3.4.1 Flexural strength

Flexural testing is made on a three-point bending device with different sizes of samples according to the procedure followed by the authors. However, usually, 40x40x160 mm^3 samples are used but some authors used specific dimensions such as very large samples with no square section (Concha-Riedel et al., 2019) or some samples cut from the produced blocks (Costi de Castrillo et al., 2021) or even directly the usage of mud bricks on 2 supports (Corrêa, Protásio, et al., 2015). A specific case is the usage of notched samples (Araya-Letelier et al., 2019; Aymerich et al., 2012) to specifically study the impact of fibres. Table A 13 in APPENDIX A gives the dimensions of the specimens used in the literature.

2.3.4.2 Compressive strength

Procedures for compressive tests are following different standards (ASTM C170, ASTM D1633 or EN 1015) with prismatic or cylindrical samples but according to the research of Pkla, Mesbah, Rigassi and Morel (Pkla et al., 2003) or Azeredo, Morel and Barbosa (2007) on earth mortars, the size, shape and presence or absence of kneecap is influencing the results of tests and that testing "*samples coming from the bending tests underestimate strength*" (Azeredo et al., 2007, p. 30). The authors suggest the usage of non-confined slender samples (height/width=2) for more accurate results and Rojat et al. (2014) show that surfacing the samples is not necessary and that orientation of samples is not an important parameter despite the orientation of fibres. Determining the accurate failure of earth plaster can also be challenging due to the ductile failure and large deformation of samples as underlined by Lerner and Donahue (2003) or Aubert, Fabbri, Morel and Maillard (2013) and therefore some authors suggest not using the maximum compressive strength but the strength at 1.5% strain (Laborel-Préneron et al., 2015). Authors working on mortars for mud bricks often used the brick itself for testing (Piattoni et al., 2011) or the combination of 2 half bricks on each other (Corrêa, Mendes, et al., 2015; Gandia et al., 2019) The dimensions of the samples used are given in Table A 13 in APPENDIX A

Not only the samples' dimensions and shapes are different but also the loading protocol with different speeds of the press varying between 0.5 mm/min (Babé et al., 2020) or 0.7 mm/min (Santos et al., 2017; Santos, Gomes, et al., 2020) to 3 mm/min (Laborel-Préneron, Aubert, et al., 2017).

2.3.4.3 Shear Strength/ adhesive strength

According to Hamard et al. (2013), in addition to shrinkage, one of the more important features of plasters is their bond to the wall. 2 types of test are described in the literature, one derived from the cement-based plaster and adopted by the DIN 18947 and one simple field test based on the adequacy of the plaster to its support. (Delinière et al., 2014; Hamard et al., 2013) The test described in the DIN 18947 is a pull-out test on a plaster sample applied on a masonry unit and its results (Figure 2-13) highly depend on the support and the preparation of the support (Delinière et al., 2014; Faria et al., 2016) whereas the other test is based on shear strength of a small sample (40x50mm) of plaster directly applied on the wall (Figure 2-14). According to Faria, et al., (2015) such tests will be more reliable to assess the real behaviour of plaster on a wall.

Sample	Standard procedure					Modified procedure			Category	
	1	2	3	4	5	1	2	4	S I	S II
Adhesive strength values (kPa)						74				
			18	25		106	98			
	38	2	22	32	4	128	100	78		
	42	5	32	103	5	169	100	79	≥50	≥100
	47	8	32	110	7	175	125	141		
	58	8	34	150	9	188	137	147		
Average (kPa)	46	6	28	84	6	140	120	111		

Figure 2-13: Adhesive strength pull-out device (Deliniere et al., 2014) (The standard procedure corresponds to the plaster directly applied on a concrete panel whereas the modified procedure consists in applying a clay slip on the concrete panel before applying the plaster)

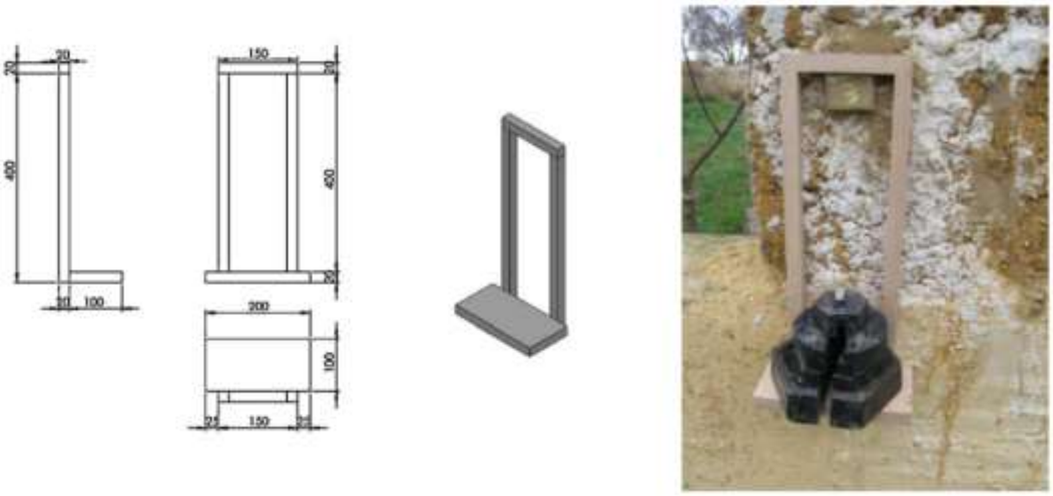

Figure 2-14: Shear strength loading device (Hamard, et al., 2013, p.111)

2.3.5 Durability

The durability of plaster is depending on several factors related to holding the properties of the plaster through time. Due to the weak resistance to shock or water of earthen plaster, the main considerations of durability are the resistance to weather conditions (rain, snow, freeze and thaw cycles, wind, sun and UV…), the water absorption, resistance to abrasion or shocks and resistance to erosion (Maheri et al., 2011; Morel et al., 2012). The review by Medvey and Dobszay (2020) explains most of the procedures used to determine the durability of earthen materials. These procedures might be standardized and easily reproducible such as the Geelong test (dip test) which simulates the resistance to rain (NZS 4298, 1998) or the brush test for abrasion (DIN18947, 2013). However, even a standardized drip test can have several variations such as the test duration, the amount of water used, and the reading of the results which are shown by the former authors in their review.

In the corpus used in this review the test and procedures used to determine the durability of the samples are presented Table A 14 in APPENDIX A. From this table, it can be understood that comparison between authors is impossible because of the diversity of tests.

The most usual laboratory tests used to assess the durability of earth construction are the ‘spray test’, the ‘drip test’, the ‘stability in static water test’ the ‘saturated-to-dry strength ratio’ and the ‘wire brush test’ (Morel et al., 2012). These tests are often used also for plasters, each research using the most convenient test and procedure according to its needs.

2.3.5.1 Liquid water resistance

The issue of earth mortar in the long-term is to resist the water therefore determining its capacity for water absorption and the change in properties due to the absorption is important.

2.3.5.1.1 Dry to saturated strength ratio

The ‘dry to saturated strength ratio test’ has been developed for stabilized earth construction and to assess the strength of saturated materials and their capacity to function. However, as underlined by Morel et al. (2012) several authors found it too severe since not representative of real weather conditions and is impossible to use with non-stabilized samples. The test consists in testing the compressive strength of water-saturated samples (Camões et al., 2012) and comparing the ratio between dry strength and saturated strength. Vilane (2010) used capillarity water-saturated blocks placed in contact with water for 7 days whereas Achenza and Fenu (2007) only dipped the samples in water for two hours.

2.3.5.1.2 Stability in water

The ‘stability in water test’ is described by Minke (2012) and the disused Turkish Mud-brick construction standard (TS 2514, 1977) and consists in hanging a sample in 5cm of water and observing its destruction rate. Turkish Mud-brick construction standard gives a threshold of 45 min for the mortar to be considered resistant. A similar test based on the polish standard BN-62/6738-02 for clay test has been used by Brzyski & Suchorab (2018).

Other authors have used similar tests by fully immersing samples in water and observing their degradation rate (Bock-Hyeng et al., 2016; Degirmenci, 2008; Lerner & Donahue, 2003; Sasui et al., 2018) or measuring their weight loss after submersion for a given period (Brzyski & Grudzińska, 2020; Brzyski & Suchorab, 2018; Corrêa, Mendes, et al., 2015; Costi de Castrillo et al., 2021). However, the experimental set-ups are fully different for each author, as different sizes of samples are used and the immersion period varies from seconds (Brzyski & Grudzińska, 2020) to days (Sasui et al., 2018) depending on the usage of plain earth or stabilized mortars (Brzyski & Grudzińska, 2020).

2.3.5.1.3 Erosion tests

According to Morel et al., (2012) the 'spray test' (Figure 2-15) "*simulates two conditions of the erosion of earth walls due to rainfall: humidification (...) and kinetic energy impinging on earth material (...).*" (Morel et al., 2012, p. 288). The spray test consists in spraying water with a shower head on the sample applied on a wall at a given distance and pressure (Eires, 2013; Morel et al., 2012). The test is conducted for 1 h or until total erosion of the sample. The size of the deeper pit is recorded at 15 minutes intervals with a 10mm diameter probe. Even if the accuracy and representativity of the test is questioned, it is easy to implement (Heathcote & Moor, 2002).

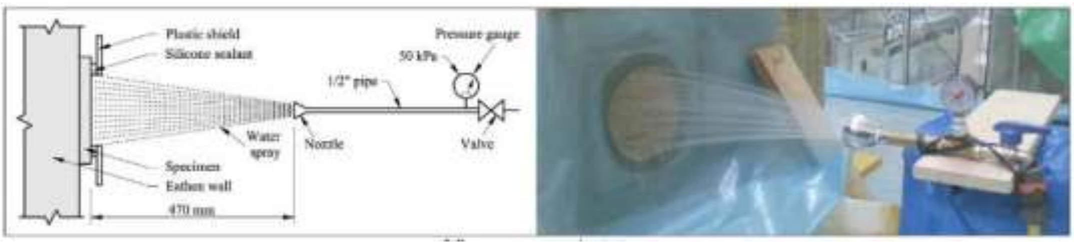

Figure 2-15: Spray test apparatus (Stazi et al., 2015)

The “drip test” or Geelong test (Figure 2-16) is recommended by Norton (1986) and codified by the New-Zealand Earth Construction Standard (NZS 4298 Materials and workmanship for earth buildings, 1998) and used by Lerner and Donahue (2003) and Ashour, et al (2010) for their test of suitable earthen plaster for straw-bale buildings. This test also represents the action of rain falling on the plaster but its accuracy to represent rainfall is questioned (Morel et al., 2012). The test consists of dripping water dripping at regular ınterval from 40cm height on an inclined sample. The sample of plaster is inclined at 30° and 100 ml of water is dripped for 30 min. to 1 hour. The deepness of the pit is then measured with a 3.15mm thick probe. However, despite the test being standardized (NZS 4298 Materials and workmanship for earth buildings, 1998) authors have modified the inclination of the sample (Stazi et al., 2015), the height of the water source (Nakamatsu et al., 2017; K. A. J. Ouedraogo, 2019) or the amount of time of water dripped according to the resistance of the samples (Achenza & Fenu, 2007; García et al., 2013; Giroudon et al., 2019)

A specific set-up called Swinburne Accelerated Erosion Test (SAET) standardized for Compressed Earth Brick is the spanish standard UNE 41410:2008 (Navarro et al., 2015) is derived from the Geelong test but with a higher amount and stronger impact of water. It has been used by some authors working with heavily stabilized mortars (Clausell & Solà, 2017; Muñoz et al., 2020)

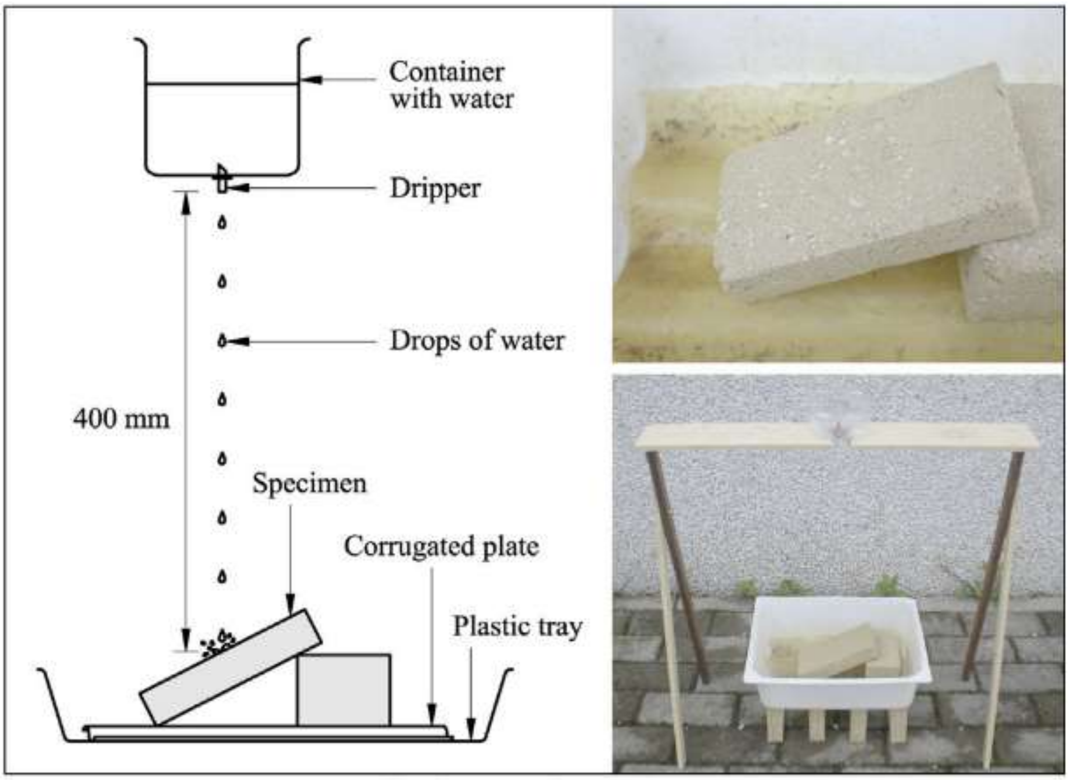

Figure 2-16: "Drip test' apparatus (Stazi et al., 2015)

Other methods for testing the resistance to rainfall testing been developed by different researchers to test only prismatic samples but are less likely used even if more accurate in the reproduction of rain conditions such as the rain simulator described by Maheri, et al. (2011) or the ones developed for testing chemical polymers stabilized plasters in Czech Republic (Svoboda & Procházka, 2012) or UK (Ogunye & Boussabaine, 2002)

2.3.5.2 Abrasion test

Abrasion tests have been developed to determine the resistance to the repetitive action of rubbing. However, due to the weak cohesion of non-stabilized earth mortar, specific set-ups have been developed and some have been standardized or comprehensive protocols have been written.

The German Standards for earth plasters (DIN18947, 2013) describes a test involving the rotation of a plastic brush loaded with 2kg. However, despite this test described in the standards, only a few authors have been using it (Laborel-Préneron et al., 2021; Lima et al., 2020; Santos et al., 2018) and the exact type of brush used hasn't been given which can lead to very different results according to Faria et al. (2016) which tested similar mortars with 3 different types of brushes.

Another test, derived from the French Standard for CEB has been more widely used and even described in the French Protocol for Earth Plaster (*Guide de bonnes pratiques des enduits en terre,* 2016). This test is based on the movement forth and back of a brush with metallic wires loaded with a specific load (Giroudon et al., 2019). However, authors using this test have used different protocols in terms of loads and movements of the brush.

The sand erosion test has been used by Atzeni et al. (2006, 2007) for determining the resistance of the surface to sand storms.

2.3.5.3 Behaviour under cyclic conditions

'Freeze and thaw test and 'humidity expansion test' are tests based on the cyclic behaviour of material and allow to determine the resistance and compatibility of plasters with other materials.

The 'freeze and thaw test' is standardized in the ASTM D560 and consists in placing a sample in saturated conditions at -23°C and then +23°C. The surface is brushed between cycles and the amount of material removed is calculated. According to Morel et al. (2012) despite a large usage, this test is too severe for earth samples.

The 'humidity expansion test' (Bourges et al. in Vissac et al., 2013) consists in placing the sample in a climatic chamber and quickly changing the humidity level and monitoring the dimension of the samples.

2.3.5.4 Durability field tests:

A more reliable test for durability includes the long-period testing of plaster under real conditions. According to Morel et al. (2012), such tests are more reliable than weathering tests to determine the durability of walls. This test can be made on wall samples such as described by Agnew (1990) Lawrence, Heath and Walker (2009) or Faria et al. (2014) or only on samples exposed to weather (Bourges, et al. in Vissac et al., 2013). According to these authors, exposition to weather can also determine the changing of appearance and aesthetics due to ageing.

2.3.5.5 Impact tests

The resistance of plaster to impact has been tested with three different methods on specially made walls – ultrasound, a durometer following the ASTM D2240 and a pendular sclerometer based on the ASTM C805 by Faria et al. (2014). According to the authors, the results differ for the same plaster depending on the wall material and the testing procedures with not all the devices suitable for all wall types.

Another type of impact test is presented by Giroudon et al. (2019) which consists in projecting a small metallic ball on the wall. However, according to the authors, the results of the test are difficult to understand as they are only qualified by the diameter of the impact point.

2.3.6 Surface properties

Surface properties are the resistance of the uppermost layer of the mortar and determine the durability of the surface against impact, abrasion or water penetration.

The surface water penetration – which determines the impact of water on the plaster – has been tested through two new procedures by Bourges, Anger, Fontaine and Joffroy (2012). The angle formed by a drop of water placed on the samples is calculated and it determines if the surface of the mortar is hydrophilic or hydrophobic. Pictures are taken at different time intervals and the angle is measured to determine the 'wettability' of the surface (Stazi et al., 2015). The second procedure determines the capillarity absorption of the surface layer through the pressing of a humid sponge on the plaster with a determined pressure and time and measuring the amount of water passing to the plaster. However, according to Colas & Bourges (2013) who used a test developed for testing on-site wall materials the sponge is pressed on the sample placed vertically whereas Paul and Changali (2020) placed the sample on the sample hold horizontally.

Another usual test dealing with surface cohesion is the tape test as described by Colas & Bourges (2013) which consists in determining the amount of plaster sticking on a tape after removal of the tape. However, as explained by Faria et al. (2016) this test is not very standardized and only using the mass of the material detached could lead to mistakes. The authors proposed also a visual characterization of the material stuck on the tape. Other authors proposed to place a mass during a certain period on the tape to achieve similar pressure on all tested specimens (Santos et al., 2018).

2.3.7 Hydric properties

Hydric properties of earth mortars deal with the water absorption of the mortar – absorption rate and amount – and the water desorption and drying rate.

2.3.7.1 Water capillarity absorption

Water capillarity absorption of earth plaster samples is usually made following modified procedures either from the EN 1015 (Faria et al., 2016), the DIN 52617 (Minke, 2012; Straube, 2003), LNEC (Camões et al., 2012; Eires, 2013) or Rilem TC 25-PEM (Gomes et al., 2012). The test consists in calculating the rate of water absorbed by the sample during a determined time either by laying the sample in water. Because of the nature of the sample, test procedures are modified as explained by Minke (2012) or Faria et al. (2015). A thin cloth or filter paper (Guihéneuf et al.,

2020) is fixed on the bottom part of the sample that is in contact with water – directly or indirectly through the usage of a sponge - to prevent material loss and sides are waterproofed with resin or polyethene film (Faria et al., 2016) or samples are laid on wet sand (Camões et al., 2012). Sizes of samples are depending on the researchers from prismatic 4x4x4cm for Faria et al. (2015) to 25x25x5cm (Straube, 2003) or cylindrical samples (Eires, et al. 2012, 2013). As suggested by Guiheneuf et al. (2020), the amount of water absorbed depends on the thickness of the sample since the capillarity forces are governing the absorption until the top surface of the sample is reached and then the saturation is attained by the dissolution of air in water. Therefore sample dimensions are important for the comparison of the total absorption. This process is visible in Figure 2-17.

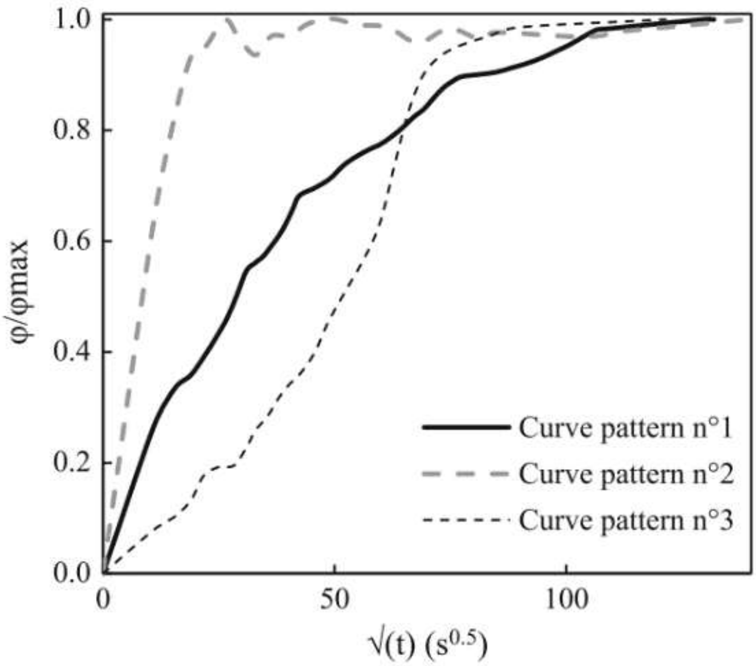

Figure 2-17: Water capillarity patterns with different times of reaching the surface of the sample and different absorption rates.

Karsten tubes following the recommendation of Rilem II.4 are also used to determine the water capillarity of samples (Bourgès et al., 2012; Minke, 2012; Stazi et al., 2015) without impacting the results (Minke, 2012) and allowing on-site experiments (Bourgès et al., 2012; Navarro et al., 2015). Samples are sometimes placed vertically (Lima et al., 2020) and sometimes horizontally (Lišková et al., 2016)

Other experimental procedures have also been followed by different researchers based on the observation of the capillarity rise and water level in the samples (Araya-Letelier et al., 2021; Corrêa, Protásio, et al., 2015; Pinto et al., 2014) or by the measurement of the weight increase for samples placed during a short time in water (Ashour, Bahnasawy, et al., 2010; Bock-Hyeng et al., 2016; Braun, 2017b)

2.3.7.2 Drying behavior

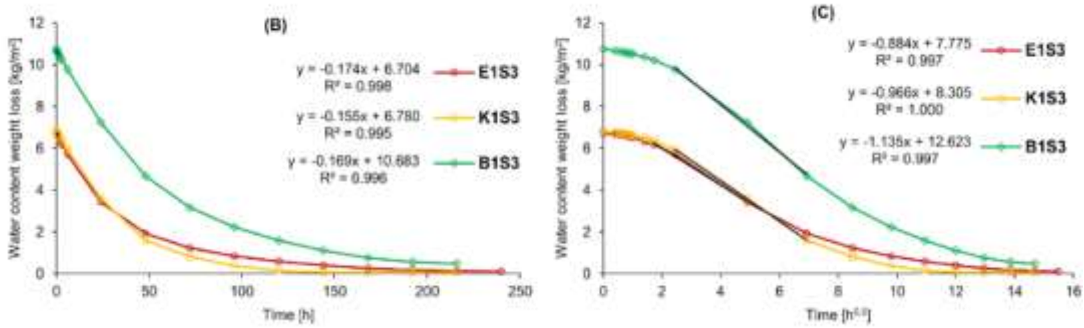

Figure 2-18: Determination of the pDR (left) and sDR (right) as shown by Lima et al. (2020)

Drying behaviour is assessed by modifying the procedures of EN 16322 (Faria et al., 2016), RILEM Test No. II.5 (Faria & Santos, 2014) or Rilem TC 25-PEM (Gomes et al., 2012) on the same samples used for water capillarity absorption. Non-saturated samples are used to calculate the drying behaviour or the drying index (Faria et al., 2016). According to Lima et al. (2020), the drying behaviour can be separated as primary drying and secondary drying which represent respectively the desorption of water and the drying by evaporation of water vapour. Figure 2-18 shows the difference between these 2 behaviours.

2.3.8 Hygric properties

The hygric properties of mortars consist in determining how much a material will adsorb and desorb water vapour which is important for the humidity regulation of a room and then transfer it to its environment which is important for the combination of materials together in a wall. In addition, sorption isotherms are determined to understand the impact of the environment on the adsorption rate.

2.3.8.1 Water vapour permeability

Water vapour permeability of earth plaster is standardized in the DIN 18947 on 9 cm diameter 2 cm thick samples (Faria et al., 2016; Faria & Santos, 2014) but also modified procedures from EN 1015 (Eires, 2013; Liuzzi et al., 2013), ISO 12572 (Fouchal et al., 2015; Simons et al., 2015), EN 15803 (Stazi et al., 2015) and ASTM E96 (Straube, 2003) based on the wet cup and dry cup procedures have been used. The sample thickness varies between 1 cm (García et al., 2013) and 5 cm (Laborel-Préneron et al., 2018) and the open surface is also of different sizes.

Samples' sides are waterproofed and samples are placed above a cup of water and the assembly is placed in a chamber at constant RH and temperature (Laborel-Préneron et al., 2018). The decrease in weight of the assembly due to humidity transfer through the sample is then measured and the coefficient of water vapour permeability is calculated. The procedure described by Straube (2003) involve also a double box system to keep the samples at a constant humidity level. Fouchal et al., (2015) tested the same samples with the wet cup and the dry cup. The permeability of samples was found dependent on the type of test.

2.3.8.2 Water vapour adsorption and desorption

According to DIN 18947 (Faria et al., 2016), the sorption/desorption rate is to be determined on large samples (15x200x500mm) by varying the moisture level of a climatic chamber from 50% to 80% and back forwards at given time intervals. However, the same authors also used smaller samples and different thicknesses and showed that the sorption/desorption rate is not largely affected by the size of the sample.

2.3.8.3 Sorptions isotherms

Sorption isotherms for earthen mortar are determined according to ISO 12571 (Fouchal et al., 2015; Liuzzi et al., 2013; Liuzzi & Stefanizzi, 2014) or ISO 12271 Equilibrium moisture content (Ashour et al., 2011). Samples are placed in climatic chambers where the temperature was fixed at 23 °C, and the relative humidity (RH) was varied in steps at 20, 30, 50, 65, 80, and 95% RH. The samples are weighed regularly to determine the weight evolution curves as a function of the time and the equilibrium moisture content is recorded. Laborel-Préneron et al. (2018) used different salts to create the same effect of a humid environment while comparing the results with the Dynamic Vapour Sorption (DVS) methods have shown that results are similar.

CHAPTER 3

MATERIAL AND METHODOLOGY

This Chapter presents the materials and the methodology used for this research. The first part of the chapter will present the materials used for the production of mortars, whereas the second part will present the different experimental set-ups used to determine materials and samples properties and the last part will present the different mortars used to create samples.

3.1 Research Materials

To prepare the various earth plasters, local clayey earth, and several types of sands and fibres have been used. Most of them have been collected locally or were easily available in local shops. These have been classified under four groups; i.e. types of earth used, types of aggregates, types of fibres, and additives to improve the plaster properties. a visual description of these materials as well as their provenance and their preparation are given in the following sections.

3.1.1 Earth

The earth used for the experiment was taken from the Sahmuratli village in Sorgun, Yozgat area in the Central Anatolian region of Turkey. It is a whitish clayey earth that includes some granite stones and unidentified brittle white lumps. This earth has been locally used to produce mud bricks for the construction of the village as well as for plastering the walls.

3.1.2 Sands

The sands for the mortars were obtained from local sources. Ten types of sand with different PSD or grain shapes were selected. Before adding them to the earth mortar, the sands were dried and sieved to obtain the desired particle size distribution (PSD).

The colour and particle size of the sands were used to easily identify the different types of sand used in the experiments.

3.1.2.1.1 Grey Sand (GS)

The commercial plaster sand obtained from Sorgun (from where the earth was also obtained) was used as the reference sand and called the grey sand (**GS**) due to its colour; its grains have subangular edges and a slightly higher content of fine particles than the other commercial plaster sand used in these experiments.

This sand was passed through a 4.5 mm sieve to obtain the coarse grey sand (**CGS**).

3.1.2.1.2 Yellow Sand (YS)

Another plaster sand was obtained from Ankara having a yellowish colour and more mid-sized grains with very sharp angles. This sand was sieved thrice: first with a 2mm sieve to obtain the so-called yellow sand (**YS**), then with a 4.5 mm sieve to obtain the coarse yellow sand (**CYS**) and finally with a 0.8 mm sieve to obtain the fine yellow sand (**FYS**). Yellow Sand was also washed to take away the fine particles (below 0.8mm). This sand was called washed yellow sand (**WYS**)

3.1.2.1.3 White Sand (WS)

Other sands used were: white sand (**WS**) which is commonly used for cement concrete, and which has a large number of fine particles and which has been sieved with a 2mm sieve to eliminate particles larger than 2mm. This sand was also washed to take away the fine particles (below 0.8mm) and the resulting sand was called Washed White Sand (WWS)

3.1.2.1.4 Silicate Sand (Si)

A light yellow graded siliceous river sand (**Si**) with round grains; and a coarse siliceous river sand (**CSi**) mostly composed of particles between 1 and 2 mm. Si and CSi sands were commercially available without fine particles.

Grey Sand and Yellow Sand are both considered reference sands. Two types of references sands were used as the continuity of the delivery could not be ensured.

The physical characteristics of these sands, i.e. grain shape, size and colour, and loose bulk density of the sand, as well as information on whether it was washed or not before use, are given in Table 4-3 while Figure 3-1 shows the different sands used in the production of earth mortars.

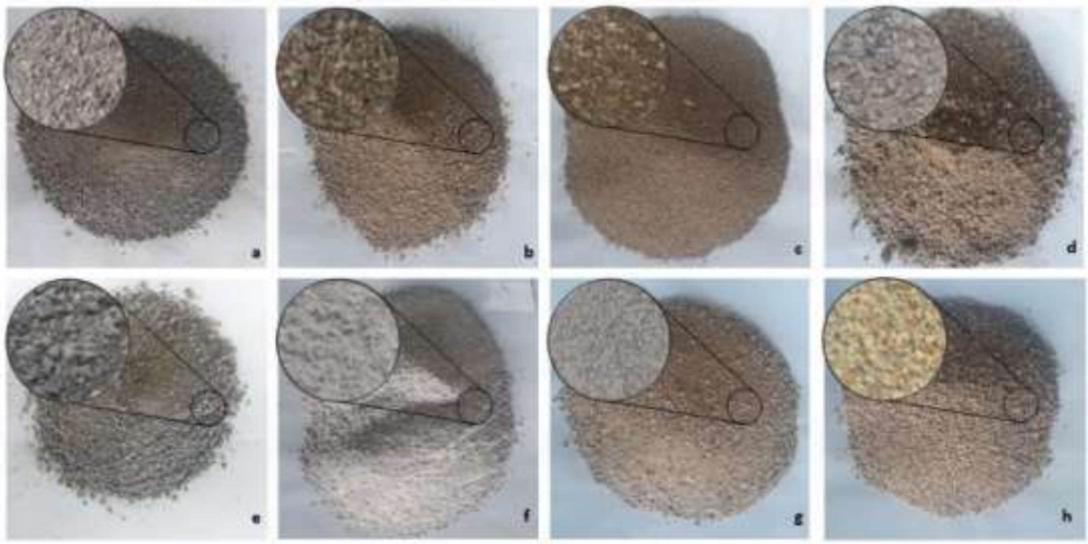

Figure 3-1: A selection of sands used for the earth mortars (a: Grey Sand, b: Yellow Sand, c: Fine Yellow Sand, d: Coarse Yellow Sand, e: Coarse Grey Sand, f: White Sand, g: Siliceous Sand, h: Coarse Siliceous Sand)

3.1.3 Fibres

Different types of fibres have been used in the production of plasters, from plant or animal origins. One synthetic fibre that is conventionally used for reinforced concrete has also been tested in earth plasters. Table 3-1 summarizes the description of the different fibres used in the production of experimental earth plasters. They are also described in the following sections.

3.1.3.1 Plant fibres

Plant fibres used in this research were wheat threshing (chaff and straw) with different preparation methods, flax as an easily available fibre and pine needle as a local replacement for chaff.

3.1.3.1.1 Chaff and straw

The main type of fibre used (called Chaff - Ch) was a mix of chaff and broken straw coming from the same village (Şahmuratli) as the earth. This mix is usually used as animal fodder for winter months by the villagers and consists of the top part of the wheat stalks broken down into short pieces and cleaned of the grains. It is used by the villager in the earth plasterwork as shown by archaeologists in their restoration work (Seeher, 2007).

4 other types of fibres derived from this mix have been used: Chaff has also been sieved with 2 different sieves to determine the impact of using fibres without dust and small fibres (WCh) and of using only small fibres (SCh); on one occasion, chaff has been put in water for 48h (Ch48h) and for 2 months (Ch2m) to see the effect of using water-saturated fibres as to prevent using a high amount of water (Andres et al., 2016a).

Wheat straw (coming from the thick part of the stalk) has also been used after having been manually cut into small pieces (4 cm length max.). The main difference with

Chaff is the length, the thickness of the fibres and the number of hollow fibres. It is called Straw (St) in this study.

3.1.3.1.2 Other fibres

Flax fibres (Fl) coming from a construction store have been used. Flax fibres are used to enhance the seal provided by the gasket in plumbing pipe connections and are long and very thin fibres. They have been cut into 3 cm length fibres on average.

The last type of plant fibre is local pine needles (PN). Dry pine needles from a pine species (Scott Pine) producing short needles have been collected on the ground and their impurities removed. Their average length is about 3 cm. Pine needles have been selected as they are sometimes used as fibre replacement in mud-brick production (Sharma et al., 2016)

3.1.3.2 Animal fibres

Three types of animal fibres have been used, one type of cow hair, and two types of sheep wool.

Cow hairs (Co) have been shaved on cow skin, washed and boiled to remove the attached cow dung and cut into 3-cm-long to 4-cm-long pieces.

Sheep wool comes from a shop and is usually used to make blankets. The chosen wools are washed wools of two types of sheep. One type is long straight fibres (LW) and the other one is thinner and more curly fibres (SW).

3.1.3.3 Synthetic fibres

Polyethene fibres used for reinforced concrete have also been used. They are white fibres with a non-smooth surface. Their length is about 6 cm.

Table 3-1: Fibres type and visual descriptions

Name	Code	Provenance	Maximum Thickness (mm)	Fibre Length (mm)	Description	Preparation
Plant Fibre						
Chaff	**01**	Wheat threshing	3	0 - 30	Brittle & dusty, large & small particles	Not required
Clean Chaff	**10**	Wheat threshing	3	5 - 30	Clean large particles	Separated from dust
Short Chaff	**12**	Wheat threshing	2	5 - 10	Clean small particles	Separated from dust & sieved
48 h. water-saturated Chaff	**02**	Wheat threshing	3	0 - 30	Brittle & dusty, large & small particles	Plunged in water for 48 h.
2 months water-saturated Chaff	**03**	Wheat threshing	3	0 - 30	Brittle & dusty, large & small particles	Plunged in water for 2 months.
Straw	**11**	Wheat Straw	5	30 - 40	Resistant to tear, large fibres	Cut to size 40 mm
Flax	**06**	Shop bought	1	25 - 30	Very flexible and long fibres	Cut to size 30 mm
Pine Needles	**05**	Pine Tree	2	10 -40	Very brittle, rough fibres	Cleaned from other organic elements
Animal Fibre						
Cow Hair	**07**	Cow skin	2	30 - 40	Thick fibres, stiff	Washed, boiled, and cut to size 40 mm
Long Wool	**08**	Shop bought	1	10 - 70	Thin fibres, flexible, difficult to separate	Bundles manually separated
Short Wool	**09**	Shop bought	1	10 - 40	Thin fibres, very curly	Bundles manually separated
Synthetic Fibre						
Polyethene fibre	**04**	Shop bought	3	60	Thick, very stiff, rough	Not required

3.1.4 Additives

12 types of additives have been used for the stabilization of plasters. All of them are natural additives, either directly extracted from natural materials or waste materials from the agricultural industry. Most of them are commonly used additives for earth construction such as cow dung, casein, egg-white or flour paste; whereas others are local additives or were used because of their potential impacts on the properties of earth materials. Table 3-2 summarizes the properties of the additives which are classified below according to their active polymers.

3.1.4.1 Polysaccharides

Polysaccharides coming from 5 different products have been used in this research.

3.1.4.1.1 Fermented fibres

Two types of fermented fibres from 2 different sources of fibres have been tested

a- *decomposition juice of hay*. Fresh hay has been cut locally and then put in water. It has then been let to wait in water in anaerobic condition for 6 months following the recipe of T. Rijven cited by Vissac et al. (2013)

b- *juice of straw*. Chaff used as fibres have been let to steep in the water for 2 months and this water has then been used.

3.1.4.1.2 Hollyhock products

Two types of juice have been produced from the hollyhock plant, following different sources. Hollyhock stalk juice (HSJ) has been made by cutting the stalks into small pieces and boiling them for 1 hour. Hollyhock flower juice (HFJ) has been made by keeping fresh flowers in water at ambient conditions for 2 weeks.

3.1.4.1.3 Starch

The starch used in this research has been integrated into the mortar as a flour paste following Vissac et al. (2016)'s procedure. Commercial white wheat flour and tap water have been used as the main component of the flour paste. 1 L of flour (695g of flour) has been mixed with 6 L of water and then boiled for 5 min. until obtaining a thick and sticky paste. It has then been let to cool down before being used.

The flour paste has been mixed with the dry component of the mortar without previous dilution. Its quantity has been determined as part of the liquid needed to make the plaster mortar and then converted into a % per weight.

3.1.4.1.4 Molasses

Non-processed industrial molasses has been bought from a sugar factory using sugar beets. It is a dark brown viscous and sticky product with a density of 0.98. It has a very strong smell.

Molasses has been added directly to the dry mortar without being diluted with water.

3.1.4.2 Lipids

Two types of lipids (linseed oil and olive oil) with different provenances and properties have been used for the research.

3.1.4.2.1 Linseed oil:

A commercial linseed oil sold under the name “refined” linseed oil has been used this oil has a specific gravity of 0.927 – 0.933 gr/cm³ and a low acid value. It has a strong smell and a very gluey touch.

The amount of oil used has been determined according to previous research as a % of the dry mass or reference mortar. It has been added to the dry mortar before the addition of water.

3.1.4.2.2 Used frying oil

Olive oil was collected from a family kitchen after it has been used for frying vegetables. It has been sieved and the suspended particles have been removed before usage. It is characterized by a strong smell and is more liquid than linseed oil.

Oil has been added as a percentage of the total volume of dry materials similar to the one used for linseed oil. Used cooking oil has been added to the dry earth mortar before the addition of water.

3.1.4.3 Proteins

Two types of proteins have been used in this research, albumin coming from egg whites and casein from milk.

3.1.4.3.1 Egg white

Egg whites have been extracted from fresh eggs bought in the market and special care has been taken not to include any yolk. Egg whites have been diluted in water before being added to the dry mix.

3.1.4.3.2 Casein

Casein has been extracted from milk in the laboratory. Two litres of whole milk have been mixed with vinegar at a low temperature. The solid obtained (mostly casein molecules) have been separated from the whey and then ammonia has been added to dissociate the casein molecules and improve fluidity.

3.1.4.4 Complex mixes

Two types of complex mixes have been used which contained both proteins and lipids.

3.1.4.4.1 Mayonnaise

Mayonnaise made from linseed oil and egg yolk has been made following the recipe of Tom Rijven (in Vissac et al., 2013, p. 30). 5 yolks taken from commercial eggs have been whipped with half a litre of linseed oil until obtaining a lasting emulsion.

3.1.4.4.2 Cow-dung

Fresh cow dung. The cow dung has been used humid, a few days after being collected on a farm where animals were fed only with dry hay and straw.

Dried cow dung. The cow dung has been used after it was passed through a processor that shreds the fibres and extracts the liquid. Then it has been air-dried in the sun for about one month before being stored.

Table 3-2: Additives type and visual description

Type/name		Provenance	Preparation	Consistency
Polysaccharides				
Juice of fermented hay	02	decomposition of hay	fresh hay cut and left to decompose for 6 months in water)	liquid
Molasses	06	sugar factory	none	viscous - sticky
Flour paste	05	white wheat flour	flour mixed with water and boiled	viscous
Hollyhock mucilage	13	hollyhock stalk	boiled during 3h	liquid
hollyhock flowers mucilage	14	hollyhock flowers	let to decompose in water and then boiled	liquid
Straw washing water	09	decomposition of straw	juice of straw let to decompose during 1 month in water	liquid
Lipids				
Used frying oil	08	olive oil waste from frying	sieved	viscous
Linseed oil	10	commercial	none	viscous - sticky
Proteins				
Egg white	01	commercial	separation of white and yolk	viscous
Casein	15	from milk	separation from milk and then dissolution of the paste	liquid
Complex mix				
Mayonnaise	11	linseed oil and yolks	Mix from linseed oil and yolks	sticky
Fresh cow dung	07	cow-farm	none	viscous - fibres
Dried cow dung	12	Cow-farm	Cowdung passed through a processor and air-dried in the field	Thin fibres

3.2 Composition of mortars

Several mortars were produced to determine the impact of different stabilizers on the properties of earth plasters. As this research started with a material whose needs for stabilization were unknown a preliminary study was made using only earth, conventional fibres (chaff) and conventional aggregates (plaster sand) in order to determine the optimum composition in terms of shrinkage and mechanical strength. This preliminary study allowed the researchers to determine a reference plaster that has been altered subsequently by the addition of additives or the exchange of some of its components (chaff and sand) for alternative ones.

As the properties of the plaster can also be impacted by several parameters exterior to its composition, some of these parameters – water amount, settling time, sample size) were tested to determine their impact on the main properties of the plasters.

The different mortars that were prepared for this research are presented in the paragraphs below.

3.2.1 Preliminary study

The first set of mortars was made and tested to determine a reference mortar that was to be used throughout the research. The reference mortar was made by iteration steps altering slowly the reference earth by adding a small amount of sand, chaff and water. The different mortars used to determine the reference mortars are given in Table 3-3.

The aggregate amount was determined by varying the volume of aggregates from 20% to 75% of the mix.

The impact of fibre was determined by varying the volume of fibre from 5% to 50% of the mix.

To determine a more appropriate mix, both aggregate and fibres were added to the mortar and their amount was varied. The volume of aggregate varied from 25% to 57% of the mortar and the volume of fibres varied from 14% to 33% of the mix.

Table 3-3: Design of mortars using sand and/or straw with earth

	Volume	Volumetric ratio (by volume of mix)		Volumetric ratio (by volume of earth)	
	Earth	*Sand*	*Fibre*	*Sand*	*Fibre*
Earth	100	0	0	0	0
Sand 20	80	20	0	25	0
Sand 33	67	33	0	50	0
Sand 50	50	50	0	100	0
Sand 67	33	67	0	200	0
Sand 75	25	75	0	300	0
Straw 5	95	0	5	0	5
Straw 10	90	0	10	0	11
Straw 20	80	0	20	0	25
Straw 30	70	0	30	0	42
Straw 40	60	0	40	0	66
Straw 50	50	0	50	0	100
Sand/Straw 25/25	50	25	25	50	50
Sand/Straw 33/33	34	33	33	100	100
Sand/Straw 30/20	50	30	20	60	40
Sand/Straw 40/20	40	40	20	100	50
Sand/Straw 53/20	37	53	20	145	55
Sand/Straw 57/14	36	57	14	160	40

3.2.2 Impact of the different materials

After determining the reference plaster and the optimum amount of fibres and aggregates, the impact of different stabilizers were studied by either substituting one of the components (fibre by another type of fibre or aggregates by another type of aggregate) or by adding some materials in the mix.

3.2.2.1 Impact of aggregates

The impact of aggregates on the plaster properties was studied by substituting the reference sand with other types of aggregates as described in Paragraph 3.1.2 and keeping the aggregate amount and aggregate type as in the reference plaster.

3.2.2.2 Impact of fibres

The impact of fibres on the plaster properties was studied by substituting the reference straw with other types of fibres as described in Paragraph 3.1.3 and keeping the fibre amount and fibre type as in the reference plaster.

3.2.2.3 Impact of additives

The impact of additives was studied by adding different types of additives to the reference mix. The additives added are presented in § 1.1.121. The different additives were added in different quantities according to previous work underlined in the literature review. Table 3-4 shows the quantity of additives added to the mortars either by volume or by weight depending on the type of additives.

Table 3-4: Quantity of additives in the mortar

Additive naming code	Additive	Quantity	Measurement
01	Egg- white	0.33 - 0.66 - 1	egg/L soil
02	Hay juice	0.01 - 0.05 - 0.1 - 0.7	L/L dry earth
04	Flour paste	0.175 - 0.325 - 0.75	L/L dry earth
07	Fresh cow dung	0.25 - 0.375 - 0.5	L/L dry earth
12	Dried cow-dung	5.6	% wt. dry mix
13	Hollyhock stalk juice	0.625	L/L dry earth
14	Hollyhock flower juice	0.5	L/L dry earth
09	Straw juice	0.66	L/L dry earth
08	Used oil	2 - 4 - 6 - 8	% wt. dry mix
10	Linseed oil	1 - 2 - 4 - 6	% wt. dry mix
11	Mayonnaise	1 - 2 - 3	% wt. dry mix
15	Casein	2 - 5 - 10	% wt. dry mix
06	Molasses	2 - 5 - 15 - 20	% wt. dry mix

3.2.3 Summary of the mortars

For the research, a total number of 122 mortars have been prepared and are presented in Table 3-5: Composition of mortars made by mixing only earth and water and the number of samples and their dimensionsTable 3-5 to Table 3-14. These tables summarize the composition of the mortars and give the names used throughout the study. The term mortar should be here understood in a broad way, i.e., not only the composition of the mortar in volume – and the materials used – might differ, but also its composition by weight, the water amount, and the settling time. For these reasons some mortars that might seem the same at first look might have 2 different names.

The names of the mortars are given as such and as explained in Figure 3-2;

- The two first digits represent the additives,
- the 2 two middle digits represent the aggregates and

- the two last digits representing the fibres.
- The digits placed after the dash represent the amount of materials (earth, sand, fibre) and then, the number of the mortar with the same composition.
- When mortars are not made with any stabilizer, the code is simplified in the second part to ease the reading.

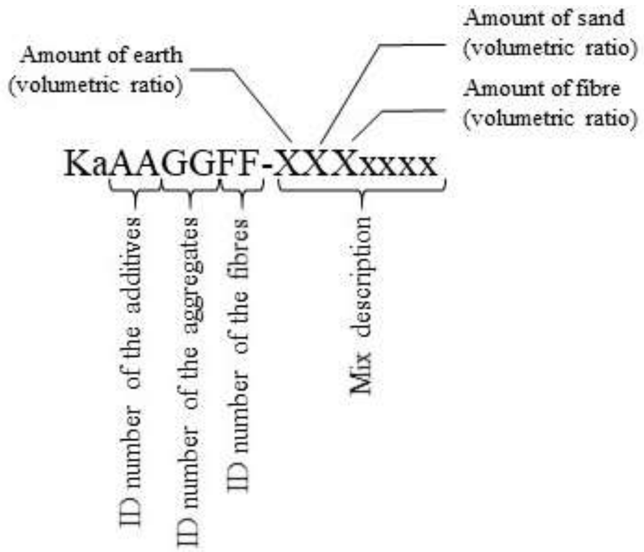

Figure 3-2: Explanation of the name of the mortars

The different types of mortars have been grouped according to their content in different tables for a better understanding.

- The mortars Ka000000-01 to Ka000000-12 (12 mortars, Table 3-5) were prepared only with earth as a binder and water.
- The mortars Ka000100-**20**1 to Ka000200-**50**1 (11 mortars,
-
- Table 3-6) were prepared with earth as a binder and sand. Grey Sand (mortars starting with Ka000100) and Yellow Sand (mortars starting with Ka000200) were used. The amount of sand added is recorded in the name of the mortars, the two digits after the dash giving the amount of sand as a volumetric percentage in the mix.

- The mortars Ka000001-**05**01 to Ka000001-**50**04 (25 mortars, Table 3-7) were prepared with earth as a binder with chaff. The amount of chaff varies from 5% by volume to 50% and it is recorded in the name as the two digits after the dash (05 for 5% and 50 for 50%)
- The mortars Ka000101-**111**001 to Ka000101-**483**001 (13 mortars, Table 3-8) were made by mixing earth as a binder with Chaff and Grey Sand. Grey Sand has been added in volume varying from 30% to 57% whereas Chaff has been added in volume varying from 20% to 33%. The three digits after the dash represent the relative amount of earth (1^{st} digit), aggregate (2^{nd} digit) and fibres (3^{rd} digit), e.g., the mortar Ka000101-**483**001 contains 4 parts of earth, 8 parts of sand and 3 parts of fibres.
- The mortars Ka000201-2210001 to Ka 000201- 2210014 (10 mortars, Table 3-9) were made by mixing earth as a binder with Chaff and Yellow Sand. For all mortars, 40% of earth, 40% of Yellow Sand and 20% of Chaff by volume have been mixed.
- The mortars Ka00**03**01-221001 to Ka00**10**01-221001 (8 mortars, Table 3-10) were made by mixing earth as a binder with Chaff as fibre and alternative aggregates. For all mortars, 40% of earth, 40% of aggregates and 20% of Chaff by volume have been mixed. The two middle digits of the name indicate the aggregate that has been used, e.g., Ka00**03**01, which means that aggregate 03 (Coarse Grey Sand) has been used (Table 4-2 and Table 4-3).
- The mortars Ka0001**02**-221001 to Ka0002**12**-221001 (11 mortars, Table 3-11) were made by mixing earth as a binder with Grey Sand or Yellow Sand as aggregates and alternative fibres. For all mortars, 40% of earth, 40% of sand and 20% of fibres by volume have been mixed. The two last digits of the name indicate the aggregate that has been used, e.g., Ka0002**12**, which means that fibre 12 (Short wheat straw) has been used.
- The mortars Ka**01**0101-221051 to Ka**06**0100-210201 (49 mortars, Table 3-12 and Table 3-13) were prepared by mixing the reference mortar (2 earth, 2 sand and 1 fibre by volume) with different additives. Table 3-12 presents the mortars made with Grey Sand and Table 3-13 presents the mortars made with

Yellow Sand. The type and amount of additives put in the mortar are recorded in the name with the two first digits representing the code of the additive and the middle digits after the dash representing the amount of additives, e.g., Ka**01**0101-221**05**1 means a mixing using 05% of egg whites (additive 01).

- The mortars Ka060100-210021 to Ka060100-201201 (4 mortars Table 3-14) were prepared using only earth and Grey Sand as mixing organic fibres and molasses is not suitable. They were prepared with 66% of earth by volume and 33% of Grey Sand. The 2 middle digits after the dash give the amount of additive use, e.g., Ka**06**0100-201**20**1 means 20% of molasses (additive 06)

Table 3-5: Composition of mortars made by mixing only earth and water and the number of samples and their dimensions

Mix name	Amount of earth (%vol.)	Amount of earth (% weight)	Amount of water (%wt.)	Type of sample	Number of samples	Settling time (days)
Ka000000-01	100	100	17%	16x4; 24x20	4	0
Ka000000-02	100	100	20%	16x4	3	0
Ka000000-03	100	100	24%	16x4	3	0
Ka000000-04	100	100	31%	16x4	3	0
Ka000000-05	100	100	n.a.	16x4	3	1
Ka000000-06	100	100	n.a.	16x4	3	1
Ka000000-07	100	100	n.a.	16x4	3	2
Ka000000-10	100	100	n.a.	24x20	2	2
Ka000000-11	100	100	33%	30x7; 24x20	4	0
Ka000000-12	100	100	40%	16x4; 24x20; 30x7	8	2

Table 3-6: Composition of mortars made by mixing earth as a binder and Grey Sand and Yellow Sand as an aggregate with water and the number of samples and their dimensions

	Amount of earth (%vol.)	Amount of earth (% weight)	Type of aggregate	Amount of aggregate (%vol)	Amount of aggregate (%wt.)	Amount of water (%wt.)	Type of specimen	Number of specimens	Settling time (day)
Ka000100-201	80	83	Grey Sand	20	17	32	30x7; 24x20	6	0
Ka000100-331	67	61	Grey Sand	33	39	26	16x4; 24x20	7	2
Ka000100-332	67	60	Grey Sand	33	40	26	30x7; 24x20	5	0
Ka000100-501	50	43	Grey Sand	50	57	22	16x4; 24x20	5	2
Ka000100-502	50	43	Grey Sand	50	57	23	30x7; 24x20	5	0
Ka000100-671	33	27	Grey Sand	67	73	21	16x4; 24x20	7	2
Ka000100-672	33	31	Grey Sand	67	69	14	24x20	4	2
Ka000100-673	33	28	Grey Sand	67	72	21	30x7; 24x20	4	0
Ka000100-751	25	20	Grey Sand	75	80	19	16x4; 24x20	7	2
Ka000100-752	25	20	Grey Sand	75	80	19	30x7; 24x20	5	0
Ka000200-501	50	46	Yellow Sand	50	54	21	30x7; 24x20	6	0

Table 3-7: Composition of mortars made by mixing earth as a binder and Chaff as a fibre with water and the number of samples and their dimensions

	Amount of earth (%vol.)	Amount of earth (% weight)	Type of fibre	Amount of fibre (%vol)	Amount of fibre (%wt.)	Amount of water (%wt.)	Type of sample	Number of samples	Settling time
Ka000001-0501	95	99.4	chaff	5	0.6	37	24x20	3	1
Ka000001-0503	95	99.7	chaff	5	0.3	41	16x4; 30x7; 24x20	8	2
Ka000001-1001	90	98.9	chaff	10	1.1	38	24x20	3	1
Ka000001-1003	90	99.4	chaff	10	0.6	39	16x4; 30x7; 24x20	8	2
Ka000001-2001	80	98.3	chaff	20	1.7	20	24x20	3	0
Ka000001-2002	80	98.4	chaff	20	1.6	26	24x20	1	0
Ka000001-2003	80	98.4	chaff	20	1.6	n.a.	24x20	1	1
Ka000001-2005	80	98.4	chaff	20	1.6	59	24x20	4	0
Ka000001-2007	80	98.3	chaff	20	1.7	39	24x20	1	0
Ka000001-2008	80	98.3	chaff	20	1.7	n.a.	24x20	3	1
Ka000001-2010	80	98.7	chaff	20	1.3	42	24x20	2	1
Ka000001-2013	80	98.4	chaff	20	1.6	39	24x20	3	2
Ka000001-2014	80	98.7	chaff	20	1.3	41	16x4; 30x7; 24x20	7	2
Ka000001-3001	70	97.8	chaff	30	2.2	34	24x20	3	0
Ka000001-3002	70	97.4	chaff	30	2.6	38	24x20	1	0
Ka000001-4001	60	96.3	chaff	40	3.7	38	24x20	3	0
Ka000001-4002	60	96.2	chaff	40	3.8	43	24x20	1	0
Ka000001-4003	60	96.2	chaff	40	3.8	n.a.	24x20	1	1
Ka000001-4005	60	95.9	chaff	40	4.1	61	24x20	1	0
Ka000001-4006	60	94.6	chaff	40	5.4	46	24x20	1	0
Ka000001-4009	60	96.8	chaff	40	3.2	49	24x20	2	1
Ka000001-4012	60	96.7	chaff	40	3.3	50	16x4; 30x7; 24x20	7	2
Ka000001-5001	50	94.3	chaff	50	5.7	47	24x20	3	0
Ka000001-5002	50	94.0	chaff	50	6.0	51	24x20	1	0
Ka000001-5004	50	95.1	chaff	50	4.9	59	16x4; 30x7; 24x20	7	2

Table 3-8: Composition of mortars made by mixing earth as a binder, Grey Sand as an aggregate and Chaff as a fibre with water and the number of samples and their dimensions

	Amount of earth (%vol.)	Amount of earth (% weight)	Amount of aggregate (%vol)	Amount of aggregate (%wt.)	Amount of fibre (%vol)	Amount of fibre (%wt.)	Amount of water (%wt.)	Type of sample	Number of samples	Settling time
Ka000101-111001	34	45.1	33	53	33	2.3	36	24x20	4	2
Ka000101-111002	34	41.1	33	56	33	2.4	36	16x4; 30x7; 24x20	7	2
Ka000101-112001	50	57.8	25	41	25	1.4	35	30x7; 24x20	6	2
Ka000101-2210001	40	45.1	40	54	20	1.2	29	24x20	3	2
Ka000101-2210004	40	47.4	40	51	20	1.2	28	24x20	2	2
Ka000101-2210006	40	44.7	40	54	20	1.2	30	24x20	4	2
Ka000101-2210007	40	41.5	40	57	20	1.2	29	16x4; 30x7; 24x20	9	2
Ka000101-2210008	40	41.4	40	58	20	1.1	29	16x4; 24x20	6	2
Ka000101-2210009	40	43.8	40	55	20	1.2	29	24x20	3	1
Ka000101-241001	29	26.3	57	73	14	0.8	27	16x4; 30x7; 24x20	7	2
Ka000101-334001	50	42.8	30	54	20	2.9	37	24x20	3	1
Ka000101-334003	50	66.9	30	30	20	3.1	41	16x4; 30x7; 24x20	9	2
Ka000101-483001	27	28.0	53	71	20	1.0	26	24x20	3	1

Table 3-9: Composition of mortars made by mixing earth as a binder Yellow Sand as an aggregate and Chaff as a fibre with water and the number of samples and their dimensions

	Amount of earth (%vol.)	Amount of earth (% weight)	Amount of aggregate (%vol)	Amount of aggregate (%wt.)	Amount of fibre (%vol)	Amount of fibre (%wt.)	Amount of water (%wt.)	Type of sample	Number of samples	Settling time
Ka000201-2210001	40	44.5	40	55	20	1.0	24	16x4; 24x20	5	2
Ka000201-2210002	40	44.5	40	55	20	1.0	25	16x4; 24x20	5	2
Ka000201-2210003	40	44.5	40	55	20	1.0	26	16x4; 24x20	5	2
Ka000201-2210004	40	44.5	40	55	20	1.0	26	16x4; 24x20	5	2
Ka000201-2210005	40	44.5	40	55	20	1.0	28	16x4; 24x20	5	2
Ka000201-2210006	40	44.5	40	55	20	1.0	29	16x4; 24x20	5	2
Ka000201-2210007	40	44.5	40	55	20	1.0	25	16x4; 24x20	5	0
Ka000201-2210008	40	44.5	40	55	20	1.0	27	16x4; 24x20	5	1
Ka000201-2210012	40	45.5	40	53	20	1.1	29	16x4; 30x7; 24x20	8	2
Ka000201-2210014	40	49.1	40	50	20	1.0	23	24x20	3	2

Table 3-10: Composition of mortars made by mixing 40% of earth by volume, 20% of Chaff by volume and 40% by volume of alternative sands with water and the number of samples and their dimensions

	Amount of earth (% weight)	Sand naming code	Type of sand	Amount of sand (%wt.)	Amount of fibre (%wt.)	Amount of water (%wt.)	Type of sample	Number of samples	Settling time
Ka000301-221001	40.0	03	Grey Sand < 4.75 mm	59	1.0	28	16x4; 30x7;24x20	10	2
Ka000401-221001	44.7	04	White Sand (WS)	54	1.2	29	24x20	4	2
Ka000501-221001	40.3	05	Silice	59	1.1	26	24x20	4	2
Ka000601-221001	44.4	06	Yellow Sand < 0.875 mm	55	1.0	28	24x20	3	2
Ka000701-221001	41.2	07	Yellow Sand < 4.75 mm	58	0.9	24	24x20	3	2
Ka000801-221001	42.9	08	Yellow sand washed and dry	56	1.0	23	24x20	3	2
Ka000901-221001	41.1	09	WS washed and dry	58	0.9	28	16x4; 24x20	5	2
Ka001001-221001	43.3	10	Coarse Siliceous Sand	56	0.8	21	16x4; 24x20	6	2

Table 3-11: Composition of mortars made by mixing 40% of earth by volume, 20% of sand by volume and 40% by volume of alternative fibres with water and the number of samples and their dimensions

	Amount of earth (% weight)	Type of sand	Amount of sand (%wt.)	Type of fibre	Amount of fibre (%wt.)	Amount of water (%wt.)	Type of sample	Number of samples	Settling time
Ka000102-221001	44.8	Grey Sand	54	48h Sat	1.3	25	24x20	4	2
Ka000103-221001	44.8	Grey Sand	54	2m Sat	1.2	25	24x20	4	2
Ka000104-221001	45.5	Grey Sand	53	Plastic	1.1	27	24x20	4	2
Ka000205-221001	43.9	Yellow Sand	54	Pine needle	1.9	28	24x20	4	2
Ka000206-221001	44.5	Yellow Sand	55	Linen	0.2	23	24x20	3	2
Ka000207-221001	44.1	Yellow Sand	55	Cow hair	0.7	23	24x20	3	2
Ka000208-221001	44.6	Yellow Sand	55	Long sheep	0.2	24	24x20	3	2
Ka000209-221001	45.0	Yellow Sand	55	Short sheep	0.2	24	24x20	3	2
Ka000210-221001	44.7	Yellow Sand	55	Washed straw	0.8	25	24x20	3	2
Ka000211-221001	44.8	Yellow Sand	55	Long straw	0.3	23	24x20	3	2
Ka000212-221001	44.6	Yellow Sand	54	Short washed straw	0.9	26	24x20	3	2

Table 3-12:Composition of mortars made by mixing 40% by volume of earth, 40% by volume of Grey Sand and 20% by volume of Chaff with additives and water.

	Amount of earth (% weight)	Amount of aggregate (%wt.)	Amount of fibre (%wt.)	Additive naming code	Type of additive	Amount of additive (%wt.)	Amount of water (%wt.)	Type of sample	Number of samples	Settling time (days)
Ka010101-221051	46.9	52	1.1	01	Egg	0.5	1.1	24x20	4	2
Ka010101-221101	45.0	54	1.3	01	Egg	1.1	2.4	24x20	4	2
Ka010101-221151	46.0	53	1.1	01	Egg	1.6	3.4	24x20	4	2
Ka020101-221011	47.4	51	1.1	02	D. juice	0.9	27	24x20	3	2
Ka020101-221051	48.0	51	1.1	02	D. juice	4.6	22	24x20	3	2
Ka020101-221101	47.7	51	1.1	02	D. juice	8.9	19	24x20	3	2
Ka040101-221081	46.1	53	1.3	04	Flour paste	8.4	24	24x20	3	2
Ka040101-221161	46.1	53	1.3	04	Flour paste	15	16	24x20	3	2
Ka040101-221351	46.1	53	1.3	04	Flour paste	35	0	24x20	3	2
Ka080101-22121	47.3	52	1.2	08	Used oil	2.0	28	24x20	4	2
Ka080101-22141	47.0	52	1.1	08	Used oil	4.0	28	24x20	4	2
Ka080101-22161	47.4	51	1.2	08	Used oil	5.9	28	24x20	4	2
Ka080101-22181	47.3	52	1.1	08	Used oil	7.9	23	24x20	4	2
Ka090101-221301	45.6	53	1.1	09	straw juice	30	0	24x20	4	2
Ka100101-221011	41.1	58	1.1	10	Linseed oil	1.0	29	24x20	5	2
Ka100101-221021	41.1	58	1.1	10	Linseed oil	2.0	28	24x20	5	2
Ka100101-221041	41.1	58	1.1	10	Linseed oil	4.0	28	24x20	5	2
Ka100101-221061	41.1	58	1.1	10	Linseed oil	6.0	28	24x20	5	2

Table 3-13: Composition of mortars made by mixing 40% by volume of earth, 40% by volume of Yellow Sand and 20% by volume of Chaff with additives and water

	Amount of earth (% weight)	Amount of aggregate (%wt.)	Amount of fibre (%wt.)	Additive naming code	Type of additive	Amount of additive (%wt.)	Amount of water (%wt.)	Type of sample	Number of samples	Settling time (days)
Ka070201-221031	44.8	54	0.9	07	Cow dung	2.9	28	24x20	6	30
Ka070201-221061	45.1	54	0.9	07	Cow dung	5.9	29	24x20	3	30
Ka070201-221111	44.9	54	0.9	07	Cow dung	11	28	24x20	4	30
Ka110201-221011	45.5	54	0.9	11	Mayonnaise	0.8	26	24x20	3	2
Ka110201-221021	45.0	54	0.9	11	Mayonnaise	1.7	26	24x20	7	2
Ka110201-221031	45.2	54	0.9	11	Mayonnaise	3.3	26	24x20	3	2
Ka120201-221061	45.2	54	0.9	12	6 month CD	5.6	30	24x20	4	30
Ka130201-221251	45.0	54	0.9	13	HH stalk	25	2	24x20	6	2
Ka140201-221201	45.5	54	0.9	14	HH flower	19	5	24x20	3	2
Ka150201-22102	44.9	54	0.9	15	Casein	2.5	27	24x20	3	2
Ka150201-22105	42.3	57	0.9	15	Casein	4.9	27	24x20	5	2
Ka150201-22110	43.3	56	0.9	15	Casein	9.3	26	24x20	3	2

Table 3-14: Composition of mortars made by mixing 66% by volume of earth, 33% by volume of Grey Sand with additives and water

	Amount of earth (% weight)	Amount of aggregate (%wt.)	Amount of fibre (%wt.)	Additive naming code	Type of additive	Amount of additive (%wt.)	Amount of water (%wt.)	Type of sample	Number of samples	Settling time (days)
Ka060100-210021	31.4	69	0	06	Molasses	2.0	n.a.	24x20	4	2
Ka060100-210051	31.3	69	0	06	Molasses	5.2	n.a.	24x20	4	2
Ka060100-210151	32.2	68	0	06	Molasses	15	n.a.	24x20	4	2
Ka060100-210201	32.2	68	0	06	Molasses	20	n.a.	24x20	4	2

3.3 Methodology

The study of earth plaster has been made in two parts. A preliminary study has been made to determine the right composition of the mortar (in terms of fibres, sand and water amount) and then a deeper study of the determined samples and the impact of different sand fibres and additives have been made following the methodology determined by the DIN 18947 (DIN18947, 2013) and expanded by Faria et al. (2016). More experiments have been made taken from the literature to determine different properties of plasters not covered by the precedently cited sources.

3.3.1 Materials properties

The first part of the research consists of determining the properties of the materials that will be used for the research. Earth, sand and fibres' physical and chemical properties were determined.

3.3.1.1 Earth properties

Three main properties of earth for construction were determined; particle size distribution, Atterberg limits and mineral composition.

(i) Particle size distribution:

Particle size distribution (PSD) was determined according to ASTM D422 and ASTM D7928. For particles bigger than 75µm and particles smaller than 75µm.

The PSD of soil particles bigger than 75µm was determined on a 2kg sample of soil according to ASTM D422. Oven-dried soil was passed through a set of sieves and the mass of soil retained in each sieve was measured. The results of it are plotted on a graph.

The PSD of particles finer than 75µm was determined according to ASTM D7928. A sample of 50.00g of soil was measured and sieved through 75µm. The particles finer than 75µm were used to determine the amount of silt and clays inside the soil through the use of a hydrometer. The amount of time needed for the particles to set was recorded over a 24h period.

(ii) Atterberg limits

Liquid limit LL, plastic limit PL and plasticity index PI were determined according to ASTM D4318 on a sample of soil passing through a 425µm sieve. The LL was determined by allowing a sample with a specific amount of water to flow under shocks made by a standard device. The LL was calculated from at least 3 experiments made with different amounts of water in the soil.

The PL is determined by rolling soil into a 3.2 mm thread until the thread crumbles. The amount of water in the soil at this point is the plastic limit.

The PI is the difference between the PL and the LL.

(iii) Soil classification

The soil classification was determined using the results of the PSD and the Atterberg limits according to ASTM D2487 depending on the amount of fine particles passing the 75µm sieve.

3.3.1.2 Aggregates properties

Particle size distribution was determined according to ASTM D422 on a 2kg oven-dried sample of aggregates. The weight of material retained on each sieve was measured and then plotted. Material passing the 75µm sieve was considered as fines.

3.3.2 Mortar preparation

The mortars reserached in this work are planned to be used as plaster mortars. Therefore they were prepared following the DIN 18947 (DIN18947, 2013) with some differences to account for the manual production and application of mortars and variables such as settling time or amount of water.

3.3.2.1 Materials preparation

All the materials were used at laboratory temperature and humidity levels after being stored in laboratory conditions for a minimum of 2 months. The real amount of water in the material was not taken into account. Measurement of materials volume was done either using a 1L or 2L transparent measure. The weight of the materials was determined on a precision scale, with a precision of 0.1g. The materials' weights were measured just before being used.

The soil was ground with a specific apparatus and then sieved with a 2 mm sieve to avoid large particles entering the mortar.

3.3.2.2 Mortar preparation

Mortars were prepared according to DIN18994. Sieved soil was placed into a bucket. If it was the case, aggregates and fibres were added and the dry materials were mixed by hand for 10 minutes. Then water was added in small quantities until the mortar reached an approximately good consistency. The water amount was then adjusted to reach the optimum workability (§3.3.4.1)

If the mortar was not to be used immediately (i.e. long settling time) the mortar was placed in an airtight receptacle for the necessary amount of time. Before being used, the water amount was then adjusted again, if necessary.

3.3.2.3 Mortar application

The moulds were oiled to prevent the mortar from sticking to the different surfaces. The mo mortar was implemented in 3 successive layers and worked with a trowel as if it was plaster on a wall. After 1 week, the mould was removed and the samples turned. After two weeks of drying the samples were stored for a minimum time of a month until their usage.

3.3.3 Specimen size and type

To conduct the different tests, different sizes of samples were produced according to the size needed for the experiments. All the thickness of the samples was 4 cm to reproduce a real plaster thickness. Large samples were used to allow the implementation of plaster as it is applied to a wall (Rojat et al., 2015) and to prevent the corner effect described as the accumulation of fibres in the corner of a mould, which changes the properties of a sample (Minke, 2012). Other samples used were conventional samples of 16x4x4 cm^3 as used in most of the literature and larger prisms of 35x7x4 cm^3 produced specially to study the mechanical strength of slender samples.

3.3.3.1 Large samples 24x20 cm^2

Large samples of 24x20 cm^2 and 4cm thickness were produced in metallic mould. As the moulds are just a frame, a nylon sheet was placed below to avoid the mortar sticking to the support (Rojat et al., 2014). After drying, large samples were cut into three different sample sizes to use for the different experiments, as needed (Figure 3-3 and Figure 3-4). From the large samples, two samples of 16x4 cm^2 were cut, one sample of 12x12 cm^2 and one sample of 12x4 cm^2. As explained in Table 3-15, the different sizes were used for different experiments.

Figure 3-3: Samples prepared in different dimensions and let to dry

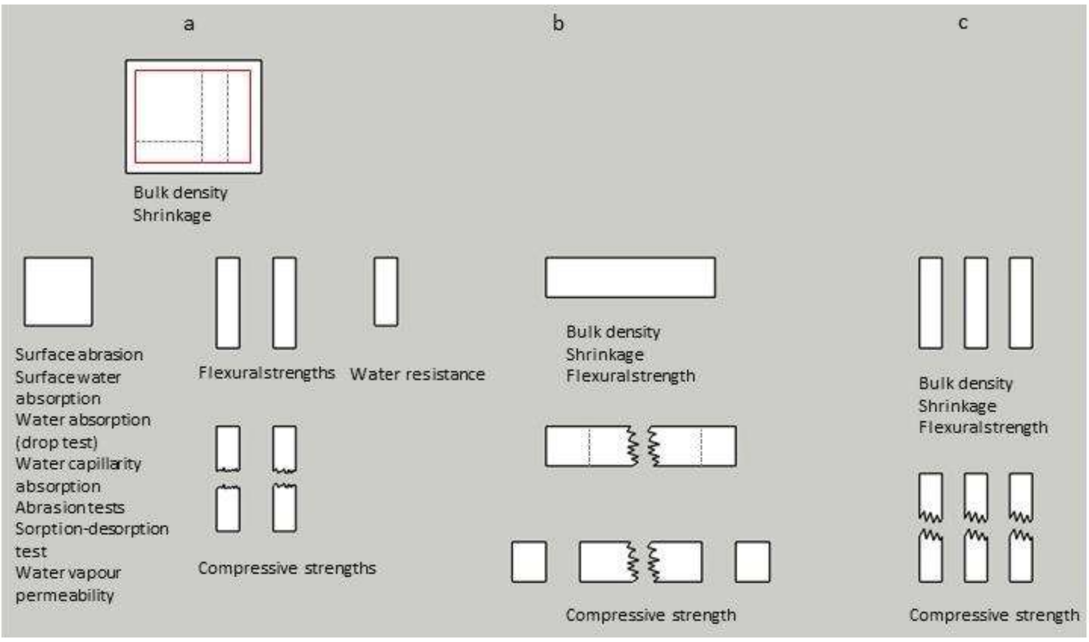

Figure 3-4: Dimensions and usage of the different samples

3.3.3.2 ASTM samples

16x4x4cm³ standardized steel moulds were used for the production of plasters. As it is not possible to work the material with a trowel, the material was put in and the moulds were shaken 20 times in 1 min. to evacuate air bubbles and provide minimal compression of the material.

3.3.4 Fresh mortar properties

Two main properties of fresh mortar are measured, following Faria et al. (2016), the workability (which determines the amount of water in the mortar) and its fresh density.

Figure 3-5: Set-up to determine the consistency of fresh mortars (flow table test)

3.3.4.1 Fresh mortar workability

According to Faria et al. (2015), the workability of plaster is determined on a flow table. However, the consistency was not determined for a flow of 17 cm after 20 shocks but for a flow of 17cm after 30 shocks to take into account the fact that a thick coat of plasters applied by hand should be thicker than projected plasters. The flow was determined by measuring the plaster diameter on the table with a Vernier calliper in two perpendicular directions (Figure 3-5).

3.3.4.2 Fresh plaster density

The fresh mortar density was determined by using a 3L measure. The mortar was put in the measure and air bubbles were removed by inserting a trowel 20 times. The weight of the mortar in the measure was then determined.

3.3.5 Dry mortar properties

Mortar properties are separated into five main groups which are all important to determine the quality of the plaster and its properties. According to some standards (DIN18947, 2013) or professional rules (Enduits en Terre, 2018; *Lehmbau Regeln*, 2002; Reseau Ecobatir, 2013), there are some minimum qualities that plaster should achieve in terms of strength, abrasion resistance, and water vapour absorption. Other properties were used to determine the suitability of the plaster or its performance.

Table 3-15 presents the experiments made and the sources describing the experimental procedure. The procedure used in this research is further described in the paragraphs below.

Table 3-15: Experiments made on samples

experiment name	aim	sample type	method	sample preparation	outcomes	source
Physical properties						
Linear shrinkage	Size reduction	All sizes	Measured on the long side	No	% of size diminution	
Density	Compaction / weight	All sizes	Measured on all sides and weighted	Large samples cut to avoid corner effect	Density	(Minke, 2012)
Mechanical properties						
Flexural strength	Strength	16x4cm² - 30x7cm²	3-points-bending apparatus	Large samples cut to 16x4cm²	Strength	(DIN18947, 2013; Hamard et al., 2013)
Compressive strength	Strength	16x4cm² - 30x7cm²	Compressive strength with 4x4cm² without capping	Broken pieces of flexural strength test	Strength	(DIN18947, 2013)
Surface properties						
Surface abrasion	Surface resistance to light touch	12x12cm²	Applying a tape under 5kg during 1min	Brushing the dust with a smooth brush	Weight of material detached/amount of particle on the tape	(Faria et al., 2016)
Surface absorption	Capillarity absorption on the surface layer	12x12cm²	Applying a wet sponge under 5kg during 1 min	Brushing the dust with a smooth brush	Weight of water absorbed	(Faria et al., 2016)
Durability properties						
Flexural strength (humid)	Strength	16x4cm² - 30x7cm²	3-points-bending apparatus	Large samples cut to 16x4cm²	Strength	
Compressive strength (humid)	Strength	16x4cm² - 30x7cm²	Compressive strength with 4x4cm² without capping	Broken pieces of flexural strength test	Strength	
Abrasion	Resistance to friction	12x12cm²	20 rotation of a plastic brush with 5kg weight	Brushing the dust with a smooth brush	Amount of material detached	(Faria et al., 2016)
Abrasion	Resistance to friction	12x12cm²	20 way and back of a metallic brush loaded with 2kg weight	Brushing the dust with a smooth brush	Amount of material detached + depth of the created depression	(Enduits en Terre, 2018)
Drip test	Resistance to rain	12x12cm²	Dripping 100ml of water from 40cm during 30min	No	Depth and width of the erosion depression	(NZS 4298, 1998)
Water resistance	Resistance to water action by immersion	4x4cm²	Suspension of samples in water		Resistance in min	(TS 2514, 1977)

Table 3-15: Continued

experiment name	aim	sample type	method	sample preparation	outcomes	source
Hygric properties						
Water capillarity absorption	Water absorption speed	12x12cm²	Putting 1 face of the sample in water	Waterproofing of the sample side	Rate of water absorption	(Faria et al., 2016)
Drying rates	Drying speed	12x12cm²	Letting the sample dry in a controlled environment	Waterproofing of the sample side and bottom surface	Rates of water desorption/drying index	(Faria et al., 2016)
Hydric properties						
Water vapour resistance	Transmission of vapour	12x12cm²	Measurement of the sample weight at regular interval	Waterproofing of the sample sides and placing above a cup full of water	Rate of vapour transmission	(Faria et al., 2016)
Water vapour absorption	Vapour absorption speed	12x12cm²	Measurement of the sample weight at regular interval	Waterproofing of the sample side and placing it in a humid room for 48h	Amount and rate of water absorption	(Faria et al., 2016)
Water vapour desorption	Vapour desorption speed	12x12cm²	Measurement of the sample weight at regular interval	Waterproofing of the sample side and placing it in a dry room for 48h	Amount and rate of water desorption	(Faria et al., 2016)

3.3.5.1 Physical properties of mortars

The procedures used to determine the shrinkage and the density are presented in the paragraphs below.

3.3.5.1.1 Shrinkage

Shrinkage of plaster was determined on the dried samples kept for 3 weeks minimum at laboratory temperature and humidity level. 2 types of shrinkage were determined;

a- Length-wise shrinkage where the longer size of the sample was measured and compared to the mould size,

b- Volumetric shrinkage where all the sides of the samples were measured was determined for large samples.

To get the accurate size of a sample’s side, each side was measured 3 times and the average of these three measurements was taken as the sample’s side size. The heights of samples were measured 4 times and the average of these 4 measurements was taken into account.

3.3.5.1.2 Density

The density of specimens was determined on three types of specimens;

a- On the 16x4 cm^2 and 30x7 cm^2 specimens after drying,

b- On the 24x20 cm^2 specimens after a border of 2 cm width has been cut on each side to remove the corners of the sample that might be broken or may contain packed fibres.

c- On 16x4 cm^2 specimens cut from the 24x20 cm^2 samples to get the real density of each of the specimens used for mechanical strength.

Density was determined by weighing the specimens kept for 3 weeks minimum at laboratory temperature and humidity level on a precision scale (0.1g) and obtaining the different dimensions of the specimen’s sides with a Vernier calliper. On large samples, (24x20 cm^2 and 30x7 cm^2) the dimension was obtained as an average of 3 measurements.

3.3.5.2 Mechanical properties of mortars

The mechanical properties of mortars were determined in two conditions, laboratory-dried and humidity-saturated conditions. Flexural and compressive strength were determined on different specimens' sizes and types, following DIN 18947 (DIN18947, 2013).

Mechanical strength was determined using a testing device that applies compression with a precision of 2 kgf.

Dry mechanical strength has been determined on dry specimens kept in laboratory conditions (about 40%RH and 23°C) for a minimum of 3 weeks after full drying was achieved.

Humid mechanical strength was determined on previously dried specimens kept in a humid room with 80% RH and 23°C for 2 months and sprinkled with water to achieve a humidity-saturated level reproducing rain conditions. The weight of specimens was recorded before the test to calculate the amount of water absorbed by the samples.

3.3.5.2.1 Flexural strength

Flexural strength was measured with a 3-point loading device on the cut prisms of size 16x4x4 cm^3 in compliance with the dimensions prescribed by DIN 18947 and EN. A specific set of mortars has also been moulded in large samples of 35x7x4 cm^3.

3.3.5.2.2 Compressive strength

The two halves of the broken 16x4x4 cm^3 prisms were used to determine the compressive strength. Broken parts of specimens were inserted into a specific device with a rotula to make sure that the weight was applied perpendicularly to the surface of the samples.

For samples with a 7x4 cm² section, 4 small samples of 7 cm height were taken out of the broken part of the large samples and tested for compressive strength. No specific device with a rotula could be used to determine the strength.

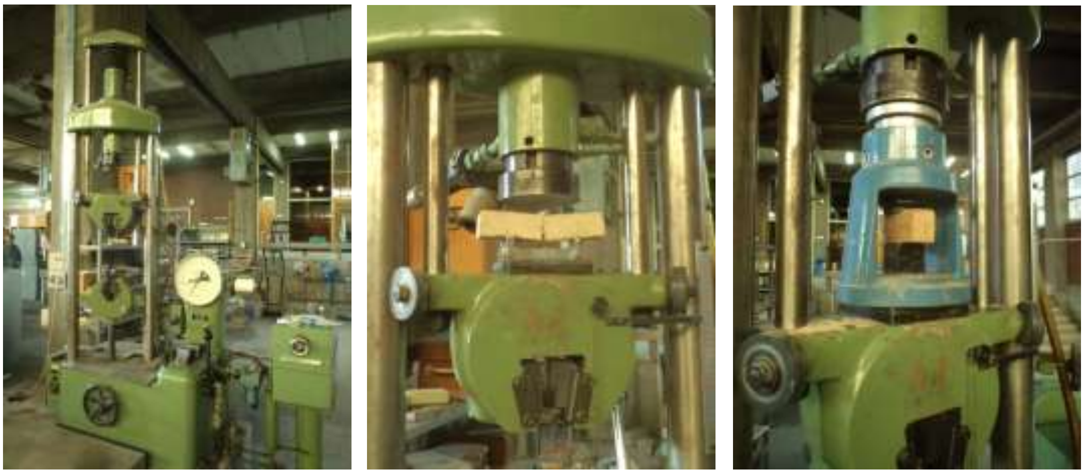

Figure 3-6: Device and set-up used to determine the flexural and compressive strength

3.3.5.3 Surface properties of mortars

Two surface properties of earth plasters were determined by simple tests, surface abrasion and surface water absorption.

3.3.5.3.1 Surface abrasion (peeling test)

Surface abrasion was determined by the tape test as described by Colas and Bourgès (2013) and Faria et al. (2015). A 6x6 cm² duct tape is applied to the surface of the plaster and then removed. The amount of material staying on the tape is then weighed, but also visually evaluated. To get more standard results, the test has been modified as such: the pressure exerted on the tape is not exerted by finger but by applying a 5kg weight on the tape for 60 seconds. Because of the asperities on the surface of the samples, thick foam is placed between the tape and the weight to distribute the load evenly.

Figure 3-7: Set-up for surface resistance tests

3.3.5.3.2 Surface water absorption

Surface water absorption was made with the sponge test following Colas and Bourgès (2013) and (Vandevoorde et al., 2013). A 6x6cm² sponge was saturated with water and placed in a container whose weight was checked after placing the sponge to ensure the same amount of water for each test. The plaster sample was then placed on the sponge with a 5kg weight to ensure equal pressure on all tests for 90 seconds before being removed. The amount of water absorbed was then calculated by the weight difference between the dried sample and the water-saturated sample.

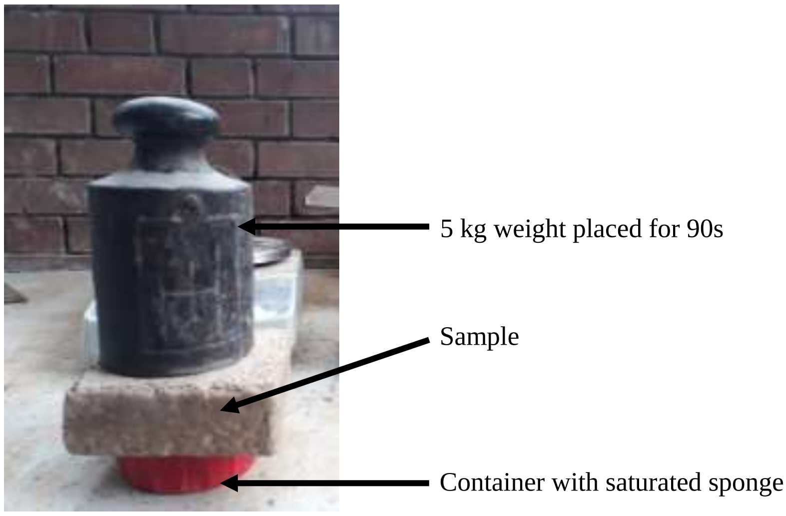

Figure 3-8: Contact sponge method set-up.

3.3.5.4 Durability of mortars

The durability of plasters is evaluated by their ability to resist friction, water and rain. To evaluate this capacity, six tests were made, two on the abrasion resistance, two on the water resistance and two tests on the water absorption and desorption rate.

3.3.5.4.1 Resistance to abrasion (DIN 18947)

The abrasion resistance was determined according to DIN 18947 by applying 20 rotations of a 6.5 cm plastic brush with a pressure of 2 kg. The rotations were applied during a period of 15 s to 25 s. The sample was weighed before and after the test and the amount of material loss was calculated. According to the DIN 18947, two resistance classes are defined, class 2 with a loss lower than 0.7 g and class 1 with a loss lower than 1.5 g.

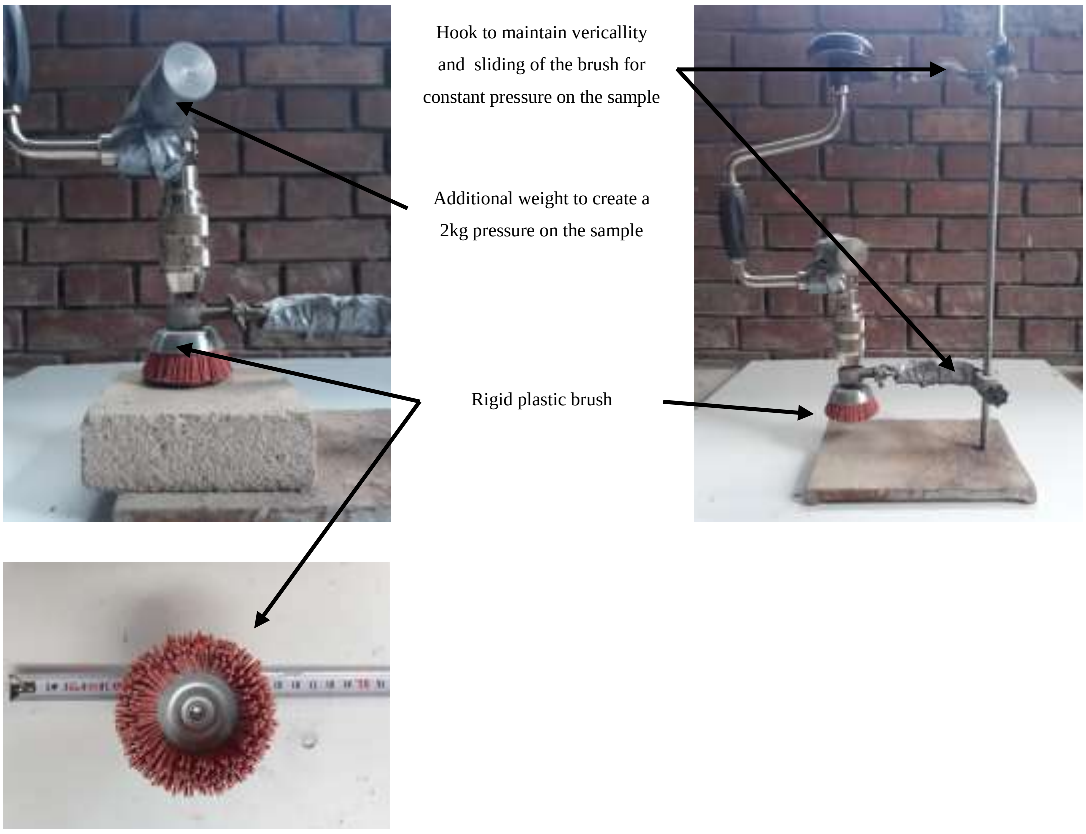

Figure 3-9: Apparatus to determine the abrasion resistance

3.3.5.4.2 Resistance to abrasion (French rules)

The abrasion resistance was also calculated on 12x12 cm² samples according to the draft of the French Professional Rules for Earth Plaster (*Guide de bonnes pratiques des enduits en terre*, 2016). A 2.5 cm large metallic brush loaded with 3 kg was pushed back and forth 30 times on the plaster. The resistance of abrasion is given by the depth of the trace. The French Professional rules recommend a trace with a depth smaller than 2 mm. As this test is derivated from the French Standard XP P13-901 for compressed earth bricks, the abrasion coefficient C_a in cm²/g will also be calculated with the Equation 1 as described by Giroudon et al. (2019)

$$C_a = \frac{S}{(m_0 - m_1)} \quad (1)$$

Where S is the surface of the brushed area, m_0 is the mass before brushing and m_1 the mass after 30 roundtrips. Therefore, the higher the coefficient, the more resistant to abrasion the material.

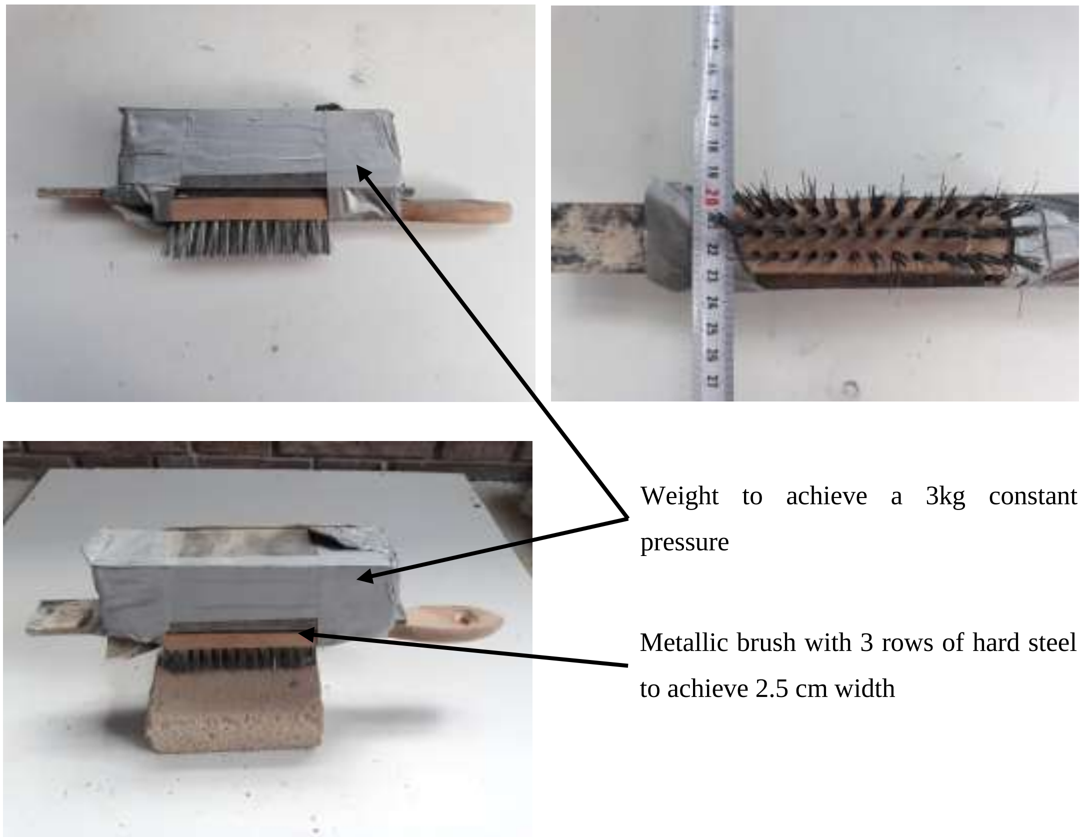

Figure 3-10: Set-up for the abrasion test according to French regulations

3.3.5.4.3 Water resistance

The water resistance was determined based on the disused Turkish Standard on adobe (TS 2514, 1977) and other similar water resistance tests (Svoboda & Procházka, 2012). A sample of a 4x4 cm² section was hung in water to a depth of 4 cm. The time needed to destroy the immersed part was measured. According to the standard, a material is considered water-resistant if the time needed is higher than 45min. The setup used for the determination of the water resistance is presented in Figure 3-11.

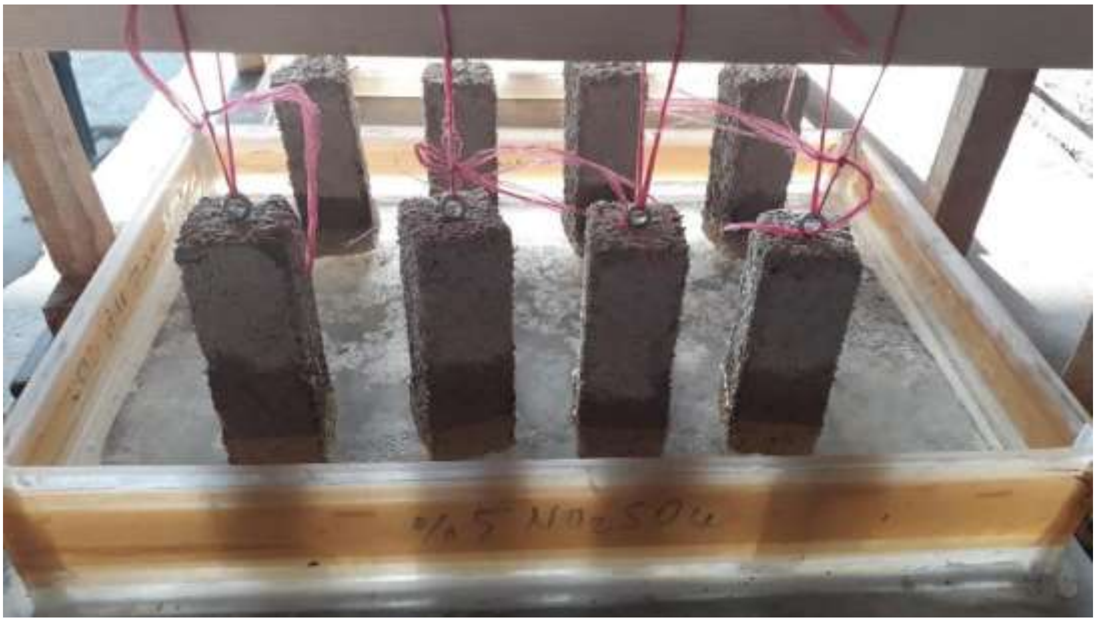

Figure 3-11: Set-up for measuring the water resistance of samples – The length of the strings was calculated for the samples to be hung 4cm in water

3.3.5.4.4 Erosion resistance

Erosion resistance was determined according to NZ 4298 (NZS 4298, 1998) and Stazi et al. (2015). A sample was placed at 30° angle below a 100 mL receptacle. The water was dripped for 30 to 45 min from 40cm height (Figure 3-12). The depth of the hole made by the drops was then recorded.

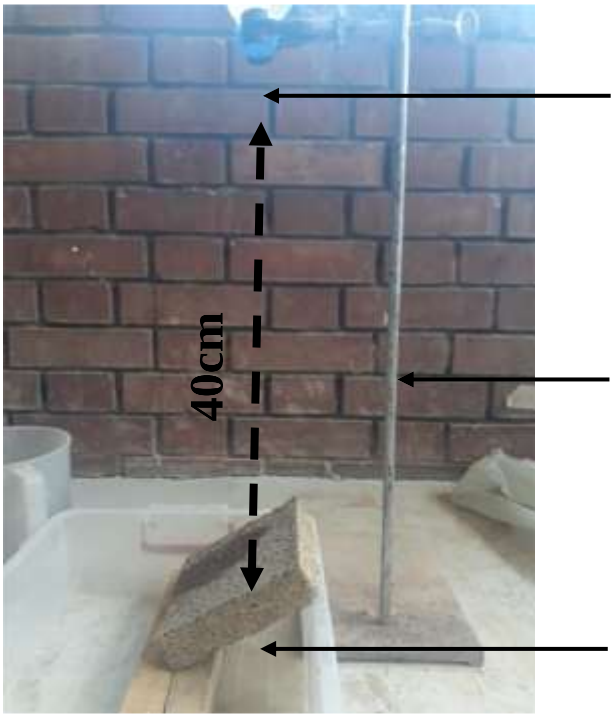

Figure 3-12: Set-up used to determine the water erosion

3.3.5.5 Hydric properties of mortars

The hydric properties are evaluated in terms of water absorption rate and the total amount of water absorbed after 4h through the water capillarity absorption test and in terms of drying rate through the drying test.

3.3.5.5.1 Water capillarity absorption

Water capillarity absorption was measured on 12x12 cm² samples following the method of Minke (2012) and Faria et al. (2015). The specimens' sides were waterproofed with wax and an absorbing filtration paper was placed on the bottom surface to keep the destroyed materials. The sample was then put in a tray with 2 mm of water and then its weight was recorded at specific intervals for 12 hours. A graph was plotted with the amount of water absorbed through capillary action, in kg/m², on the X-axis and the square root of the duration of capillary action, in minutes, on the

Y-axis. From the representative initial segment of the plotted line, its slope was calculated to obtain the initial capillary coefficient (CC) of the plaster mix. Therefor CC is expressed in $kg/m^2 \cdot min^{-0.5}$. Figure 3-13 shows the set-up used to determine the water capillarity absorption of samples.

Figure 3-13: Samples placed in a waterproof container to determine the water capillarity absorption

3.3.5.5.2 Drying capacity

The drying capacity of the plaster was tested following Faria et al. (2015) and Lima et al. (2020). Specimens wetted by the capillarity absorption test were left to dry in laboratory conditions (23°C and 40%RH). The drying specimens were weighed every hour for the first 6 hours and then daily for 14 days. A graph was plotted with the recorded weight of samples on the Y-axis and the time on the X-axis and a second graph with plotting the square root of time on the X-axis. These graphs were used to calculate the drying behaviour.

The drying behaviour is determined with three different indicators which show the behaviour during 2 different phases of the drying and during the complete drying period. The first phase corresponds to the drying through the desorption of liquid vapour and is characterized by the primary Drying Rate (pDR) and the second phase is slower and corresponds to the drying of the material by the evaporation of the water content and is characterized as secondary Drying Rate (sDR). The third indicator, the Drying Index (DI) corresponds to the setting up of an equilibrium between the internal water amount and the exterior conditions. Because samples are placed in a controlled environment and exchange water and energy with the environment, the temperature and RH of the drying area are extremely important.

The pDR was determined by calculating the slope of the straight segment of the curve with hours in X-axis whereas the sDR was determined as the slope of the linear regression of the weight loss plotted against the square root of time (Figure 2-18).

The Drying Index (DI) which represents the time necessary to achieve full drying was calculated with Equation (2) following the procedure of Grilo et al. (2014).

$$DI = \frac{\sum_{i=1}^{i=n}\left[\left(t_i - t_1\right)\times\left(\frac{w_{t_{i-1}} + w_{t_i}}{2}\right)\right]}{w_{max}\times t_f} \qquad (2)$$

DI (–): drying index,

t_i (h): test time,

t_f (h): total duration of the test,

w_{t_i} (%): water content in time t_i,

w_{max} (%): maximum water content at initial testing time.

The accuracy of the drying rates and drying index have been checked using the squared Pearson correlation coefficient (R^2) and the R^2 is indicated on the tables, following the drying rates values and the DI value.

3.3.5.6 Hygric properties of mortars

The hygric properties determined in this dissertation are the water vapour permeability, the water vapour adsorption rate and the water vapour desorption rate.

3.3.5.6.1 Water vapour permeability

Water vapour permeability was determined following the DIN 18947 methodology using 12x12 cm^2 square samples with 4 cm thickness. The wet cup method was used with a cup having an opening of 8x8cm^2 and being filled with water. The distance between the water and the sample was set between 1 cm and 1.5 cm. The cups were placed in a laboratory environment with an average temperature of 23°C and 40% RH. The weight of the cups was recorded regularly for 2 months. From this experiment, the water vapour permeability (δ, kg/(m s Pa)) have been calculated with Equation (3) (Liuzzi et al., 2018). The water vapour diffusion resistance factor (μ, -) was calculated according to Cagnon et al. (2014) and Luizzi et al. (2018) using Equation (5). The equivalent air layer (Sd, m) was calculated with Equation 6 (Stazi et al., 2015).

$$\delta = \mathit{\Lambda} \times e \tag{3}$$

Where $\mathit{\Lambda}$ [kg/(m^2 s Pa)] is the permeance of the sample calculated according to EN EN1015-19 (Liuzzi et al., 2018) and *e* (m) is the thickness of the sample.

$$\mathit{\Lambda} = \frac{1}{\frac{A \times \mathit{\Delta}p}{flux\ of\ vapor}} \tag{4}$$

Where A (m^2) is the area of the opening of the cup, $\mathit{\Delta}_p$ (Pa) is the vapour pressure gradient between the testing environment and the cup and the *flux of wapor* (kg/s) is the slope of the measured data after the weight loss was stabilized for 7 days. $\mathit{\Delta}_p$ has been estimated at 2537 Pa for a room at 22.5 °C and 35% RH in average.

$$\mu = \frac{\delta_{air}}{\delta} \quad (6)$$

Where δ_{air} is the air permeability at 22 °C and is taken as 1.96 10^{-10} kg/(m s Pa)

$$Sd = \mu \times e \quad (6)$$

Where e (m) is the thickness of the sample

3.3.5.6.2 Water vapour absorption capacity

The sorption of the mortar was determined with 12x12 cm^2 samples of 4 cm thickness initially in equilibrium at 50% RH in a laboratory environment, according to DIN 18947. Samples were waterproofed on 5 sides with a polyethene sheet and then placed in a humid room (23°C and 80% humidity) and the weight of samples was recorded at regular intervals (0.5h to 48h) using a 0.1g scale.

The water vapour adsorption capacity was determined by plotting the time in h on the X-axis and the increase of mass by surface units in g/m^2 on the Y-axis and reading the amount of water absorbed after 12h (DIN18947, 2013). The primary absorption rate and secondary absorption rate ($g/m^2 \cdot h$) used to compare the curves were determined by calculating the slope of the curves during the 3 first hours of humidity exposure and during the last 24h.

3.3.5.6.3 Water vapour desorption capacity

The desorption of the plasters, initially at equilibrium at 80% RH, was also determined. The samples were placed in a dry room with 50% RH at 23°C and the weight decrease of the same samples during the same period (from 0.5 up to 48 h) was determined.

The water vapour desorption capacity was determined by plotting the time in h on the X-axis and the decrease of mass by surface unit in g/m^2 on the Y-axis and reading the amount of water absorbed after 12h (DIN18947, 2013). The primary desorption rate and secondary desorption rate ($g/m^2 \cdot h$) used to compare the curves were determined by calculating the slope of the curves during the 3 first hours of drying and during the last 24h of the drying process.

CHAPTER 4

PROPERTIES OF SELECTED EARTH AND SAND

In this Chapter, the properties of earth and sand as construction materials are determined. The first section deals with the properties and classification of raw earth and the determination of its characteristics relevant to earth construction. The second section analyses the different types of sand used in terms of particle shape and particle size distribution.

4.1 Characteristics of plain earth

The main properties of the plain earth used in this research have been determined and the particle size distribution, the geotechnical characteristics and the ASTM soil classification of the raw earth are presented in this section.

4.1.1 Particle size distribution

The Particle Size Distribution (PSD) of the earth used has been determined through dry sieving for the coarse fraction of the particles – larger than 75 µm – and the finer fraction has been analysed by sedimentation through hydrometer analysis according to ASTM D7928. The results of these analyses are presented in Figure 4-1 and Table 4-1.

The results show that the amount of clay – the fraction of the earth finer than 2 µm - present in the non-crushed and non-sieved earth is 29.5%, while there is 21% of silt and 39% of sand whereas the results for the crushed and sieved earth are slightly different with only 24.5% of clay particles (Table 4-1). This difference might be explained by the fact that gravels are crushed to sand during the crushing process and therefore the amount of sand is higher.

The comparison of the earth used with the recommendations concerning the contents of the different earth fractions for mud-brick synthesized by Delgado et al. (2007) shows that the studied earth is within the limits of the *Australian Earth Building Handbook* and its amount of clay follows the recommendation of Houben and Guillaud (2008) as also shown Figure 4-1. Moreover, when the amount of clay and the amount of fines are compared with the literature, their amounts are in the same range as 25% of the literature (19 earth studied out of 79 have a clay amount between 20% and 30% and 28 articles out of 95 shows an amount of fines between 30% and 60%)

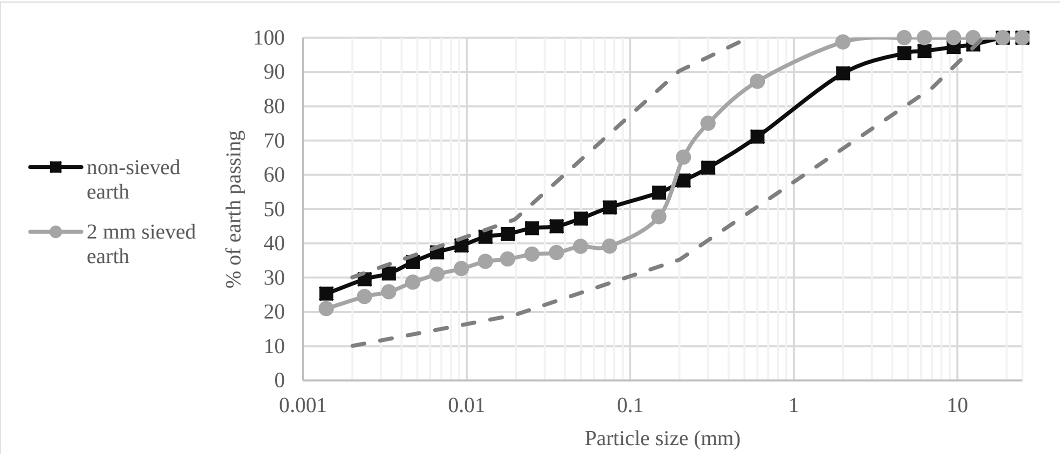

Figure 4-1 Particle size distribution of the non-crushed and non-sieved earth and of the crushed and 2mm sieved earth (as used in experiments). The dashed lines represent the upper and lower limits of the particle size distribution of earth for mud bricks as defined by Houben & Guillaud *(2008)*

Table 4-1: Amount of the different particles present in the earth used in the research

	Clay (%)	Silt (%)	Sand (%)	Gravel (%)
Non-sieved and non-crushed earth (natural earth)	29.5	21	39	10.5
Sieved and crushed earth (experimental earth)	24.5	14.5	6 0	0

4.1.2 Geotechnical characteristics

Atterberg limits were performed on the fines fraction of the earth. The Liquid Limit was determined as 42.8 and the Plastic Limit as 20.6, therefore the Plasticity Index was calculated as 22.2 which classify the earth as medium plastic according to Lagouin et al. (2021). This is in accordance to most of the articles published where authors used medium plastic earth.

Delgado et al. (2007) determined that the Atterberg limits for adobe construction should be between 31 and 50 for the liquid limit and 16 and 33 for the plastic limit. Therefore, the studied earth is compelling with the respective recommendations as also shown in Figure 4-2.

From this information, it can be determined that the optimum amount of water for wet paste mortar should be around 32% if the formulation proposed in the literature is to be followed (Mellaikhafi et al., 2021; M. Ouedraogo et al., 2019).

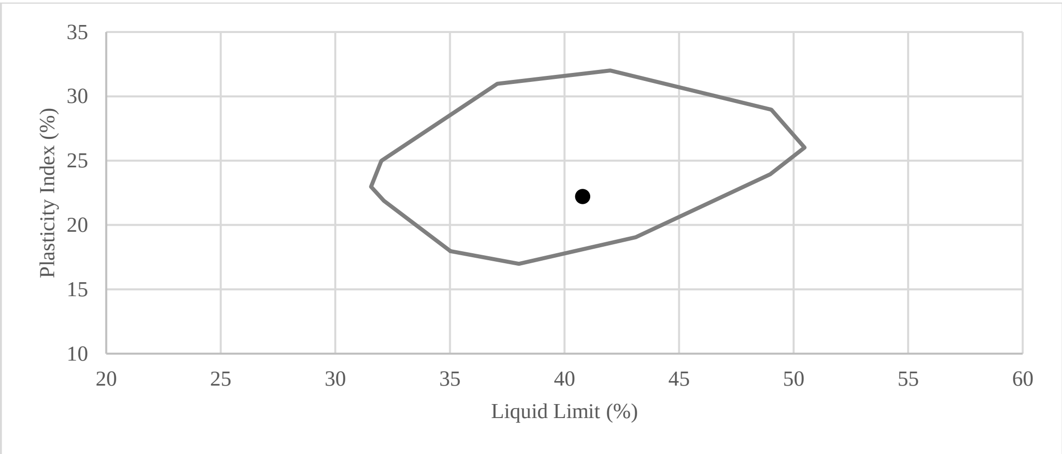

Figure 4-2: Plasticity Index plotted against Liquid Limit for the studied earth. The zone inside the grey lines shows the recommended range of Plasticity Index and Liquid Limits *(Houben & Guillaud, 2008)*

4.1.3 Specific gravity

The specific gravity of the earth has been calculated on two samples of about 25 g. The average specific density for the soil is 2.59. This gravity is in the low range of the earth used for wet paste mortars, as the data from the literature varies from 1.98 to 2.70 with the median value of 25 values being 2.67.

4.1.4 Soil classification

From the outcome of the sieve analysis and the Atterberg Limits, according to ASTM D2487, the earth used can be classified as Sandy Clay using the USCS classification. Most of the earth reviewed in the literature review also are classified similarly.

4.2 Characteristics of sands

The properties of sands have been measured in order to compare them and evaluate their impact on the properties of earth mortars. Particle size distribution, loose bulk density and grain shape were determined and the results are presented in this section.

4.2.1 Particle size distribution of sands

The particle size distributions (PSD) of the aggregates used for this work have been determined through dry sieving with meshes larger than 75 µm. The results of the sieving are presented in Table 4-2 and Figure 4-3, Figure 4-4 and Figure 4-5. Figure 4-3 shows the PSD of Sand 1 and Sand 2 which are used as reference sands whereas Figure 4-4 and Figure 4-5 shows the PSD of the other sands depending on the Reference Sand they are based on.

From the results of the test, it can be assumed that Sand 1 and Sand 2 have an identical PSD (Figure 4-3) which was expected as they are both commercially sold as “plasterer sand”. The only slight difference is the amount of larger particles –

above 0.85 mm –which is slightly higher for Sand 2 (Table 4-2). The PSD of coarse sands based on Sand 1 and Sand 2 – which are non-sieved Sand 1 and Sand 2 – is also identical for the same reason, showing again the same slight difference for particles larger than 0.85mm.

The White Sand used has the largest amount of fine particles – below 0.075 mm – whereas the washed sand and siliceous sands – sold as washed sands - have the lowest amount of fine particles. However, the main difference is the distribution of the particles with siliceous sand having a short range of particles size – more than 80% of Si particles are between 0.425 mm and 2 mm and more than 90% of Csi particles are between 0.85 mm and 2 mm – which leads to an ungraded distribution and therefore a high amount of voids in the matrix which could lead to a weakness of the mortar. On the opposite, the well-graded distribution of the Grey sand and Yellow Sand prevents the formation of larger voids and therefore increases the possibility of higher strength of the mortars.

Table 4-2: Particle size distribution of the different sands used in the research

	particle amount in % (range in mm)							
	>4.75	**4.75-2.00**	**1.99-0.85**	**0.84-0.425**	**0.424-0.250**	**0.249-0.106**	**0.105-0.075**	**<0.075**
Sand 1	**0**	**2.3**	**33.9**	**29.8**	**15.1**	**11.3**	**1.3**	**6.3**
CGS	0	37.8	21.7	14.0	9.4	9.4	1.6	6.2
Sand 2	**0**	**2.8**	**37.9**	**28.9**	**15.8**	**7.6**	**1.1**	**5.7**
CYS	0	38.4	22.0	14.2	9.5	9.5	1.6	4.7
FYS	0	0.0	0.0	53.2	25.3	11.7	2.0	7.7
WYS	0	3.0	40.2	30.6	16.8	8.1	1.2	0.0
WS	0	3.1	39.3	21.0	9.6	8.6	2.5	15.9
WWS	0	0.6	50.6	26.9	11.6	7.3	1.2	1.8
Si	0	6.1	33.4	50.7	8.6	1.1	0.0	0.1
CSi	0	2.1	92.9	4.8	0.1	0.0	0.0	0.2

4.2.2 Physical properties of sands

The physical properties of sands (bulk density and grain shape) have been determined experimentally for the sake of comparing the different materials. They are summarized in Table 4-3.

4.2.2.1 Loose bulk density of sands

The loose bulk density was calculated as an average of 5 measurements of the weight of a 3L bucket filled with non-compacted sand. The density varies from 1240 kg/m³ for white sand to 1660 kg/m³ for coarse grey sand and 1630 kg/m³ for coarse yellow sand. The two reference sand (Grey Sand and Yellow Sand) have the same density (1440 kg/m³) which is also very similar to the one of the Fine Yellow Sand. Whereas other sands have densities varying around 1550 kg/m³. Therefore despite using different types of sand and particle size distribution, it seems that it doesn't impact strongly the density except for the usage of White Sand or Coarse Sand.

4.2.2.2 Grain shape of sands

The grain shape of sands has been determined visually and the classification between the very granular particles of White Sand and the round-shaped particles of Siliceous Sand has been determined. It appears that, despite being sold as the same material, Yellow Sand and Grey Sand have different grain shapes. The particles of Yellow Sand are sharpest and present more broken angles than the ones of Grey Sand. This difference in granularity is an important feature as using granular sand is recommended for plasters and mud bricks (Henderson, 2013)

Table 4-3: Summary of properties of the different sands used in the research

Name	Code	Color	Grain Shape	Washed	Max. Grain Size (mm)	Loose Bulk Density (kg/m³)
Grey Sand	**GS**	Grey	Subangular	no	2.0	1440
Coarse Grey Sand	**CGS**	Grey	Subangular	no	4.5	1660
Yellow Sand	**YS**	Dark Yellow	Angular	no	2.0	1440
Coarse Yellow Sand	**CYS**	Dark Yellow	Angular	no	4.5	1630
Fine Yellow Sand	**FYS**	Dark Yellow	Angular	no	0.75	1460
Washed Yellow Sand	**WYS**	Dark Yellow	Angular	yes	2.0	1540
Silicious River Sand	**Si**	Light Yellow	Well Rounded	yes	2.0	1520
Coarse Silicious River Sand	**CSi**	Light Yellow	Well Rounded	yes	2.0	1570
White Sand	**WS**	White	Very Angular	no	2.0	1240
Washed White Sand	**WWS**	White	Very Angular	yes	2.0	1590

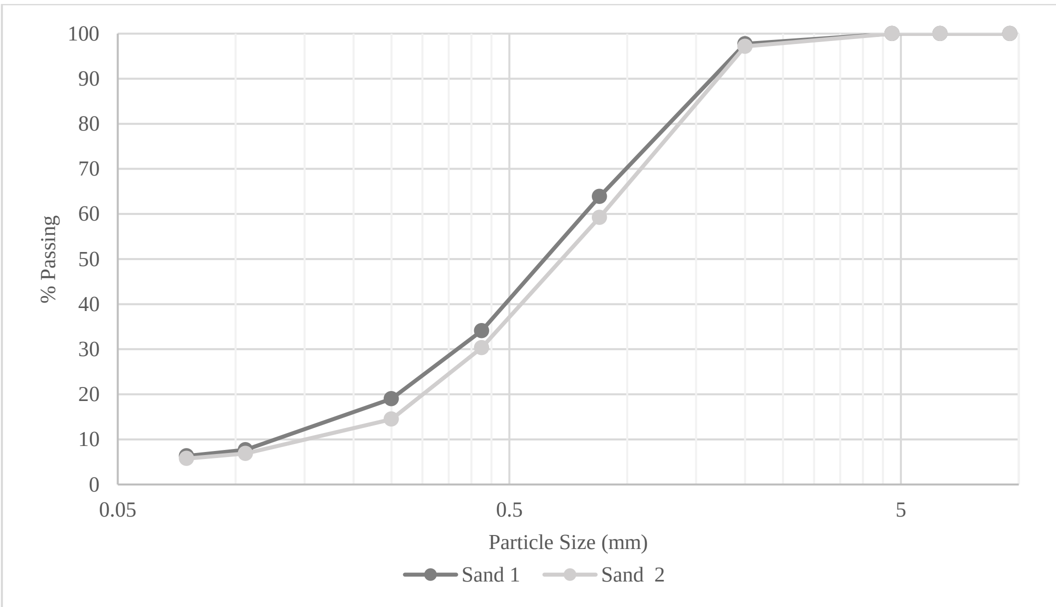

Figure 4-3: Particle size distribution of the two reference sands

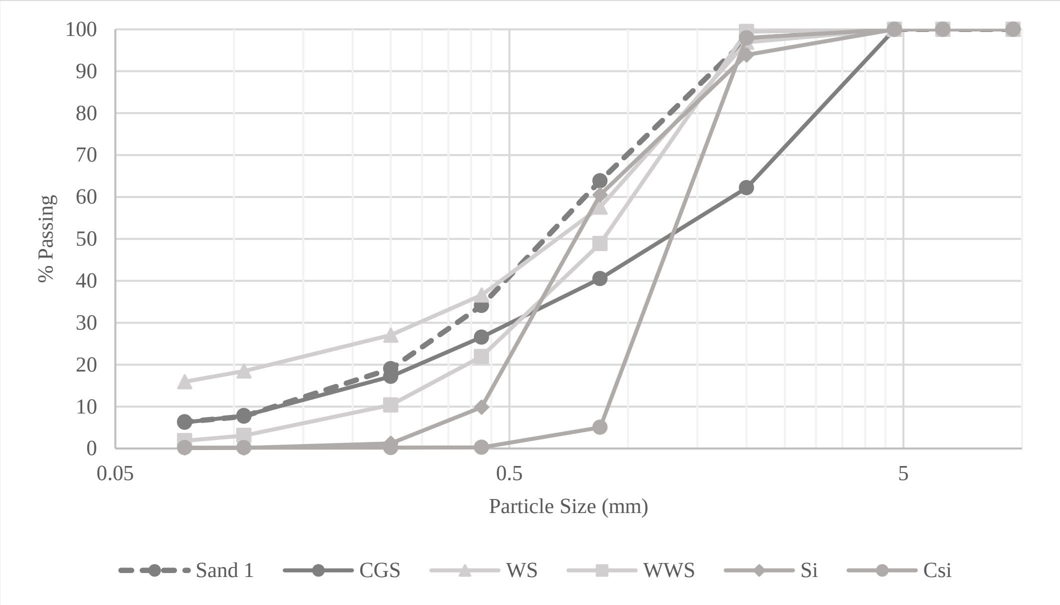

Figure 4-4: Particle size distribution of sands based on Sand 1 and other sands

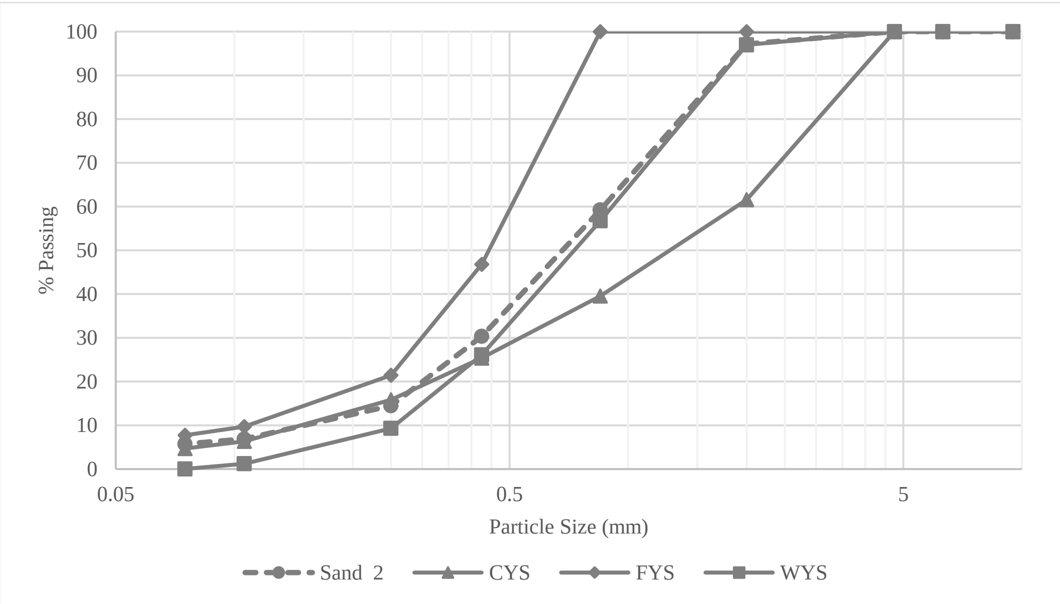

Figure 4-5: Particle size distribution of sands based on the modification of sand 2

CHAPTER 5

PROPERTIES OF NON-STABILIZED EARTH MORTARS

In this chapter, the dry properties of non-stabilized earth mortars – i.e. earth mortars which have not been modified by the addition of additives leading to chemical transformations – are presented. All mortars have been prepared and tested following the experimental program explained in CHAPTER 3. All mortars have been prepared with a similar amount of water – as recommended by the experience – and with a similar settling period between 0 days and 2 days. However, due to some inconsistencies in the preparation of samples and the failure of some samples during the drying phase, the number of samples tested might vary.

The amount of material added to the mortar (sands, fibres or water) is expressed in percentage by volume in the dissertation. When a percentage by weight is used, then it is indicated after the concerned number.

The properties of non-reinforced earth mortars – i.e, mortars made only with earth – are presented in the first section, and then the properties of earth mortars reinforced with sand and with chaff are presented in section 2 and section 3.

5.1 Properties of non-reinforced and non-stabilized earth mortar

The properties of plain earth mortars have been tested on different mixes made uniquely with earth and no other materials but with different amounts of water. Moreover, the dimensions of the specimens have been changed to stick to similar conditions with other mortars but also to be able to get proper testing specimens.

5.1.1 Physical properties of non-reinforced and non-stabilized earth mortar

Physical properties– have been determined on dry non-reinforced and non-stabilized mortars. 12 different mortars have been produced to determine average properties. The average shrinkage and density are summarized in Table 5-1.

Table 5-1: Physical properties of non-reinforced and non-stabilized earth mortars

mix name	Amount of water (%)	Slump test (cm)	Settling time	24x20 samples						16x4 samples			
				Shrinkage (%)	*Standard dev.*	Average dry density of uncut samples (kg/m³)	*Standard dev.*	Average dry density of large (kg/m³)	*Standard dev.*	Shrinkage (%)	*Standard dev.*	Average dry density (kg/m³)	*Standard dev.*
Ka000000-01	17		0	7.3	*0*	1698		1776				1695	*4*
Ka000000-02	20	13.1	0							7.3	*0.1*	1684	*2.3*
Ka000000-03	24	13.5	0							7.5	*0.3*	1689	*5.5*
Ka000000-04	31	15.1	0							7.8	*0.3*	1670	*13*
Ka000000-05		14.1	1							7.3	*0.1*	1687	*6.4*
Ka000000-06		15.2	1							8.5	*0.1*	1683	*12*
Ka000000-07		15.1	2							6.2	*0.2*	1685	*14*
Ka000000-10	39	17.1	2	6.5	*1.1*	1741	*8.2*	1750	0.2				
Ka000000-11	33	16.8	0			1648		1738					
Ka000000-12	40	16.9	2	7.4	*0*	1677	*24.1*	1716	7.5	8.4	*0.3*	1677	*2.1*

5.1.1.1 Shrinkage

The overall shrinkage of non-reinforced and non-stabilized mortars varies from 6.2% (Ka000000-07) to 8.5% (Ka000000-06) which shows a large variation of shrinkage not related to the dimension of the specimens, even if specimens with an elongated shape tend to have a larger shrinkage. Different amounts of water have been used in different mortars to determine if it would impact the shrinkage as suggested by the literature. Despite the amount of added water varying from 20% to 40%, the shrinkage only varies from 7.3% to 8.4% for these two specific samples (Ka000000-02 and Ka000000-12 respectively). However, when outliers are removed from the data – the very low shrinkage of Ka000000-10 – then it can be observed that increasing the water amount increases shrinkage (Figure 5-1).

Mortars with settling times between 0 days – i.e. implementation of the mix 2h after preparation – and 2 days with a similar amount of water have been tested. The shrinkage for samples Ka000000-04, Ka000000-06, and Ka000000-07 varies between 6.2% and 8.5%, the largest being 1 day settling and the smallest 2 days settling.

Therefore, it can be concluded that in the condition of the research, on earth mortars without fibres - settling time has no consistent impact on the shrinkage, but the amount of water – or the consistency – has. For further comparison, the shrinkage used will be an average of the different shrinkages found, using 0 days and 2 days settling and consistency between 15.5 cm and 17.5 cm.

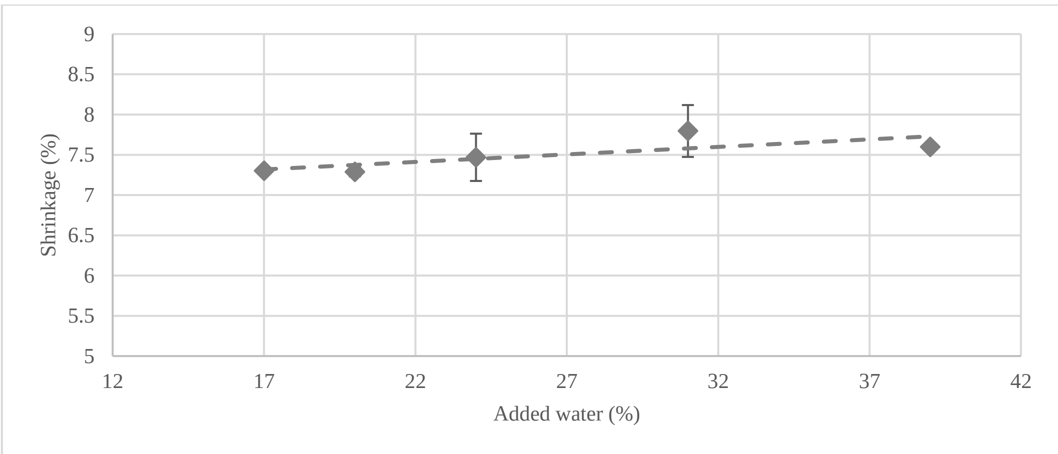

Figure 5-1: Impact of the amount of added water on the shrinkage of earth mortars

5.1.1.2 Density

The overall average density varies between 1648 kg/m³ (Ka000000-10) and 1741 kg/m³ (Ka000000-11) for uncut samples – independently of the size – and from 1716 kg/m³ (Ka000000-12) and 1776 kg/m³ (Ka000000-01) for cut samples, which show a slight increase of density when the sides of the samples are removed. Cutting the edges of samples allow to get rid of the less homogeneous part of the specimens as described by Minke (2012) and therefore the overall density increases – from 1691 kg/m³ to 1745 kg/m³ but most importantly, the spread of the values is lower – the standard deviation changes from 37.2 to 21.6 from uncut to cut samples.

For 16x4 samples the average density varies from 1670 kg/m³ (Ka000000-04) to 1695 kg/m³ (Ka000000-01) which is a low variation. The density of 16x4 samples is much lower than the density of 24x20 samples which shows that the production process impacts the density as underlined by Bras et al. (2019) and the spread of data is also lower due to a more controlled casting process. The density found for these mortars is lower than the one found in the literature for similar raw earth mortars (Andres et al., 2016b; Araya-Letelier et al., 2020; Babé et al., 2020; Bamogo et al., 2020; Muñoz et al., 2020) but higher than the values found by Mellaikhafi et al. (2021) or Salih et al. (2020a).

As it has been described above for shrinkage, there is no relation between density and settling time but there is a weak correlation between the increasing amount of water and the decrease in density. This relation is seen especially when samples of 16x4x4 cm are examined, as their production process is fairly straightforward and standardized, therefore easily reproducible from one specimen to another. If the large specimens are taken into account this relation vanishes because of the spread of the data due to the casting process. These results show that for the comparison of samples, it is preferable to compare identically-sized specimens with a similar amount of water.

5.1.2 Mechanical properties of non-reinforced and non-stabilized earth mortar

The flexural and compressive strength of non-reinforced and non-stabilized earth mortars are presented in the two flowing sections. The average results of the test are presented in Table 5-2.

5.1.2.1 Flexural strength

The average flexural strength of non-reinforced and non-stabilized mortar varies between 0.94 MPa (Ka000000-05) and 1.60 MPa (Ka000000-12) for 16x4x4 samples, i.e. 60% of the variation, with an average of 1.31 MPa. For specimens cut from large samples, the average strength varies from 1.31 MPa (Ka000000-12) to 1.84 MPa (Ka000000-11), with a larger variation (70%) between the smallest and highest average mix strength value. Flexural strength on 35x7x4 cm^3 samples could only be measured on one sample because of the failure of other samples and its strength is higher than on other sample sizes.

The large disparity of results for the same type of specimens is difficult to apprehend as it is neither related to the density, nor to the amount of water. It might be due to a casting problem or a lack of homogeneity in the mix which might cause some weak samples since when the standard deviations are taken into account, most mortars have at least one of the specimens tested with a strength value close to the average strength (Figure 5-2).

The generally high flexural strength and the difference in strength between the specimens' sizes that the studied mortar has a high flexural strength compared to similar mortars seen in the literature (Hamard et al., 2013; Lima, Faria, et al., 2016; Stazi et al., 2015) but more importantly that the strength is dependent on the production method – i.e. how the fresh mortar is poured in the mould and pressed into shape (Brás et al., 2019; Guihéneuf et al., 2019b; Kouakou & Morel, 2009) – and on the size of samples.

5.1.2.2 Compressive strength

The average compressive strength on non-reinforced and non-stabilized earth mortars vary between 4.74 MPa (Ka000000-12) and 5.85 MPa (Ka000000-03) with an average of 5.39 MPa for uncut specimens of 16x4x4 cm^3. The strength of cut specimens is slightly lower as it varies between 4.15 MPa (Ka000000-10) and 4.82 MPa (Ka000000-12). The strength of the 35x7x4 cm^3 samples is even lower. When the values obtained for the different specimens' sizes for mortar Ka000000-12 are compared, it is seen that specimens with the same dimensions either cut or cast have similar strength – 4.57 +/-0.23 MPa and 4.74 +/-0.11 MPa for cut and cast specimens respectively – whereas the specimen with a more slender section – 35x7x4 cm^3– have a lower strength.

Except for the mortar Ka000000-12, all average strengths are very high – above 5.25 MPa – which shows that the compressive strength of this earth is very high compared to other earth with similar clay content. Only Ouedragogo et al (2019) and Sanou et al. (2019) found similar values for raw earth mortars. This high strength is probably due to the high amount of clay content – above 30% – and the type clay of the non-modified earth which makes it prone to shrinkage but also gives a high bond between the different particles.

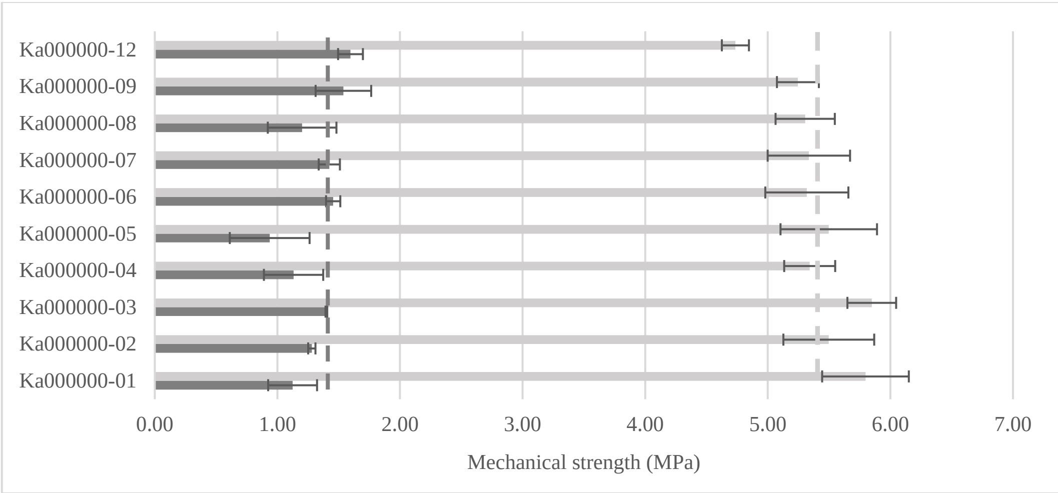

Figure 5-2: Flexural and compressive strength of non-reinforced and non-stabilized earth mortars. The dashed lines show the average strength of the mortars.

Table 5-2: Average mechanical strength of non-reinforced and non-stabilized earth mortars

mix name	Slump test (cm)	Settling time	24x20 samples				16x4 samples				35x7 samples		
			Average flexural strength (MPa)	*Standard dev.*	Average compressive strength (MPa)	*standard dev.*	Average flexural strength (MPa)	*Standard dev.*	Average compressive strength (MPa)	*standard dev.*	Average flexural strength (MPa)	Average compressive strength (MPa)	*standard dev.*
Ka000000-01		0					1.12	*0.20*	5.80	*0.35*			
Ka000000-02	13.1	0					1.28	*0.03*	5.50	*0.37*			
Ka000000-03	13.5	0					1.40	*0.01*	5.85	*0.20*			
Ka000000-04	15.1	0					1.13	*0.24*	5.34	*0.21*			
Ka000000-05	14.1	1					0.94	*0.33*	5.50	*0.39*			
Ka000000-06	15.2	1					1.46	*0.06*	5.32	*0.34*			
Ka000000-07	15.1	2					1.42	*0.09*	5.34	*0.34*			
Ka000000-10	17.1	2	1.54	*0.02*	4.15	0.12							
Ka000000-11	16.8	0	1.81	*0.36*	4.82	0.58						3.47	*0.58*
Ka000000-12	16.9	2	1.31	*0.04*	4.57	0.23	1.60	*0.10*	4.74	*0.11*	2.14	3.67	*0.47*

5.1.3 Surface properties of non-reinforced and non-stabilized earth mortars

The surface properties of non-reinforced and non-stabilized earth mortars have been determined on four different mortars (two specimens were tested for each mortar). The results are summarized in Table 5-3 below.

Table 5-3: Average surface properties of non-reinforced and non-stabilized earth mortars

Mortar Name	Amount of water (% weight of dry earth)	slump test (cm)	settling time	Surface water absorption ($g/m^2 \cdot s$) for 90 s.	Peeling test – virgin samples (g)	Visual scale (1-10)	Peeling coefficient (g/cm^2)	Peeling test – tested samples (g)	Visual scale (1-10)
Ka000000-01	17	n.a.	0	13.2	0.02	2	0.5		
Ka000000-10	n.a.	17.1	2	14.7	0.00	1	0	0.39	4
Ka000000-11	33	16.8	0		0.04	1	1.1		
Ka000000-12	40	16.9	2		0.04	1	1.2		

5.1.3.1 Surface water absorption

The amount of water absorbed during the surface water absorption for non-reinforced and non-stabilized mortars submitted to the absorption test has been tested on only two mortars and it is comprised of between 4.27 g (Ka000000-01) and 4.93 g of water (Ka000000-10) for an exposition to water for 90 seconds. For a better comparison, these numbers have been converted into $g/m^2 \cdot s$ therefore, therefore the water absorption is comprised between 13.2 $g/m^2 \cdot s$ (Ka000000-01) and 14.7 $g/m^2 \cdot s$ (Ka000000-10).

This test has only been conducted on similar mortar by two groups of researchers, but the results are very different, probably due to the set-up used. Paul & Changali (2020) found a water absorption of 0.43 g/m²·s for a 3-minute exposition to water, with the water source above the samples, whereas Colas and Bourges (2013) found a water absorption between 6.0 g/m²·s and 7.5 g/m²·s for an earth mortar and a water source placed vertically on the side of the samples after an application for 90 seconds. Despite a similar duration of the test, the absorption results found for the earth mortar tested in this research are higher than the one of Colas & Bourges (2013) probably because of the position of the samples and much higher than the one of Paul & Changali (2020).

5.1.3.2 Surface cohesion

The results of the modified peeling test show two different types of results. For a virgin surface, dusted beforehand, a very low amount of dust – between 0.00 g (Ka000000-10) and 0.04 g (Ka000000-11; -12) – adhere to the tape whereas, on a surface which has been tested for water absorption after drying occurred, a larger amount of dust adheres – 0.33 g to 0.43 g. Moreover, the visual identification of the results, shows that the number of particles sticking to the tape is very low for virgin samples. These results show that non-stabilized and non-reinforced earth has good surface cohesion, the large amount of clay providing enough binding force between the remaining other particles. However, after some degradation due to water exposure, the binding force is lowered, with the clay washed by the water and therefore the cohesion is much lower.

These results are confirmed by the ones of Colas & Bourges (2013) who found, with a different set-up a decreasing cohesion of the surface of earth mortars when the test is repeated on the same surface. However, the results for the first test (0.02 g of mortar adhering to the tape) are similar to the one found in this research, demonstrating the good surface cohesion of non-reinforced and non-stabilized earth mortars. The results for the non-reinforced and non-stabilized mortars can also be compared to the one published by Santos & Faria (2020) for reinforced plasters and the studied mortar show better cohesion than reinforced ones.

5.1.4 Durability properties of non-reinforced and non-stabilized earth mortars

The durability properties of non-reinforced and non-stabilized earth mortars are summarized in Table 5-4 and discussed in the following paragraphs. Due to the long testing time and amount of material needed, these properties have only been tested on two mortars of similar composition.

Table 5-4: Average durability properties of non-reinforced and non-stabilized earth mortars

Mortar Name	Slump test (cm)	Settling time	Humidity level (weight increase in %)	Humid flexural strength (MPa)	Loss in strength (weight increase in %)	Humid compressive strength (MPa)	Loss in strength (%)	Water resistance (min)	Abrasion resistance (DIN18947) Material loss (g)	Abrasion resistance (French rules) Abrasion Coefficient (cm²/g)	Abrasion resistance (French rules) Depression depth (cm)
Ka000000-01		0	2.5	0.60	-46	3.35	-42	35	0.8		
Ka000000-10	17.1	2	2.5	0.62	-60	2.71	-35	20	2.9	6.4	1.25

5.1.4.1 Humid mechanical strength

The humid mechanical strength of earth mortars has been tested on samples kept for two months in a humid room. The weight of the samples stopped increasing after a 2.5% weight increase and therefore their humidity level was accepted as 2.5%. The two mortars tested were found to have a very similar humid flexural strength –

respectively 0.60 MPa for Ka000000-01 and 0.62 MPa for Ka000000-10 – but very different compressive strengths. The loss of strength compared to dry strength for Ka000000-01 is similar for flexural and compressive strength (-46% and -42%) whereas there is a very large difference for Ka000000-10 (-60% and -35%). However, this large difference might be due to several factors with the main one being the small number of specimens tested and therefore the lack of precision of the results.

The loss of strength of the humidity-saturated mortars is similar to the one found by Guiheneuf et al. (2019a) and Wiehle (2022) for earth mortars with a loss of about 40% to 50% of the strength when the humidity level increases from 1% to 3% and the one shown by Abhilash et al (2022) in their review of rammed-earth materials. Moreover, as shown by Champiré et al. (2016) not only the amount of humidity in the samples is important to determine the behaviour of the samples, but also the conditioning of these samples. Therefore, since all samples have been conditioned in the same room with the same amount of humidity, a similar loss of strength is expected but not the same final strength.

5.1.4.2 Water resistance by immersion

Samples have been partially immersed in water to determine the amount of time necessary for disaggregation. A large difference is seen with Ka000000-01 needing 35 minutes to disaggregate whereas Ka000000-10 need only 20 minutes. Despite a large difference, both samples are unable to comply with the inactive Turkish standard on mud bricks (TS 2514, 1977) which sets a minimum disaggregation time of 45 minutes.

5.1.4.3 Abrasion resistance (DIN 18947)

Samples have been tested for abrasion resistance with a medium-hardness plastic brush. The average material loss is 0.8 g for Ka000000-01 and 2.9 g for Ka000000-

10. These values are very different and also it would classify these mortar into two different classes as defined by German Standards (DIN18947, 2013). Ka000000-01 would be class S1 whereas Ka000000-10 would not be usable as above the defined limits for abrasion. However, as the results for Ka000000-10 are an average of the results on 2 different samples, with one of them having a material loss of 0.9 g and the other of 4.3 g, this large difference might come from some previous weakness in the sample. No other data from tested non-reinforced and non-stabilized earth mortars are available for comparison, however, the results are low in comparison to other published articles dealing with non-stabilized plasters but close to the one of reinforced illitic earth whereas it is much lower than the abrasion of kaolinitic and montmorillonitic mortars. (Lima et al., 2019; Santos & Faria, 2020)

5.1.4.4 Abrasion resistance (Regles Pro)

The abrasion resistance could only be calculated on the Ka000000-10 mortar on 2 specimens. The average abrasion coefficient is 6.4cm²/g and the depth of the depression is 1.25 mm which qualifies the mortar to be used as plaster according to French Professional Protocol for Earth Plaster (*Guide de bonnes pratiques des enduits en terre*, 2016).

When the abrasion coefficient is compared to other values in the literature, it seems that the studied earth has better cohesive properties as the abrasion coefficient is more than double of the ones found by Giroudon et al. (2019) or Gonzalez-Calderon et al. (2020) for unreinforced earth but much lower than the one found by Millogo et al. (2014). It is important to note that the cited results are given for a test lasting 60 cycles as described in XP P13-901 or by Boubekeur and Rigassi (2000) in opposition to the current testing procedure that uses only 30 cycles.

5.1.5 Hydric properties of non-reinforced and non-stabilized earth mortars

The hydric properties – capillarity absorption and drying behaviour – have been tested on one specimen of two different earth mortars. The results determined according to Lima et al. (2020) and Grilo et al. (2014) have been summarized in Table 5-5 and have been discussed in the following paragraphs.

Table 5-5: Hydric properties of non-reinforced and non-stabilized earth mortars

Mortar Name	Slump test (cm)	Settling time	Capillarity coefficient (kg/m²/min$^{0.5}$)	*R^2 (-)*	Drying rate (1st phase) (kg/m²/h)	*R^2 (-)*	Drying rate (2nd phase) (kg/m²/h$^{0.5}$)	*R^2 (-)*	Drying index
Ka000000-10	17.1	2	1.0	*1.00*	0.15	*1.00*	1.35	*0.99*	0.29
Ka000000-11	16.8	0	1.0	*1.00*	0.14	*0.99*	1.28	*0.99*	0.32

5.1.5.1 Water capillarity absorption

The absorption behaviour is determined through the capillarity coefficient. Both mortars present a very similar behaviour with a capillarity coefficient of 1.0 kg/m²/min$^{0.5}$. When this capillarity coefficient is compared to other samples with similar properties (Faria et al., 2016; Gomes et al., 2018; Lima et al., 2020), it shows that the coefficient is very high compared to kaolinitic and illitic mortars but only half of montmorillonitic mortars. However, due to slight differences in test set-ups such as the thickness of samples or waterproofing mediums, data are difficult to be properly compared. Moreover, the cited authors used mortars with a much lower clay content than the one used in this research, showing the importance of the clay amount in water absorption as well as the clay type as demonstrated by Lima et al. (2020).

5.1.5.2 Drying behaviour

The drying behaviour is characterized by the Drying Rate (DR) in the 1st and 2nd phases and by the Drying Index (DI). The value obtained for the studied mortars are very close to each other, with a primary DR of 0.15 kg/m²/h and 0.14 kg/m²/h, a secondary DR of 1.35 kg/m²/h$^{0.5}$ and 1.28 kg/m²/h$^{0.5}$ and a DI of 0.43 and 0.48 for Ka000000-10 and Ka000000-11 respectively. According to the value found by Faria et al. (2016), Gomes et al. (2018) and Lima et al. (2020) the first drying phase is similar to other non-stabilized earth mortars but the loss of water during the second phase is much faster. The DI is much higher than the one found by Faria et al. (2016), or Gomes et al. (2018) meaning that the total drying was longer to achieve. However, these differences might be due to the amount of clay in the samples but also due to the drying conditions and especially the moisture content which was not controlled in this research.

5.1.6 Hygric properties of non-reinforced and non-stabilized earth mortar

The hygric properties of earth mortars are given in Table 5-6 and discussed in the following paragraphs.

Table 5-6: Hygric properties of non-reinforced and non-stabilized earth mortars

Mortar Name	Slump test (cm)	Density (kg/m³)	Water vapour permeability (x10⁻¹¹ kg/m*s*Pa)	Water vapour diffusion resistance factor (-)	Equivalent air layer (m)	Water vapour adsorption (12h - g/m²)	primary adsorption rate - first 6h (g/m²h)	secondary adsorption rate – 6h – 24h (g/m²h)	water vapour desorption (12h - g/m²)	primary desorption rate - first 3h (g/m²h)	secondary desorption rate - 12h-48h (g/m²h)
Ka000000-10	17.1	1741	4.83	4.1	0.16	158	*18.7*	*9.7*	167	*20.4*	*5.2*
Ka000000-11	16.8	1648	4.94	4.0	0.14	148	*15.6*	*9.5*	127	*14.7*	*3.9*
Ka000000-12		1677	5.22	3.8	0.14						

5.1.6.1 Water vapour permeability

The water vapour permeability has been assessed on 3 different mixes (one sample per mix) and the water vapour diffusion resistance factor (μ) and the equivalent air layer (S_d) have been determined for comparison purposes with the literature. All μ-values are fairly close despite different testing conditions and different mixes which shows both the reliability of the testing condition and the fact that the water vapour diffusion resistance factor is low compared to the literature and the range determined in DIN18947 (DIN18947, 2013). Cagnon et al. (2014) tested earth bricks with similar clay content but higher density and obtained a water vapour diffusion resistance factor varying between 3 and 7 whereas Laborel et al (2018) obtained a water vapour diffusion resistance factor of 4.9 for a mortar made only with quarry fines. Other authors studied mortars with a lower amount of clay and found also higher water vapour diffusion resistance factor (Faria & Santos, 2014; Guihéneuf et al., 2020; Lima & Faria, 2017; Liuzzi et al., 2013; Palumbo et al., 2016). However, the difference might also come from the experimental conditions with a very different thickness of material (4 cm instead of 2 cm generally) and different densities which impact the water vapour permeability (Faria et al., 2016; Guihéneuf et al., 2020).

5.1.6.2 Dynamic water vapour adsorption and desorption behaviour

The water vapour adsorption and desorption behaviour of non-reinforced earth mortars are presented in Table 5-6 and Figure 5-3 for the two tested mortars. The highest amount of vapour adsorbed and desorbed after 12h is recorded for Ka000000-10 and the highest adsorption and desorption rates also. However, the difference in vapour adsorbed and desorbed at 12h is low and their behaviour can be considered similar. However, after 24h the adsorption and desorption rates of sample Ka000000-11 is reduced and the total amount of vapour adsorbed and desorbed is much lower. Therefore, the mortar Ka000000-10 will be accepted as the Reference Earth in the following sections.

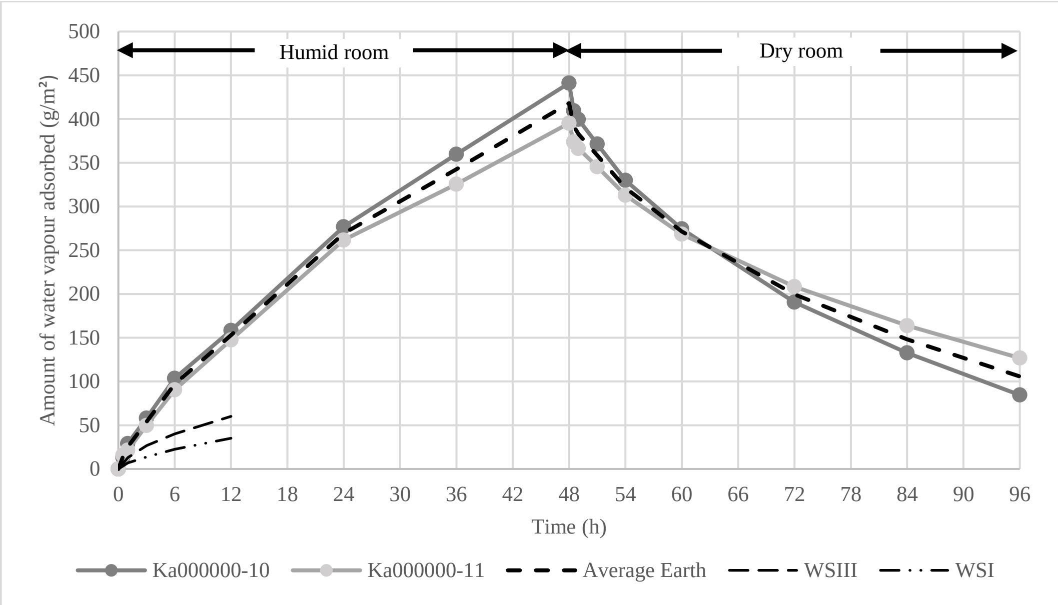

Figure 5-3: Dynamic water vapour adsorption and desorption of non-reinforced and non-stabilized mortars. WSIII and WSI stand for the vapour absorption curves class I and III according to German Standard *(DIN18947, 2013)*.

5.2 Properties of earth mortar reinforced with Grey Sand and Yellow Sand

This section presents the results of the tests on earth mortars reinforced with sand. Ten mortars produced with 6 different amounts of Grey Sand (20%, 33%, 50%, 67%, and 75% of the dry mix by volume) and 1 mortar produced with 67% Yellow Sand have been tested with different amounts of water.

The properties of mortars reinforced with sands are compared with the so-called Reference Earth which is a mortar that average value as calculated from the results of the test of plain earth mortars (section 5.1). The properties of the Reference Earth are summarized in APPENDIX B.

The physical properties, mechanical properties, surface properties, durability properties, hydric properties and hygric properties of these mortars are given and discussed in paragraphs 5.2.1 to 5.2.6.

5.2.1 Physical properties earth mortar reinforced with Grey Sand and Yellow Sand

The shrinkage and the density of mortars reinforced with Grey Sand are presented and they are discussed in the following sections. When possible, results are compared with the literature.

5.2.1.1 Shrinkage

The shrinkage of sands stabilized plasters is summarized in Table 5-7 and the properties of the reference earth are also presented together for comparison. Average shrinkage and standard deviation are given for the different types of specimens and water amounts. Shrinkage varies 4.8% (Ka000100-201) to 0.2% (Ka000100-751) for large samples, from 3.9% (Ka000100-331) to 0.6% (Ka000100-751) for short samples and from 6.6% (Ka000100-201) to 1.5% (Ka000100-752) for long samples. Independently of the type of sample and the settling time, the shrinkage decreases with the increase of added sands (Figure 5-4). These results are following the results of the different authors adding sand in earth mortars who all see a decrease in shrinkage while adding sand (Emiroğlu et al., 2015; Hamard et al., 2013; Lagouin et al., 2019; Lagouin, Aubert, et al., 2021; Lima, Faria, et al., 2016; Santos et al., 2018; Stazi et al., 2015).

The comparison of the shrinkage between the mortars reinforced with Grey Sand and Yellow Sand shows that the values are very similar - 2.8% instead of 2.4 or 2.7% for 24x20 specimens and 4.2% instead of 4.1% for 30x7 specimens. Therefore it can be assumed using Grey Sand instead of Yellow Sand has no impact on the shrinkage of the mortars.

Table 5-7: Shrinkage properties of earth mortars reinforced with Grey sand Yellow Sand

Mix name	Amount of sand (%weight)	Amount of clay (%weight)	Slump test (cm)	Settling time (days)	Sample type 24x20 Shrinkage (%)	24x20 *Standard dev.*	16x4 Shrinkage (%)	16x4 *Standard dev.*	30x5 Shrinkage (%)	30x5 *Standard dev.*
Reference Earth	**0**	**24.5**	**15.1** **17.1**	**0-2**	**7.1**	***0.8***	**7.7**	***0.9***	**5.6**	
Ka000100-201	17	20	16.6	0	4.8	*0.3*			6.6	
Ka000100-331	39	15	16.9	2	3.9	*0.6*	3.9	*0.5*		
Ka000100-332	40	15	16.6	0	2.5				5.7	*0.2*
Ka000100-501	57	11	17.2	2	2.7	*0.2*	2.9	*0.2*		
Ka000100-502	57	10	16.5	0	2.4	*0.3*			4.1	
Ka000100-671	73	7	17	2	0.7	*0.0*	1.5	*0.4*		
Ka000100-673	72	7	16.3	0	0.9	*0.2*			2.3	*0.3*
Ka000100-751	80	5	16.9	2	0.2	*0.3*	0.6	*0.1*		
Ka000100-752	80	5	19	0	0.4	*0.3*			1.5	*0.1*
Ka000200-501	50	11	16.5	0	2.8	*n.a.*			4.2	*0.1*

5.2.1.2 Density

The average density of plasters stabilized with sands is presented in Table 5-8 and the properties of the reference earth are also presented together for comparison. The density varies from 1659kg/m³ (Ka000100-671) to 1786 kg/m³ (Ka000100-501) for 24x20 uncut samples, and from 1691kg/m³ (Ka000100-752) to 1780kg/m³ (Ka000100-501) for 24x20 cut samples and 1717kg/m³ (Ka000100-751) to 1764kg/m³ (Ka000100-501) for 16x4 samples or 1679 kg/m³ (Ka000100-751) to 1701 kg/m³ (Ka000100-332) for 35x7 samples. It can be seen that the densities are varying according to the type of specimen used, with cut samples having a higher density and less variations than uncut large samples. However, the highest and lowest densities are seen for the same mixes, 50% sand added and 75% sand added respectively. From these data, it seems that there is an optimal amount of sand to create a higher density and this amount would be between 33% and 50% of sand and a general decrease in density after the optimum amount (see Figure 5-4). A similar trend of decrease of the density can be observed in the work of Lima et al. (2016) who started to test the mortar with an amount of sand already of 67% of the mix and increased it to 80%. This might be because after a certain amount of sand, the addition of more large particles creates a porosity that can't be filled by the fines present in the mix.

The comparison between the mortars made with Grey Sand and Yellow Sand shows that for the same amount of sand, the average density of mortars with Yellow Sand is slightly higher -less than 2% - but the variation of density values is also higher, therefore it can be assumed that using either Grey Sand or Yellow Sand has no impact on the density.

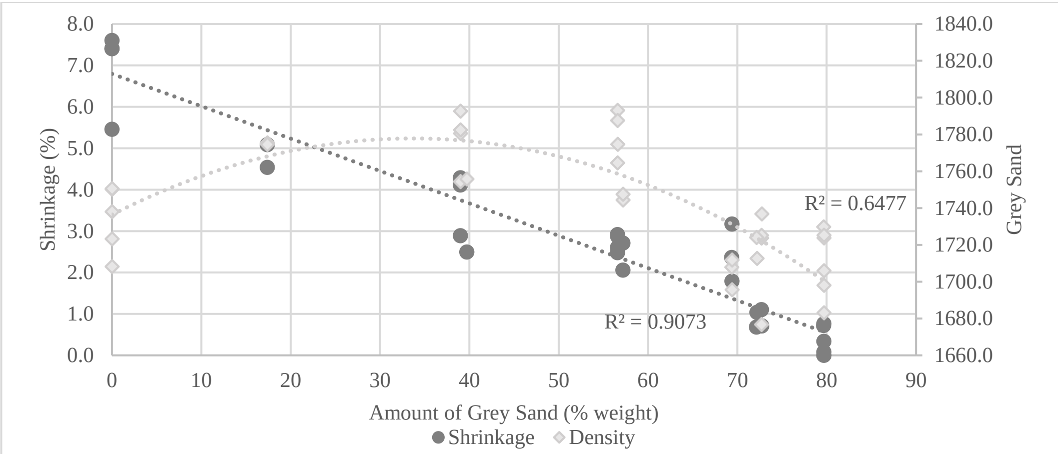

Figure 5-4: Impact of the amount of Grey Sand on the shrinkage and density of earth mortars. All specimen values have been plotted, not only the average.

Table 5-8: Average density of mortars reinforced with Grey Sand and Yellow Sand

mix name	amount of sand (%vol)	slump test (cm)	settling time (days)	Sample type: 24x20 average dry density of uncut samples (kg/m³)	*standard dev.*	average dry density of large samples (kg/m³)	*standard dev.*	16x4 average dry density (kg/m³)	*standard dev.*	30x5 average dry density (kg/m³)	*standard dev.*
Reference Earth	**0**	**15.1-17.1**	**0-2**	**1691**	***22***	**1745**	***37***	**1682**	***12***	**1698**	
Ka000100-201	20	16.6	0	1743	*13*	1775	*0*			1686	
Ka000100-331	33	16.9	2	1777	*14*	1777	*14*	1752	*10*		
Ka000100-332	33	16.6	0	1693		1756				1701	*35*
Ka000100-501	50	17.2	2	1786	*13*	1780	*11*	1764	*17*		
Ka000100-502	50	16.5	0	1720	*9*	1746	*2*			1687	*30*
Ka000100-671	67	17	2	1659	*14*	1712	*26*	1748	*8*		
Ka000100-673	67	16.3	0	1700	*17*	1718	*6*			1681	*15*
Ka000100-751	75	16.9	2	1732	*12*	1721	*9*	1717	*13*		
Ka000100-752	75	19	0	1701	*16*	1691	*8*			1679	*15*
Ka000200-501	50	16.5	0	1763	*26*	1786	*30*			1736	*n.a.*

5.2.2 Mechanical properties of earth mortar reinforced with Grey Sand and Yellow Sand

The flexural strength and the compressive strength of earth mortars reinforced with Grey Sand are presented and discussed in the following sections. Table 5-9 and Figure 5-5 shows the values of mechanical strengths for the different specimen size and the correlation between sand amount and strength.

Table 5-9: Average mechanical strength of earth mortars reinforced with Grey Sand and Yellow Sand

					Sample type							
					24x20 (cut samples)				16x4			
mix name	amount of sand (%vol)	Amount of clay (%)	slump test (cm)	settling time (days)	average dry flexural strength (MPa)	*standard dev.*	average dry compressive strength (MPa)	*standard dev.*	average dry flexural strength (MPa)	*standard dev.*	average dry compressive strength (MPa)	*standard dev.*
Reference Earth	**0**	**24.5**	**16.9**	**2**	**1.55**	**0.29**	**4.51**	**0.46**	**1.35**	**0.22**	**5.31**	**0.46**
Ka000100-201	20	20	16.6	0	0.80	*0.01*	3.57	*0.32*				
Ka000100-331	33	15	16.9	2	1.07	*0.02*	2.32	*0.19*	1.26	*0.03*	3.77	0.28
Ka000100-332	33	15	16.6	0	1.02	*0.23*	2.44	*0.20*				
Ka000100-501	50	11	17.2	2	0.81	*0.06*	1.43	*0.30*	0.94	*0.00*	2.57	0.14
Ka000100-502	50	11	16.5	0	0.90	*0.07*	1.76	*0.17*				
Ka000100-671	67	7	17	2	0.57	*0.02*	1.26	*0.36*	0.61	*0.01*	2.13	0.07
Ka000100-673	67	7	16.3	0	0.67	*0.05*	1.40	*0.14*				
Ka000100-751	75	5	16.9	2	0.49	*0.02*	1.08	*0.14*	0.55	*0.02*	2.19	0.37
Ka000100-752	75	5	19	0	0.58	*0.01*	1.22	*0.07*				
Ka000200-501	50	11	16.7	0	0.89	*0.17*	2.60	*0.35*				

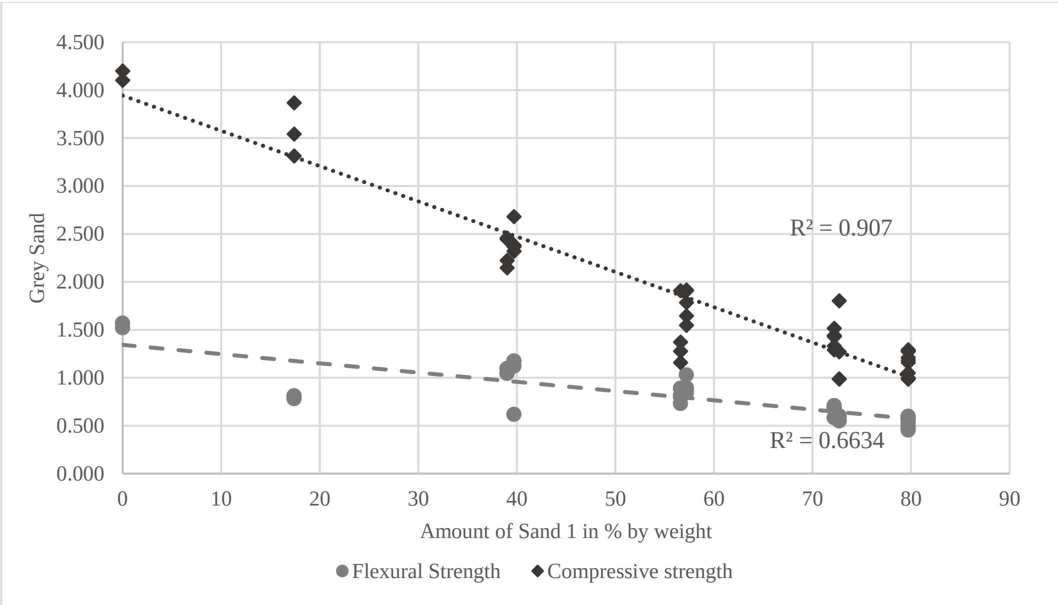

Figure 5-5: Impact of the amount of Grey Sand on the mechanical strength of the earth mortars.

5.2.2.1 Flexural strength

The flexural and compressive strength of earth mortars reinforced with sand have been measured and are presented in Table 5-9.

The flexural strength varies slightly for the different types of specimens but can be assumed similar and therefore only the strength of 24x20 specimens will be discussed. Maximum flexural strength is recorded for the mortar with 33% of sand (Ka000100-332; 1.07 MPa) and the minimum flexural strength is found for the mortar with 75% of sand (Ka000100-751; 0.58 MPa). The values found are similar to the ones found in the literature with a flexural strength varying between 0.9 MPa for the highest values and 0.3 MPa for the lowest (Hamard et al., 2013; Lagouin, Laborel-Préneron, et al., 2021) whereas Lima et al. (2016) found very low values below 0.25 MPa.

Different flexural strengths have been found for different settling times and water amounts (Table 5-9) – measured with the slump test – however, no relation between any of these variables and the strength could be found.

All flexural strength values are lower than the flexural strength of the Reference Earth (1.55 MPa). This result is similar to Hamard et al. (2013) and Lima et al. (2016) whereas Lagouin et al. (2021) show that depending on the type of earth, there might be an optimum amount of clay (around 10%) which would increase the flexural strength. The higher values for Ka000100-331 and -332 probably come from the higher density of the specimens as can be seen in Figure 5-6.

The flexural strength of mortars made with Yellow Sand is 0.89 MPa, similar to the flexural strength of mortars made with the same amount of Grey Sand (0.81 MPa and 0.90 MPa depending on the settling time and amount of water)

5.2.2.2 Compressive strength

The maximum compressive strength is recorded for the mortar with 20% of sand (Ka000100-201; 3.57 MPa) and the minimum strength was found for the mortar with 75% of sand (Ka000100-751; 1.08 MPa), independently of the specimen size, however, there is a large difference of strength if the sample tested is cast or cut. The values found for the compressive strength are comparable with the work of Lagouin et al. (2021) for a similar amount of clay but lower than the results found by Emiroğlu et al. (2015) and higher than the ones found by Taylor et al. (2006) or Lima et al. (2016) for a similar ratio of sand and earth. The compressive strength experiences a constant decrease with the addition of sand which is expected since the strength of the stabilized earth is high however, no local optimum strength can be found in the opposite of other works done (Emiroğlu et al., 2015; Lagouin, Laborel-Préneron, et al., 2021).

Similarly to the flexural strength, it seems that no settling increases the strength of the mortar, however, the reason for it is unclear and the difference is low with the 2 days settling time mortars.

The compressive strength of earth mortar reinforced with 50% of Yellow Sand is 2.60 MPa, much higher than the one of mortar reinforced with Grey Sand (1.43 MPa and 1.76 MPa depending on the settling time). The large difference in strength is probably due to the type of sand used which are more angular and therefore might better lock in-between each other under compression.

5.2.2.3 Correlation between strength and density

Figure 5-6 presents the mechanical strength of each tested specimen – flexural strength and average compressive strength of the 2 broken specimens – according to the density of the specimen tested (density of the 16x4x4 specimens cut from the 24x20x4 plates). From this figure, it is clear that there is a correlation between the strength and the density, with as expected, a decrease in strength for a decrease in density. As seen in section 5.2.1, the maximum density is found for mixes including between 20% and 33% of sand, therefore, the maximal strength found for samples with 20% or 33% of sand is in line with the density and the literature. This correlation is similar to the one given by Kouako and Morel (2009) or Perrot et al. (2018) for compressive strength.

Moreover, as some authors (Lagouin, Aubert, et al., 2021; Lagouin, Laborel-Préneron, et al., 2021) have tried to demonstrate, a strong correlation can be seen between compressive and flexural strength – especially when the results of mortar Ka000100-201 are omitted (Figure 5-7). Mortar Ka000100-201 presents a very high compressive strength and a low flexural strength when plotted with other sand-reinforced mortars, therefore the results can be considered as outliers.

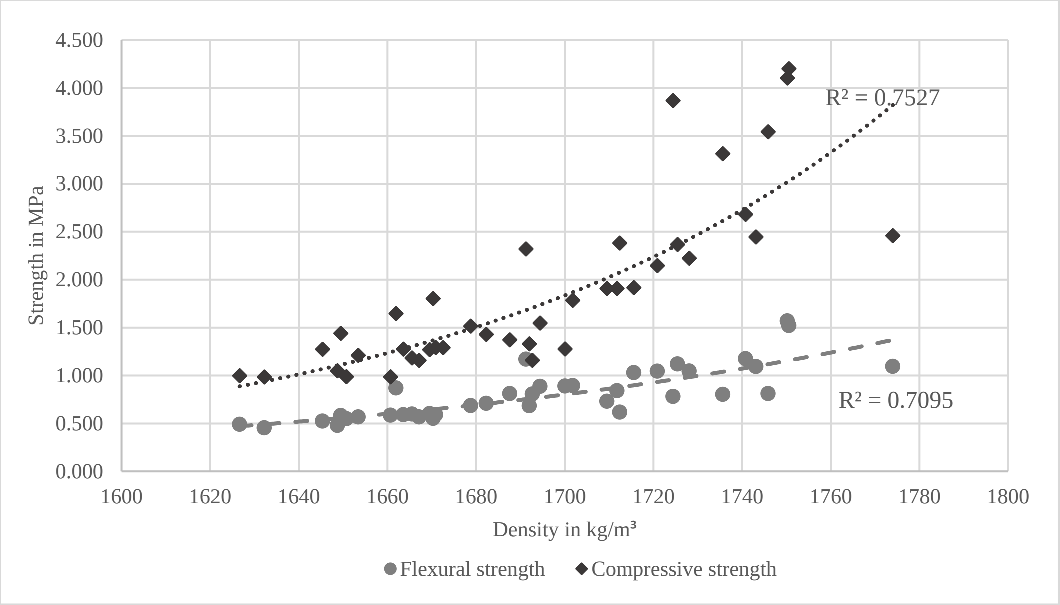

Figure 5-6: Impact of the density on the compressive and flexural strength of earth mortar reinforced with Grey Sand

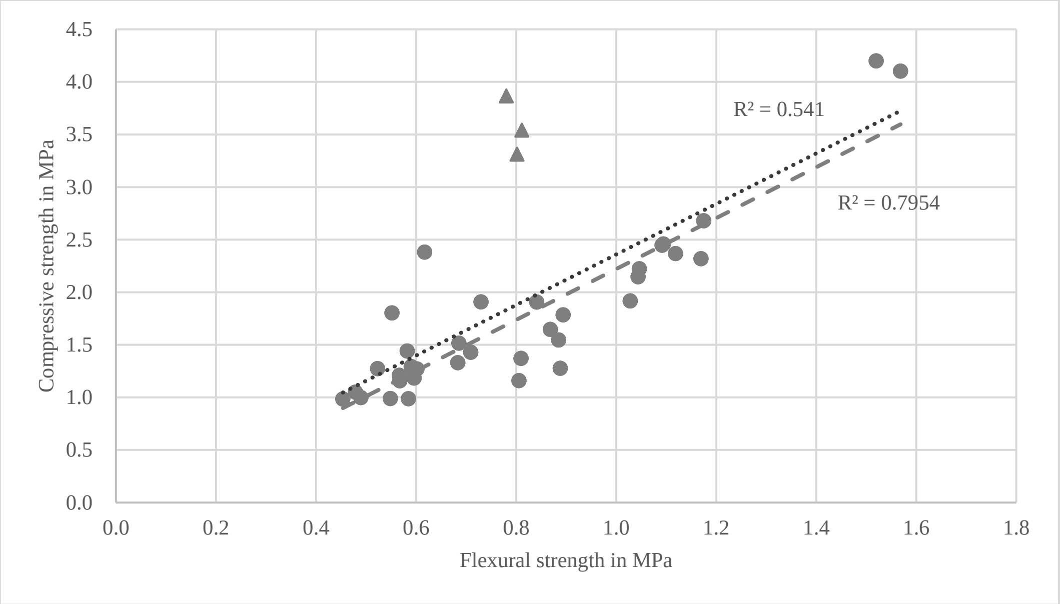

Figure 5-7: Relation between compressive and flexural strength. The dotted line represents the linear correlation using all data whereas the dashed line represents the linear correlation excluding the mortars Ka0010000-201 (represented by triangle markers)

5.2.3 Surface properties of earth mortars reinforced with Grey Sand and Yellow Sand

The results of the sponge test and the band test are presented in Table 5-10 together with the average properties of the Reference Earth. The impact of the addition of sand is discussed in the following sections.

Table 5-10: Surface properties of earth mortars reinforced with Grey Sand

Mortar Name	Amount of clay (% weight of dry mix)	Amount of sand (%weight of dry mix)	Amount of water (% weight of dry earth)	slump test (cm)	settling time	Surface water absorption (g/m²·s) for 90 s.	Peeling test – (µg/cm²)	Visual scale (1-10)
Reference Earth	**24.5**	**0**	**30**	**17**	**2**	**14.0**	**264**	**1**
Ka000100-331	14.9	39	26	16.9	2	18.6	188	1
Ka000100-501	10.6	57	22	17.2	2	25.2	236	1
Ka000100-671	6.7	73	21	17.0	2	29.3	639	2
Ka000100-751	5.0	80	19	16.9	2	31.5	1292	2

5.2.3.1 Surface water absorption

The surface water absorption of mortars reinforced with sand varies from 18.6 g/m²·s for Ka000100-331 (33% of sand) to 31.5 g/m²·s for Ka000100-751 (75% of sand). The results show that there is a direct link between the amount of added sand – i.e. the amount of clay – and the absorption of water. The addition of more sand creates more pores in the dry mix, and therefore a better absorption of the water that is not slowed by the clay particles.

5.2.3.2 Surface cohesion

Results of the peeling test vary from 264 µg/cm² for Ka000100-331 (33% of sand) to 1292 µg/cm² for Ka000100-751 (75% of sand). However, the numerical or visual results don't show a linear variation of the detached material but more a fast increase past a certain amount of added sand. Moreover, when results are compared with the results of the reference earth, it shows that this increase is not so high and is not due to a higher amount of particles sticking to the band, but more to a higher weight of particles as demonstrated by the visual scale results (2 on a 10 level scale) as shown in Figure 5-8. Therefore, it can be said that the cohesion as calculated through this test depends on the amount of clay – as a binding material – but also on the size of particles and specifically their weight. Moreover, the results for Ka000100-751 are similar to the results of Faria et al. (2016) and Parracha et al. (2021) for a ready-made plaster with a similar amount of clay and the results of Ka000100-671 are in between the results found by García-Vera et al. (2018) for two plasters with similar shrinkage and density but different clay type and very close to the results of Lima et al. (2016; 2016) for a plaster made of 1 volume of earth and 3 volume of sand.

The impact of the sand content is similar to the one found by Santos et al. (2018) for plaster applied on bricks and the results are also similar to the one of this research for a similar amount of added sand.

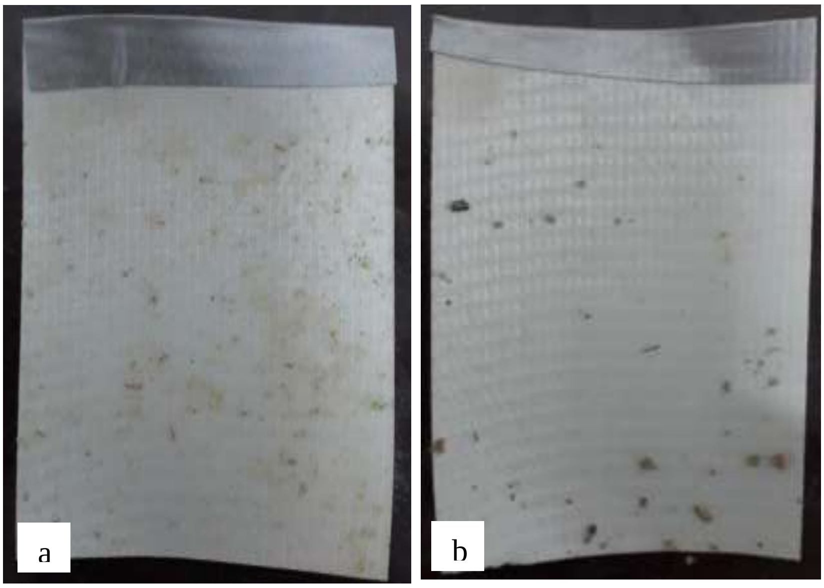

Figure 5-8: Impact of the amount of sand on the surface properties of earth mortars. The left picture (a) shows the results of the tape test for the Reference Earth and the right one (b) shows the results of the test for Ka000100-501

5.2.4 Durability of earth mortar reinforced with Grey Sand and Yellow Sand

The durability properties of earth mortars reinforced with sand are given in Table 5-11 together with the amount of clay in the mortars. The behaviour of the mortars and their different properties (humid mechanical strength, resistance to immersion in water, resistance to abrasion and resistance to erosion) are discussed in the following paragraphs.

Table 5-11: Durability of earth mortars reinforced with Grey Sand and Yellow Sand

Mortar Name	Amount of clay (% weight of dry mix)	Humidity level (weight increase in %)	Humid flexural strength (MPa)	Loss in strength (%)	Humid compressive strength (MPa)	Loss in strength (%)	Water resistance (min)	Abrasion resistance (DIN18947) Material loss (g)	Abrasion resistance (French rules) Abrasion Coefficient (cm²/g)	Abrasion resistance (French rules) Depression depth (cm)	Erosion resistance Hole depth (mm)	Erosion resistance Hole diameter (mm)
Reference Earth	**24.5**	**2.5**	**0.60**	**-46**	**3.35**	**-42**	**28**	**1.9**	**6.4**	**1.3**		
Ka000100-201	20.2	1.6	0.59	-26	1.76	-51	---	1.3	2.0	2.8	6	20
Ka000100-331	14.9	1.9	0.42	-61	1.50	-35	5	3.6	1.0	2.3	6	22
Ka000100-501	10.6	1.5	0.24	-71	0.87	-39	1	5.9	0.5	10.0	5.5	28
Ka000100-671	6.7	1.3	0.27	-53	0.56	-56	2	10.5	0.4	12.5	10	20
Ka000100-751	5.0	1.2	0.25	-49	0.48	-56	1	11.7	0.3	10	13	20
Ka000200-501	10.5	1.1	0.39	-56	0.85	-67	7	3.1	0.5	9		

5.2.4.1 Humid mechanical strength

The humid mechanical strength of earth mortars reinforced with Grey Sand is given in Table 5-11. The amount of humidity was determined by weighing the sample before putting it in a humid room and before testing it for flexural strength. Both the strength and the loss of strength compared to the dry sample are given in Table 5-11. The highest flexural and compressive strength are recorded for Ka000100-201 (20% of Grey Sand) whereas the lowest strength is recorded for Ka000100-751 (75% of Grey Sand) exactly as for the dry strength. The loss of strength varies from 26% to 71% for flexural strength and from 39% to 56% for compressive strength, but no relation between loss of strength and amount of sand, or amount of humidity could be established, as it even seems that an amount of humidity as low as 0.5% is leading to a very high loss of strength (Ka000100-672)

5.2.4.2 Water resistance by immersion

The resistance to immersion in water varies from 5 min. (Ka000100-331) to 1 min. (Ka000100-501 or Ka000100-751). It means that samples reinforced with Grey Sand lose their cohesion after a few minutes in water but as the amount of sand is increased, faster is the dissolution in water. The results are as expected, as the amount of binder – i.e. clay – is reduced, the water resistance is reduced.

5.2.4.3 Abrasion resistance (DIN 18947)

The mass loss due to the brushing of the samples according to the DIN 18947 varies from 1.3g (Ka000100-201) to 11.7g (Ka000100-751). Except for the sample Ka000100-201 with a low amount of added sand which seems to prevent partially the abrasion, the addition of sand reduces the cohesion of the samples and increases the material loss.

5.2.4.4 Abrasion resistance (French rules)

The abrasion resistance of the mortar tested according to French regulation varies from 2 cm^2/g for Ka000100-201 to 0.4 cm^2/g for Ka000100-671. And the average depth of the depression made by the brushes varies from 2.3 mm to 12.5 mm. All these values are showing that samples with added sand decrease the abrasion resistance and the more the addition of sand, the lesser the resistance. This conclusion is supported by the work of Hamard et al. (2013) on earth plaster which shows that the higher the amount of clay, the lowest the abrasion

5.2.4.5 Erosion resistance

The erosion resistance of samples is tested by measuring the depth of the hole created by the dropping of water. The depth varies from 6 mm for samples with 20% of Grey

Sand (Ka000100-201) to 13 mm for samples with 75% of Grey Sand (Ka000100-751). The addition of sand reduces the resistance to erosion as the increasing amount of sand reduces the amount of clay which is the binding material.

5.2.5 Hydric properties of mortars reinforced with Grey Sand and Yellow Sand

The hydric properties of earth mortars reinforced with Grey Sand and Yellow Sand are shown in Table 5-12. Both the water absorption behaviour characterized by the Capillarity Coefficient (CC) and the drying behaviour characterized by the primary Drying Rate (pDR) and secondary Drying Rate (sDR) and the Drying Index are shown. The table is completed with Figure 5-9 and Figure 5-11 displayed in the following paragraphs.

Table 5-12: Hydric properties of mortars reinforced with Grey and Yellow Sands

	Amount of clay (% weight of dry mix)	Amount of sand (% weight of dry mix)	Capillarity coefficient (kg/(m²·min$^{0.5}$))	*R² (-)*	Drying rate (1st phase) (kg/m²/h)	*R² (-)*	Drying rate (2nd phase) (kg/m²/h$^{0.5}$)	*R² (-)*	Drying index
Reference Earth	24.5	0	1.00		0.14		1.32		0.30
Ka000100-201	20.2	17	0.95	*1.00*	0.15	*1.00*	1.24	*0.99*	0.31
Ka000100-331	14.9	39	1.07	*1.00*	0.14	*1.00*	1.28	*1.00*	0.26
Ka000100-501	10. 6	57	0.83	*1.00*	0.11	*0.99*	0.97	*0.99*	0.25
Ka000100-671	6.7	73	1.06	*1.00*	0.12	*0.97*	1.03	*0.99*	0.27
Ka000100-751	5.0	80	1.08	*1.00*	0.14	*1.00*	0.96	*0.99*	0.16
Ka000200-501	11.3	54	0.67	*1.00*	0.12	1.00	0.97	*1.00*	0.27

5.2.5.1 Water capillarity absorption

The water capillarity absorption for the mortars reinforced with sand is plotted in Figure 5-9. The CC is presented in Table 5-12. According to the results, the lowest CC is calculated for the mortar Ka000100-5011 and the highest for the mortar Ka000100-331. The CC values found in this work are different from the ones found for similar mortars by Lima & Faria (2017) who found values 4 times lower which is probably due to the experimental setup (Faria et al., 2016). When the CC is compared with the amount of sand added, there seems to be an impact of the sand addition, but as shown by Lima & Faria (2017), it is difficult to relate to the amount of sand used. However, as only one specimen of each mortar has been used, there might be some errors which prevent correlating the amount of sand or the density with the absorption rate.

However, the difference in absorption rate is not very large 0.13 $kg/(m^2 \cdot min^{0.5})$ if Ka000100-1001 is omitted – as its absorption curve seems very different from others in Figure 5-9 – and the fast rate of absorption is counterbalanced by the fact that the samples with a high amount of sand will stop absorbing water more rapidly (after 49 min for Ka00010-751) whereas other samples will continue to absorb water until the end of the test.

Figure 5-10 compares the behaviour of mortars reinforced with the same amount of Grey Sand and Yellow Sand. It is seen that despite the same amount of sand used, their behaviour is quite different with Ka000100-501 having a faster absorption rate than Ka000200-501 but the total amount of water absorbed at the end of the test is similar.

In conclusion, it can be told that a high amount of clay prevents a fast absorption but at the same time mortars with a high amount of clay can store a higher amount of water than sandy ones. Moreover, the type of sand seems more important than the amount of sand to modify the absorption rate.

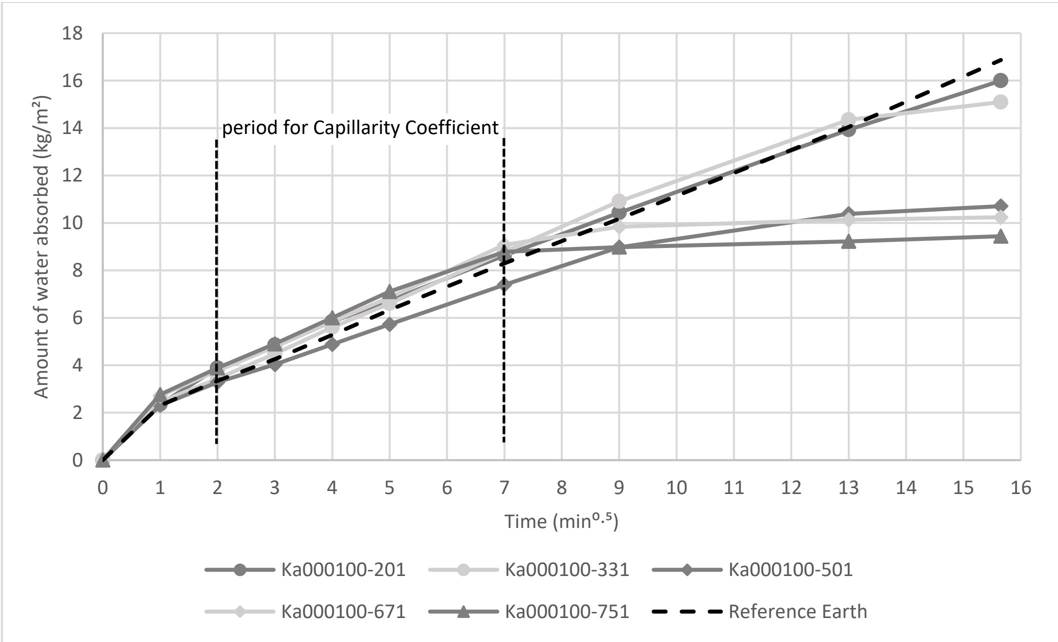

Figure 5-9: Water capillarity absorption of mortars reinforced with Grey Sand

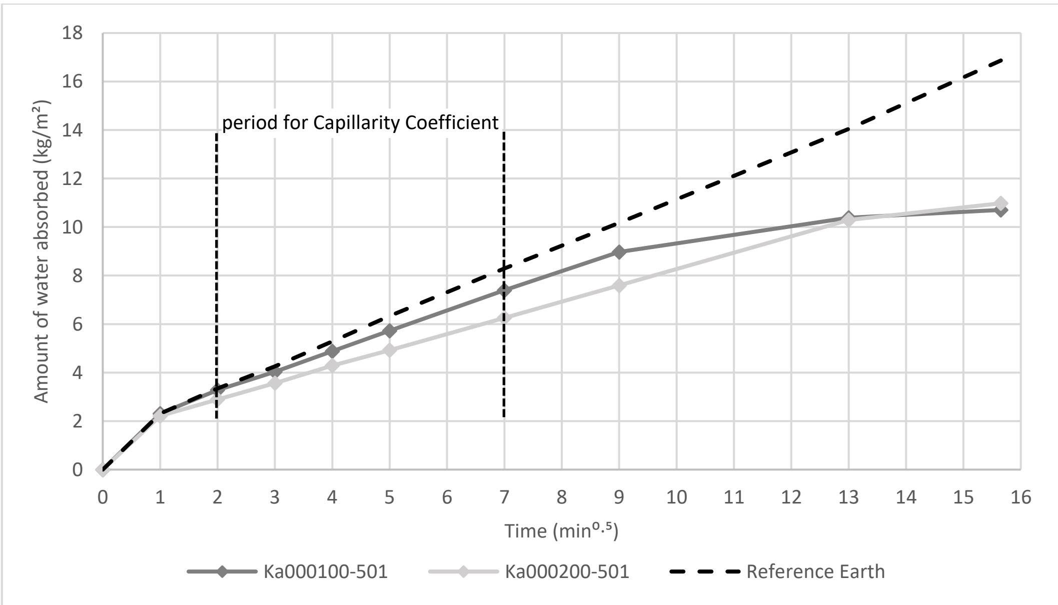

Figure 5-10: Comparison of the water absorption of mortars reinforced with Grey Sand and Yellow Sand

5.2.5.2 Drying behaviour

The drying behaviour of mortars is represented by 3 different coefficients which show the initial water loss (primary Drying Rate, pDR), the secondary drying through evaporation (secondary Drying Rate, sDR) and the difficulty to achieve complete drying (Drying Index, DI). These values are presented in Table 5-12and the drying curves are presented in Figure 5-11. The primary drying rates of the mortar were calculated during the first 24h of drying whereas the secondary drying rate was calculated from day 2 to day 6.

The primary drying rate varies between 0.11 kg/m²/h (Ka000100-501) and 0.15 kg/m²/h (Ka000100-201) but Ka000100-751 has also a similar pDR (0.14 kg/m²/h) so it seems that the amount of sand has only a relative impact on the primary DR as shown by Lima & Faria (2017). On the other hand, the secondary drying rate is getting lower with the addition of sand as also underlined by the previous authors which shows that it is more difficult for the mortar to achieve a complete drying by evaporation, probably because of the difficulty of the water to migrate internally from the bottom of the sample to the top. Mortars with a higher clay amount will dry faster, as can also be seen in Figure 5-11 where the earth mortar achieves a full drying before other mortar despite a higher initial water content.

The Drying Index of earth mortars reinforced with Sand varies from 0.16 (Ka000100-751) to 0.31 (Ka000100-201) with a decrease of the DR with the amount of sand. A lower DI means an easier achievement of full drying of mortars, therefore, it seems that the addition of sand leads to an easier drying of the mortar, probably because the molecules of water are not trapped between the clay particles as the amount of clay is lower.

Figure 5-12 compares the drying behaviour of earth mortars reinforced with Grey Sand and Yellow Sand. It can be seen that following the drying rate, mortar Ka000200-501 has a faster primary drying rate, but the secondary drying rate is smaller and therefore the total drying seems more difficult to achieve.

In conclusion, it can be told that the addition of sand reduces the drying rate during the first period but decreases the total drying time as the water molecules will not be trapped between the clay particles but free to migrate through the material.

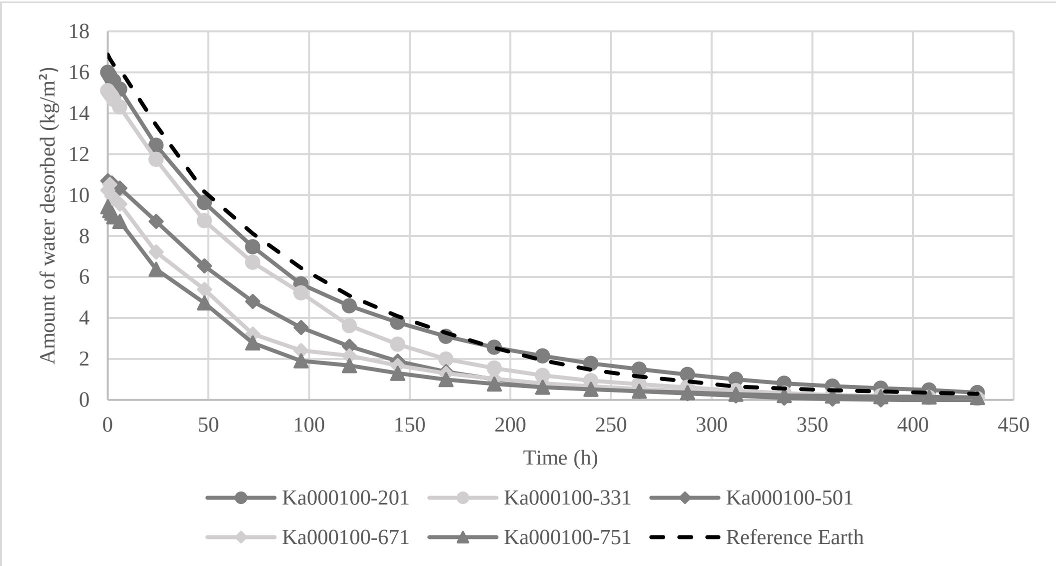

Figure 5-11: Drying behaviour of mortars reinforced with Grey Sand

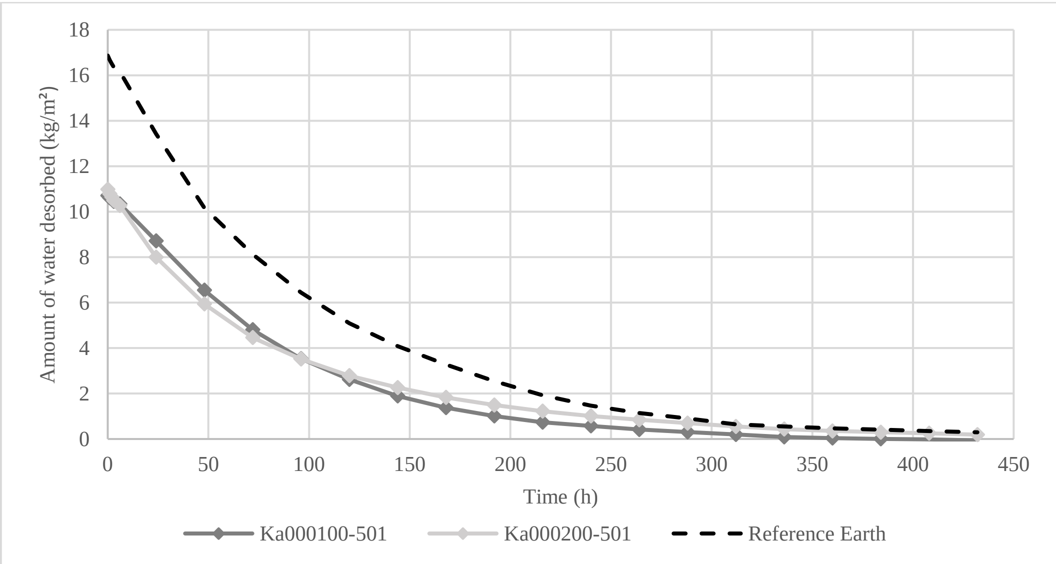

Figure 5-12: Comparison of the drying behaviour of mortars reinforced with Grey Sand and Yellow Sand

5.2.6 Hygric properties of earth mortars reinforced with Grey Sand and Yellow Sand

The hygric properties of earth mortars reinforced with Grey Sand and Yellow Sand are presented in Table 5-13 and the water vapour permability, the water vapour absorption and the water vapour desorption of earth mortars reinforced with Grey Sand and Yellow Sand are discussed in the following sections.

Table 5-13: Hygric properties of earth mortars reinforced with Grey Sand and Yellow Sand

Mortar Name	Amount of clay (% weight of dry mix)	Density (kg/m³)	Water vapour permeability (x10⁻¹¹ kg/m*s*Pa)	Water vapour diffusion resistance factor (-)	Equivalent air layer (m)	Water vapour adsorption (12h - g/m²)	primary adsorption rate - first 3h (g/m²h)	secondary adsorption rate – 24h-48h (g/m²h)	water vapour desorption (12h - g/m²)	primary desorption rate - first 3h (g/m²h)	secondary desorption rate - 12h-48h (g/m²h)
Reference Earth	**24.5**	**1735**	**5.0**	**3.9**	**0.15**	**153.0**	**14.3**	**6.2**	**147.0**	**17.6**	**4.6**
Ka000100-201	20.2	1775	5.0	3.9	0.15	164.5	16.6	6.7	160.4	20.4	3.7
Ka000100-331	14.9	1781	4.4	4.5	0.17	160.1	15.7	5.9	149.5	17.9	4.2
Ka000100-501	10.6	1775	4.4	4.4	0.17	137.9	13.1	4.9	129.9	16.6	3.5
Ka000100-672	7.5	1708	3.9	5.1	0.20	130.6	12.6	4.8	126.4	17.0	3.4
Ka000100-671	6.7	1737	4.0	4.9	0.20	119.1	11.6	4.0	116.8	14.5	3.3
Ka000100-751	5.0	1730	4.6	4.3	0.18	113.3	11.9	3.9	130.1	17.3	3.1
Ka000200-501	11.3	1786	4.3	4.6	0.18	143.4	15.0	5.3	135.8	18.3	3.3

5.2.6.1 Water vapour permeability

The water vapour permeability of sand-reinforced earth mortars is presented in Table 5-13 together with the density of the samples. The values for mortars reinforced with Grey Sand range from 3.6 (Ka000100-201 with 20% of Grey Sand) to 5.1 for Ka000100-672 (67% of Grey Sand) whereas the mortar reinforced with 50% of Yellow Sand has a water vapour diffusion resistance factor of 4.6 similar to the one reinforced with the same amount of Grey Sand. All those samples have a very low vapour resistance, as expected for samples mortars containing earth. It seems that the amount or the type of sand has little impact on this resistance as all the value are close to the one of the Reference Earth, but still, as the amount of sand is increasing the diffusion resistance seem to slightly increase. However, as only one specimen has been tested for each mortar, it is difficult to conclude anything. The trend is contrary to the one shown by Lima et al (2017) who studied plasters with different amounts of sand with a decrease in permeability for the addition of sand.

5.2.6.2 Water vapour adsorption

The dynamic water vapour adsorption behaviour is shown in Table 5-13 and Figure 5-13. The lower limits for plaster class I and class III according to DIN 18947 are also represented in Figure 5-13. The mortar with the highest adsorption of water vapour at 12h is Ka000100-201 (20% of Grey Sand) whereas the one with the lower adsorption amount is Ka000100-751 (75% of Grey Sand). If the total amount of vapour adsorbed after 48h (duration of the test) is considered, the same order applies as seen in Figure 5-13. However, the amount of water vapour absorbed is much higher in this study than in the literature (Faria & Santos, 2014; Lima, Faria, et al., 2016).

The primary and secondary adsorption rates as shown in Table 5-13 also show the decreasing adsorption of vapour by the mortars with an increasing amount of sand. This behaviour is similar to the one described by Lima et al. (2016) who tested plasters with different amounts of sand and found that the vapour adsorption at 12h was linearly related to the amount of clayish earth (i.e. clay) present in the mix. However, for this research, if only the mortars with earth and sand are tested, a similar trend is found (Figure 5-14) but if the Reference Earth is taken into account, then it seems to be an optimum of clay content and a higher amount of clay in the mix will decrease the water vapour absorption.

Similarly to the water vapour permeability, the type of sand seems to have no impact as the difference in behaviour seen in Figure 5-15 is explained by the slightly different amount of clay between the mortars Ka000101-501 and Ka000201-501 (Figure 5-14 and Table 5-13)

5.2.6.3 Water vapour desorption

The dynamic water vapour desorption behaviour is shown in Table 5-13 and Figure 5-13. The mortar with the highest desorption of water vapour at 12h is Ka000100-201 (20% of Grey Sand) whereas the lower desorption is Ka000100-671 (67% of sand). The primary desorption also shows the same with a decreasing desorption rate for an increasing amount of sand – except for mortar Ka000100-751 (75% of Grey Sand) which seems to have a faster desorption rate than other samples. However, for the secondary desorption rate (between 12h and 48h in the dry room) the desorption seems correlated with the amount of clay similar to the behaviour shown by Lima et al. (2016). However, probably due to the test conditions – i.e. the thickness of the samples and the humidity and the temperature of the dry room – the total desorption of samples is lower than the one given by the previous authors and after 48h in the dry room, a large amount of humidity is still present in the samples (Figure 5-13). Moreover, when the desorption behaviour is compared with the Reference Earth, it is seen that despite the Reference Earth having lower desorption after 12h in the dry room than mortars with a low amount of sand, its desorption rate is much higher after 24h in the dry room, probably due to the better transfer of the water vapour from the bottom of the sample to the surface through the clay particles.

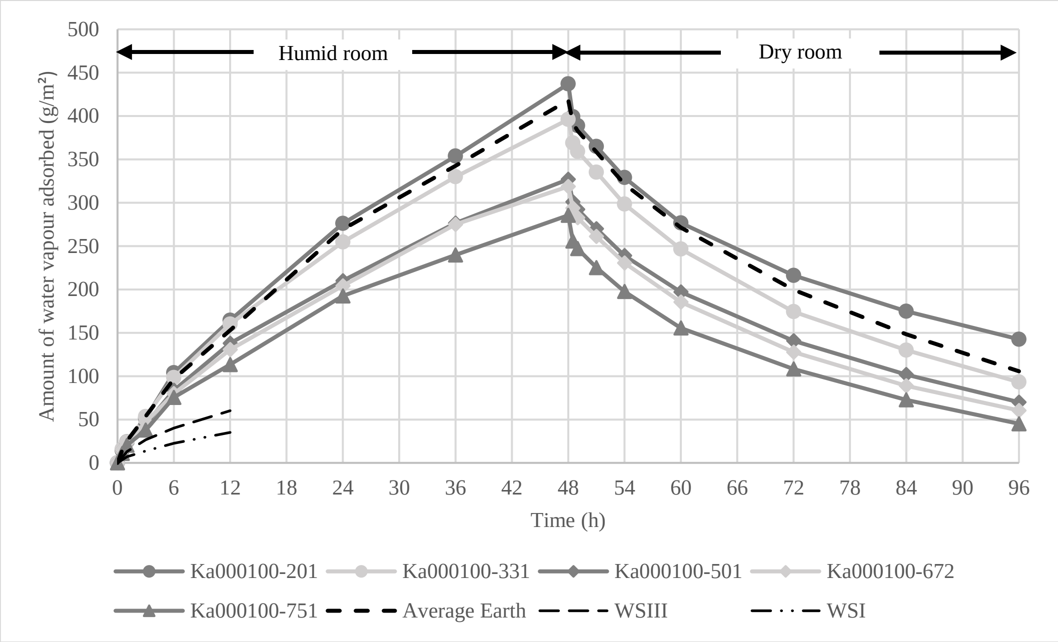

Figure 5-13: Water vapour adsorption and desorption behaviour of earth mortars reinforced with Grey Sand

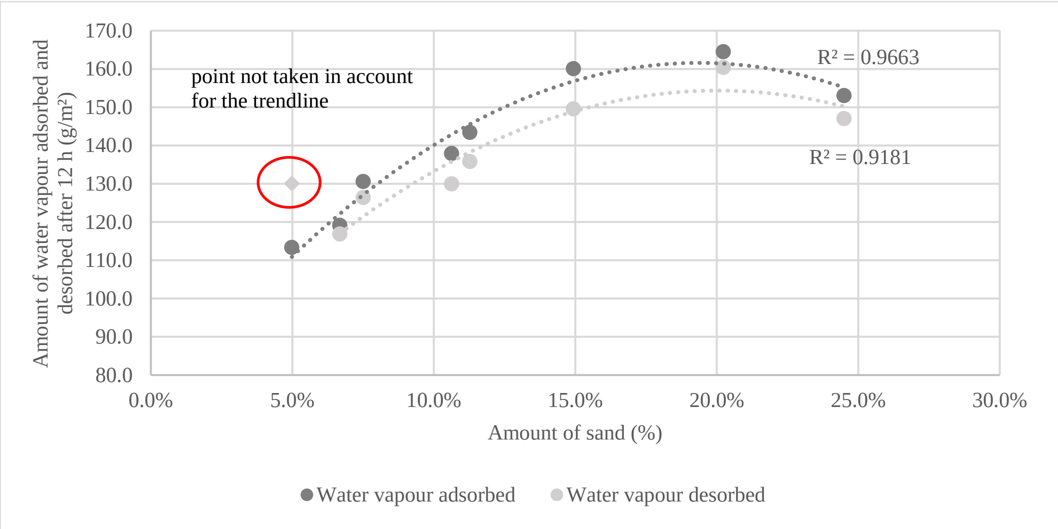

Figure 5-14: Amount of water vapour adsorbed after 12h in relation to the amount of clay.

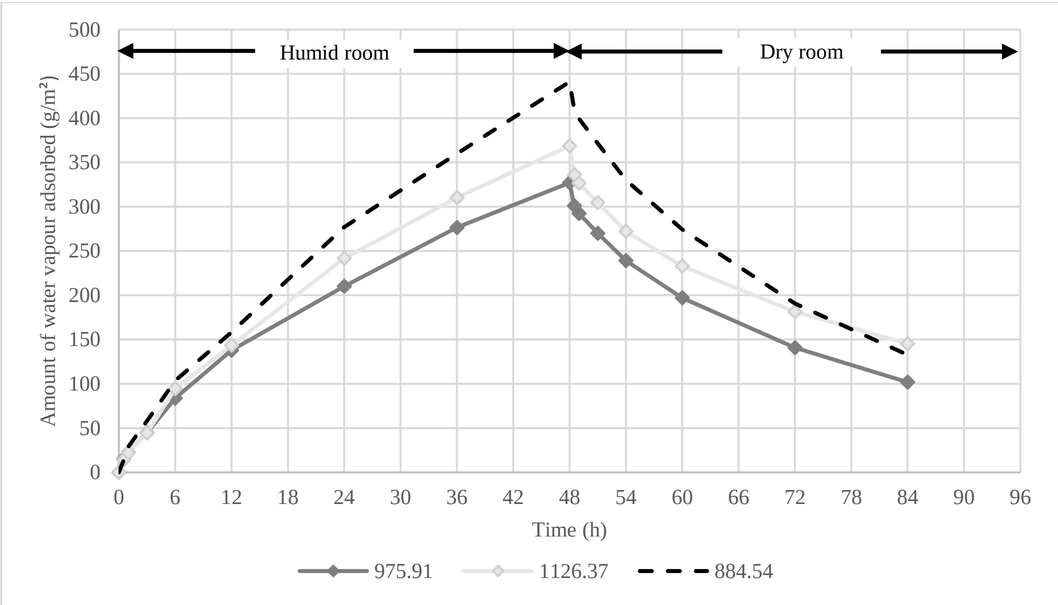

Figure 5-15: Comparison of the dynamic water vapour adsorption and desorption of earth mortars reinforced with Grey Sand and Yellow Sand

5.3 Properties of earth mortars reinforced with Chaff

This section presents the results of the tests on earth mortars reinforced with Chaff. 27 mortars produced with 6 different amounts of Chaff (5%, 10%, 20%, 30%, 40% and 50% of the dry mix by volume) have been tested with different amounts of water and a settling time between 0 days and 3 days. The physical properties, mechanical properties, surface properties, durability properties, hydric properties and hygric properties of these mortars are given and discussed in paragraphs 0 to 5.3.6.

5.3.1 Physical properties of earth mortars reinforced with Chaff

The shrinkage and the density have been calculated on the earth mortars reinforced with chaff and their values are presented in Table 5-14, Table 5-15 and Figure 5-16 and discussed in the following paragraphs.

5.3.1.1 Shrinkage

The shrinkage of fibre-stabilized plasters is summarized in Table 5-14 and presented in Figure 5-16. The shrinkage of samples has been given for large samples, short samples and long samples. The shrinkage of large samples varies from 7.0% (Ka000001-0501 and -0503) to 0.8% (Ka000001-5004) for large samples (24x20x4 cm³) from 7.0% (Ka000001-0503) to 0.2% (Ka000001-5004) for short samples (16x4x4cm³) and from 8.1% (Ka000001-0503) to 1.0% (Ka000001-5004) for long samples (30x5x4cm³). The shrinkage decreases with the increasing amount of fibres which is in line with the literature as shown for example the works Araya-Letelier et al. (2018, 2020, 2021) on different types of fibres or the works of Lima et al (2016) and Laborel-Prénerom et al. (2017) on different stem fibres. However, despite the addition of fibres directly lowering the shrinkage, a very large amount of fibre (about 50% by volume, i.e. 5% to 6% by weight) is still necessary to pass the threshold of 3% of shrinkage which is required by DIN18947 (DIN18947, 2013). A similar range of values was found by Yetgin et al. (2008) and Bouhicha et al. (2005) for earth with high content of clay.

Moreover, the dispersion of the data for each type of mortar is high and even more when all shrinkages are taken for one type of dry mix, e.g. the mortar with 20% of fibres. For 24x20 samples, the shrinkage varies from 3% to 6% for Ka000001-2001 and Ka000001-2006 (100% increase) which can be explained by the doubling of the amount of water (20% for Ka000001-2001 and 39% for Ka000001-2006), whereas the amount of fibres and settling time are identical (1.7% and 0 days). This increase in shrinkage according to the amount of water is also clearly seen when comparing other samples and has also been found by Yetgin et al. (2008). Another variable which might increase the shrinkage is the settling time, as it seems that the mortar with longer settling will have a higher shrinkage, probably because the amount of water stored in the fibres is higher, therefore there is a need for more water to achieve the same consistency – water is added at 2 different times, first when preparing the paste, and then just before application to adjust the consistency.

Table 5-14: Shrinkage properties of earth mortars reinforced with chaff

Mortar Name	Amount of Chaff (% by weight)	Amount of clay (% by weight)	slump test (cm)	Settling time (days)	Sample type					
					24x20		16x4		35x7	
					Shrinkage (%)	*St. Dev.*	Shrinkage (%)	*St. Dev.*	Shrinkage (%)	*St. Dev.*
Reference Earth	**0**		**15.1** **17.1**	**0-2**	**7.1**	***0.8***	**7.7**	***0.9***	**5.6**	
Ka000001-0501	0.6	24.4	16.3	1	7.0	*0.4*				
Ka000001-0503	0.3	24.4	16.1	2	7.0	*1.1*	7.0	*0.3*	8.1	*0.1*
Ka000001-1001	1.1	24.2	16.1	1	6.3	*0.4*				
Ka000001-1003	0.6	24.4	16.9	2	4.8	*0.1*	5.8	*0.3*	5.9	*0.2*
Ka000001-2001	1.7	24.1	-	0	3.0	*0.4*				
Ka000001-2002	1.6	24.1	15	0	4.9					
Ka000001-2003	1.6	24.1	15	1	5.5					
Ka000001-2004	1.6	24.1	15	3	5.9					
Ka000001-2005	1.6	24.1	15.1	0	5.2					
Ka000001-2007	1.6	24.1	17.4	0	6					
Ka000001-2008	1.7	24.1	17.4	0	5.9	*0.3*				
Ka000001-2010	1.3	24.2	16.8	1	4.3	*0.5*				
Ka000001-2013	1.6	24.1	15.6	2	3.9	*0.3*				
Ka000001-2014	1.3	24.2	16.9	2	4.1		4.8	*0.4*	3.9	*0.2*
Ka000001-3001	2.2	23.9	-	0	2.9	*0.3*				
Ka000001-3002	2.6	23.9	15	0	3.6					
Ka000001-4001	3.7	23.6	-	0	1.6	*0.1*				
Ka000001-4002	3.8	23.6	15	0	3.2	*0.5*				
Ka000001-4003	3.8	23.6	15	1	3.0					
Ka000001-4004	3.8	23.6	15	3	3.6					
Ka000001-4005	4.1	23.5	15.1	0	3.0					
Ka000001-4007	5.4	23.2	16.1	0	3.0					
Ka000001-4009	3.2	23.7	16	1	2.2	*0.2*				
Ka000001-4012	3.8	23.7	16.9	2	1.3		1.4	*0*	1.5	*0.4*
Ka000001-5001	5.7	23.1	-	0	1.2	*0*				
Ka000001-5002	6	23.0	14.9	0	2.1					
Ka000001-5004	4.9	23.3	16.7	2	0.8		0.2	*0.2*	1	*0.2*

5.3.1.2 Density

The average density of fibres stabilized plasters is presented in Table 5-15. The average density varies from 1141 kg/m³ (Ka000001-5002) with 50% of fibres by volume to 1656 kg/m³ (Ka000001-0501) with 5% of fibres for uncut specimens, from 1165kg/m³ (Ka000001-5001) with 50% of fibres, to 1666 kg/m³ (Ka000001-0501) with 5% of fibres for large cut samples. All densities are lower than the density of non-reinforced mortars. Similar trends are seen for the mortars directly produced in elongated prisms. Therefore, it can be concluded that the amount of fibres reduces the density as expected from the results of the literature (Araya-Letelier et al., 2020; Babé et al., 2020; Mellaikhafi et al., 2021; Olacia et al., 2020) which also show similar density values. This behaviour is seen in Figure 5-16 where the amount of fibres by weight is plotted against the density however, the large disparity of density for the same amount of fibres is also seen in this figure. This dispersion of results is probably due to the lack of homogeneity of the fibres and their difference in size which permits them to be or not be crushed while applied.

Moreover, it can be seen that samples that have been cut (either only the sides removed or cut 16x4x4cm³ samples cut from large samples) have a higher average density than non-cut samples probably because of the so-called "side-effect" (Kouakou & Morel, 2009; Minke, 2012) that is seen on fibrous plasters, especially when the fibres are longer than the dimensions of the mould. Removing the sides prevent this impact.

Table 5-15: Average density of mortars reinforced with Chaff

Mortar Name	Amount of fiber (%vol)	Amount of fibres (% weight)	Amount of water (%wt)	Slump test (cm)	Settling time	Sample type: 24x20 Dry density of large uncut samples (kg/m³)	24x20 *Standard dev.*	24x20 Dry density of large cut (kg/m³)	24x20 *Standard dev.*	16x4 Dry density (kg/m³)	16x4 *Standard dev.*	35x7 Dry density (kg/m³)	35x7 *Standard dev.*
Reference Earth	**0**	**0**	**35**	**15.1 17.1**	**0 - 2**	**1691**	***22***	**1745**	***37***	**1682**	***12***	**1698**	
Ka000001-0501	5	0.6	37	16.3	1	1656	*3*	1666	*2*				
Ka000001-0503	5	0.3	41	16.1	2	1612	*24*	1643	*17*	1641	*13*	1598	*12*
Ka000001-1001	10	1.1	38	16.1	1	1588	*9*	1604	*7*				
Ka000001-1003	10	0.6	39	16.9	2	1604	*0*	1638	*14*	1600	*19*	1555	*18*
Ka000001-2001	20	1.7	20	-	0	1514	*10*	1501	*9*				
Ka000001-2002	20	1.6	26	15	0	1495		1517					
Ka000001-2003	20	1.6		15	1	1500		1510					
Ka000001-2005	20	1.6	59	15.1	0	1543		1548					
Ka000001-2007	20	1.6	39	17.4	0	1570		1574					
Ka000001-2008	20	1.7		17.4	0	1560	*8*	1593	*5*				
Ka000001-2010	20	1.3	42	16.8	1	1390	*98*	1500	.				
Ka000001-2013	20	1.6	39	15.6	2	1515	*7*	1537	*8*				
Ka000001-2014	20	1.3	41	16.9	2	1496		1547		1510	*14*	1456	*27*
Ka000001-3001	30	2.2	34	-	0	1431	*7*	1461	*12*				
Ka000001-3002	30	2.6	38	15	0	1403		1329					
Ka000001-4001	40	3.7	38	-	0	1260	*10*	1250	*10*				
Ka000001-4002	40	3.8	43	15	0	1340	*25*	1338	*6*				
Ka000001-4003	40	3.8		15	1	1285	*0*	1310	*0*				
Ka000001-4005	40	4.1	61	15.1	0	1285		1310					
Ka000001-4006	40	5.4	46	16.1	0	1309		1335					
Ka000001-4009	40	3.2	49	16	1	1323	*12*	1343	*2*				
Ka000001-4012	40	3.8	50	16.9	2	1278	*0*	1328	*0*	1326	*18*	1265	*14*
Ka000001-5001	50	5.7	47	-	0	1162	*11*	1165	*11*				
Ka000001-5002	50	6	51	14.9	0	1141		1184					
Ka000001-5004	50	4.9	49	16.7	2	1169		1198		1183	*25*	1127	*24*

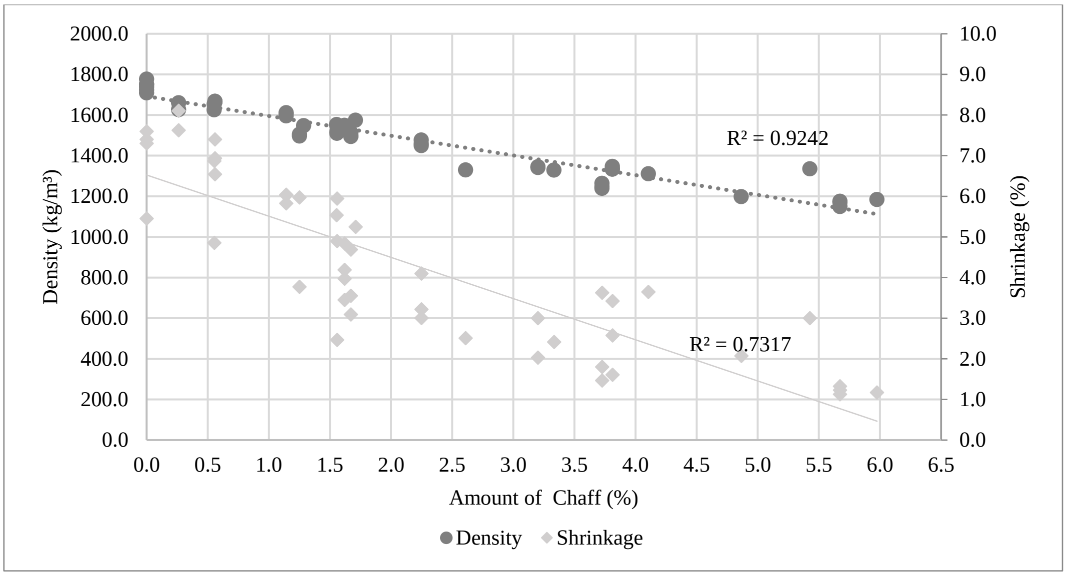

Figure 5-16: Impact of fibre amount on shrinkage and density

5.3.2 Mechanical properties of earth mortars reinforced with Chaff

The flexural and compressive strengths of mortars have been determined on several mixes with different specimen sizes. A summary of the average strength of these mortars is presented in Table 5-16 and Table 5-17 together with the strength of the reference earth. Maximum strength – both compressive and flexural – is achieved for mortars with 5% of fibres, even reaching a similar strength with the reference earth, while the lowest strength is achieved by mortars with 50% of fibres.

5.3.2.1 Flexural strength

Average flexural strength for 16x4 cut specimens varies from 1.67 MPa with 5% fibres (Ka000001-0503) to 0.87 MPa for 50% fibres (Ka000001-5002). Increasing the amount of fibres decreases the strength of the mortars, but not in a linear manner with mortars with 5% to 20% of fibres having a very large range of flexural strength – from 0.83 MPa (Ka000001-2001) to 1.167 MPa (Ka000001-0503) – and a very large range of amount of fibres by weight for similar volumes added (Table 5-16).

The strength is therefore clearly depending on the amount of fibres by weight as seen in Figure 5-18 which shows the impact of the amount of fibres by weight on the mechanical strength of fibres. Until about 1.5% of fibres by weight, the flexural strength is constant and starts to decrease only after this amount. However, the squared Pearson correlation coefficient (R^2) is low probably due to the lack of reproducibility and homogeneity of the mortars. The results seem to correspond to the results of the literature as the flexural strength with 5 % of fibres is similar compared to the Reference Earth – 1.67 MPa and 1.47 MPa for Ka000001-503 and -501 whereas the strength of Reference Earth is 1.55 MPa. Araya-Letelier et al. (2020), Olacia et al. (2020), Ouedraogo et al. (2017) and others show similar results of similar or higher strength with low fibres content, as clearly explained by Danso et al. (2014, 2017) on earth mortars and other types of earthen materials. With a higher content of fibres, the strength decreases but only slightly, probably due to the increase of resistance brought by the addition of fibres, similarly to the outcomes of Babé et al. (2020), Bertelsen et al. (2019) or Caballero-Caballero et al. (2017).

Similar behaviour si observed for other sizes of samples as shown in Table 5-16.

The main outcome of the study of the addition of fibres couldn’t be statistically studied and recorded, however, as it can be observed in Figure 5-17 despite the appearance of large cracks, samples keep a high residual strength which shows the increase of ductility. This outcome was expected regarding the reviewed papers which clearly stated such behaviour (Araya-Letelier et al., 2021; Bertelsen et al., 2019). This is in complete opposition with the failure of sand-reinforced mortar which breaks suddenly as seen in section 5.2.2.

Figure 5-17: Conservation of the strength of the mortar reinforced with chaff despite the appearance of cracks on the surface of the specimen (circled on the picture)

Table 5-16: Flexural strength of Chaff reinforced earth mortars

Mortar Name	amount of fiber (%vol)	Amount of fibres (% weight)	slump test (cm)	Amount of water (% weight)	settling time	Specimen type: 24x20 average flexural strength (MPa)	24x20 *standard* dev.	16x4 average flexural strength (MPa)	16x4 *standard dev.*	30x5 average flexural strength (MPa)	30x5 *standard dev.*
Reference Earth	**0**	**0**	**15.1 17.1**	**35**	**2**	**1.55**	**0.29**	**1.35**	**0.22**	**2.14**	
Ka000001-0501	5	0.6	16.3	37	1	1.45	*0.20*				
Ka000001-0503	5	0.3	16.1	41	2	1.67	*0.20*	1.49	*0.16*	2.71	*0.16*
Ka000001-1001	10	1.1	16.1	38	1	1.63	*0.18*				
Ka000001-1003	10	0.6	16.9	39	2	1.42	*0.12*	1.05	*0.04*	1.44	*0.11*
Ka000001-2001	20	1.7	-	20	0	0.83	*0.16*				
Ka000001-2002	20	1.6	15.0	26	0	1.19	*0.19*				
Ka000001-2003	20	1.6	15.0		1	1.37					
Ka000001-2005	20	1.6	15.1	59	0	0.84	*0.04*				
Ka000001-2007	20	1.6	17.4	39	0	1.48					
Ka000001-2008	20	1.7	17.4		0	1.51	*0.20*				
Ka000001-2010	20	1.3	16.8	42	1	1.03	*0.01*				
Ka000001-2013	20	1.6	15.6	39	2	0.95	*0.15*				
Ka000001-2014	20	1.3	16.9	41	2	1.54	*0.10*	0.94	*0.03*	1.36	*0.05*
Ka000001-3001	30	2.2	-	34	0	0.76	*0.09*				
Ka000001-3002	30	2.6	15.0	38	0	0.84	*0.02*				
Ka000001-4001	40	3.7	-	38	0	0.80	*0.15*				
Ka000001-4002	40	3.8	15.0	43	0	1.03					
Ka000001-4003	40	3.8	15.0		1	0.99					
Ka000001-4005	40	4.1	15.1	61	0	0.81	*0.01*				
Ka000001-4006	40	5.4	16.1	46	0	1.53					
Ka000001-4009	40	3.2	16.0	49	1	1.10	*0.00*				
Ka000001-4012	40	3.8	16.9	50	2	1.06	*0.18*	0.80	*0.06*	1.46	*0.04*
Ka000001-5001	50	5.7	-	47	0	0.77	*0.11*				
Ka000001-5002	50	6	14.9	51	0	0.87	*0.01*				
Ka000001-5004	50	4.9	16.7	49	2	1.06	*0.15*	0.99	*0.09*	1.23	*0.13*

5.3.2.2 Compressive strength

The average compressive strength for 16x4 cut specimens varies from 4.73 MPa with 5% of fibres (Ka000001-0503) to 1.24 MPa for 50% of fibres (Ka000001-5004). Increasing the amount of fibre from 5% to 50% decreases 3 times the strength as can be seen in Figure 5-18. However, samples reinforced with 5% of fibres seem to have a similar or even slightly higher strength than the Reference Earth – between 4.17 MPa and 4.73 MPa for reinforced samples and 4.51 MPa for Reference Earth – and then showing a decreasing strength with the addition of more fibres. In that manner, the compressive strength behaviour shows a trend similar to some authors (Al-Ajmi et al., 2016; Araya-Letelier et al., 2019; Bouhicha et al., 2005; Călătan et al., 2016; Gandia et al., 2019; Ige & Danso, 2021; Lima & Faria, 2016; Olacia et al., 2019; M. Ouedraogo et al., 2017, 2019; Piattoni et al., 2011; Serrano et al., 2016; Vatani Oskouei et al., 2017). These authors show that for a little addition of fibres – lower than 1% for Ige & Danso (2021), between 1% and 2% for Bouhicha et al. (2005) with straw fibres or until 10% for Gandia et al. (2019) for GRPF there is an increase of strength depending of the type of earth and fibres used, but for larger amount, the strength decreases. According to the literature (Ige & Danso, 2021; M. Ouedraogo et al., 2019), this improvement in strength is due to the fact that a small amount of fibres will prevent the development of cracks and therefore increase the strength.

Moreover, as underlined for mortars reinforced with Grey Sand, there seems to be a strong correlation between density and compressive strength, however, because a different material is used in different quantities, this correlation is different. (Figure 5-19) There is a decrease in strength with the decrease in density, however, this decrease is much slower and the remaining strength is higher for lower density. Therefore, it can be said that not only the density has an impact on the strength but also the inner properties of the materials and especially how the chaff interacts with the clay particles to create a strong skeleton, preventing a fast loss of strength.

Table 5-17: Compressive strength of earth mortars reinforced with Chaff

Mortar Name	amount of fibre (%vol)	Amount of fibres (% weight)	slump test (cm)	Amount of water (% weight)	settling time	Sample Type 24x20 average compressive strength (MPa)	24x20 *standard dev.*	16x4 average compressive strength (MPa)	16x4 *standard dev.*	30x5 average compressive strength (MPa)	30x5 *standard dev.*
Reference Earth	**0**	**0**	**15.1 17.1**	**35**	**2**	**4.51**	**0.46**	**5.31**	***0.46***	**3.57**	***0.53***
Ka000001-0501	5	0.6	16.3	37	1	4.17	*0.235*				
Ka000001-0503	5	0.3	16.1	41	2	4.73	*0.087*	4.12	*0.53*	3.88	*0.42*
Ka000001-1001	10	1.1	16.1	38	1	4.29	*0.246*				
Ka000001-1003	10	0.6	16.9	39	2	3.22	*0.202*	3.45	*0.22*	2.68	*0.31*
Ka000001-2001	20	1.7	-	20	0	2.06	*0.153*				
Ka000001-2002	20	1.6	15.0	26	0	2.82	*0.142*				
Ka000001-2003	20	1.6	15.0		1	2.91	0.056				
Ka000001-2005	20	1.6	15.1	59	0	2.98	*0.203*				
Ka000001-2007	20	1.6	17.4	39	0	4.21	*0.135*				
Ka000001-2008	20	1.7	17.4		0	3.45	*0.375*				
Ka000001-2010	20	1.3	16.8	42	1	2.98	*0.163*				
Ka000001-2013	20	1.6	15.6	39	2	2.99	*0.318*				
Ka000001-2014	20	1.3	16.9	41	2	2.56	*0.189*	2.70	*0.27*	2.19	*0.33*
Ka000001-3001	30	2.2	-	34	0	2.10	*0.222*				
Ka000001-3002	30	2.6	15.0	38	0	2.40	*0.202*				
Ka000001-4001	40	3.7	-	38	0	1.41	*0.150*				
Ka000001-4002	40	3.8	15.0	43	0	1.68	*0.037*				
Ka000001-4003	40	3.8	15.0		1	1.77	*0.081*				
Ka000001-4005	40	4.1	15.1	61	0	2.07	*0.179*				
Ka000001-4006	40	5.4	16.1	46	0	2.30	*0.146*				
Ka000001-4009	40	3.2	16.0	49	1	2.40	*0.200*				
Ka000001-4012	40	3.8	16.9	50	2	1.24	*0.138*	1.73	*0.26*	1.51	*0.10*
Ka000001-5001	50	5.7	-	47	0	1.36	*0.112*				
Ka000001-5002	50	6	14.9	51	0	1.58	*0.114*				
Ka000001-5004	50	4.9	16.7	49	2	1.24	*0.114*	1.54	*0.08*	1.11	*0.11*

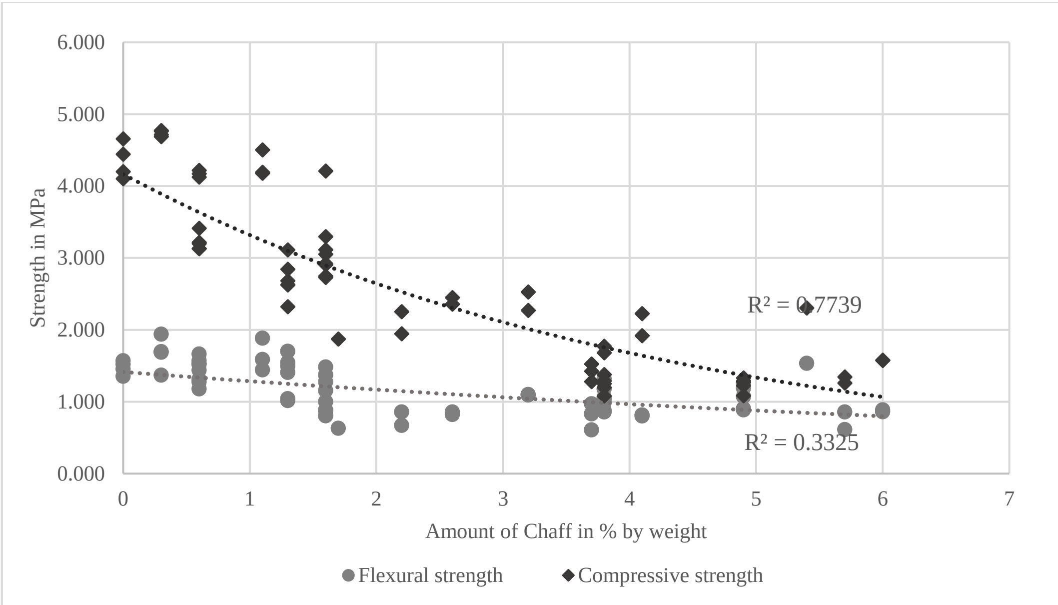

Figure 5-18: Impact of the amount of Chaff (proportion by weight) on the mechanical strength of earth mortars

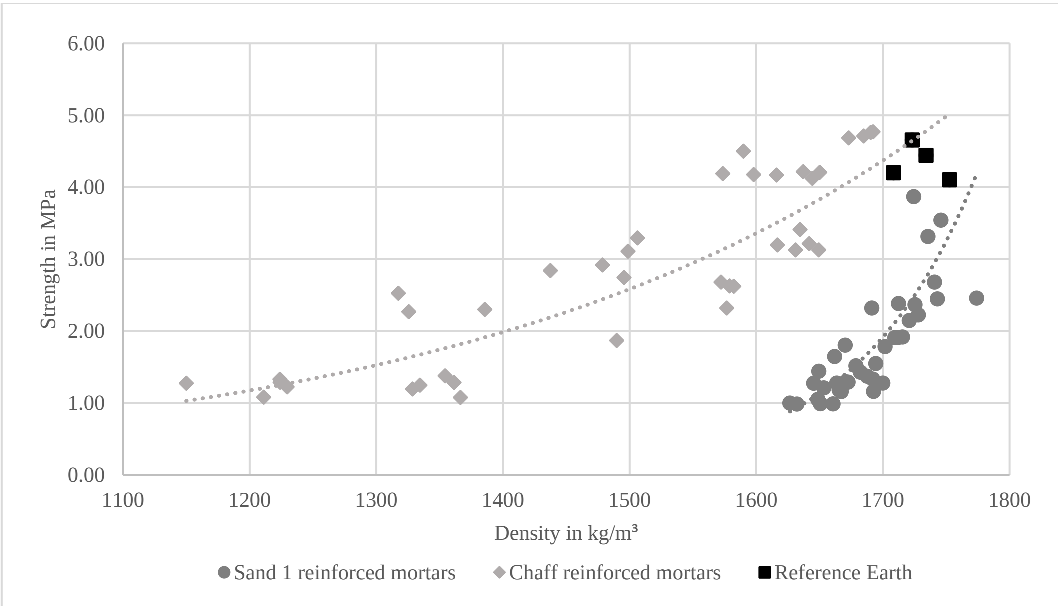

Figure 5-19: Impact of the density on the compressive strength of Grey Sand and Chaff-reinforced mortars

5.3.3 Surface properties of earth mortars reinforced with Chaff

The results of the sponge test for surface water absorption and the peeling test for surface cohesion are presented in Table 5-18 and detailed results and a discussion of the impacts are presented in the following paragraphs.

Table 5-18: Surface properties of earth mortars reinforced with chaff

	Amount of clay (% weight of dry mix)	Amount of chaff (%weight of dry mix)	Amount of water (% weight of dry earth)	slump test (cm)	settling time	Surface water absorption (g/m²·s) for 90 s.	Peeling test – (µg/cm²)	Visual scale (1-10)
Reference Earth	**24.5**	**0**	**30**	**17**	**2**	**14.0**	**264**	**1**
Ka000001-0501	24.4%	0.6%	37%	16.3	1	10.5	944	2
Ka000001-1001	24.2%	1.1%	38%	16.1	1	11.2	1231	2
Ka000001-2001	24.1%	1.7%	20%	-	0	15.7	750	4
Ka000001-2002	24.1%	1.6%	26%	15	0	20.7	472	4
Ka000001-2003	24.1%	1.6%	u.	15	1	22.5	361	4
Average of -200				*15*	*0*	*19.6*	*528*	*4*
Ka000001-3001	23.9%	2.2%	34%	-	0	23.0	639	4
Ka000001-4001	23.6%	3.7%	38%	-	0	24.3	1287	5
Ka000001-4002	23.6%	3.8%	43%	15	0	23.1	1722	5
Ka000001-4003	23.6%	3.8%	u.	15	1	17.0	1611	5
Average of -400				*15*	*0*	*21.5*	*1540*	*5*
Ka000001-5001	23.1%	5.7%	47%	-	0	21.6	954	3

5.3.3.1 Surface water resistance

The surface water absorption of individual samples varies from 10.5 g/m²·s for Ka000001-0501 (5% of fibres) to 24.3 g/m²·s for Ka000001-4001 (40% of fibres).

It seems that the increase of amount of fibres increases the water absorption but not in a linear way as an optimum seems to be reached for approximately 4% of fibres in the dry mix. Moreover, it seems that a low amount of fibre reduces the water absorption compared to non-reinforced mortar. The decrease of water absorption with a low amount of fibres might be because the open and surface porosity might be reduced with the addition of less than 1% of fibres as lots of dust is added. But with higher fibre content, the chaff might contribute to bringing the water in the sample and therefore largely increase the water absorption.

5.3.3.2 Surface cohesion

The numerical results of the peeling test point to a large dispersion of material loss (Table 5-18), varying from 361 μg/cm² for Ka000001-2003 (20% of fibres) to 1722 μg/cm² for Ka000001-4002 (40% of fibres) but material for mortars with 5% or 10% of fibres is higher than the ones with 20% of fibres. On the other hand, if the visual inspection is used, it seems that there is an increasing amount of particles sticking to the tape until 40% of fibres and then it seems to decrease. This shows that the surface cohesion decreases with the addition of fibres. The difference in weight might be due to the low amount of specimens tested and the fact that some of the particles might be much heavier than others, especially if in some cases more sand than chaff is separated from the specimen.

Figure 5-20: Difference of type of particles attached to the band accounting for the weight difference even if the number of particles is similar. a) samples reinforced with a large amount of sand and few fibres. b) mortars reinforced with a large amount of fibres but few sand.

5.3.4 Durability properties of earth mortars reinforced with Chaff

The durability properties of earth mortars reinforced with Chaff have been determined and the average values are reported in Table 5-19. The following paragraphs will present the results of the humid state mechanical strength, the resistance to immersion in water, the resistance to abrasion and the resistance to water erosion. Several mortars could not be tested as a sufficient amount of specimens has not been produced, however, for each amount of added Chaff, at least one mortar was tested.

Table 5-19: Durability properties of earth mortars reinforced with Chaff

	Amount of clay (% weight of dry mix)	Humidity level (weight increase in %)	Humid flexural strength (MPa)	Loss in strength (%)	Humid compressive strength (MPa)	Loss in strength (%)	Water resistance (min)	Abrasion resistance (DIN18947) Material loss (g)	Abrasion resistance (French rules) Abrasion Coefficient (cm²/g)	Abrasion resistance (French rules) Depression depth (cm)	Erosion resistance Hole depth (mm)	Erosion resistance Hole diameter (mm)
Reference Earth	**24.5**	**2.5**	**0.60**	**-46**	**3.35**	**-42**	**28**	**1.9**	**6.4**	**1.3**		
Ka000001-0501	24.4	4.3	0.68	-53	1.71	-59	30	0.1			6.5	27
Ka000001-1001	24.2	4.0	0.67	-59	1.88	-56	62	0.1			5.5	23
Ka000001-2001	24.1	2.9	0.55	-34	1.45	-30					6.5	20
Ka000001-2002	24.1	2.9	0.72	-39	1.68	-40	90					
Ka000001-2003	24.1	4.5	0.53	-61	1.21	-58	90					
Ka000001-2004	24.1	4.5	0.54	-36	1.41	-53						
Ka000001-2005	24.1	2.6	0.62	-58	2.30	-45						
Ka000001-2007	24.1	2.5	0.76	-50	2.39	-31		0.9	14.3	0.5		
Ka000001-2010	24.2	1.9	0.58	-43	1.08	-64	11	2.2	5.7	1.5		
Ka000001-2013	24.1	2.7	0.52	-45	1.60	-46	12	2.3	3.4	2.3	6.0	22
Ka000001-3001	23.9	2.8	0.75	-2	1.74	-17		0.2			5.5	15
Ka000001-3002	23.9	3	0.61	-28	1.03	-57	150					
Ka000001-4001	23.6	2.9	0.70	-12	1.21	-14		2.0			5.0	19
Ka000001-4002	23.6	4.8	0.61	-41	1.02	-39	2880					
Ka000001-4003	23.6	4.8	0.42	-57	0.94	-47	390					
Ka000001-4005	23.5	4.8	0.57	-29	0.82	-60	2880					
Ka000001-4006	23.2	2.6	0.56	-64	1.37	-40	370		3.3	3.0		
Ka000001-4009	23.7	3	0.76	-31	1.60	-33	17	1.6	1.6	3.0	3.5	22
Ka000001-5001	23.1	3.0	0.76	-1	1.17	-14		1.8			0.5	20
Ka000001-5002	23.0	4.9	0.57	-34	0.60	-62	2880				5	25

5.3.4.1 Humid mechanical strength

The humid mechanical strength of mortars reinforced with Chaff is given in Table 5-19 together with the humidity amount and the loss of strength of the mortar comparing a dry and a humid specimen cut from the same large sample.

The humid flexural strength varies from 0.57 MPa (Ka000001-5002; -34%) to 0.76 MPa (Ka000001-2008; -50%) with humidity amount as different as 2.5% for Ka000001-5002 and 4.9% for Ka000001-5002 and loss of flexural strength for all mortars varying from 1% and 61%. The compressive strength varies from 0.60 MPa (Ka000001-5002; -62%) to 2.39 MPa (Ka000001-2008; -31%) with respective humidity amount of 4.9% and 2.6%. The loss of compressive strength varies from 14% to 62%. Therefore, it can be said that despite large variation of strength loss, mortars with the higher dry mechanical strength conserve their strength while saturated with humidity but a smaller range of strength is observed for humid strength compared to dry strength with a variation of 0.87 MPa between the higher and lower flexural strength for dry mortars and only 0.18 MPa difference between the higher and lower saturated strength. A similar trend is observed for compressive strengths.

Another conclusion that can be drawn from the measured data, is that even if there is no increase of humidity absorbed with increase of chaff amount in mortar, a large difference of humidity absorbed can be found between reinforced and non-reinforced mortars with Reference Earth having a weight increase of 2.5% whereas the reinforced mortars have an average weight increase of 3.4%, with some peaks to 4.9%. Moreover, two sets of mortars can be found, mortars with a weight increase larger than 4% and mortars with a weight increase lower than 2%. However, strength loss is not impact and is similar for these two sets. It is possible that a slightly different type of earth or chaff – coming from a different batch – have been used for the mortars in the different sets, therefore creating such large difference in humidity absorption.

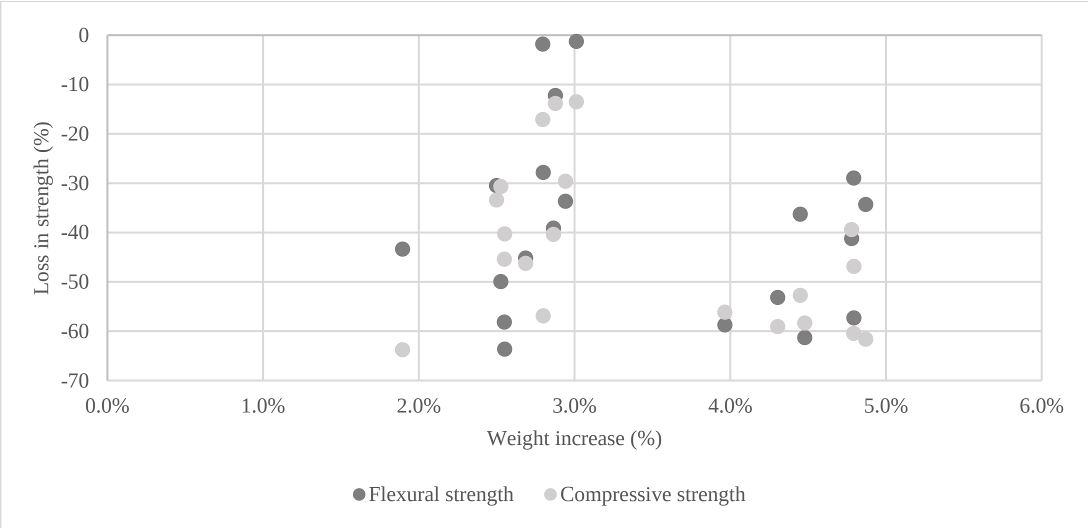

Figure 5-21: Impact of the humidity absorption on the strength loss of mortars reinforced with chaff.

5.3.4.2 Water resistance by immersion

The resistance to immersion of water varies from 11 min. or 12min (Ka000001-2010 and -2012) to 2880 min. (48h – end of the test) for Ka000001-20010 and Ka000001-5002 or -4002 and -4005. If the samples Ka000001-2010, -2013 and 4009, which seem to have a very low water resistance compared to similar mortars, are omitted, it seems that an increasing amount of fibres increases the water resistance. Generally speaking, the samples with a high amount of fibres (above 40%) seem to hold better in water and get less destroyed by the absorbed water. If a failure occurs it is due to the fall of the sample into the recipient as the cohesive strength of the humid mortar is not sufficient enough to keep the hook attached in the sample (sample Ka000001-4003 and -4006).

However, some of these samples seem to have a low resistance despite a high amount of fibres (Ka000001-2010, -2013 and 4009). The large difference between these samples and the others might be due to the type of chaff used to prepare these samples as they were all prepared at the same time, using the same batch of chaff. Despite precaution in the delivery of chaff, some of it might have been slightly different (aka shorter fibres) and therefore all samples made with this type present a lower water resistance as the water resistance is linked with the length of the fibres which creates a net preventing the wet material to fall in water by being connected on one side to dry material and on the other side to the wet material.

5.3.4.3 Abrasion resistance

The abrasion resistance has been determined according to 2 different set-ups, one following the German Standards (DIN18947, 2013) and one following the recommendations of the draft of French Professional Rules (*Guide de bonnes pratiques des enduits en terre,* 2016) (Regles Pro).

5.3.4.3.1 Abrasion resistance (DIN 18947)

The material loss of earth mortars reinforced with Chaff is summarized in Table 5-19

The smallest lost – 0.1g – is found for Ka000001-0501 and -1001. However, only one specimen of these mortars could be tested. The highest loss is 2.0g for Ka000001-4001 with 40% of Chaff. The mortars with 50% of Chaff or with no Chaff at all (Reference Earth) also see a similar amount of material loss (1.8g and 1.9g respectively). This feature tends to show that there is an increase of material loss with a high amount of fibre but a low amount of fibre leads to better material cohesion. This conclusion is supported by the work of Babé et al. (2020) which also shows that there is a decrease in abrasion for a small quantity of added fibres, but after a certain amount of fibres, the resistance decreases again. This result concords with the one of Gonzalez-Calderon et al (2020) who shows that the addition of fibres in small quantity (until 1% per weight) increases the abrasion resistance when tested in similar condition

5.3.4.3.2 Abrasion resistance (Regles Pro)

Only a few samples could be tested following the French regulation and the values found are very dispersed for all tested samples. The abrasion coefficient of samples with 20% of Chaff varies between 14.3 cm²/g and 3.4 cm²/g whereas the abrasion coefficient for samples with 40% of Chaff varies between 3.3 cm²/g and 1.6 cm²/g which suggests that there is a loss of cohesion when fibres are added to the mix. This trend is reinforced when Reference Earth is considered. The abrasion coefficient of the Reference is 6.4 cm²/g, higher than most of the other mortars, therefore, it can be assumed that the addition of Chaff decreases the abrasion resistance. The same conclusion is given by Giroudon et al. (2019) for mortars reinforced with a similar amount of barley straw whereas the authors show an opposite behaviour – an increase of resistance – with the addition of lavender straw.

5.3.4.3.3 Conclusions on abrasion

The results of both DIN 18947 and Regles Pro suggest that the addition of fibres decreases the resistance of mortars to erosion. When these results are compared with the results of the tape test (section 5.3.3.2). it shows a similar result with a large decrease in cohesion with the addition of fibres, and a higher visual loss, due to the loss of fibres, especially short and thick fibres which couldn't resist the pulling out due to the test.

5.3.4.4 Erosion resistance

The erosion of earth mortars reinforced with Chaff is given Table 5-19 as the depth and diameter of the hole made by the dripping of water. The depth varies between 0.5 mm (Ka000001-5001) and 6.5 mm (Ka000001-0501). Despite most values being comprised of between 5.0 mm and 6.5 mm, there seems to be a decrease in the depth of the hole with an increasing amount of fibres. Especially if both depth and diameter are taken in account, then the erosion of the samples Ka000001-0501 is larger than the one of Ka000001-2001 because its diameter is much larger. This conclusion would be similar to the one of Lerner & Donahue (2003) who used a similar test and found that the addition of straw reduces erosion whereas Muñoz et al. (2020), Araya-Letelier et al. (2020), Giroudon at al. (2019) and Babé et al. (2020) obtained similar results with a different test on mortars reinforced with paper pulp residues, chicken feather fibres, barley straw and lavender straw respectively.

5.3.5 Hydric properties of earth mortars reinforced with Chaff

The hydric properties of earth mortars reinforced with Chaff are shown in Table 5-20. Both the water absorption behaviour characterized by the Capillarity Coefficient (CC) and the drying behaviour characterized by the primary Drying Rate (pDR), the secondary Drying Rate (sDR) and the Drying Index are shown. The results of CC, water absorption behaviour and drying behaviour are discussed below and compared with the literature when possible.

Table 5-20: Hydric properties of earth mortars reinforced with Chaff

	Amount of clay (% weight of dry mix)	Amount of Chaff (% weight of dry mix)	Capillarity coefficient (kg/m²/min$^{0.5}$)	*R^2 (-)*	Drying rate (1st phase) (kg/m²/h)	*R^2 (-)*	Drying rate (2nd phase) (kg/m²/h$^{0.5}$)	*R^2 (-)*	Drying index (-)
Reference Earth	**24.5**	**0**	**0.99**		**0.14**		**1.32**		**0.30**
Ka000001-0501	24.4	0.6	0.93	*1.00*	0.17	*0.99*	1.37	*0.99*	0.45
Ka000001-1001	24.2	1.1	0.72	*0.99*	0.13	*1.00*	0.97	*1.00*	0.16
Ka000001-2001	24.1	1.7	1.14	*1.00*	0.17	*0.99*	1.08	*1.00*	0.29
Ka000001-2002	24.1	1.6	1.18	*1.00*	0.16	*0.99*	1.05	*1.00*	0.29
Ka000001-2003	24.1	1.6	1.09	*1.00*	0.15	*1.00*	1.01	*0.98*	0.34
Ka000001-2004	24.1	1.6	1.04	*1.00*	0.13	*0.99*	1.07	*1.00*	0.35
Ka000001-2010	24.2	1.3	1.02	*1.00*	0.21	*0.99*	1.30	*0.99*	0.27
Ka000001-2013	24.1	1.6	1.13	*1.00*	0.15	*1.00*	1.32	*0.99*	0.25
Ka000001-3001	23.9	2.2	1.09	*1.00*	0.13	*0.99*	1.17	*0.99*	0.30
Ka000001-4001	23.6	3.7	1.02	*1.00*	0.14	*0.99*	1.09	*1.00*	0.28
Ka000001-4002	23.6	3.8	1.24	*1.00*	0.14	*0.99*	0.98	*1.00*	0.34
Ka000001-4004	23.6	3.8	1.22	*1.00*	0.14	*0.99*	0.92	*0.99*	0.36
Ka000001-5001	23.1	5.7	1.07	*0.99*	0.18	*0.99*	1.03	*0.99*	0.27

5.3.5.1 Water capillarity absorption

The water capillarity absorption is represented by the Capillarity Coefficient (CC) given in Table 5-20 and by the amount of water absorbed shown for some representative mortars in Figure 5-22. The CC varies from 0.72 kg/(m²·min$^{0.5}$) for Ka000001-1001 and 1.24 kg/(m²·min$^{0.5}$) for Ka000001-4002. However, the variation of the CC is very large as the other mortar with 40% of Chaff (Ka000001-4001) has a CC of 1.02 kg/(m²·min$^{0.5}$) and the CC of mortars with 20% of Chaff varies from 1.02 kg/(m²·min$^{0.5}$) and 1.14 kg/(m²·min$^{0.5}$). In Figure 5-22 the absorption behaviour of mortars can be observed and compared with the one of mortar without fibres. After the first absorption (0 to 4 min), the absorption is stable until 49 minutes for Ka000001-5001 and -4001 and it is stable until 169 minutes for Ka000001-3001 and -2010. After this time the absorption slows down and is almost none between 169 min. and 256 min. except for the mortars Ka000001-0501 and -1001 with a low content of fibres. These mortars have a continuous absorption similar to the non-reinforced mortar. Therefore, it can be said that similarly to mortars reinforced with sand, the addition of fibres increases the absorption rate but decreases the total absorption amount of water absorbed.

Similar results have been shown by Gomes et al. (2018) on mortars reinforced with hemp fibres which present a much higher capillarity coefficient than the one made without fibres for a similar total absorption. Lima & Faria (2017) who tested oat straw and typha fibres show that the addition of fibres increases the capillarity coefficient independently of the amount of fibres but that the total amount of absorbed water was increasing with an increase of fibres, for both types of fibres, however, it is not known if the samples reached saturation at the end of the test. These results contradict the results of Gonzalez-Calderon et al (2020) and Araya-Letelier et al. (2021) which show also an increase in the absorption rate but a large increase in the total amount of absorbed water with mortars reinforced with a large quantity of jute and chicken feathers. However, as the test set-up and the fibre type were different, total saturation was not achieved and therefore, the total amount of water was not reached.

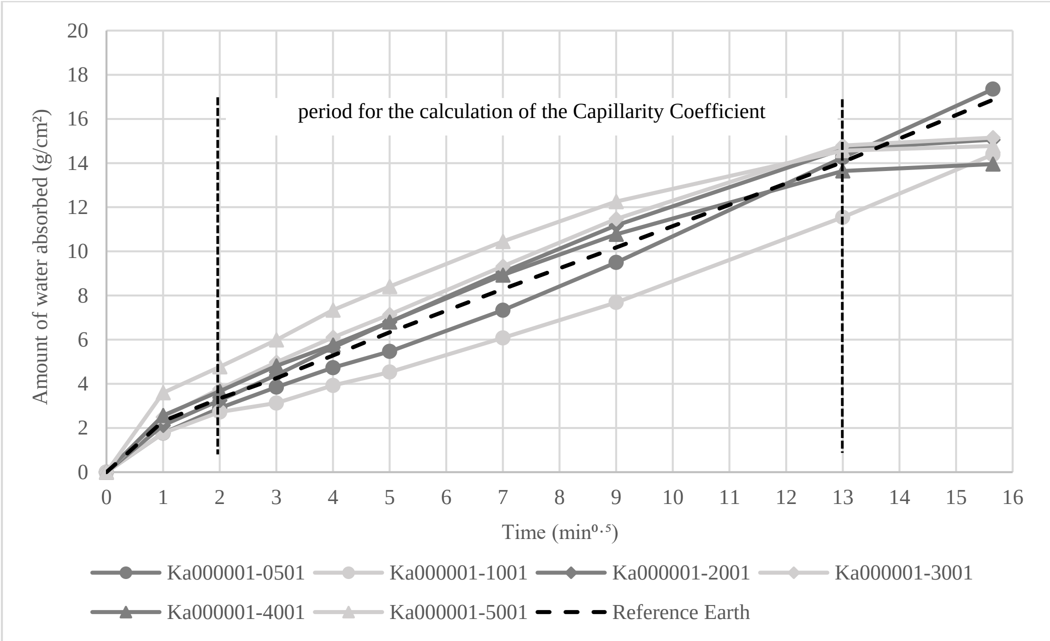

Figure 5-22 Water capillarity absorption of some selected earth mortars reinforced with Chaff

5.3.5.2 Drying behaviour

The Drying Rates (DR) and the Drying Index (DI) are given in Table 5-20 for all tested mortars whereas the drying behaviour of selected representative mortars is shown in Figure 5-23.

5.3.5.2.1 Drying Rates

The primary DR (pDR) of mortars varies between 0.13 kg/m²/h (Ka000001-1001, -2004 and -3001) and 0.21 kg/m²/h (Ka000001-2010) which shows that except for

Ka000001-2010, they have a close initial drying similar and even slightly higher than the one of non-reinforced earth (0.14 kg/m²/h), probably due to the fibres on the surface on the sample that are drying faster. On the opposite, the secondary DR (sDR) which is related to the drying through vapour diffusion (Lima et al., 2020) is lower than the sDR of non-reinforced mortars except again for Ka000001-2010 and -2013. This similarity of value for the pDR, independently of the amount of fibres is close to the one found by Lima & Faria (2017) for plasters reinforced with 10% and 20% by volume of barley straw however, on the other hand the authors found an increasing sDR for an increase of fibre amount which is not seen on the tested mortars which have very different secondary drying rate for the same amount of fibres.

5.3.5.2.2 Drying Index

The Drying Index varies from 0.16 (Ka000001-1001) to 0.45 (Ka000001-0501). These extreme values are probably outliers as all other values, independently of the amount of Chaff are similar – between 0.27 and 0.36 – and close to the value of the non-reinforced earth. This might mean that the addition of fibres has no or very little impact on the long-term drying of earth mortars, as it can also be understood from the drying curves Figure 5-23 where no large differences are seen on the amount of water desorbed after 300 h.

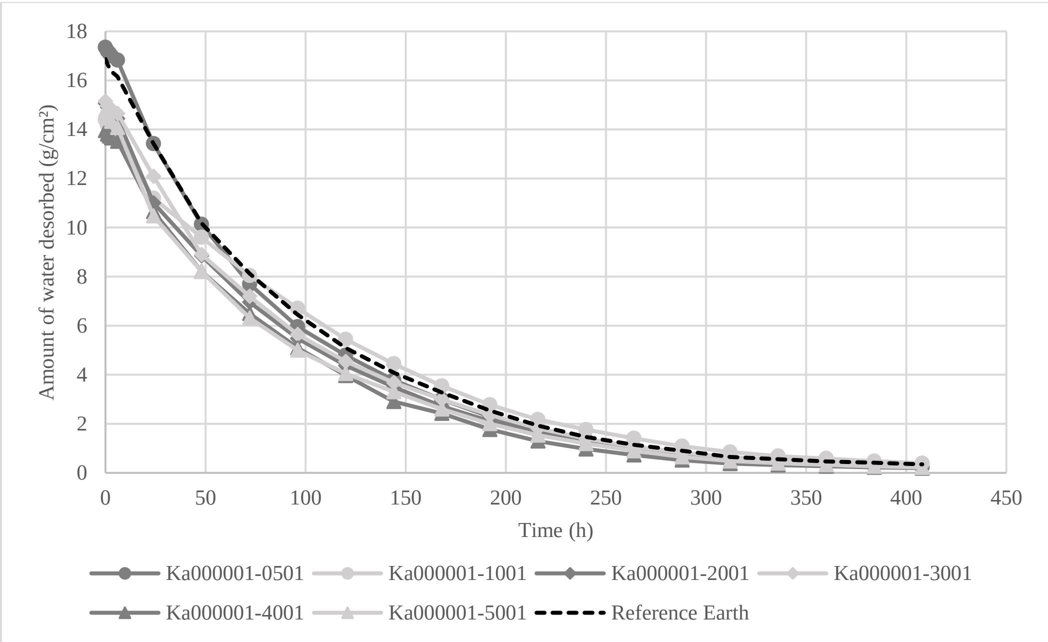

Figure 5-23: Drying behaviour of some selected Earth mortars reinforced with Chaff

5.3.6 Hygric properties of earth mortars reinforced with Chaff

The hygric properties of earth mortars reinforced with Chaff are plotted in Table 5-21 and the water vapour permeability and the dynamic water vapour adsorption and desorption are detailed in the following paragraphs.

Table 5-21: Hygric properties of earth mortars reinforced with Chaff with a settling time between 0 days and 2 days.

	Amount of clay (% weight of dry mix)	Density (kg/m³)	Water vapour permeability (x10⁻¹¹ kg/m*s*Pa)	Water vapour diffusion resistance factor (-)	Equivalent air layer (m)	Water vapour adsorption (12h - g/m²)	Primary adsorption rate - first 3h (g/m²h)	Secondary adsorption rate - 12h-48h (g/m²h)	Water vapour desorption (12h - g/m²)	Primary desorption rate - first 3h (g/m²h)	Secondary desorption rate - 12h-48h (g/m²h)
Reference Earth	**24.5**	**1745**		**3.9**	**0.1**	**158**	**16.7**	**9.7**	**167**	**20.4**	**5.2**
Ka000001-0501	24.4	1666	4.49	4.4	0.16	164	15.5	7.7	154	18.6	3.9
Ka000001-1001	24.2	1604	4.49	4.4	0.16	184	17.7	8.0	166	22.7	4.8
Ka000001-2001	24.1	1501	3.78	5.2	0.19	185	18.3	8.3	169	22.3	4.5
Ka000001-2002	24.1	1517	3.89	5.0	0.18	175	17.6	8.6	166	21.7	4.8
Ka000001-2003	24.1	1510	3.87	5.1	0.17	195	19.8	9.0	183	23.1	5.4
Ka000001-2004	24.1	1553	4.03	4.9	0.17	187	19.2	8.5	180	23.0	5.0
Ka000001-2007	24.1	1574	4.15	4.7	0.18						
Ka000001-2010	24.2	1500	5.07	3.9	0.14						
Ka000001-2013	24.1	1537	5.37	3.6	0.15	179	16.7	7.5	146	16.9	4.5
Ka000001-3001	23.9	1461	3.98	4.9	0.18	200	20.1	8.2	183	22.7	4.8
Ka000001-4001	23.6	1250	4.33	4.9	0.18	188	18.5	7.7	181	23.9	4.8
Ka000001-4002	23.6	1338	4.73	4.1	0.15	181	17.6	7.6	176	21.7	4.6
Ka000001-4003	23.6	1310	3.94	5.0	0.18						
Ka000001-4006	23.2	1335	4.63	4.2	0.16						
Ka000001-4009	23.7	1343	4.70	4.2	0.15						
Ka000001-5001	23.1	1165	3.88	5.1	0.18	171	16.6	7.3	158	19.7	4.6

5.3.6.1 Water vapour permeability

The water vapour diffusion resistance (μ-value) of earth mortars varies from 3.6 for Ka000001-2013 (20% of Chaff) to 5.2 for Ka0000001-2001 (20% of Chaff). There is a large variation in μ-value but this variation doesn't seem related to the amount of Chaff used as similar mortars will have very different values. The variations might be due to changes in the experimental conditions as when the results are organized by testing groups, their results are very close to each other, independently to the amount of chaff or the density (APPENDIX D).

The addition of Chaff decreases the water vapour permeability compared to the Reference Earth, but only slightly and increasing the amount has only a low impact on it. This conclusion is similar to the one given by Palumbo et al. (2016) who tested different amounts of corn pith and straw and from Lima et al. (2017) who tested mortars reinforced with different amounts of straw and typha wool and found only little differences of water vapour permeability.

5.3.6.2 Dynamic water vapour adsorption and desorption behaviour

The behaviour of mortar during dynamic water vapour adsorption and desorption tests is shown in Table 5-21 and Figure 5-24. Figure 5-24 only show some selected representative mortars with different amount of Chaff to be readable.

The highest adsorption and desorption after 12h is recorded for Ka000001-3001 (30% of Chaff) whereas the lowest is recorded for Ka000001-0501 (5% of Chaff). All tested mortars, independently of their amount of fibres have higher adsorption and desorption than Reference Earth. As all these mortars have been tested at the same time and in the same way, the results are considered to be comparable. Therefore, it seems that the addition of fibres increases the water vapour adsorption and desorption until a maximum amount of fibres. It is particularly clear that the addition of fibres increases the primary adsorption and desorption, with a primary adsorption rate much higher than the one of the Reference Earth (201 g/m²h for

Ka000001-3001 instead of 14.3 g/m²h for the Reference Earth), however, the total amount of adsorbed water is not significantly different after 48h. Moreover, in the long term, the desorption rate of the Reference Earth is faster than the mortars made reinforced with Chaff. On the opposite, Lima & Faria (2016) show that the amount of fibre has no impact on the adsorption and desorption of plaster made with oat straw and typha wool. However, the amount of fibres tested was much lower than the amount tested in this research – max. 1% by weight for oat straw and 0.3% by weight for typha wool compared to 2.2% of fibres by weight for Ka000001-3001 and a maximum value of 5.7% of fibres by weight for Ka000001-5001. The amount of fibres tested by Lima & Faria (2016) corresponds to the mortars Ka000001-0501 which has very similar values with the Reference Earth.

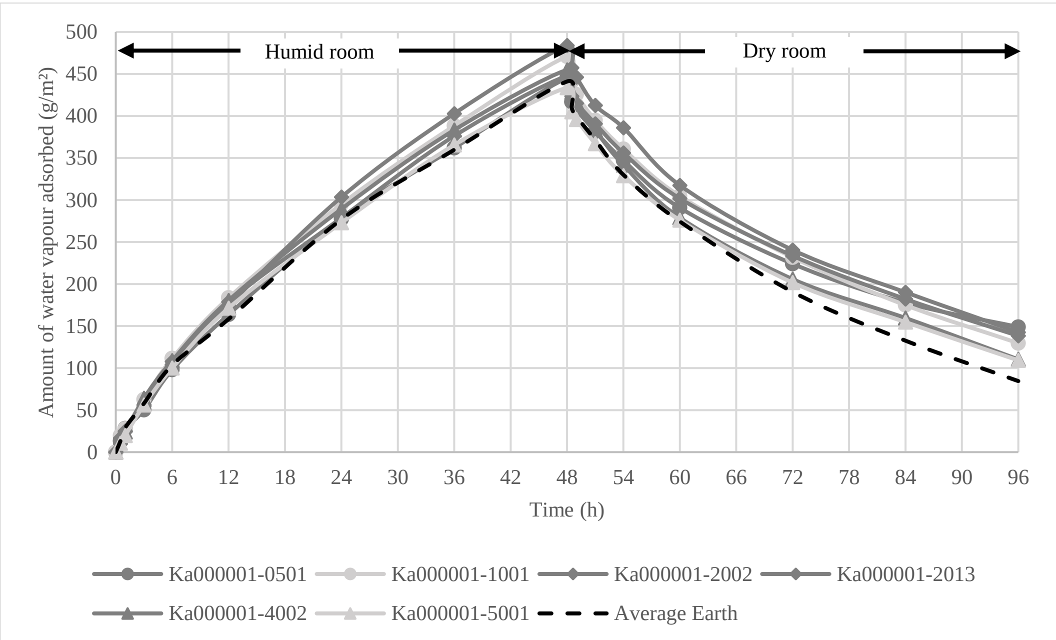

Figure 5-24: Water vapour adsorption and desorption behaviour of some selected earth mortars reinforced with Chaff

5.4 Properties of earth mortars reinforced with Grey Sand and Chaff

The properties of mortars reinforced with either sand or fibres have been described in sections 5.2 and 5.3. It appears that neither the addition of only sand nor only fibres is sufficient to obtain an earth mortar with high density, low shrinkage and high strength to compel with earth construction standards. Therefore, mortars reinforced with both Grey Sand, Yellow Sand and Chaff have been produced and tested. The results of these tests are presented in this section. All mixes have been made with an earth content lower than 50% by volume and amount of sand and chaff varying between 27% and 57% and 14% and 40% respectively, according to the results of sections 5.2 and section 5.3. All mortars have a settling time between 0 days and 2 days and a slump with a diameter comprised between 16 cm and 17 cm.

5.4.1 Physical properties of earth mortars reinforced with Grey Sand and Chaff

Mortars made with different amounts of earth, Grey Sand and Chaff have been tested for shrinkage and density. Results are presented Table 5-22 and discussed in the sections below and compared with the results of the literature

5.4.1.1 Shrinkage

All mortars have a shrinkage below the threshold of 3% as needed to comply with German Standards (DIN18947, 2013) and this, independently of the shape of the specimens. The highest shrinkage is seen on mortars with the highest amount of earth by weight (2.6%; Ka000101-112001 for 24x20 cm specimens) whereas the lowest shrinkage is seen on mortars with the lowest amount of earth by weight (0.2%; Ka00101-241001 for 24x20 cm specimens) despite not being the lowest amount of earth by volume. As expected and already shown in the literature, decreasing the amount of earth decrease the shrinkage.

Table 5-22: Shrinkage of earth mortars reinforced with Grey Sand and Chaff

FINAL mix name	Amount of caly (%vol)	amount of sand (%vol)	amount of fibre (%vol)	slump test (cm)	Type of samples 24x20 shrinkage (%)	24x20 *standard dev.*	16x4 shrinkage (%)	16x4 *standard dev.*	30x5 shrinkage (%)	30x5 *standard dev.*
Reference Earth	**24.5**	**0**	**0**	**16.9**	**7.0**	***0.8***	**8.4**	***0.3***	**5.5**	
Ka000101-112001	14.2	41	1.4	16.8	2.6	*0.3*				
Ka000101-2210001	11.0	54	1.2	16.4	2	*0*				
Ka000101-2210004	11.6	51	1.2	16.2	2	*0.4*	2	*0.3*	2.1	*0.1*
Ka000101-2210006	11.0	54	1.2	16.6	1.9	*0.4*				
Ka000101-2210007	10.2	57	1.1	18	1.4	*0*				
Ka000101-2210008	10.1	58	1.2	16.5	1.8	*0.2*	1	*0.2*	1.3	*0.1*
Ka000101-2210009	10.7	55	1.2	16.8	1.2	*0.3*				
Ka000101-111001	11.1	53	2.3	16.6	1.4	*0.3*				
Ka000101-111002	10.1	56	2.4	16.8	0.9	*0.3*				
Ka000101-334001	10.5	54	2.9	16.2	0.9	*0.3*	0.9	*0.7*	1.2	*0.3*
Ka000101-334003	10.0	56	2.1	16.9	0.7	*0.3*				
Ka000101-241001	6.4	73	0.8	18.1	0.2	*0*				
Ka000101-483001	6.9	71	1.0	17.2	0.7	*0.5*	0.5	*0.3*	1.1	*0*

5.4.1.2 Density

Table 5-23 presents the density of earth mortars settled between 0 and 2 days. The results have been presented according to the earth's amount by volume. From these results, it can be seen that the density is no much affected by the variations of Grey Sand amount and Chaff amount used, as the results vary from 1598 kg/m³ for the highest density (40% of Grey Sand and 20% of fibres) and 1337 kg/m³ for the lowest density (30% of Grey Sand and 40% of fibres) for cut 24x20 specimens. Moreover, as expected from previous sections (sections 0 and 5.3.1.2) the results of density tests show that the volume of fibres used has the highest impact on density. All mortars have a lower density than Reference Earth due to their high content in fibres (more than 14%).

Table 5-23: Average density of earth plasters reinforced with Grey Sand and Chaff

Mortar Name	Amount of sand (%vol)	Amount of fibre (%vol)	Slump test (cm)	Sample type: 24x20 — Average dry density of raw samples (kg/m³)	24x20 — *Standard dev.*	24x20 — Average dry density of large (kg/m³)	24x20 — *Standard dev.*	16x4 — Average dry density (kg/m³)	16x4 — *Standard dev.*	30x5 — Average dry density (kg/m³)	30x5 — *Standard dev.*
Reference Earth	**0**	**0**	**15.1** **17.1**	**1691**	***22***	**1745**	***37***	**1682**	***12***	**1698**	
Ka000101-112001	25	25	16.8	1565	*8.3*	1577	*5.4*			1508	*22.2*
Ka000101-2210001	40	20	16.4	1564	*10.0*	1547	*16.2*				
Ka000101-2210004	40	20	16.2	1555	*1.7*	1556	*5.8*				
Ka000101-2210006	40	20	16.6	1602	*8.1*	1598	*2.4*				
Ka000101-2210007	40	20	18	1545	*10.1*	1555	*4.6*	1556	*12.7*	1546	*8.7*
Ka000101-2210008	40	20	16.5	1591	*22.0*	1591	*5.7*	1593	*9.8*		
Ka000101-2210009	40	20	16.8	1589	*6.6*	1562	*23.1*				
Ka000101-111001	33	33	16.6	1449	*9.9*	1442	*5.3*				
Ka000101-111002	33	33	16.8	1424	*20.8*	1426	*11.0*	1428	*14.9*	1384	*22.0*
Ka000101-334001	30	40	16.2	1440	*38.4*	1396	*21.1*				
Ka000101-334003	30	40	16.9	1330	*12.8*	1337	*14.1*	1346	*19.0*	1320	*25.5*
Ka000101-241001	57	14	18.1	1585	*8.1*	1572	*3.7*	1588	*18.3*	1557	*10.2*
Ka000101-483001	53	20	17.2	1604	*8.1*	1579	*4.5*				

5.4.2 Mechanical properties of earth mortars reinforced with Grey Sand and Chaff

Flexural strength and compressive strength of earth mortars reinforced with Grey Sand and Chaff have been measured on 3 types of specimens. Results are analysed and discussed in the following sections.

5.4.2.1 Flexural strength

The average flexural strength of Grey Sand and Chaff reinforced mortars is presented in Table 5-24. The results are discussed for the 16x4x4 cm³ specimens cut from the large specimens but all results are presented in Table 5-24 and similar trends can be observed.

The maximum strength measured is 0.93 MPa for mortars containing 50% of earth (Ka000101-112001) and the minimum strength is 0.46 MPa for mortars containing 29% of earth and 14% of chaff (Ka000101-241001). From Table 5-24, it can be understood that the amount of earth – more precisely the amount of clay – is the main determining factor of the flexural strength. However, the amount of chaff also imports as it can be seen while comparing samples with a close amount of earth but different flexural strengths. MortarsKa000101-334001, -111001 and -2410001 have between 29% and 34% of earth content by volume but the amount of chaff is 40%, 33% and 14% respectively and their average strength varies between 0.82 MPa and 0.46 MPa and therefore it can be concluded that a higher amount of chaff leads to a higher strength, in opposition to the conclusion of section 5.3.2.1. This impact of fibres might be due to the generally low cohesion of the mortars and therefore the tensile strength of fibres prevents the direct loss of strength.

Another conclusion that might be drawn from the analysis of the flexural strength is that in the opposite of mortars reinforced only by Grey Sand or with Chaff, it seems to be an impact of the settling time, as the R^2 of the trendline for flexural strength become higher when values of mortars that settled only one day are omitted (Figure

5-25). Moreover, as consistency varies more for these mortars than for previously tested mortars, an impact of the amount of water can be seen also when mortars with a slump of 18 cm diameter are omitted as understood with the change of R^2 on the relevant trendline (Figure 5-25).

5.4.2.2 Compressive strength

The average compressive strengths are presented in Table 5-25 together with the compressive strength of the Reference Earth. The compressive strengths of 16x4x4 cm^3 specimens are discussed below, but the same conclusions apply to other specimens as their strength follows the same trend.

Maximum compressive strength is achieved by the mix containing 50% of earth (1.63 MPa, Ka000101-112001) and the minimum strengths are achieved by the mixes containing 30% or less of earth (0.98 MPa, Ka000101-334003; 1.07 MPa, -241001; 0.99 MPa -483001) and the strength shows a decrease of 63% to 77% respectively compared to the strength of Reference Mortar. A constant decrease of strength can be seen with the increasing amount of reinforcing materials in the same way it is observed for mortars containing either only Grey Sand or Chaff.

These results oppose the ones of Piattoni et al. (2011; 2010) who found that a large increase in sand and fibre amount might improve the strength. Similar results were achieved by Al-Ajmi et al. (2016) and Ashour et al. (2010) who found that increasing the amount of fibres for a constant ratio earth/sand increases the strength whereas the increase of sand amount for a constant earth/fibre ratio reduces the strength. However, in addition to a possible increase in strength due to the addition of a small amount of fibres (section 5.3.2.2) and an increase in density with the addition of sand (section 5.2.2.3), Laborel-Preneron et al. (2015) underline that these differences in behaviour are probably due to the amount of displacement while using the ultimate strength as compressive strength and recommend to use the strength at 1.5% strain as higher stresses are not acceptable in construction.

Table 5-24: Average flexural strength of Grey Sand and Chaff reinforced mortars with a settling time of 1 or 2 days

				Sample type					
				24x20		16x4		30x5	
Mortar Name	Amount of sand (%vol)	Amount of fibre (%vol)	Slump test (cm)	Average flexural strength (mpa)	*Standard dev.*	Average flexural strength (mpa)	*Standard dev.*	Average flexural strength (mpa)	*Standard dev.*
Reference Earth	**0**	**0**	**15.1** **17.1**	**1.55**	**0.29**	**1.35**	**0.22**	**2.14**	
Ka000101-112001	25	25	16.8	0.93	*0.09*			1.35	*0.02*
Ka000101-2210001	40	20	16.4	0.60	*0.04*				
Ka000101-2210004	40	20	16.2	0.84	*0.08*				
Ka000101-2210006	40	20	16.6	0.84	*0.04*				
Ka000101-2210007	40	20	18	0.57	*0.02*	0.63	*0.09*	0.94	*0.08*
Ka000101-2210008	40	20	16.5	0.72	*0.10*	0.64	*0.06*		
Ka000101-2210009	40	20	16.8	0.86	*0.07*				
Ka000101-111001	33	33	16.6	0.69	*0.08*				
Ka000101-111002	33	33	16.8	0.67	*0.05*	0.81	*0.08*	0.64	*0.04*
Ka000101-334001	30	40	16.2	0.82	*0.12*				
Ka000101-334003	30	40	16.9	0.65	*0.03*	0.70	*0.05*	1.05	*0.09*
Ka000101-241001	57	14	18.1	0.46	*0.00*	0.43	*0.08*	0.87	*0.04*
Ka000101-483001	53	20	17.2	0.65	*0.06*				

Table 5-25: Average compressive strength of earth mortars reinforced with Grey Sand and Chaff with a settling time of 1 or 2 days

				Sample type					
				24x20		16x4		30x5	
Mortar Name	Amount of sand (%vol)	Amount of fibre (%vol)	Slump test (cm)	Average compressive strength (Mpa)	*Standard dev.*	Average compressive strength (Mpa)	*Standard dev.*	Average compressive strength (Mpa)	*Standard dev.*
Reference Earth	**0**	**0**	**15.1** **17.1**	**4.51**	**0.46**	**5.31**	***0.46***	**3.57**	***0.53***
Ka000101-112001	25	25	16.8	1.63	*0.15*			0.88	*0.09*
Ka000101-2210001	40	20	16.4	1.21	*0.07*				
Ka000101-2210004	40	20	16.2	1.43	*0.09*				
Ka000101-2210006	40	20	16.6	1.46	*0.09*				
Ka000101-2210007	40	20	18	1.22	*0.08*	1.75	*0.07*	0.74	*0.08*
Ka000101-2210008	40	20	16.5	1.32	*0.07*	1.76	*0.12*		
Ka000101-2210009	40	20	16.8	1.28	*0.15*				
Ka000101-111001	33	33	16.6	1.32	*0.07*				
Ka000101-111002	33	33	16.8	1.12	*0.06*	1.55	*0.09*	0.63	*0.04*
Ka000101-334001	30	40	16.2	1.14	*0.25*				
Ka000101-334003	30	40	16.9	0.98	*0.04*	1.30	*0.10*	0.53	*0.04*
Ka000101-241001	57	14	18.1	1.07	*0.02*	1.47	*0.06*	0.72	*0.04*
Ka000101-483001	53	20	17.2	0.99	*0.09*				

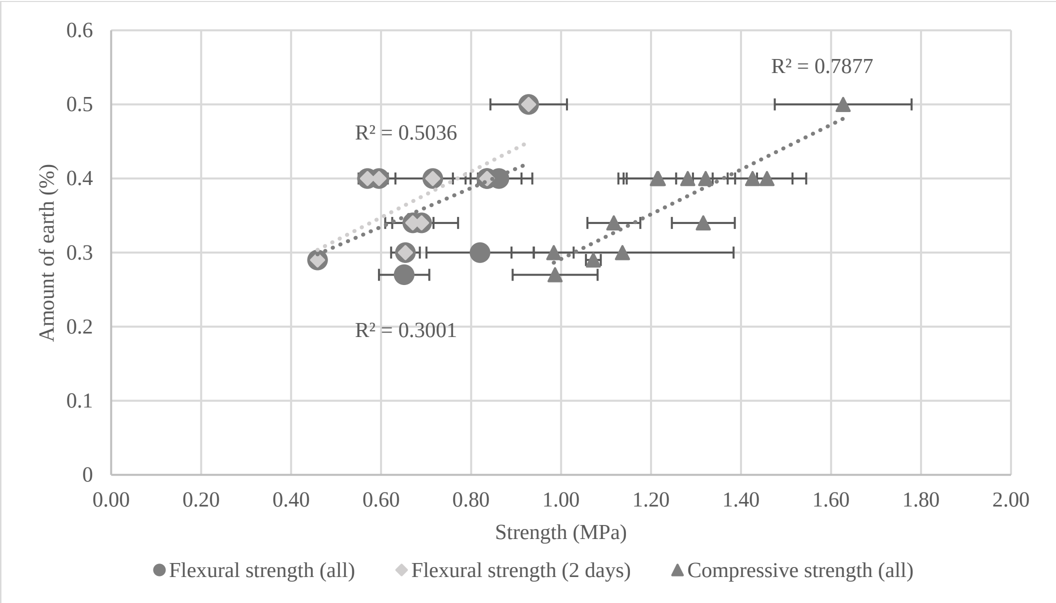

Figure 5-25: Mechanical strength of earth mortars reinforced with Grey Sand and Chaff

5.4.3 Surface properties of earth mortars reinforced with Grey Sand and Chaff

The surface properties of mortars reinforced with Grey Sand and Chaff are summarized in Table 5-26. The surface water absorption and the surface cohesion of the mortars are discussed in the following paragraphs.

5.4.3.1 Surface water absorption

The surface water absorption of earth mortars reinforced with Grey Sand and Chaff has been tested on only one sample per mortar type and varies from 17.8 g/m²·s for Ka000101-11201 (41% of Grey Sand and 1.4% of Chaff) to 30.2 g/m²·s for Ka000101-22109 (55% of Grey Sand and 1.2% of Chaff). The average absorption is 25.3 g/m²·s with a deviation of only 3.5 g/m²·s which shows that the absorption of all samples is very close despite a large difference in the amount of Grey Sand – from 41% to 71%) or Chaff – from 0.8% to 3.1%. This behaviour is different from the one found for mortars only reinforced with Grey Sand or Chaff (sections 0 and 5.3.3.1). However, when only the amount of Grey Sand is checked, all samples except Ka000101-112001 have an amount of sand above 50% and according to the results of the experiment on earth mortars reinforced with Sand (section 0), their water absorption is expected to be between 25 g/m²·s and 31 g/m²·s which is the case. Therefore, it might be safe to assume that the surface water absorption is primarily related to the amount of sand in the samples and secondary related to the amount of fibres.

5.4.3.2 Surface cohesion

The surface cohesion has been evaluated through the peeling test and the amount of material attached to the tape is shown in Table 5-26. This amount varies from 806 µg/cm² (Ka000101-221006, 54% of Grey Sand and 1.2% of Chaff) to 5806 µg/cm² (Ka000101-111002). However, these values are only averages and are not representative of the real behaviour as there is a large difference in individual results on the different specimens and a large variation between similar mortars – e.g. the amount of material attached to the tape for mortars Ka000101-11101 and Ka000101-11102 varies from 1708 µg/cm² to 5806 µg/cm². Therefore, it is difficult to conclude anything from this experiment except that the cohesion is lowered by the addition of both sand and fibres in comparison with non-reinforced mortars – average detached material 264 µg/cm² – or mortars only reinforced either with sand – maximum detached material 1262 µg/cm² for 75% of Grey Sand – or mortars only reinforced with Chaff – maximum detached material 1722 µg/cm² for mortars reinforced with 3.8% of Chaff.

Table 5-26: Surface properties of mortars reinforced with Grey Sand and Chaff with a settling time of 1 or 2 days

Mortar Name	Amount of Grey Sand (% weight of dry mix)	Amount of chaff (% weight of dry mix)	Amount of water (% weight of dry earth)	Surface water absorption ($g/m^2 \cdot s$) for 90 s.	Peeling test – ($\mu g/cm^2$)	Visual scale (1-10)
Reference Earth	**0**	**0**	**30**	**14.0**	**264**	**1**
Ka000101-111001	53	2.3	36	25.3	1708	
Ka000101-111002	56	2.4	36	24.8	5806	
Ka000101-112001	41	1.4	35	17.8	1458	
Ka000101-2210001	54	1.2	29	28.6	1961	
Ka000101-2210004	51	1.2	28	23.2	1868	
Ka000101-2210006	54	1.2	30	27.9	806	
Ka000101-2210007	57	1.2	29	22.9	1333	
Ka000101-2210008	58	1.1	29	21.0	2597	
Ka000101-2210009	55	1.2	29	30.2	3840	
Ka000101-334001	54	2.9	37	26.7	3519	
Ka000101-334003	56	3.1	41		3093	
Ka000101-241001	73	0.8	27	26.2	1917	
Ka000101-483001	71	1.0	26	29.5	4009	

5.4.4 Durability properties of earth mortars reinforced with Grey Sand and Chaff

The durability properties of earth mortars reinforced with Grey Sand and Chaff are presented in Table 5-27 and the humid mechanical strength, the resistance to immersion in water, the resistance to abrasion and the resistance to erosion will are discussed in the following paragraphs.

Table 5-27: Durability properties of earth mortars reinforced with Grey Sand and Chaff

	Amount of clay (% weight of dry mix)	Humidity level (weight increase in %)	Humid flexural strength (MPa)	Loss in strength (%)	Humid compressive strength (MPa)	Loss in strength (%)	Water resistance (min)	Abrasion resistance (DIN18947) Material loss (g)	Abrasion resistance (French rules) Abrasion Coefficient (cm^2/g)	Erosion resistance Hole depth (mm)	Erosion resistance Hole diameter (mm)
Reference Earth	**24.5**	**2.5**	**0.60**	**-46**	**3.35**	**-42**	**28**	**1.9**	**6.4**		
Ka000101-111001	11.1	1.6	0.44	-36	0.77	-41	20	9.4	0.5	6.5	21
Ka000101-111002	10.1	0.9	0.53	-21	0.80	-29		8.6	0.4	6.5	23
Ka000101-112001	14.2	1.2	0.55	-41	0.96	-41		3.1	1.3	8	26
Ka000101-2210001	11.0	1.0	0.25	-58	0.61	-50	9	11.0	0.4	6.5	27
Ka000101-2210004	11.6	1.4	0.30	-64	0.96	-33	7	4.5	1.2	9.5	15
Ka000101-2210006	11.0	1.5	0.47	-44	0.95	-35	11	8.5	0.6	8.5	22
Ka000101-2210007	10.2							7.4	0.6		
Ka000101-2210008	10.1	0.6	0.39	-46	0.85	-36		5.7	0.5		
Ka000101-2210009	10.7	1.1	0.38	-56	0.44	-66	27	13.1	0.4	8	25
Ka000101-334001	10.5	1.1	0.40	-13	0.65	-40	5	9.2	0.5	7.5	19
Ka000101-334003	10.0	0.6	0.31	-62	0.56	-51		10.5	0.4		
Ka000101-241001	6.4	0.1	0.25	-61	0.79	-20		10.0	0.4		
Ka000101-483001	6.9	0.3	0.31	-53	0.48	-51	5	14.8		6.5	17

5.4.4.1 Humid mechanical strength

The strengths of earth mortars reinforced with Grey Sand and Chaff after being placed for 3 weeks in a humid environment have been measured and are presented in Table 5-27 together with their humidity level and their loss of strength compared to non-saturated mortars.

The amount of humidity varies from 0.1% and 1.6% and the loss of strength varies from 13% (Ka000101-334001) and 64 % (Ka000101-221004) for flexural strength and from 20% (Ka000101-214001) to 66% (Ka000101-221009) for compressive strength. The amount of humidity absorbed is changing with the amount of sand in the mortars as shown in Figure 5-26 and shown for earth mortars reinforced with Grey Sand (section 5.2.4) as mortars with a high amount of sand are absorbing less humidity than non-reinforced mortars. This relation is not as clear if the amount of fibres is taken into account since as shown on mortars reinforced with Chaff, the amount of fibres doesn’t have a large impact on the humidity absorption of mortars in the opposite of sand amount (sections 5.2.6 and 5.3.6)

Moreover, as in other tested mortars (sections 5.2.4 and 5.3.4), it seems that the loss of strength is not related to the amount of humidity as a mortar with only 0.1% of weight increase has a loss of strength of 60% and a mortar with 1.1% of weight increase has a loss of strength of 13%. This fact is illustrated by Figure 5-27 which shows the loss of strength of individual specimens according to the weight increase.

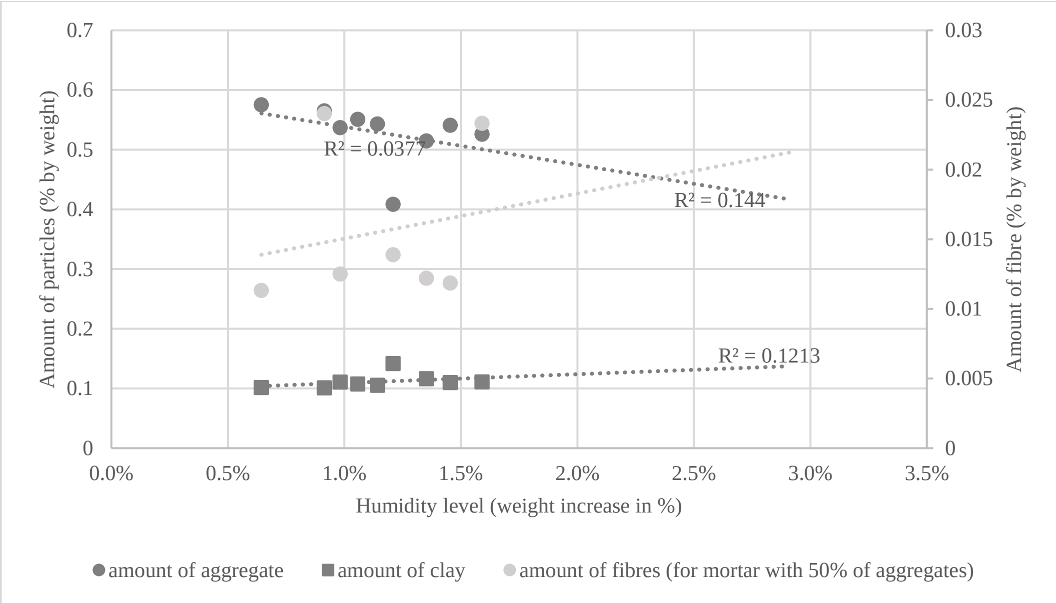

Figure 5-26: Impact of the reinforcing material on the amount of water vapour absorbed

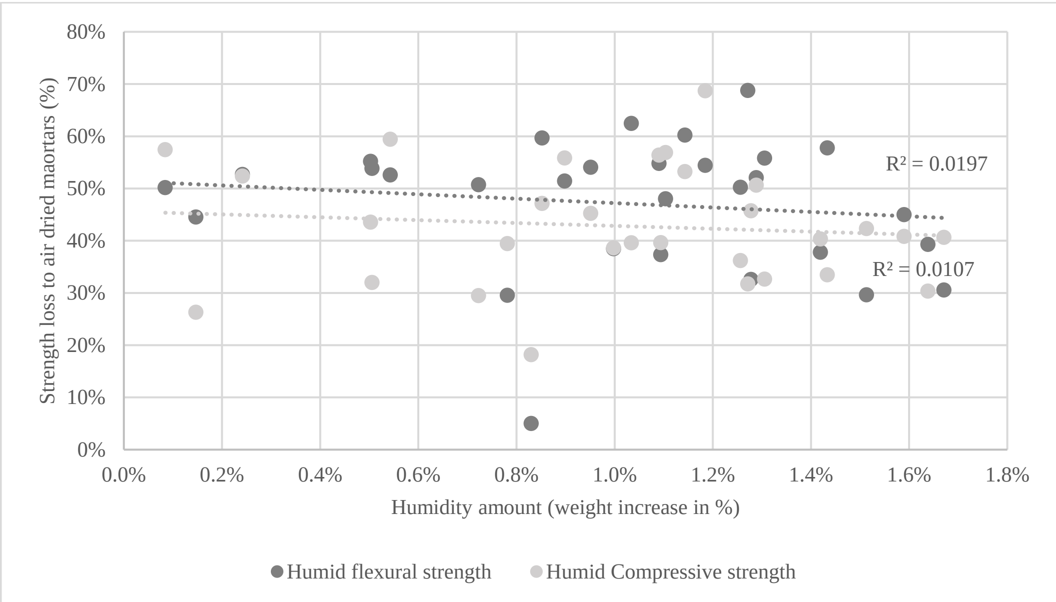

Figure 5-27: Impact of the humidity amount on the strength loss of mortars

5.4.4.2 Water resistance by immersion

The resistance to immersion in water has only been tested on a few mortars and only one specimen per mortar, therefore the data might not be representative of the real behaviour. The results of the test are given in Table 5-27.

The resistance varies from 5 min for Ka000101-334001 (30% of Grey Sand and 40% of Chaff) to 27 min for Ka000101-221009 (40% of Grey Sand and 20% of Chaff) but most of the tested mortars have low resistance in the water. If the high resistance of Ka000101-22109 is discarded as an outlier, the resistance to water of mortar shows a decrease with the decrease of clay amount as found for mortars only reinforced with sand (section 5.2.4.2). This low resistance to water shows that despite the addition of fibre to reinforce the mortar – as the addition of fibres is increasing the resistance as shown in section 5.3.6 – the low amount of clay present in the mortar is not enough to maintain the cohesion of the material.

5.4.4.3 Abrasion

The abrasion has been tested according to both the DIN18947 and the French regulation and the results of the test on some of the mortars on individual specimens are given in Table 5-27.

The lowest resistance to abrasion is seen for mortar Ka000101-483001 for the DIN18947 test and mortar Ka000101-241001 for the Regles Pro test – as Ka0001-483001 has not been tested according to Regles Pro – which are the mortars with the lowest amount of clay. As expected, the highest resistance is seen on mortar Ka000101-11201 – with the higher amount of clay – for both tests. Therefore, despite some variation in the results for mortars with a similar amount of clay, it can be said that decreasing the amount of clay lead to a decrease in abrasion resistance, as already shown for mortars reinforced with Grey Sand (section 5.4.4.3).

5.4.4.4 Erosion resistance

The results of the erosion resistance tests are given in Table 5-27. Only one specimen has been tested per mortar type.

The resistance to erosion varies very little, with the depth of the pith increasing from 6.5 mm to 9.5 mm. This depth range is similar to the depths of erosion piths of mortars reinforced with 57% to 73% of Grey Sand but slightly higher than the mortars reinforced with 0.6 % to 2.2% of Chaff (sections 5.2.4.5 and 5.3.4.4). Therefore, it might be assumed that the resistance to erosion is controlled by the amount of sand present in the samples more than the amount of fibres. However, the presence of fibres also reduces the erosion as in the case of Ka000101-483001 (73% of Grey Sand and 1.0% of Chaff) which has a similar amount of Grey Sand with Ka000100-671 (67% of Grey Sand) but only a pith of 6.5 mm instead of 10 mm probably because of the added fibres.

5.4.5 Hydric properties of earth mortars reinforced with Grey Sand and Chaff

The hydric properties of earth mortars reinforced with Grey Sand and Chaff are summarized in Table 5-28 and the capillarity absorption and the drying behaviour are discussed in the following paragraphs.

Table 5-28: Hydric properties of mortars reinforced with Grey Sand and Chaff

	Amount of clay (% weight of dry mix)	Amount of Grey Sand (% weight of dry mix)	Amount of Chaff (% weight of dry mix)	Capillarity coefficient (kg/m²/min$^{0.5}$)	R^2 (-)	Drying rate (1st phase) (kg/m²/h)	R^2 (-)	Drying rate (2nd phase) (kg/m²/h$^{0.5}$)	R^2 (-)	Drying index
Reference Earth	**24.5**	**0**	**0**	**1.00**		**0.14**		**1.32**		**0.45**
Ka000101-111001	11.1	53	2.3	1.28	1.00	0.11	0.99	0.85	1.00	0.55
Ka000101-112001	14.2	41	1.4	0.99	1.00	0.11	0.99	0.92	1.00	0.30
Ka000101-2210001	11.0	54	1.2	1.24	1.00	0.16	1.00	1.22	0.99	0.32
Ka000101-2210004	11.6	51	1.2	1.13	0.99	0.12	1.00	1.10	0.99	0.40
Ka000101-2210006	11.0	54	1.2	0.93	0.99	0.11	0.99	0.92	1.00	0.47
Ka000101-2210008	10.1	58	1.1	0.97	1.00	0.13	0.99	1.20	1.00	0.35
Ka000101-2210009	10.7	55	1.2	1.03	0.99	0.14	0.99	1.15	0.99	0.32
Ka000101-334001	10.5	54	2.9	1.02	1.00	0.12	1.00	1.22	0.99	0.36
Ka000101-483001	6.9	71	1.0	1.11	1.00	0.16	0.99	1.27	1.00	0.27

5.4.5.1 Capillarity water absorption

The water absorption by capillarity is presented as Capillarity Coefficient (CC) in Table 5-28 and plotted versus time in Figure 5-28 and Figure 5-29 for 9 different mortars representing 5 different amount of Grey Sand and Chaff.

The CC varies from 0.91 kg/(m²·min$^{0.5}$) for Ka000101-221008 (40% of Grey Sand and 20% of Chaff) to 1.21 kg/(m²·min$^{0.5}$) for Ka000101-111001 (33% of Grey Sand and 33% of Chaff). These variations are not only existing between mortars with different amounts of materials but also between mortars with the same amount of materials but made at a different time with possibly slightly different materials. This difference is illustrated in Figure 5-29 for mortars with 40% of Grey Sand and 20%

of Chaff with a CC comprised between 0.91 $kg/(m^2 \cdot min^{0.5})$ and 1.18 $kg/(m^2 \cdot min^{0.5})$, whereas mortars made the same day with different contents in materials – namely Ka000101-221009, -334001 and -483001 – have the same CC. Therefore, it is impossible to understand the impact of the amount of sand and chaff from the tested mortars, in opposition to Lima and Faria (2017) who state that for the same amount of sand and different amount of fibres, the CC is similar.

However, when the amount of absorbed water is plotted against time, it is possible to see a clear common behaviour of all mortars, similar to the one only reinforced with fibres. After 49 min (7 $min^{0.5}$) the absorption rate slows down as the mortars are saturated, except for the mortar with the highest amount of clay (Ka000101-112001) which continues to absorb water until 81 min (9 $min^{0.5}$) whereas the Reference Earth specimen which has a similar thickness (about 4 cm) but contains no sand or fibre has not reached saturation at the end of the test (Figure 5-28).

Figure 5-29 shows the capillarity absorption of the different mortars made with 40% of Grey Sand and 20% of Chaff and the average behaviour. It can be seen that despite their very different absorption rates, their saturation (due to the thickness of the specimen and the similar amount of clay) is achieved for a similar amount of water absorbed after 48h – that is 11.7g to 13.0 g.

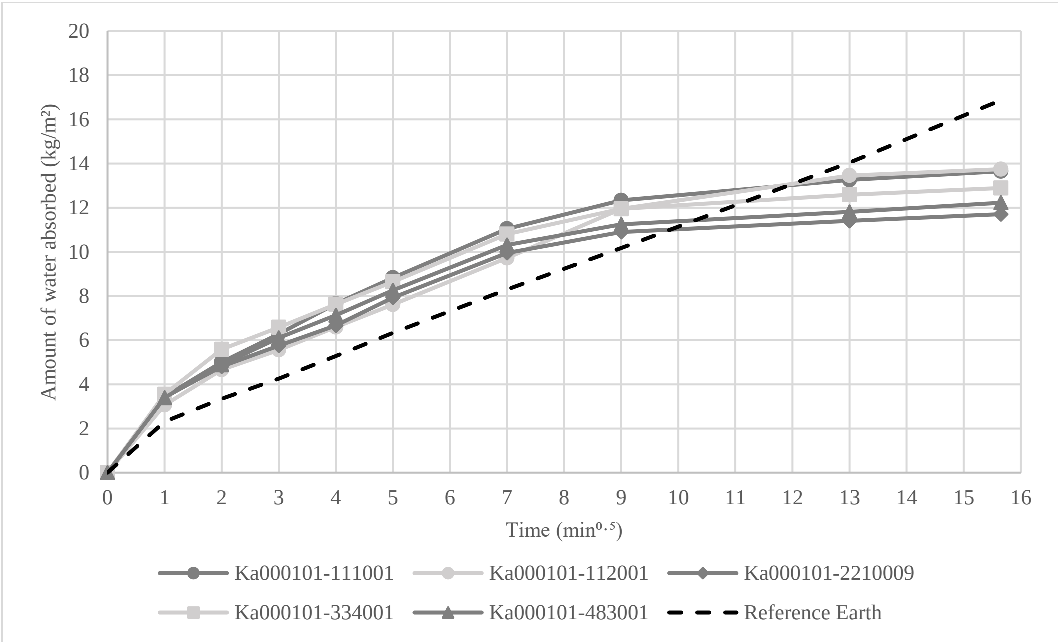

Figure 5-28: Capillarity water absorption of some selected earth mortars reinforced with Grey Sand and Chaff

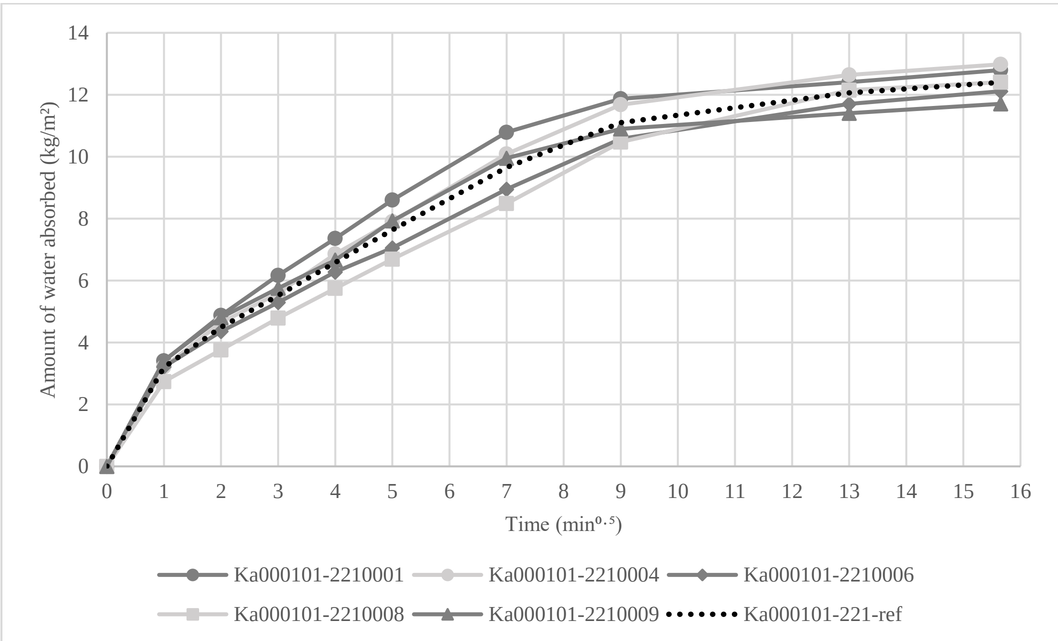

Figure 5-29: Capillarity absorption of different earth mortars reinforced with 40% of Grey Sand and 20% of Chaff and the average capillarity absorption used as Reference Mortar for comparison.

5.4.5.2 Drying behaviour

The drying behaviour of earth plaster reinforced with Grey Sand and Chaff is summarized in Table 5-28 as primary Drying Rate (pDR) and secondary Drying Rate (sDR) which represent the drying speed during the first and second part of the drying and as the Drying Index (DI) which represent the difficulty to dry. Figure 5-30 shows the drying behaviour of a selection of different mortars with the desorbed water plotted against time whereas Figure 5-31 shows the drying behaviour of the different mortars made with 40% of Grey Sand and 20% of Chaff as well as the average behaviour.

Both the DI and the drying rates show very different drying behaviours for the different samples which are related neither to the amount of sand nor to the amount of fibres nor the amount of clay. And the curves also show very different behaviours despite all samples being tested at the same time and during the same conditions. Mortar Ka000101-483001 has the fastest loss of water as it also has the smallest amount of clay but mortar Ka000101-112001 which has a similar amount of fibres but the highest amount of clay is the second lowest loss of water after mortar Ka000101-111001 which in opposite has much more fibres and less clay (Figure 5-30). However, when the drying curves of mortars of the same composition are compared (Figure 5-31), it can be seen that they have similar drying behaviour despite some exceptions (e.g. Ka000101-221006) which might be due to the material used or the position of the sample during the drying period. Moreover, they all achieve complete drying after 300 minutes.

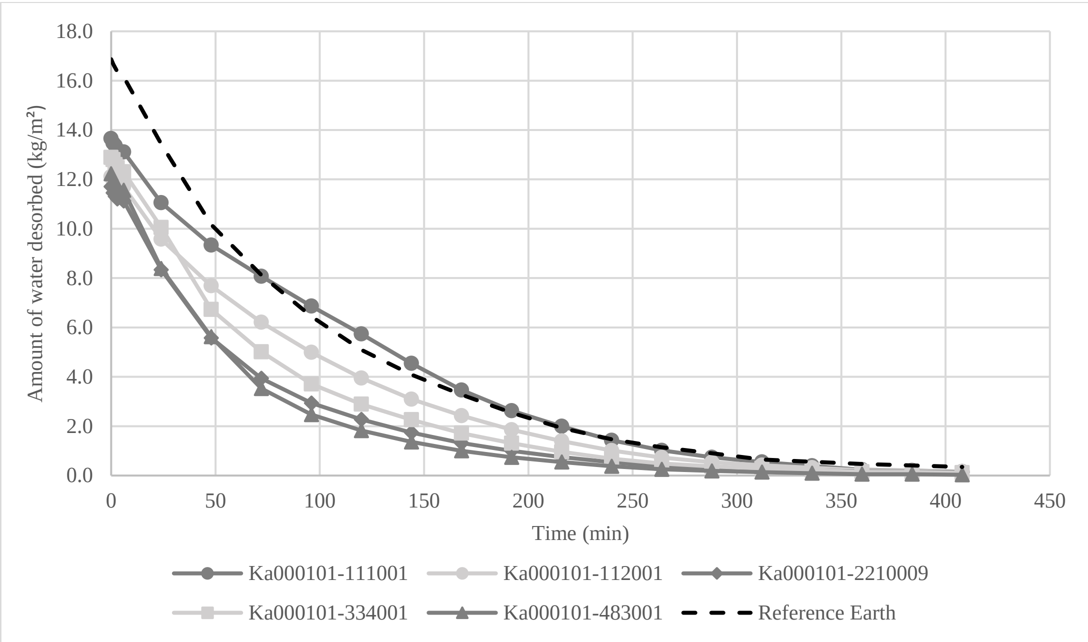

Figure 5-30: Water desorption and drying behaviour of some selected mortars reinforced with Grey Sand and Chaff

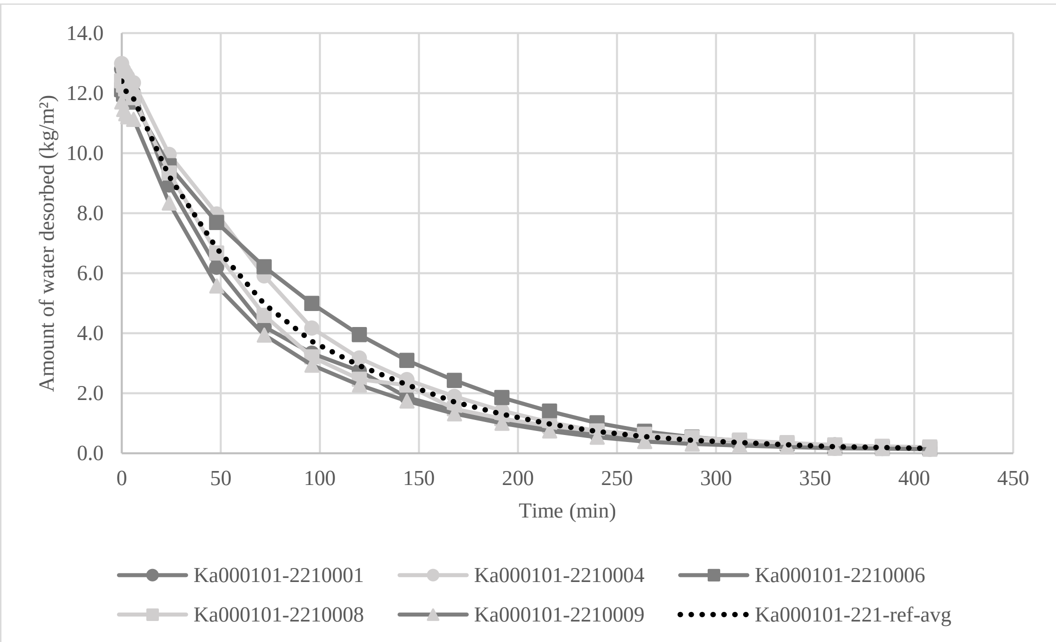

Figure 5-31: Water desorption and drying behaviour of different earth mortars reinforced with 40% of Grey Sand and 20% of Chaff and the average capillarity absorption used as Reference Mortar for comparison.

5.4.6 Hygric properties of earth mortars reinforced with Grey Sand and Chaff

The hygric properties of earth mortars reinforced with Grey Sand and Chaff are presented in Table 5-29. The water vapour permeability of the mortars and their dynamic water vapour absorption and desorption behaviours are discussed in the following paragraphs.

Table 5-29: Hygric properties of earth mortars reinforced with Grey Sand and Chaff

Mortar Name	Amount of clay (% weight of dry mix)	Amount of Grey Sand (% weight of dry mix)	Amount of Chaff (% weight of dry mix)	Water vapour diffusion resistance factor (-)	Equivalent air layer (m)	Water vapour adsorption (12h - g/m^2)	Primary adsorption rate – first 3h (g/m^2h)	Secondary adsorption rate - 12h-48h (g/m^2h)	Water vapour desorption (12h - g/m^2)	Primary desorption rate – first 3h (g/m^2h)	Secondary desorption rate - 12h-48h (g/m^2h)
Reference Earth	**24.5**	**0**	**0**	**3.9**	**0.15**	**153**	**14.3**	**7.3**	**147.0**	**17.6**	**4.6**
Ka000101-111001	11.1	53	2.3	4.1	0.16	134	12.0	4.9	114	15.0	3.7
Ka000101-112001	14.2	41	1.4	4.1	0.16	161	14.7	5.7	100	13.5	3.4
Ka000101-2210001	11.0	54	1.2	4.4	0.18	160	13.9	5.0	94	13.4	3.3
Ka000101-2210004 A	11.6	51	1.2			146	14.4	5.6	100	13.0	3.5
Ka000101-2210006 A	11.0	54	1.2	4.4	0.17	143	14.0	5.7	92	12.4	3.3
Ka000101-2210007	10.2			4.1	0.16						
Ka000101-2210008	10.1	58	1.1	4.0	0.16	154	15.6	5.8	116	15.9	3.7
Ka000101-2210009	10.7	55	1.2	3.7	0.15	144	14.6	6.3	104	14.4	3.3
Ka000101-334001	10.5	54	2.9	5.1	0.20	140	14.5	6.1	106	13.9	3.3
Ka000101-334003	10.0			4.0	0.16						
Ka000101-241001	6.4			4.1	0.17						
Ka000101-483001	6.9	71	1.0	4.1	0.17	136	13.0	error	76	11.3	2.3

5.4.6.1 Water vapour permeability

The water vapour permeability of mortars reinforced with Grey Sand and Chaff is presented in Table 5-29 together with the S_d value and the water vapour diffusion resistance factor (μ). The μ-value varies from 3.7 for Ka000101-2210009 (40% of Grey Sand and 20% of Chaff) to 5.1 for Ka000101-334001 (30% of Grey Sand and 40% of Chaff). However, except for these two values, all diffusion resistance factors are similar – between 4.0 and 4.4 – for any mortars with densities comprised between 1337 kg/m³ and 1591 kg/m³ and amount of clay ranging from 6.4% to 14.2%. Therefore, it can be concluded that despite very different amounts of clay, fibres and densities, neither the amount of clay or fibres nor the density of the samples have a significant impact on the permeability. The Reference Earth has a water vapour diffusion resistance factor in a similar range to the reinforced mortars, therefore it can be concluded that the addition of Chaff and Grey Sand in the tested quantity has no impact on the water vapour permeability of earth mortars.

5.4.6.2 Dynamic water vapour adsorption and desorption behaviour

The behaviour of earth mortars in presence of humidity is presented in Table 5-29. The adsorption after 12h hours varies from 134 g/m² (Ka000101-111001 – 33% of Grey Sand and 33% of Chaff) to 160 g/m² (Ka000101-221001 – 40% of Grey Sand and 20% of Chaff) and the desorption varies from 92 g/m² (Ka000101-221006 – 40% of Grey Sand and 20% of Chaff) to 116 g/m² (Ka000101-221008 – 40% of Grey Sand and 20% of Chaff) for samples tested in identical conditions.

According to these results and the adsorption behaviour during the first 24h (Figure 5-32) and the results of the mortars reinforced only with Sand (section 1 5.2.6.2), it seems that the main impact on water adsorption comes from the amount of sand – i.e. the amount of clay - in the mortar with mortars since the mortars with a lower amount of clay have lower adsorption after 24h. But even with this lower adsorption rate and total adsorption, they have sufficient adsorption to qualify for class I as defined by the German Standards (DIN18947, 2013)

Because of the set-up problem, no conclusion and comparison of results can be made on the desorption behaviour.

Mortars Ka000101-221001, Ka000101-221004, Ka000101-221006, and Ka000101-221008 have been tested also in different conditions (Table E 1, Figure E 1, Figure E 2 and Figure E 3 in APPENDIX E) Their absorption at 12h is similar whereas the desorption at 12h is different because, during the last 24 hours of the adsorption test, they have actually lost weight as the room was probably at a lower humidity level due to set-up problems. These data are presented here because they will be used for comparison purposes in sections 6.1.6, 6.2.6 and 7.6.

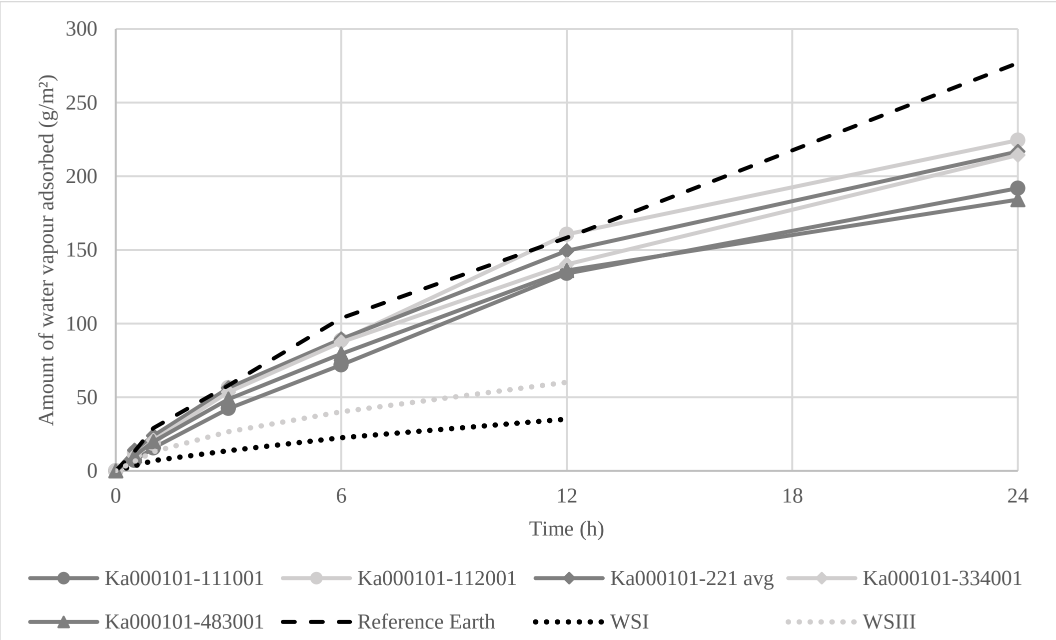

Figure 5-32: Water vapour adsorption behaviour for selected mortars during the first 24h of the test. WSI and WSIII are the water vapour absorption classes of earth mortars ((DIN18947, 2013)

5.5 Properties of mortars reinforced with Yellow Sand and Chaff

As Grey Sand used in the first part of the research was discontinued, another source of commercial sand was used. However, as its physical properties – especially angularity and amount of fine – were different than the Grey Sand, this new sand has also been tested for the same mixes defined as Reference Mortar 1, i.e. 40% of earth, 40% of sand and 20% of Chaff, all defined as volume. It has been tested in the same conditions, using a similar amount of water as defined by a slump between 16 cm and 17 cm and a similar settling time between 0 days and 2 days. In the following sections, the physical, surface, durability, hydric and hygric properties of different mixes made with these proportions of materials and different amount of water will be given and discussed.

5.5.1 Physical properties of earth mortars reinforced with Yellow Sand and Chaff

The physical properties of earth mortars reinforced with Yellow Sand and Chaff are presented Table 5-30 together with the Reference Earth and the Reference Mortar 1 – average value of the earth mortars reinforced with Grey Sand and Chaff.

5.5.1.1 Linear Shrinkage

The linear shrinkage of mortars reinforced with Yellow Sand varies from 1.3% (Ka000201-2210007) to 3.8% (Ka000201-2210014) for samples of 24x20x4 cm ^{3} and from 0.4% (Ka000201-2210002) to 2.9% (Ka000201-2210006) for samples of 16x4x4 cm^3 which is similar to the shrinkage found for Grey Sand with similar amount of material (Section 5.4.1). The shrinkage of the Reference Mortar 2 has been calculated by using only mortars with a slump of 16.0 to 17.0 cm and 2 days settling. The large shrinkage of mortar Ka000201-2210014 has been excluded and therefore the shrinkage used is 1.9% similar to the 1.8% of Reference Mortar 1.

5.5.1.2 Density

The density of the mortars varies from 1621 kg/m³ (Ka000201-2210008) to 1674 kg/m³ (Ka00201-2210014) for 24x20x4 cm ³ samples and from 1548 kg/m³ (Ka000201-2210012) to 1618 kg/m³ (Ka000201-2210003). The densities of mortars reinforced with Yellow Sand are generally slightly higher than the ones of mortars reinforced with Grey Sand therefore it can be assumed than the usage of Yellow Sand increases the density of mortars. The density calculated for Reference Mortar 2 is also higher than the one of Reference Mortar 1 (1644 kg/m³ to 1581 kg/m³) but the difference is lower due to the mortars used.

Table 5-30: Physical properties of earth mortars reinforced with Yellow Sand and Chaff

			Type of samples							
			24x20		16x4		24x20		16x4	
Mortar Name	Slump test (cm)	Settling time	Shrinkage (%)	*Standard dev.*	Shrinkage (%)	*Standard dev.*	Density (%)	*Standard dev.*	Density(%)	*Standard dev.*
Reference Earth	**16.0 17.0**	**2**	**7.1**	***0.8***	**7.7**	***0.9***	**1691**	**22**	**1682**	***12***
Ka000201-2210002	16.0	2	1.8	*0.3*	0.4	*0.2*	1651	16	1615	*24*
Ka000201-2210003	17.0	2	1.9	*0.1*	1.9	*0.3*	1645	1	1618	*14*
Ka000201-2210006	16.5	2	2.6	*0.4*	2.9	*0.2*	1635	4	1582	*19*
Ka000201-2210007	16.5	0	1.3	*0*	2.3	*0.1*	1641	2	1616	*8*
Ka000201-2210008	16.5	1	1.8	*0.2*	2.2	*0.1*	1621	8	1607	*19*
Ka000201-2210014	16.5	2	3.1	*0.4*			1674	15		
Reference Mortar 1	**16.2 16.8**	**0-2**	**1.8**	***0.5***	**1.0**	***0.4***	**1581**	**24**	**1593**	***10***
Reference Mortar 2	**16.0 17.0**	**0-2**	**1.9**	***0.7***	**2.0**	***0.9***	**1644**	**20**	**1608**	***22***

5.5.2 Mechanical properties of earth mortars reinforced with Yellow Sand and Chaff

The mechanical strength of earth mortars reinforced with Yellow Sand and Chaff is presented in Table 5-31and the impact of Yellow Sand on flexural and compressive strength is discussed in the flowing paragraphs.

Table 5-31: Mechanical strength of earth mortars reinforced with Yellow Sand and Chaff

Mortar Name	Amount of fibre (%wt.)	Density (kg/m³)	24x20 Average flexural strength (MPa)	*Standard dev.*	16x4 Average flexural strength (MPa)	*Standard dev.*	24x20 Average compressive strength (MPa)	*Standard dev.*	16x4 Average compressive strength (MPa)	*Standard dev.*
Reference Earth	**0**	**1691**	**1.55**	***0.29***	**1.35**	***0.22***	**4.51**	***0.46***	**5.31**	***0.46***
Ka000201-2210002	1.0	1651	0.88	*0.00*	0.77	*0.05*	2.00	*0.14*	2.00	*0.11*
Ka000201-2210003	1.0	1645	0.69	*0.13*	0.89	*0.02*	1.95	*0.08*	2.17	*0.07*
Ka000201-2210006	1.0	1635	1.00	*0.02*	0.74	*0.03*	1.92	*0.14*	1.84	*0.10*
Ka000201-2210007	1.0	1641	0.91	*0.13*	0.75	*0.09*	1.95	*0.06*	1.87	*0.11*
Ka000201-2210008	1.0	1621	0.97	*0.03*	0.79	*0.06*	1.91	*0.04*	1.91	*0.11*
Ka000201-2210014	1.0	1674	0.99	*0.08*			1.98	*0.21*		
Reference Mortar 1	**1.2**	**1581**	**0.77**	***0.12***	**0.64**	***0.06***	**1.34**	***0.12***	**1.76**	***0.12***
Reference Mortar 2	**1.0**	**1644**	**0.91**	***0.13***	**0.79**	***0.08***	**1.95**	***0.14***	**1.96**	***0.16***

5.5.2.1 Flexural strength

The flexural strength of earth mortars reinforced with Yellow Sand and Chaff varies from 0.69 MPa (Ka000201-2210003) to 1.00 MPa for mortars Ka000201-2210006 for 24x20x4 cm³ and from 0.74 MPa (Ka000201-2210006) to 0.89 MPa (Ka000201-2210003). The difference in flexural strength for the same mixes can't be explained based on the amount of fibres by weight as it was for mortar reinforced with Grey Sand therefore, it should be accepted as an error margin due to the testing and production methods.

The flexural strength of mortars reinforced with Yellow Sand is generally higher than the one reinforced with Grey Sand and therefore the flexural strength of Reference Mortar is calculated as 0.91MPa, higher than the 0.77 MPa from Reference Mortar 1. This higher strength is probably due to the higher density of the mortar.

5.5.2.2 Compressive strength

The compressive strength of earth mortars reinforced with Yellow Sand and Chaff varies from 1.91 MPa (Ka000201-2210008) to 2.00 MPa (Ka000201-2210002) for 24x20x4 cm³ and from 1.84 MPa (Ka000201-2210006) to 2.00 MPa (Ka000201-2210002) for 16x4 samples. The maximum and minimum compressive strength are seen on the same samples which are respectively the ones with the highest and with the lowest density if sample Ka000201-2210014 is excluded as an outlier. Moreover, when the compressive strength is plotted against the density (Figure 5-33), there is a clear trend of an increase in strength with an increase in density as underlined previously and by Kouako et al. (2009) and others.

Figure 5-33 also shows the compressive strength of the mortars reinforced with Grey Sand. For 24x20x4 cm³ samples. The compressive strength of mortars reinforced with Yellow Sand is significantly higher than the one made with Grey Sand and not only the difference of density explains the strength difference but the type of sand used also.

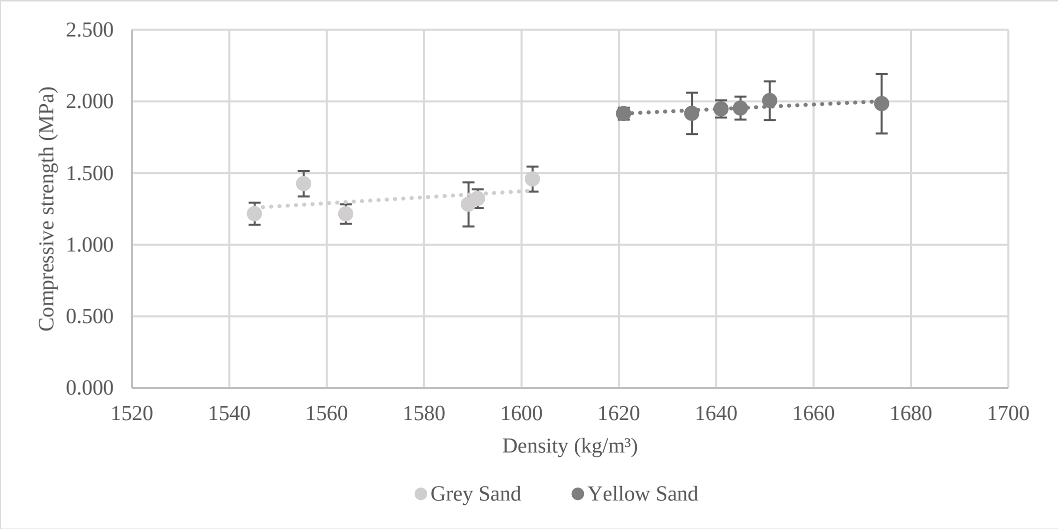

Figure 5-33: Impact of the density on the compressive strength of earth mortars reinforced with the same amount of Yellow Sand and Chaff and Grey Sand and Chaff

5.5.3 Surface properties of earth mortars reinforced with Yellow Sand and Chaff

The surface properties of earth mortars reinforced with Yellow Sand and Chaff are presented in Table 5-32 together with the surface properties of Reference Mortar 1 and Reference Earth for comparison. The surface water absorption and surface cohesion are discussed in the following paragraphs.

Table 5-32: Surface properties of earth mortars reinforced with Yellow Sand and Chaff

Mortar name	Amount of clay (% weight of dry mix)	Amount of water (% weight of dry earth)	Density (kg/m³)	Surface water absorption (g/m²·s) for 90 s.	Peeling test – (µg/cm²)
Reference Earth	**24.5**	**30**	**1691**	**14.0**	**264**
Ka000201-2210002	10.9	25	1651	17.4	1458
Ka000201-2210003	10.9	26	1645	18.8	1500
Ka000201-2210006	10.9	29	1635	20.4	750
Ka000201-2210007	10.9	25	1641	12.8	903
Ka000201-2210008	10.9	27	1621	18.0	1208
Ka000201-2210014	12.0	23	1674	16.3	1333
Reference Mortar 1.	**10.8**	**29**	**1581**	**26.1**	**2214**
Reference Mortar 2	**11.1**	**26**	**1644**	**17.3**	**1192**

5.5.3.1 Surface water resistance

The surface water resistance of mortars varies from 12.8 g/m²·s (Ka000201-2210007) to 20.4 g/m²·s (Ka000201-2210012) with an average value of 17.3 g/m²·s which is lower than the average value of mortars reinforced with Grey Sand in similar conditions (26.1 g/m²·s). The large variation of the water absorption of the samples can't be explained by their content, as it is almost identical for most samples. However, when mortar Ka000201-221007 is discarded because of its very low value, it seems to be a relation between the density and the water absorption, with samples with a higher density absorbing less water, probably because of lower open porosity. This could explain the difference in water absorption between mortars with Grey

Sand and Yellow Sand, as the density of mortars with Yellow Sand is higher and therefore they absorb less water.

5.5.3.2 Surface Cohesion

The results of the peeling test which evaluate the surface cohesion of samples are given in Table 5-33. The amount of material detached during the test varies from 750 $\mu g/cm^2$ (Ka000201-2210006) to 1500 $\mu g/cm^2$ (Ka000201-2210003) with an average value of 1192 $\mu g/cm^2$, much lower than the one of mortars reinforced with Grey Sand (2214 $\mu g/cm^2$). The large difference in surface cohesion between samples is difficult to understand as the materials and the content of the mortars are the same. Therefore, as seen for the other types of mortar, the reproducibility of the test is probably difficult to achieve and therefore there is a large disparity in results.

5.5.4 Durability properties of earth mortars reinforced with Yellow Sand and Chaff

The durability properties of earth mortars reinforced with Yellow Sand and Chaff are presented in Table 5-33. The impact of humidity on mechanical strength, the resistance to abrasion and the resistance to erosion are discussed in the following paragraphs. The humid strength and the erosion resistance have only been calculated on one of the mortar, therefore the value of it might not be totally exact.

Table 5-33: Durability properties of earth mortars reinforced with Yellow Sand and Chaff

Mortar name	Density (kg/m³)	Humidity level (weight increase in %)	Humid flexural strength (MPa)	Loss in strength (%)	Humid compressive strength (MPa)	Loss in strength (%)	Abrasion resistance (DIN18947) Material loss (g)	Abrasion resistance (French rules) Abrasion Coefficient (cm²/g)	Abrasion resistance (French rules) Depression depth (cm)	Erosion resistance Hole depth (mm)	Erosion resistance Hole diameter (mm)
Reference Earth	**1691**	**2.5**	**0.60**	**-46**	**3.35**	**-42**	**1.9**	**6.4**			
Ka000201-2210002	1651						2.8	1.1	6.0		
Ka000201-2210003	1645						2.3	1.3	5.0		
Ka000201-2210006	1635						3.1	1.1	5.5		
Ka000201-2210007	1641						2.6	1.0	5.8		
Ka000201-2210008	1621						3.0	1.0	5.3		
Ka000201-2210014	1674	0.9	0.84	-15	1.51	-24	1.7	1.6	4.3	6	25
Reference Mortar 1	**1581**	**1.1**	**0.36**		**0.76**		**8.6**	**0.6**	**9**	**8**	**22**
Reference Mortar 2	**1644**	**0.9**	**0.84**		**1.51**		**2.6**	**1.2**	**5**	**6**	**25**

5.5.4.1 Humid mechanical strength

The humid mechanical strength of earth mortars reinforced with Yellow Sand has been calculated on 1 mortar. The average flexural strength of the mortar Ka000201-2210014 is 0.84 MPa (15% of strength loss) whereas the compressive strength is 1.51 MPa (24% of strength loss). The humid mechanical strength of mortars reinforced with Yellow Sand is much higher than the one reinforced with Grey Sand, probably because of a higher dry mechanical strength and a lower amount of vapour absorbed.

5.5.4.2 Abrasion resistance

The abrasion resistance has been determined with both the German test and French test on 10 mortars. The material loss on the German test varies from 1.7g (Ka000201-2210014) to 4.3g (Ka000201-2210012) whereas the average is 2.8g of material loss much lower than the 8.4g of material loss of mortars reinforced with Grey Sand. The abrasion coefficient calculated for the French abrasion test varies from 4.3 cm^2/g (Ka000201-2210012) to 7.0 cm^2/g (Ka000201-2210014) which shows exactly the same increase of resistance to abrasion with an increase of density as presented.

5.5.4.3 Erosion resistance

The resistance to erosion has been tested on one mortar, only on one specimen. The depth of the depression is 6 mm and the diameter is 2.2 mm. These results are slightly lower than the one obtained with the mortars reinforced with Grey Sand, therefore it can be assumed that with similar sand and density of samples, the type of sand has only a little impact on the resistance to erosion.

5.5.5 Hydric properties of earth mortars reinforced with Yellow Sand and Chaff

The hydric properties of earth mortars reinforced with Yellow Sand and Chaff are presented in Table 5-34, together with the amount of clay and the density of the mortars. The capillarity absorption and the drying behaviour of the mortars are discussed in the following paragraphs.

Table 5-34: Hydric properties of earth mortars reinforced with Yellow Sand and Chaff

	Amount of clay (% weight of dry mix)	Density (kg/m^3)	Capillarity coefficient ($kg/m^2/min^{0.5}$)	*R^2 (-)*	Drying rate (1^{st} phase) ($kg/m^2/h$)	*R^2 (-)*	Drying rate (2^{nd} phase) ($kg/m^2/h^{0.5}$)	*R^2 (-)*	Drying index
Reference Earth	**24.5**	**1691**	**1.00**		**0.14**		**1.32**		**0.45**
Ka000201-2210002	10.9	1651	0.92	1.00	0.11	0.99	1.21	0.99	0.24
Ka000201-2210003	10.9	1645	0.90	1.00	0.09	1.00	1.22	0.98	0.23
Ka000201-2210006	10.9	1635	1.04	1.00	0.14	1.00	1.32	0.99	0.19
Ka000201-2210007	10.9	1641	0.89	1.00	0.11	1.00	1.17	0.99	0.24
Ka000201-2210008	10.9	1621	0.83	1.00	0.10	1.00	1.04	0.99	0.30
Ka000201-2210014	12. 0	1674	1.03	1.00	0.12	1.00	1.22	0.99	0.25
Reference Mortar 1	**11.3**	**1571**	**1.06**	***0.11****	**0.13**	***0.02****	**1.12**	***0.11****	**0.26**
Reference Mortar 2	**10.9**	**1638**	**0.94**	***0.07****	**0.11**	***0.02****	**1.20**	***0.08****	**0.24**

5.5.5.1 Water capillarity absorption

The water capillarity absorption coefficient (CC) of earth mortars reinforced with Yellow Sand and Chaff is varying from 0.83 $kg/(m^2 \cdot min^{0.5})$ (Ka000201-221008) to 1.04 $kg/(m^2 \cdot min^{0.5})$ (Ka000201-2210006) with an average of 0.94 $kg/(m^2 \cdot min^{0.5})$ and the total absorption after 1h21 – before the water reaches the top surface of the sample) varies from 8.8 kg/m² to 11.5 kg/m² which shows that despite having exactly the same composition, there are still differences due to the drying or production or homogeneity of the mix. These values are slightly lower from the ones of the mortars reinforced with Grey Sand but still in the error margin, therefore it can be assumed that using Yellow Sand or Grey Sand doesn't impact the water absorption.

5.5.5.2 Drying behaviour

The drying behaviour of earth mortars reinforced with Yellow Sand and Chaff is presented in Table 5-34 and Figure 5-34. From the figure and the numerical results, it can be assumed that all mortars have a similar drying rate with 2 mortars slightly different - Ka000201-221006 which is drying faster and Ka000201-221008 which is drying slower – but the difference is not large enough to be accounted for. Moreover, the different drying rates and the drying index are similar to the one of the mortars reinforced with Grey Sand, enforcing the conclusion that the amount of clay more than the type of sand in the mix is commanding the drying behaviour.

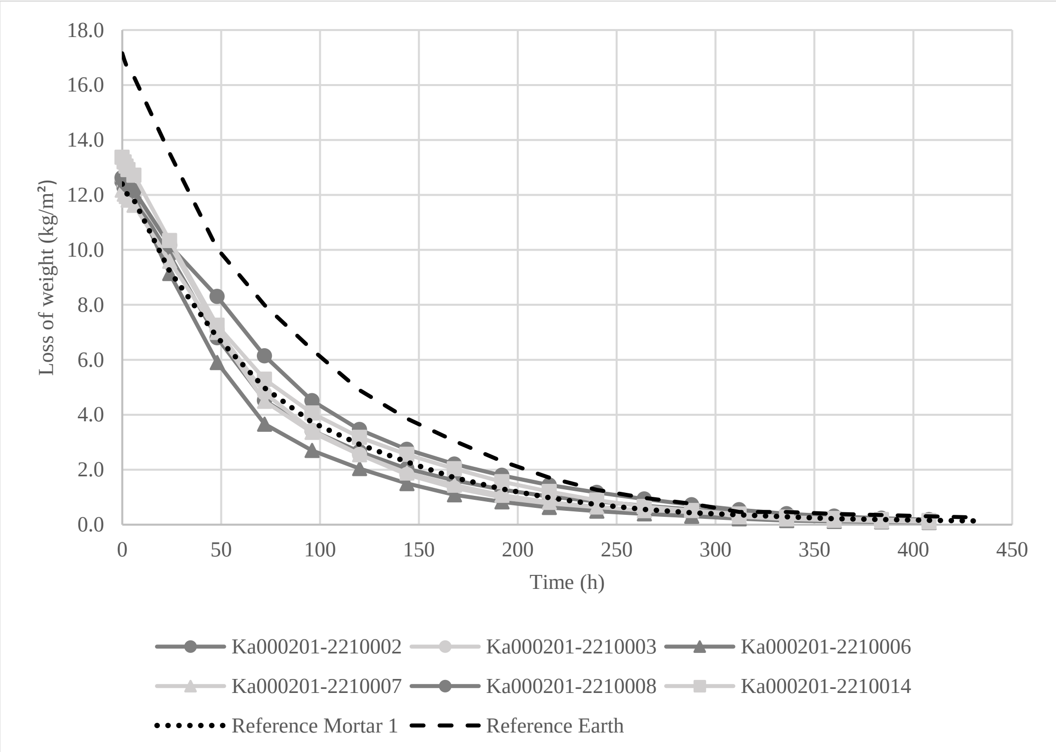

Figure 5-34: Drying behaviour of earth mortars reinforced with Yellow Sand

5.5.6 Hygric properties of earth mortars reinforced with Yellow Sand and chaff

The hygric properties of earth mortars reinforced with Yellow Sand and Chaff are presented in Table 5-35. The results of the tests on water vapour permeability, dynamic water vapour adsorption and desorption are summarized and discussed in the following paragraphs.

Table 5-35: Hygric properties of earth mortars reinforced with Yellow Sand

Mortar Name	Amount of clay (% weight of dry mix)	Water vapour diffusion resistance factor (-)	Equivalent air layer (m)	Water vapour adsorption (12h - g/m²)	Primary adsorption rate - first 3h (g/m²h)	Secondary adsorption rate - 12h-48h (g/m²h)	Water vapour desorption (12h - g/m²)	Primary desorption rate - first 3h (g/m²h)	Secondary desorption rate - 12h-48h (g/m²h)
Reference Earth	**24.5**	**3.9**	**0.1**	**153.0**	**14.3**	**7.3**	**147.0**	**17.6**	**4.6**
Ka000201-2210002	10.9	3.9	0.15	176.7	16.4	5.7	111.0	31.1	3.1
Ka000201-2210003	10.9	3.9	0.15	186.1	17.5	6.1	114.1	34.0	3.3
Ka000201-2210006	10.9	4.4	0.16	178.8	16.5	6.8	112.5	31.4	3.2
Ka000201-2210007	10.9	4.2	0.16	186.0	17.3	6.1	110.0	32.7	3.3
Ka000201-2210008	10.9	3.8	0.15	196.9	18.4	7.0	121.5	35.6	3.8
Ka000201-2210014	12.0	6.3	0.25	190.3	18.1	6.3	115.6	33.7	3.9
Reference Mortar 1	**11.3**	**4.1**	**0.16**	**149**	**14.5**		**101**	**13.8**	**3.4**
Reference Mortar 2	**10.9**	**4.4**	**0.17**	**145**	**14.5**		**84**	**11.1**	**2.9**

5.5.6.1 Water vapour permeability

The water vapour diffusion resistance varies between 3.8 (Ka000201-2210008) and 6.3 (Ka000201-2210014), however, the second highest value for the vapour diffusion resistance is 4.4 (Ka000201-2210001 and -2210006), therefore the value of 6.3 can be considered as an outlier. This shows that the mortars reinforced with Yellow Sand have a very low diffusion resistance, very similar to one of the Reference Earth or to the mortar reinforced with the same amount of Grey Sand.

5.5.6.2 Dynamic water vapour adsorption and desorption behaviour

The water vapour adsorption and desorption behaviour are represented in Figure 5-35. This graph shows that despite having a similar behaviour and a close amount of vapour adsorbed after 12h, the total adsorption might be quite different. Similar behaviour can be observed for the desorption of mortars with a 15% difference of water desorbed after 12h between Ka000201-221004 and Ka000201-221007.

The amount of adsorbed and desorbed vapour and the rates of adsorption and desorption are slightly higher than the one determined for mortars made with Grey Sand (Ka000101-221 avg. B, Table D 1 in APPENDIX D) in the same testing conditions, showing the importance of the type of sand on the vapour adsorption and desorption behaviour.

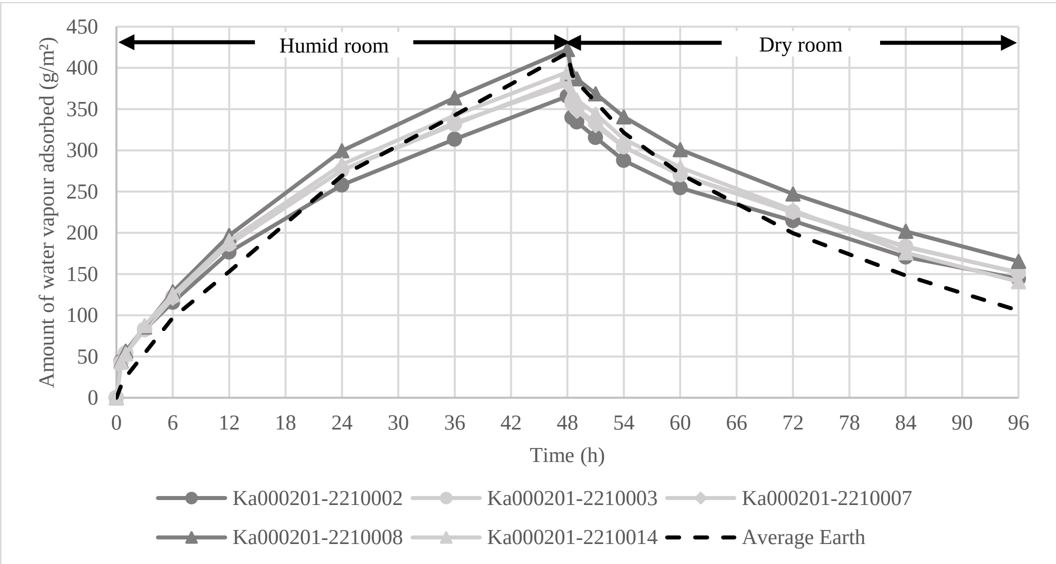

Figure 5-35: Dynamic water vapour adsorption and desorption behaviour of some selected earth mortars reinforced with Yellow Sand and Chaff.

CHAPTER 6

CHARACTERISTICS OF REINFORCED EARTH MORTARS MODIFIED WITH ALTERNATIVE SANDS AND FIBRES

In this chapter, the properties of earth mortars in which sand and fibres used for the reference mortar have been replaced by alternative sand and fibres will be determined and discussed in relation to the literature and the reference mortar properties.

6.1 Impact of alternative sands on the properties of reinforced earth mortars

In this section, the impact of alternative sands on the different properties of earth mortars will be presented and the results explained.

6.1.1 Physical properties of earth mortars reinforced with alternative sands

The physical properties of mortars made with alternative sands are presented in Table 6-1, Figure 6-1 and Figure 6-2 and their impacts on shrinkage and density are discussed in regard to the literature and previous results.

Table 6-1: Physical properties of earth mortars modified with alternative sands

Mortar Name	Sand type	Shrinkage (%)	*Standard dev.*	Difference with the Reference Mortar 1 (%)	Average dry density (kg/m³)	*Standard dev.*	Difference with the Reference Mortar 1 (%)
Reference Mortar 1	**Grey Sand**	**1.8**	**0.4**		**1571**	**24**	
Reference Mortar 2	Yellow Sand	2.0	0.5	+13	1638	13	+4.3
Ka000301-221001	Grey Sand<4.75mm	1.4	0.4	-21	1624	10	+3.4
Ka000401-221001	White Sand	1.8	0.3	-1	1651	20	+5.1
Ka000501-221001	Siliceous Sand	1.3	0.2	-26	1628	13	+3.6
Ka000601-221001	Sand2 <0.875mm	1.1	0.2	-38	1644	9	+4.6
Ka000701-221001	Sand2 <4.75mm	1.4	0.3	-20	1687	8	+7.4
Ka000801-221001	Yellow Sand washed	1.3	0.2	-27	1647	17	+4.9
Ka000901-221001	WS washed	1.7	0.4	-5	1696	4	+8.0
Ka001001-221001	Coarse Siliceous Sand	1.5	0.2	-15	1686	14	+7.3

6.1.1.1 Shrinkage

Shrinkage of the mortars using alternative sands is shown in Figure 6-1 together with the average shrinkage of reference mortars. Maximum shrinkage is seen for samples reinforced with Yellow Sand (Reference Mortar 2, 2.0%) with a shrinkage higher than the Reference Mortar 1 whereas the lowest shrinkage is seen for mortars reinforced with Fine Yellow Sand (Ka000601-221001, 1.1%).

The impact of the type of sand on shrinkage is important, as changing the sand type from medium size sand (Reference Mortar 2) to fine sand (Ka0006001-22101) can reduce the shrinkage by 45% and using coarse sand (Ka0007001-22101 or Ka000301-221001) also reduces the shrinkage by 22% to 30%. A similar behaviour has been presented by Lima et al. (2016) who tested sands with 3 different particle size distribution and by Stazi et al. (2015) who shows that using fine sand instead of medium sand lead to lower cracks. The impact of using washed sand – without fines – is not clear as some washed sand show a very low shrinkage (Washed Yellow Sand) but other have a similar shrinkage as non-washed sand. Using rounded sand also seems to reduce shrinkage.

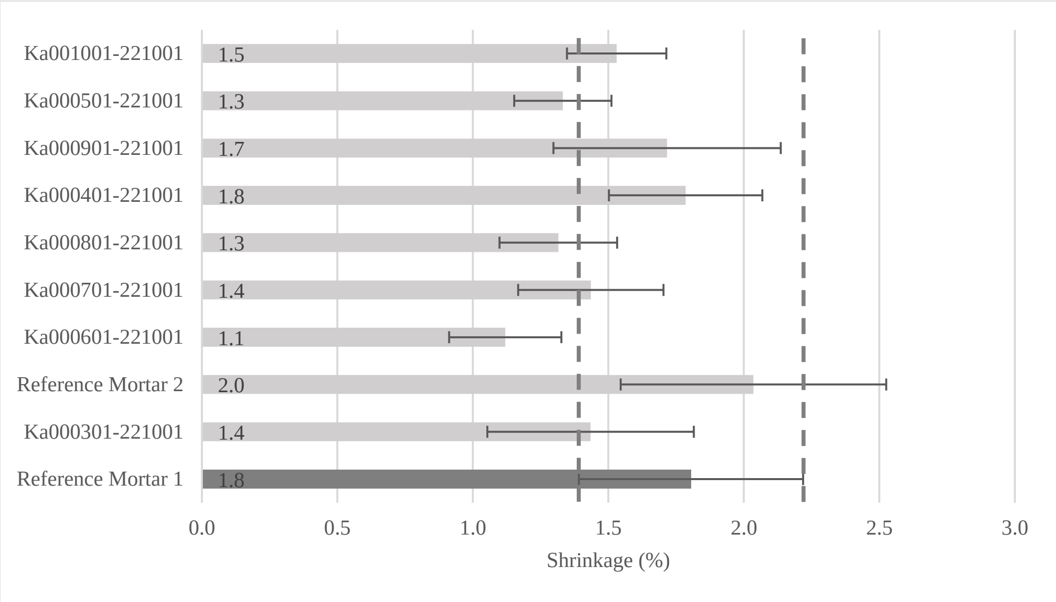

Figure 6-1: Shrinkage of mortars made with alternative sand

6.1.1.2 Density

The average density of mortars is presented in Figure 6-2 together with the average density of the Reference Mortar. The maximum density is 1696 kg/m³ for mortar reinforced with Washed White Sand (Ka000901-221001) and the minimum density is 1624 kg/m³ for mortar stabilized with Coarse Grey Sand (Ka000301-221001). All these densities are higher than the density of the Reference Mortar 1 (1571 kg/m³). It seems to be only a very little impact of the type of sand on the density as the difference in density between the highest density and the lowest density is only 8%. However, as the deviation is also low between the different specimens of the same mortar (standard deviation in Figure 6-2) it shows that this impact exists. It seems that using coarse and not graded sand (mortars Ka000301-221001, Ka000701-221001 or Ka001001-221001) leads to a higher density whereas using well-graded sands (Reference Mortar 1, Reference Mortar 2 and Ka000401-221001) leads to a lower density, probably because of a higher porosity due to a large amount of fine contained in the material – i.e. fines from the sand and the earthen material. These results are different from the ones of Lima et al. (2016) as the authors found a decrease in density while using fine or coarse sand. However, as the amount of sand used is higher and also no fibres were used, it might account for the difference.

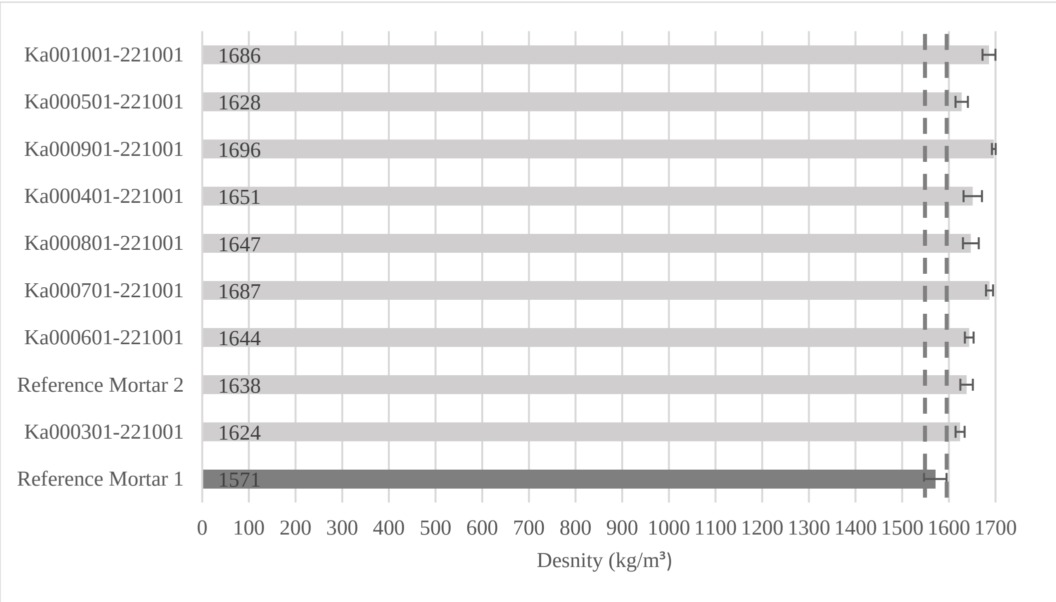

Figure 6-2: Density of mortars made with alternative sands

6.1.2 Mechanical properties of earth mortars reinforced with alternative sands

The mechanical strength of earth mortars made with alternative sands has been measured and is presented in Table 6-2. These results will be discussed in regard to the literature to assess the impact of using alternative sands on flexural and compressive strengths.

Table 6-2: Mechanical properties of earth mortars modified with alternative sands

Mortar Name	Sand type	Flexural strength (MPa)	*Standard dev.*	Difference with the Reference Mortar 1 (%)	Compressive Strength (MPa)	*Standard dev.*	Difference with the Reference Mortar 1 (%)
Reference Mortar 1	Grey Sand	0.77	0.12		1.34	0.12	
Reference Mortar 2	Yellow Sand	0.88	0.14	15.0	1.95	0.15	45.3
Ka000301-221001	Grey Sand<4.75mm	0.49	0.06	-36.3	0.79	0.06	-40.7
Ka000401-221001	White Sand	1.06	0.13	37.9	1.71	0.10	27.3
Ka000501-221001	Siliceous Sand	0.75	0.11	-2.9	1.13	0.05	-15.7
Ka000601-221001	Sand2 <0.875mm	1.17	0.05	51.6	1.86	0.14	38.5
Ka000701-221001	Sand2 <4.75mm	0.93	0.08	20.3	1.41	0.06	5.5
Ka000801-221001	Yellow Sand washed	0.89	0.07	15.8	1.40	0.10	4.8
Ka000901-221001	White Sand washed	0.90	0.13	17.6	1.80	0.10	34.3
Ka001001-221001	Coarse Siliceous Sand	0.52	0.11	-32.0	0.97	0.08	-27.8

6.1.2.1 Flexural strength

The flexural strengths of mortars made with alternative sands are presented in Table 6-2 together with the flexural strength of Reference Mortar 1.

The highest strength is achieved by the mortar reinforced with Fine Yellow Sand (Ka000601-221001; 1.17 MPa) and the lowest strength is achieved by mortars reinforced with Coarse Grey Sand (Ka000301-221001; 0.49 MPa). All mortars except the ones made with siliceous sand (Ka000501-221001, Ka001001-221001) and Coarse Grey Sand (Ka000301-221001) have a higher strength than the

Reference Mortar 1 and all mortars except the one made with Fine Yellow Sand (Ka000601-221001) and White Sand (Ka000401-221001) have lower strength than the Reference Mortar 2. Mortars with a low amount of added fines (washed sands or siliceous sands) have also a lower strength than other mortars.

The low flexural strength of mortars reinforced with coarse sand has also been shown by Lima and Faria (2016). The same authors also underline a lower strength for mortar reinforced with fine sands, however, in this study, it is not the case. The research of Lima & Faria (2016) and Santos et al. (2020) shows that using coarse or fine sand in large quantities (75%) leads to very low flexural strength and no or very little difference in strength between the different types of sands, whereas another mortar made with the same studied earth with a higher amount of fines has a higher strength.

The results of the literature and the fact that the mortars of this study made with sands with low amounts of fines have a smaller strength are explained by the weak bond between clay particles and sand, especially large sand particles (Anger, 2011). Moreover, large sand particles might also create larger pores, leading to the breaking of samples. This fact is also underlined by Santos et al. (2020).

6.1.2.2 Compressive strength

The average compressive strengths of mortars made with alternative sands are presented in Table 6-2 together with the compressive strength of Reference Mortar 1.

The highest strength was measured on samples made with Fine Yellow Sand (Ka000601-221001; 1.87 MPa) and the lowest for samples made with Coarse Grey Sand (Ka000301-221001; 0.79 MPa) similarly to the flexural strengths. Other mortars made with coarse sands (Ka000701-221001; Ka001001-221001) also display a low compressive strength or lower compressive strength than the one made with the same type of sand but using smaller particles. All mortars except the ones made with siliceous sand (Ka000501-221001, Ka001001-221001) and Coarse Grey Sand (Ka000301-221001) have a higher strength than the Reference Mortar 1 and all have a lower strength than the Reference Mortar 2.

The adverse impact of using coarse sands compared to medium or fine sand is confirmed by Lima and Faria (2016) and Santos et al. (Santos, Faria, et al., 2020). Using sands without any fines or a low amount of fines or on contrary, a too large amount of fines also decreases the compressive strength as can be seen in the case of mortars made with Washed Yellow Sand (Ka000801-221001) which have lower strength than Reference Mortar 2 (same sand but not washed) or while comparing the strength of mortar made with White Sand (Ka000401-221001) which includes a very large amount of fines and Washed White Sand (Ka000901-221001) which has a lower amount of fine but a higher compressive strength.

Another parameter that impacts the strength is the angularity of the particles (Table 4-3). Samples made with round shape particles (Ka000501-221001, Ka001001-221001) or low angularity particles (Reference Mortar 1) have lower strengths than the ones made with angular particles. This behaviour is the same that is found with cement mortars (Quiroga & Fowler, 2004) and the reason why the usage of sharp sand has been recommended for making earth mortars (Henderson, 2013; Weismann & Bryce, 2008) and this behaviour has been discussed in detail in Pedergnana & Ozkan (2021)

6.1.2.3 Correlation between strength and density of earth mortars reinforced with alternative sands

The results of the study on the addition of sand to mechanical strength show a weak but existing correlation between density and strength and between flexural strength and compressive strength (section 5.2.2.3). The same phenomenon has been studied for alternative sands and it results that the correlation exists between flexural strength and compressive strength but doesn’t exist between strength and density.

Except for mortars made with Yellow Sand, which have low flexural strength or high compressive strength compared to their density, a high flexural strength leads to high compressive strength. However, this property is not related to the density of the mortar as the density of all mortar tested are close – i.e. less than 10% difference – and the highest and lowest strength – respectively mortar Ka000601-221001 with a density of 1644 kg/m³ and mortar Ka000301-221001 with a density of 1624 kg/m³ are found for mortar with a density close to the average (1647 kg/m³). These results clearly show that using a different type of sand, especially sands with angular particles increases the strength of the mortar and its cohesion.

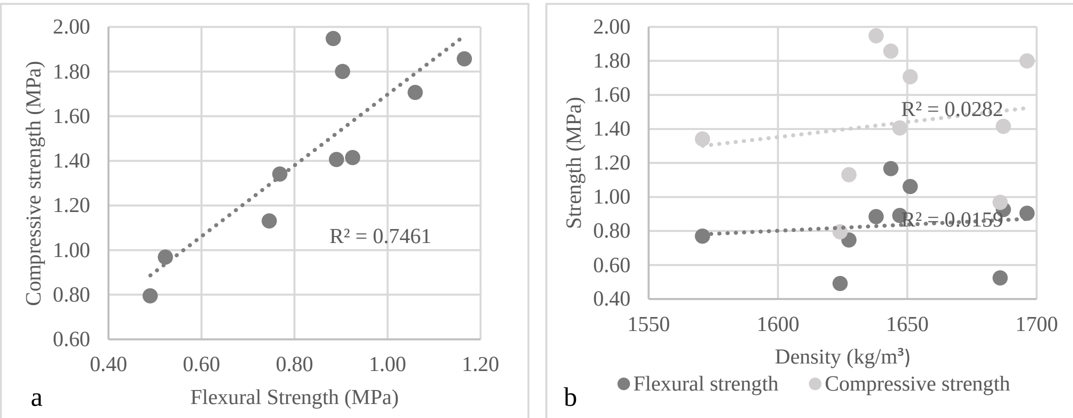

Figure 6-3: Relation between flexural strength, compressive strength and density of earth mortars modified with alternative sands

a- Relation between flexural strength and compressive strength of earth mortars modified with alternative sands

b- Relation between strength and density of earth mortars modified with alternative sands

6.1.3 Surface properties of earth mortars reinforced with alternative sands

The average surface properties of earth mortars reinforced with 20% Chaff and 40% alternative sands are presented in Table 6-3, together with the properties of

Reference Mortar 1. Their properties and the impact of the type of sand are discussed in the following paragraphs.

Table 6-3: Surface properties of earth mortars reinforced with 20% Chaff and 40% of alternative sands

Mortar Name	Sand type	Surface water absorption (g/m²·s) for 90 s.	*Standard dev.*	Difference with the Reference Mortar 1 (%)	Peeling test Material loss (µg/cm²)	*Standard dev.*	Difference with the Reference Mortar 1 (%)
Reference Mortar 1	**Grey Sand**	**26.2**	**3.5**		**2214**	**1260**	
Reference Mortar 2	Yellow Sand	17.3	2.4	-34	1192		-46
Ka000301-221001	Grey Sand<4.75mm	22.3		-15	2250	833	2
Ka000401-221001	White Sand	16.3		-38	1483	470	-33
Ka000501-221001	Siliceous Sand	27.2		4	1850	605	-16
Ka000601-221001	Sand2 <0.875mm	18.4		-30	2778	1622	25
Ka000701-221001	Sand2 <4.75mm	15.8		-39	1667	113	-25
Ka000801-221001	Yellow Sand washed	19.0		-28	3741	2166	69
Ka000901-221001	WS washed	18.8		-28	1750	556	-21
Ka001001-221001	Coarse Siliceous Sand	22.3		-15	620	261	-72

6.1.3.1 Surface water absorption

The surface water absorption has been tested on only one sample for each mortar. The results are presented in Table 6-3 and Figure 6-4.

The minimum water absorption is seen for mortar Ka000701-221001 (15.8 $g/m^2 \cdot s$) whereas the largest is seen for mortar Ka000501-221001 (27.2 $g/m^2 \cdot s$). Despite all mortars having the same amount of sand and fibre, their water absorption is very different and is related to the type of sand. Sands with a low amount of fine (washed sands and siliceous sands, i.e mortars Ka000501, Ka000801. Ka000901, Ka001001) have some of the largest water absorption or larger water absorption than the same unwashed sand – e.g. 16.3 g/m²·s for White Sand (Ka000401) and 18.8 for Washed White Sand (Ka000901) – which would be explained by the probably higher porosity of these mortars as the amount of fine is not sufficient to fill all pores. On the other hand, sands with a more graded particle size distribution – i.e including large and fine particles such as mortars with particle sizes larger than 2mm (Ka000301 or Ka000701) or different sizes of particle instead only one (Ka001001) have lower water absorption probably because of the lower porosity and compacity of these samples. However, all these results need to be better looked up as only one specimen of each mortar has been tested.

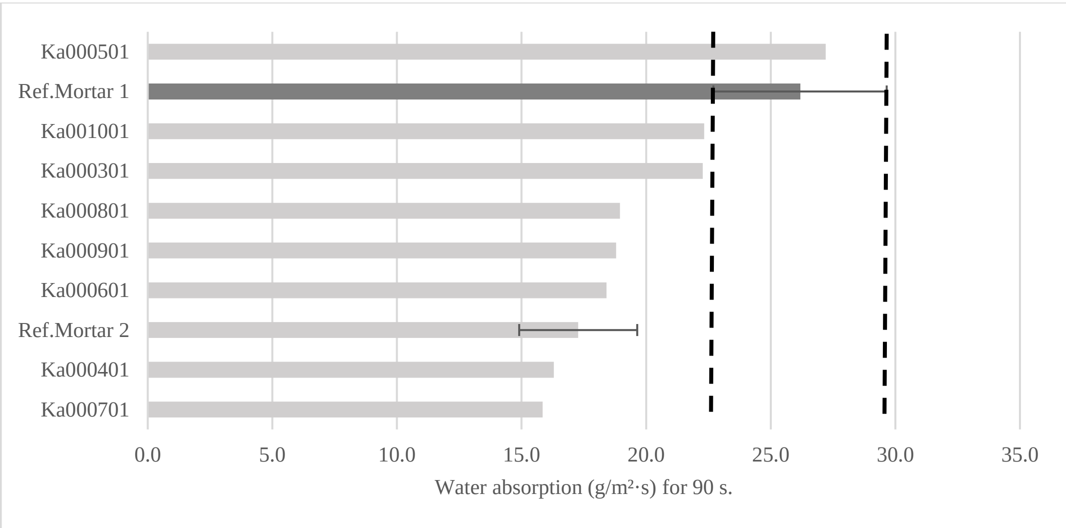

Figure 6-4: Impact of alternative sands on the results of the surface water absorption test for earth mortars reinforced with 20% of Chaff and 40% of sand.

6.1.3.2 Surface cohesion

The surface cohesion has been tested on three specimens for each mortar through the peeling test. The results are presented in Table 6-3 and Figure 6-5.

The material detached through the peeling test varies from 620 µg/cm² (Ka001001-221001) to 3741 µg/cm² (Ka000801-221001) but a very large dispersion of the results can be observed with for example results varying from 1194 µg/cm² to 6722 µg/cm² for the mortar Ka000801-221001 reinforced with washed Yellow Sand.

As can be observed in Figure 6-5 where the standard deviation of each mortar has been plotted together with the average result of the test, this large variety of results means that despite the average value being very different, the range of values for the surface cohesion is similar for all mortars and it is difficult to draw any conclusion on the impact of any material except the usage of Coarse Silicate Sand (Ka001001-221001) which seems to increase the surface cohesion and the Washed Yellow Sand which reduces the cohesion.

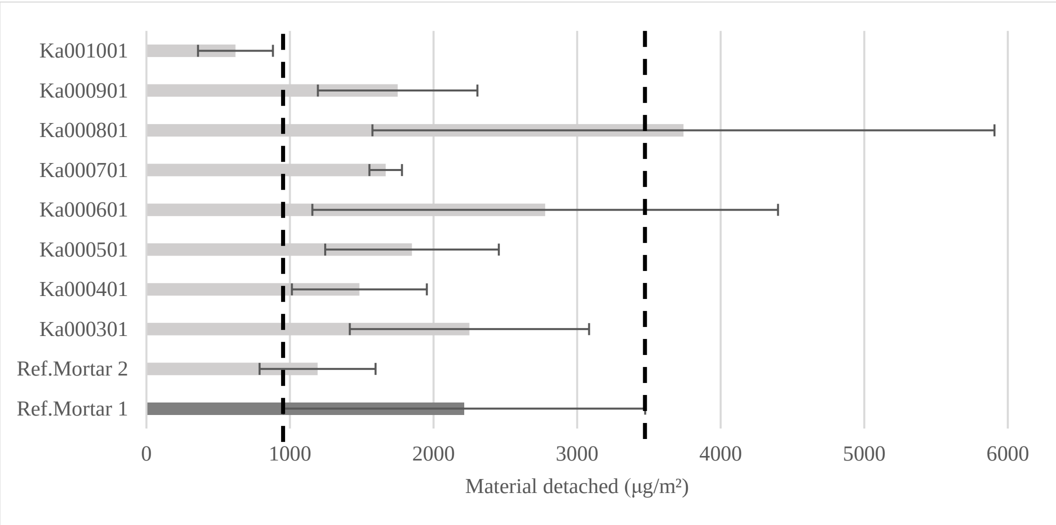

Figure 6-5: Impact of alternative sands on the results of the peeling test for earth mortars reinforced with 20% of Chaff and 40% of sand.

6.1.4 Durability properties of earth mortars reinforced with alternative sands

The durability properties of earth mortars reinforced with alternative sands are presented in Table 6-4 and Table 6-5. The impact of the alternative sands on the humid mechanical strength, the water resistance, the abrasion resistance and the erosion resistance is discussed in the following paragraphs.

6.1.4.1 Humid mechanical strength

The humid flexural strength is presented in Table 6-4. The humid flexural strength varies from 0.25 MPa (Ka000501-221001; 66% loss of strength; 2.2% of humidity) to 0.52 MPa (Ka000601-221001, 56% loss of strength, 1.0% of humidity) and the compressive strength varies from 0.41 MPa (Ka000301-221001, 49% loss of strength, 0.5% of humidity) to 1.18 MPa for the mortar Ka000601-221001. The absorption of water varies between 0.5% (Ka000301-221001) and 2.2% (Ka000501-221001) and the loss of strength varies between 21% and 66%, however, not directly related to the humidity amount.

Figure 6-6 shows the strength of mortars and the loss of strength. All mortars, except Reference Mortar 2 and Ka000601-221001 have a humid flexural strength similar to the one of the Reference Mortar 1 (0.36 MPa +/- 0.1 MPa) whereas the humid compressive strengths are much more diverse which shows that the humidity has a larger impact on the flexural strength as it weakens the bond between the clay particles as seen previously. Moreover, except for Ka000501-221001 which has a very low compressive strength, the loss of compressive strength is related to the dry compressive strength and therefore, mortars with high dry compressive strength retain high humid compressive strength independently of the humidity amount. The same is not true for flexural strength, which confirms the high impact of the humidity on the flexural strength and the lowest importance of the sand type for retaining the humid strength. In conclusion, the type of sand has no impact on the humid mechanical resistance of earth mortars as all mortars are behaving similarly.

Table 6-4: Humid mechanical strength of earth mortars modified with alternative sands

		Humidity level (weight increase in %)	Humid flexural strength (MPa)	*Standard deviation*	Loss in strength (weight increase in %)	Humid compressive strength (MPa)	*Standard deviation*	Loss in strength (%)
Reference Mortar 1	Grey Sand	0.6-1.5	0.36	*0.10*	-53	0.76	*0.22*	-43
Reference Mortar 2	Yellow Sand	0.9	0.61	*0.19*	-24	1.18	*0.33*	-37
Ka000301-221001	Grey Sand <4.75mm	0.5	0.32	*0.04*	-35	0.41	*0.02*	-49
Ka000401-221001	White Sand	1.3	0.48	*0.03*	-55	0.97	*0.15*	-43
Ka000501-221001	Siliceous Sand	2.2	0.25	*0.05*	-66	0.50	*0.11*	-56
Ka000601-221001	Yellow Sand <0.875mm	1.0	0.52	*0.04*	-56	1.18	*0.04*	-36
Ka000701-221001	Yellow Sand <4.75mm	0.8	0.36	*0.02*	-61	0.92	*0.1*	-35
Ka000801-221001	Yellow Sand washed	0.8	0.39	*0.00*	-56	0.89	*0.06*	-36
Ka000901-221001	WS washed	1.0	0.39	*0.10*	-56	1.04	*0.06*	-42
Ka001001-221001	Coarse Siliceous Sand	0.7	0.41	*0.01*	-21	0.77	*0.09*	-21

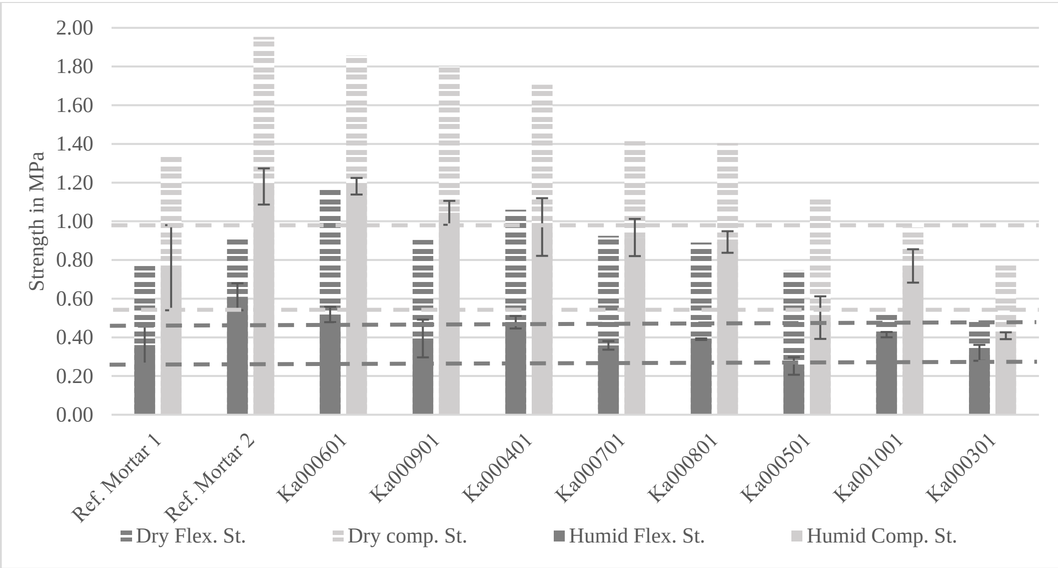

Figure 6-6: Comparison of dry and humid mechanical strength of earth mortars reinforced with alternative sands. Mortars are ordered according to their dry strength

6.1.4.2 Resistance to immersion

The immersion resistance is given in Table 6-5 as the time in minute before the immersed part of the specimen is detached. The resistance varies between 2 min (Ka000501-221001) and 40 min (Ka000601-221001), however, except mortar Ka000601-221001 and Reference Mortar 2, all resistances are lower than the resistance of Reference Mortar 1 and no mortars would be suitable for earth construction according to the Turkish Standards (TS 2514, 1977). However, when the impact of the type of sand is compared, it can be understood that sands without fine have a low resistance whereas fine graded sands have a longer resistance. Usage of coarse sand also reduces the resistance.

6.1.4.3 Resistance to abrasion

The abrasion resistance is given in Table 6-5 for both the German and French testing methods. The loss of material for samples tested according to DIN 18947 varies from

2.6g (Ref. Mortar 2) to 9.9 g (Ka000501-221001) whereas the abrasion coefficient (Regles Pro) varies from 0.5 cm²/g (Ka000501-221001) to 1.5 cm²/g (Ka000901-221001) with Reference Mortar 2 having a very close value. Figure 6-7, presents the mortars' resistance classified by order of resistance. Except for mortar Ka000501-221001 (siliceous sand), all mortars have a higher resistance than Reference Mortar 1. However, from this classification, it is difficult to understand the impact of the alternative sands on the abrasion resistance, however, it seems that more rounded sand will have less resistance (Ka000501-221001, Reference Mortar 1 and Ka000301-221001) whereas well-graded sand and more angular sand will have better resistance, probably because a higher difficulty to separate the sand particles due to their interlocking shapes.

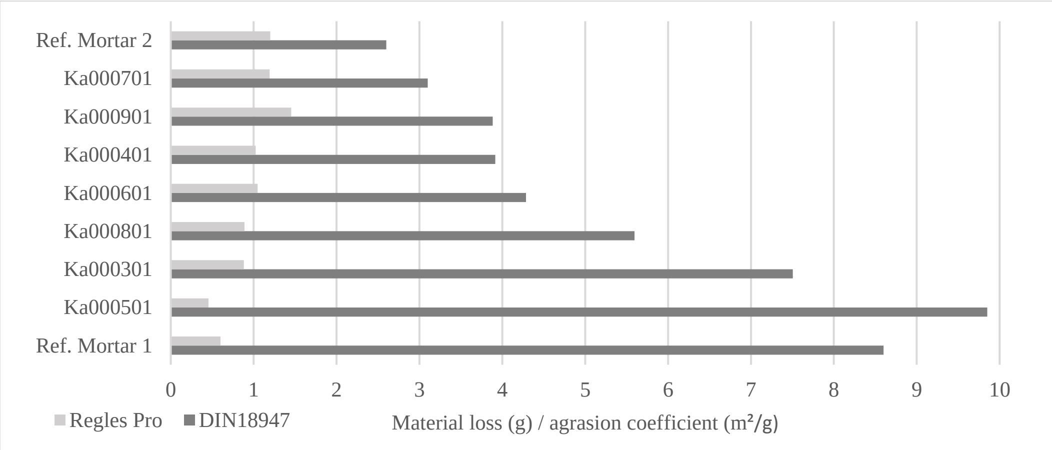

Figure 6-7: Resistance to abrasion of earth mortars reinforced with alternative sands

6.1.4.4 Resistance to erosion

The erosion resistance is given in Table 6-5 as the diameter and depth of the hole made by the dripping of water on the mortar.

The smaller hole – therefore the highest resistance – is measured on mortars reinforced with Coarse Grey Sand (Ka000301-221001, 5mm) whereas the largest hole is measured on mortar Ka000901-221001 (White Sand, 8.5 mm). All tested mortars have a higher resistance than Reference Mortar 1 (8 mm +/- 1.5 mm) except Ka000901-221001, however, the difference is not large except for mortar Ka000301-221001. Moreover, not all mortars have been tested for erosion resistance as the number of specimens was not sufficient and therefore it is difficult to conclude on the impact of sand on the resistance to erosion of earth mortars. However, Stazi et al. (2015) tested two types of different sands with the same mortar composition and similarly found a slightly better resistance of mortars made with fine sand.

Table 6-5: Other durability properties of earth mortars modified with alternative sands

Mortar name	Resistance to immersion (min)	Difference with the Reference Mortar 1 (%)	Abrasion resistance (DIN18947) Material loss (g)	Difference with the Reference Mortar 1 (%)	Abrasion resistance (French rules) Abrasion Coefficient (cm^2/g)	Difference with the Reference Mortar 1 (%)	Abrasion resistance (French rules) Depression depth (cm)	Erosion resistance Hole depth (mm)	Difference with the Reference Mortar 1 (%)	Erosion resistance Hole diameter (mm)
Reference Mortar 1	**13**		**8.6**		**0.6**		**10**	**8**		**22**
Reference Mortar 2	24	100	2.6	-70	1.2	100	5	6	-26	25
Ka000301-221001			4.6	-13	1.0	47	5	5	-38	28
Ka000401-221001	8	-38	3.9	-54	1.0	71	5	7.5	-8	27
Ka000501-221001	2	-85	9.9	15	0.5	-24	10.5	7.5	-8	19
Ka000601-221001	40	200	4.3	-50	1.0	74	6	5.5	-32	22
Ka000701-221001	11	-15	3.1	-64	1.2	99	3.75	6.5	-20	25
Ka000801-221001	9	-31	5.6	-35	0.9	48	5			
Ka000901-221001	7	-46	3.9	-55	1.5	142	4	8.5	+4	30
Ka001001-221001										

6.1.5 Hydric properties of earth mortars reinforced with alternative sands

The hydric properties of earth mortars reinforced with alternative sands are presented in Table 6-6 and Figure 6-8 to Figure 6-12. The impact of alternative sands on the capillarity water absorption and the drying behaviour of mortars is discussed in the following paragraphs.

Table 6-6: Hydric properties of earth mortars reinforced with alternative sands

		Capillarity coefficient ($kg/m^2/min^{0.5}$)	*R^2 (-)*	Drying rate (1st phase) ($kg/m^2/h$)	*R^2 (-)*	Drying rate (2nd phase) ($kg/m^2/h^{0.5}$)	*R^2 (-)*	*Drying Index (-)*
Reference Mortar 1	**Grey Sand**	**1.06**	***0.11****	**0.13**	***0.02****	**1.12**	***0.11****	**0.26**
Reference Mortar 2	Yellow Sand	0.94	*0.07**	0.11	*0.02**	1.20	*0.08**	0.24
Ka000301-221001	Grey Sand<4.75mm	1.11	*0.99*	0.11	*1.00*	1.07	*0.99*	0.27
Ka000401-221001	White Sand	0.91	*1.00*	0.10	*1.00*	0.99	*0.99*	0.28
Ka000501-221001	Siliceous Sand	1.08	*0.99*	0.10	*1.00*	1.03	*0.99*	0.27
Ka000601-221001	Sand2 <0.875mm	0.90	*1.00*	0.12	*1.00*	1.13	*0.99*	0.26
Ka000701-221001	Sand2 <4.75mm	0.92	*0.99*	0.16	*1.00*	1.07	*0.99*	0.23
Ka000801-221001	Yellow Sand washed	0.90	*1.00*	0.15	*1.00*	1.10	*1.00*	0.24
Ka000901-221001	WS washed	0.90	*1.00*	0.12	*0.99*	1.03	*1.00*	0.24

Values followed with a star for reference mortars indicate a standard deviation value

6.1.5.1 Capillarity water absorption

The capillarity coefficient of mortars varies from 0.90 $kg/(m^2 \cdot min^{0.5})$ for mortars Ka000901-221001, Ka000801-221001 and Ka000601-221001 and 1.11 $kg/(m^2 \cdot min^{0.5})$ for mortar Ka000301-221001. The Reference Mortar 1 has a capillarity absorption of 1.06 +/- 0.11 $kg/(m^2 \cdot min^{0.5})$ therefore, most mortars except Ka000301-221001 and Ka000501-221001 have a lower capillarity coefficient. This result shows that the type of sand has an impact on the absorption rate since all mortars based on Yellow Sand have a similar rate - 0.90 $kg/(m^2 \cdot min^{0.5})$ to 0.94 $kg/(m^2 \cdot min^{0.5})$ – whereas mortars based on Grey Sand or White Sand have a different absorption rate based independently on their particle size distribution and type of particle (Figure 6-8 and Figure 6-9). This behaviour conforms to the work of Lima & Faria (2017) who found similar capillarity absorption by using 3 different particle size distributions of the same sand.

Opposingly, when the saturation of specimens is observed for mortars with similar sand (Figure 6-9), it can be observed that sand with a higher amount of fine (i.e. fine sand (Ka000601-221001) or non-washed sand (Reference Mortar 2 and Ka000701-221001) absorb a higher amount of water and fine sands absorb more water than coarse sands. Again these results are conformed to the one found by Lima & Faria (2017) and similar to the results of section 5.2.5 which shows that the total amount of water absorbed depends on the amount of clay and fine particles in the mortar.

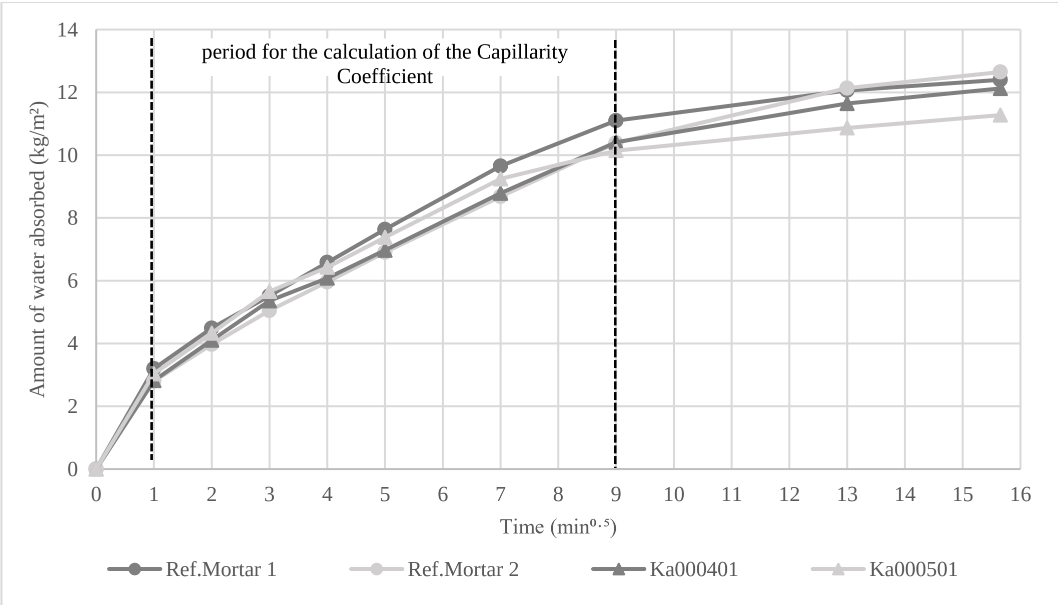

Figure 6-8: Water adsorption behaviour of selected earth mortars made with different types of sands. The period indicated for the calculation of the Capillarity Coefficient might vary according to mortars.

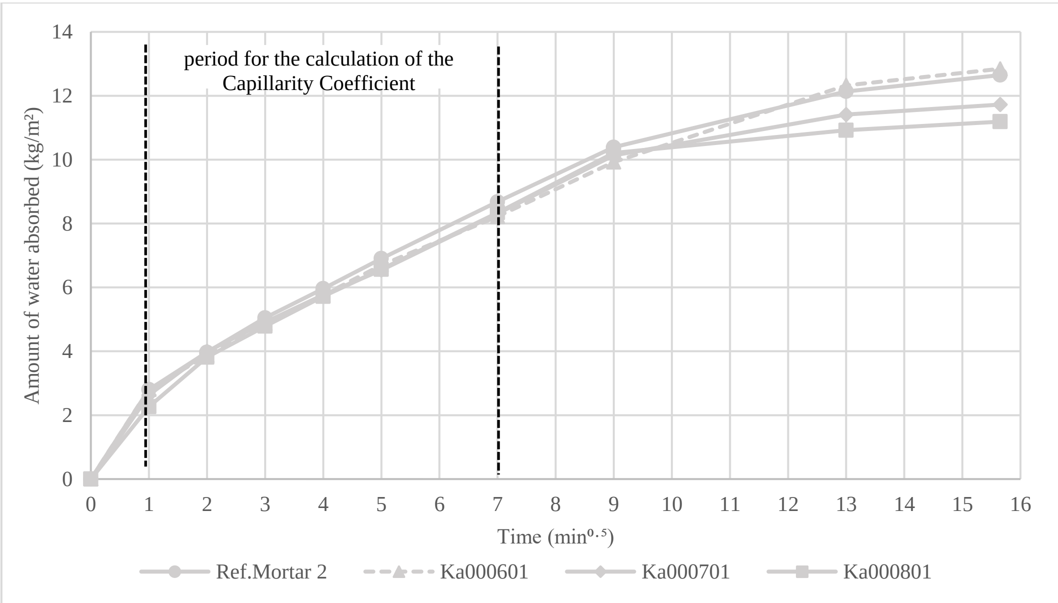

Figure 6-9: Water adsorption behaviour of earth mortars made with different particle size distributions of Yellow Sand. The period indicated for the calculation of the Capillarity Coefficient might vary according to mortars.

6.1.5.2 Drying behaviour

The drying behaviour of mortars is described in Table 6-6 and shown in Figure 6-10 to Figure 6-12.

The primary drying rate of mortars reinforced with alternative sands varies from 0.10 $kg/m^2 \cdot h^{-1}$ (Ka000401-221001 and Ka000501-221001) to 0.16 $kg/m^2 \cdot h^{-1}$ (Ka000701-221001) which is similar to the Reference Mortar 1 (0.11 +/- 0.02 $kg/m^2 \cdot h^{-1}$) whereas the secondary drying rate varies from 0.99 $kg/m^2 \cdot h^{0.5}$(Ka000401-221001) to 1.13 $kg/m^2 \cdot h^{0.5}$ (Ka000601-221001) slightly lower than the Reference Mortar 1 (1.12 +/- 0.11 $kg/m^2 \cdot h^{0.5}$). However, as can be observed in Figure 6-10, the general behaviour of all mortars is similar – all drying indexes after 300h are low and similar – and complete drying is achieved after 16 days (384 h). Therefore it seems that the type of sand and the particle size distribution has only a minor impact on the total drying behaviour. The type of sand only impacts initial drying and the first loss of water is more pronounced for Reference Mortars 1 and 2 while mortars Ka000401-221001 and Ka000501-221001 have a lower primary loss. Similar behaviour can be seen for mortars with fine sands (Ka000601-221001) which seems to have a slightly faster drying rate (Figure 6-12) if compare with other mortars made with the same sand (Reference Mortar 2, Ka000801-221001 and Ka000701-221001), but the difference is not as pronounced when compared to the work of Lima and Faria (2017).

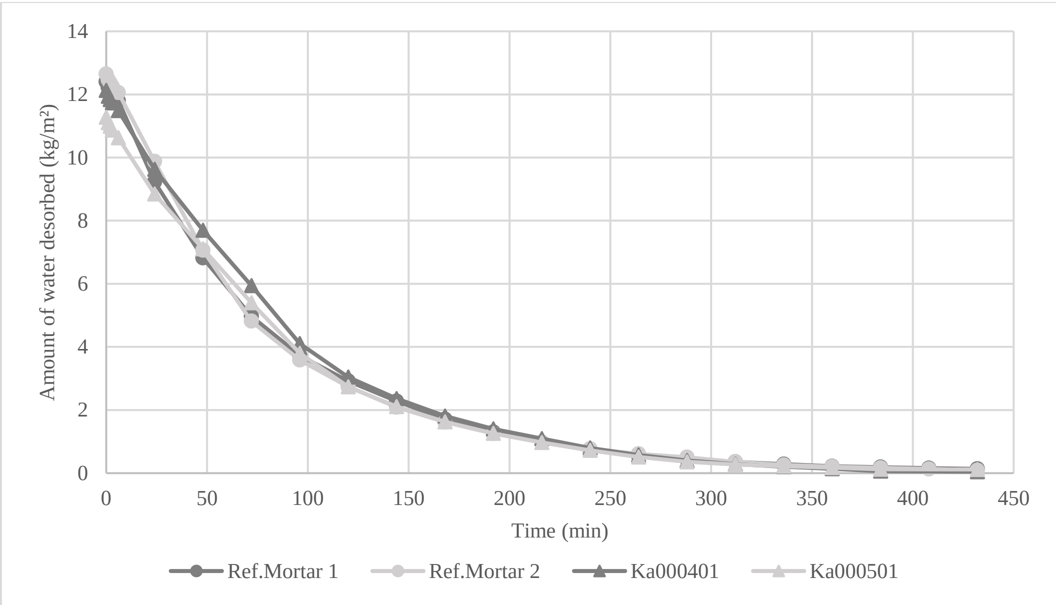

Figure 6-10: Drying behaviour of earth mortars produced with different types of sand (Grey Sand, Yellow Sand, White Sand, Siliceous Sand)

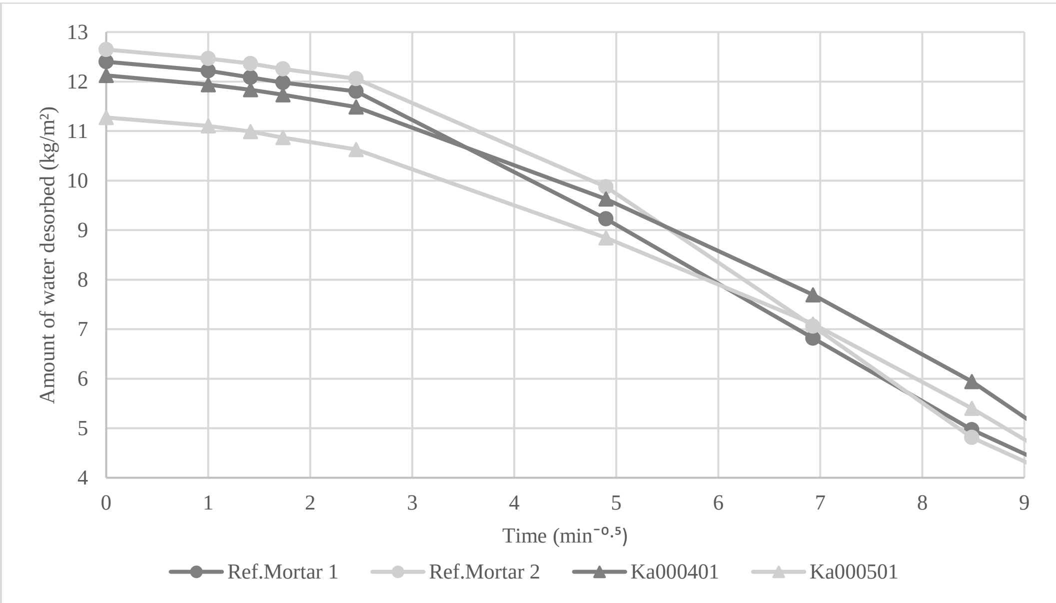

Figure 6-11: Close up on the primary drying behaviour of earth mortars produced with different types of sand (Grey Sand, Yellow Sand, White Sand, Siliceous Sand)

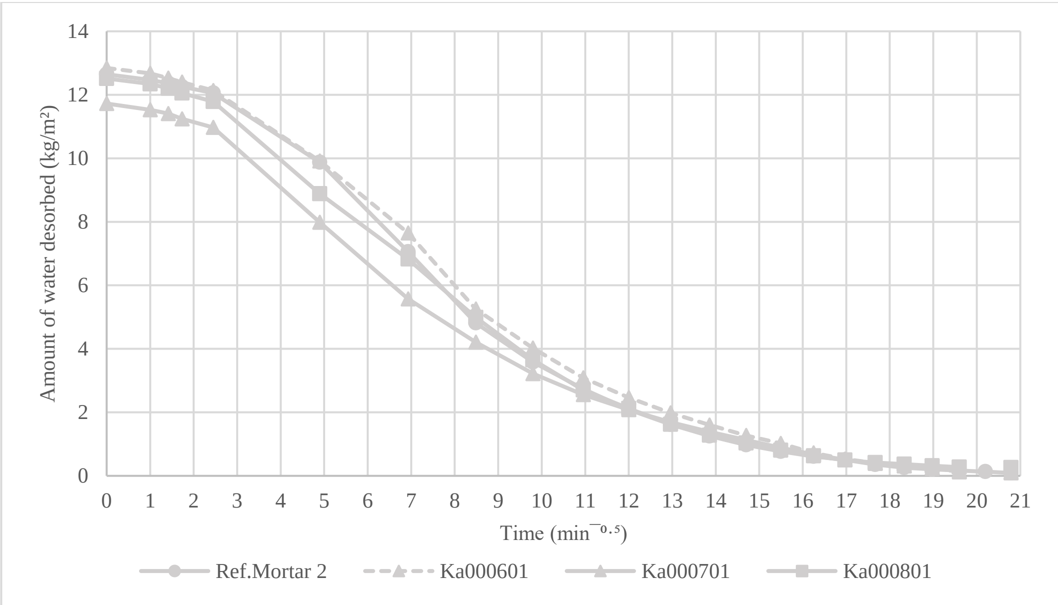

Figure 6-12: Drying behaviour of mortars made with different particle size distribution.

6.1.6 Hygric properties of earth mortars reinforced with alternative sands

The hygric properties of earth mortars reinforced with alternative sands are presented in Table 6-7 and Figure 6-13 to Figure 6-15. The water vapour permeability, the dynamic water vapour desorption and the dynamic water vapour desorption are discussed in the following paragraphs.

6.1.6.1 Water vapour permeability

The water vapour diffusion resistance factor (μ-value) of the tested mortars is comprised between 3.8 (Ka000801-221001) and 5.9 (Ka001001-221001) which is similar to the resistance factor of the Reference Mortar 1 (4.1 +/- 0.35) except for the μ-value of Ka0040101-221001 and Ka001001-221001 which are much higher. However, the reasons for the variation of the resistance factor are not clear as they are not linked to the amount of fines and the internal porosity of mortars. Similar inexplicable variations of the water vapour permeability have been found by other authors (Cagnon et al., 2014; Faria & Santos, 2014) working on materials with different types and or amounts of sand. These variations might also result from non-fully reproducible test conditions for example all μ-value of the mortars tested in the same batch with Ka001001-221001 are higher than expected.

Table 6-7: Hygric properties of earth mortars reinforced with alternative sands

	Type of sand	Water vapour diffusion resistance factor (-)	Equivalent air layer (m)	Water vapour adsorption (12h - g/m²)	Primary adsorption rate - first 3h (g/m²h)	Water vapour desorption (12h - g/m²)	Primary desorption rate - first 3h (g/m²h)	Secondary desorption rate - 12h-48h (g/m²h)
Reference Mortar 1	Grey Sand	4.1	0.16	149	14.5	101	13.8	3.4
Reference Mortar 2.	Yellow Sand	4.1	0.16	145	14.5	84	11.1	2.9
Ka000301-221001	Grey Sand <4.75mm	3.9	0.15	133	14.7	74	10.4	2.4
Ka000401-221001	White Sand	5.6	0.21	137	12.8	75	10.2	2.2
Ka000501-221001	Siliceous Sand	4.5	0.18	133	13.1	74	10.9	2.2
Ka000601-221001	Yellow Sand <0.875mm	3.9	0.15	151	15.8	86	11.8	2.8
Ka000701-221001	Yellow Sand <4.75mm	4.3	0.17	142	14.9	85	12.1	2.8
Ka000801-221001	Yellow Sand washed	3.8	0.15	145	13.8	79	10.8	2.3
Ka000901-221001	WS washed	3.9	0.15	140	14.4	81	11.5	2.6
Ka001001-221001	Coarse Siliceous Sand	5.9	0.24	138	14.2	84	11.8	2.5

6.1.6.2 Dynamic water vapour adsorption behaviour

The dynamic water vapour adsorption is characterized in Table 6-7 by the amount of vapour absorbed after 12 h and the adsorption rate. The behaviour of the earth mortars is also presented in Figure 6-13 together with the different absorption classes of the DIN18947.

The amount of water vapour absorbed varies between 133 g/m² and 151g/m², which is slightly lower than the absorption of the Reference Mortar 1 (149 +/-7 g/m²) with all mortars having a similar adsorption rate until 12h in the humid environment. After 12h, it can be seen in Figure 6-13 that some mortars have a lower absorption as they start to be saturated faster (Ka000401-221001 and Ka000501-221001) but for most, the behaviour is very similar, especially for sands of the same type (Figure 6-14). Therefore, as for water adsorption, it can be assumed that the type of sand is more important than the PSD.

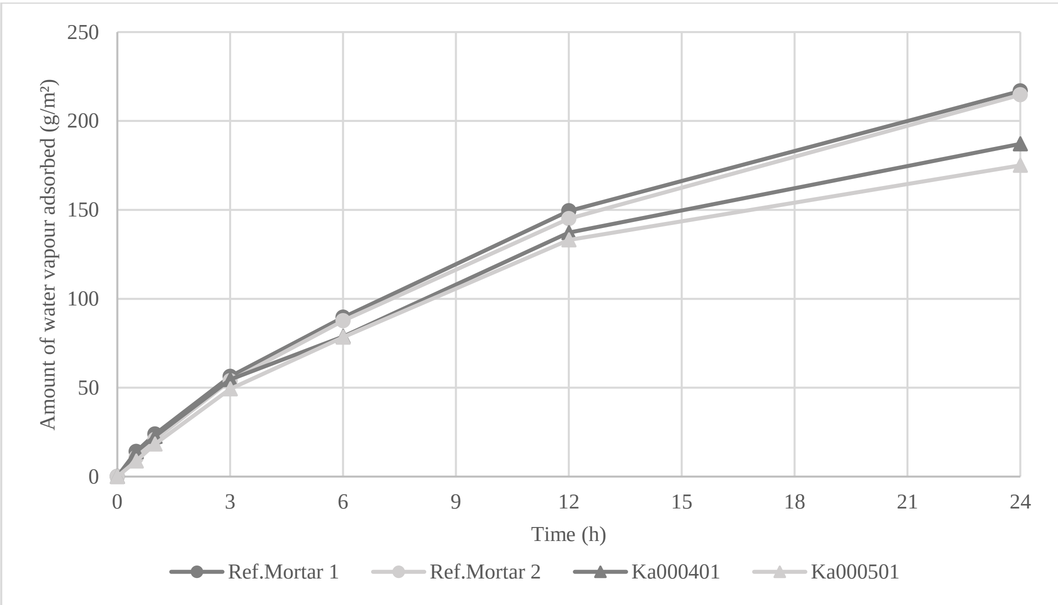

Figure 6-13: Dynamic water vapour adsorption behaviour of selected earth mortars reinforced with alternative sands.

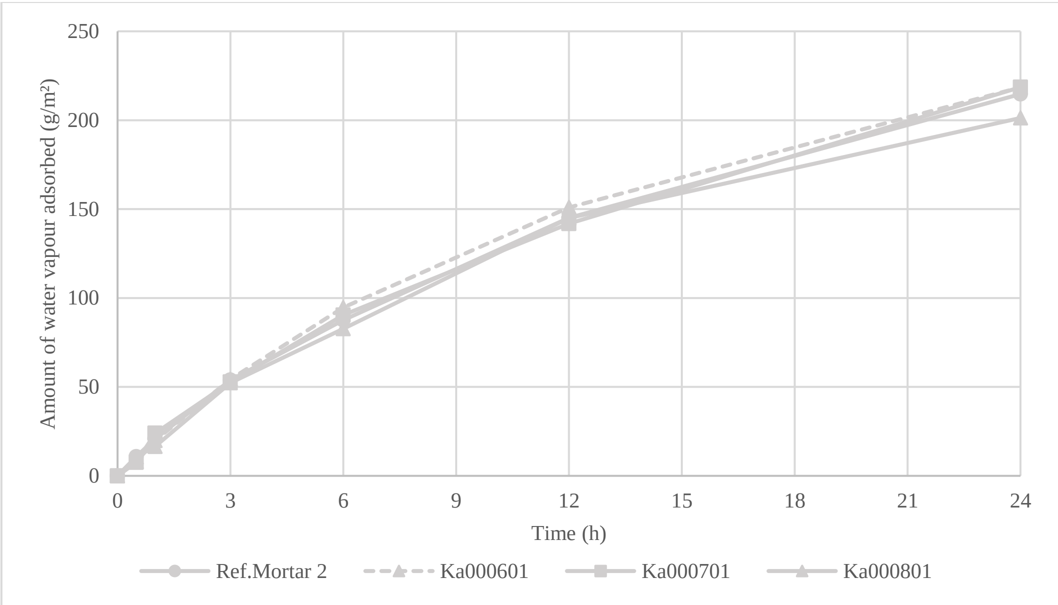

Figure 6-14: Dynamic water vapour adsorption behaviour of earth mortars made with different particle size distributions of Yellow Sand.

6.1.6.3 Dynamic water vapour desorption behaviour

The dynamic water vapour desorption is characterized in Table 6-7 by the amount of vapour released after 12 h and the desorption rate. The behaviour of the earth mortars is also presented in Figure 6-15.

The amount of water vapour desorbed at 12h varies between 74 g/m² (Ka000301-221001) and 86 g/m² (Ka000601-221001) which is much less than the Reference Mortar 1 (101 +/- 8 g/m²) and less than the amount adsorbed after 12h. The difference between the modified mortars and the Reference Mortar 1 might come from the fact that the modified mortars were exposed to less humidity – due to a problem during the experiment – and therefore the total amount of vapour adsorbed at the end of the test is lower. However, if instead of being compared with Reference Mortar 1, the desorption is compared with Reference Mortar 2 – which has very similar adsorption to Reference Mortar 1 – it can be seen in Figure 6-15 that using different sands impact slightly on the desorption after 24 h (20g/m² less vapour desorbed) but not enough to create a difference. As for the adsorption and the permeability and as also explained by Faria & Santos (2014), no important impact of the type of sand is noticeable.

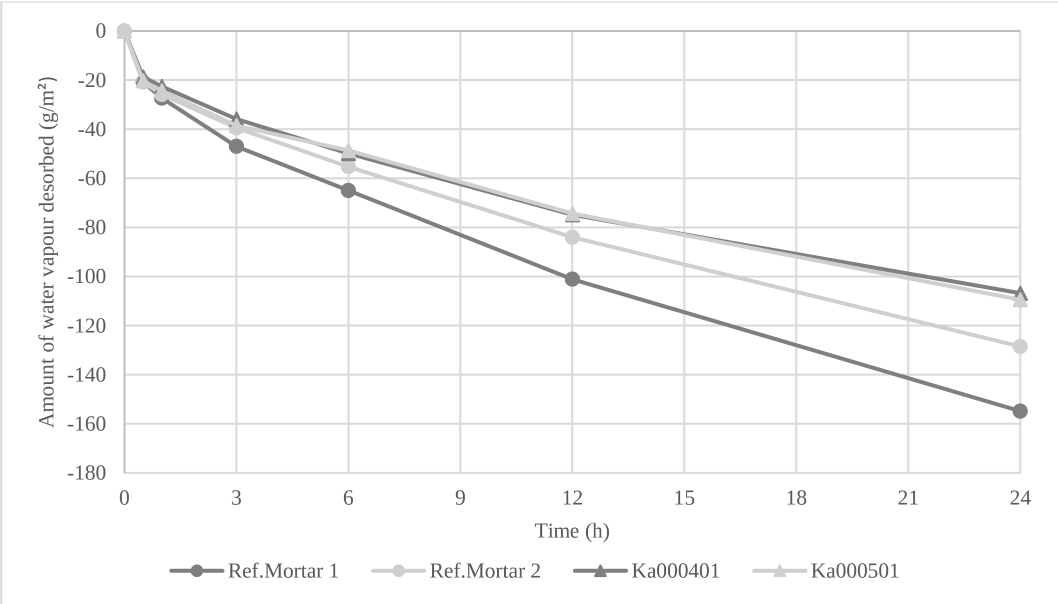

Figure 6-15: Dynamic water vapour desorption behaviour of selected earth mortars reinforced with alternative sands.

6.2 Impact of alternative fibres on the properties of earth mortars

In this section, the impact of alternative fibres on the different properties of earth mortars will be presented and the results explained. In this section, results are compared either with Reference Mortar 1 (made with Grey Sand) or Reference Mortar 2 (made with Yellow Sand) as some of the mortar have been prepared with Grey Sand (Ka000102-221001 to Ka000104-221001) and some of them have been prepared with Yellow Sand (Ka000205-221001 to Ka000212-221001). The properties of Reference Mortar 1 and Reference Mortar 2 differ largely, especially in terms of physical and mechanical properties and the results of the different experiments have been explained in section in section 5.4 and section 5.5 and APPENDIX C.

6.2.1 Physical properties of earth mortar reinforced with alternative fibres

This section presents the impacts of the replacement of Chaff with alternative fibres on the physical properties of earth mortars. The shrinkage and density of the mortars will be determined and the changes analysed in regard to the literature to determine the impact of the different types of fibres.

Table 6-8: Physical properties of earth mortars modified with alternative fibres

Mortar Name	Sand type	Shrinkage (%)	*Standard dev.*	Difference with the Reference Mortar (%)	Average dry density (kg/m³)	*Standard dev.*	Difference with the Reference Mortar (%)
Reference Mortar 1	**Chaff**	**1.8**	**0.4**		**1571**	**24**	
Ka000102-221001	48h Saturated fibres	1.7	0.3	3	1587	11	-1
Ka000103-221001	2m Saturated fibres	2.0	0.3	-13	1602	10	-2
Ka000104-221001	Plastic fibres	0.4	0.8	79	1650	14	-5
Reference Mortar 2	**Chaff**	**2.0**	**0.5**		**1638**	**13**	
Ka000205-221001	Pine needles	1.9	0.2	5	1618	4.0	1
Ka000206-221001	Flax fibres	2.6	0.4	-26	1816	11	-11
Ka000207-221001	Cow hair	0.9	0.3	55	1721	6	-5
Ka000208-221001	Long sheep wool	2.1	0.2	-4	1785	17	-9
Ka000209-221001	Short sheep wool	2.2	0.2	-7	1765	9	-8
Ka000210-221001	Washed straw	1.6	0.5	21	1691	9	-3
Ka000211-221001	Long straw	1.7	0.3	17	1746	8	-7
Ka000212-221001	Short washed straw	1.6	0.3	22	1693	10	-3

6.2.1.1 Shrinkage

The shrinkage of earth mortars prepared with alternative fibres is presented in Table 6-8 and Figure 6-17.

The highest shrinkage is measured on samples made with Flax fibres (Ka000206-221001; 2.6%) whereas the lowest shrinkage occurs on mortars reinforced with polyethene fibres (Ka000104-221001; 0.4%), however, as with samples reinforced with Cow hairs (Ka000207-221001; 0.9%), this sample presents a large number of cracks (Figure 6-16). The specimen with the lowest shrinkage not presenting any large cracks is found for mortars made with washed straw, either short or long (Ka000212-221001, Ka000210-221001). Most mortars have a lower shrinkage than Reference Mortars 1 and 2 except the ones made with Flax fibres (Ka000206-221001), Long Wool (Ka000208-221001) and Short Wool (Ka000209-221001).

Figure 6-16: Specimens of mortar Ka000207-221001 (a) and Ka000210-221001 (b) with the surface cracks visible on mortar Ka000207-221001.

The large range of shrinkage is probably due to the large difference in the physical and mechanical properties of the fibres used as they are presented in Table 3-1. The highest shrinkages are found on samples made with thin, soft and smooth fibres such as wool and flax. However, as underlined by other authors, separation of thin fibres is difficult due to their tortuosity and bundles of fibres were still present, preventing a good homogeneity of the mix and therefore preventing a positive impact on shrinkage decrease (Peetsalu et al., 2010). Moreover, as their surface is smooth and their swelling with water is high, they tend to separate from the mortar matrix, also reducing their impact on shrinkage (Jové-Sandoval et al., 2018; Rivera-Gómez et al., 2014).

Fibres with a rough surface such as cow hair or polyethene fibres have a good bond with the earth and prevent shrinkage. Moreover, these fibres have low water absorption properties, therefore the fresh mortar needs a lower amount of water to achieve similar consistency. However, because of too much stiffness and the inability to bend these fibres induces internal stress that creates large surface cracks.

Mortars reinforced with straw without dust (Ka000210-221001, Ka000211-221001 and Ka000212-221001) – in opposition to Chaff used in Reference Mortars – have also a low shrinkage, probably because of the absence of straw-dust which lower the need for water to achieve similar consistency (Kouakou & Morel, 2009), whereas tubular straw might help to drain the excess of water. However, water-saturated straw which is recommended to prevent the usage of a high amount of water has no impact on the shrinkage – the shrinkage of mortar Ka000102-221001 is similar to the shrinkage of Reference Mortar 1 – despite a slightly lower water amount used. Pine needles mortar (Ka000205-221001) has a high-water absorption capacity while low adhesion to the earth matrix (Jové-Sandoval et al., 2018); therefore, the water amount necessary to make the samples is higher, leading to a higher shrinkage.

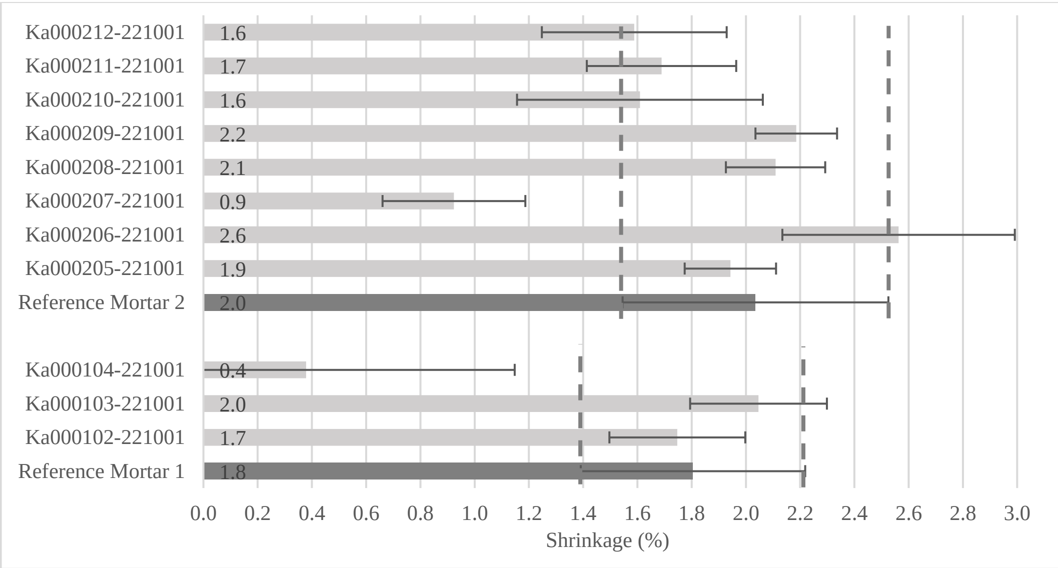

Figure 6-17: Shrinkage of earth mortars made with alternative fibres

6.2.1.2 Density

The average density of earth mortars prepared with alternative fibres is presented in Table 6-8 and Figure 6-18.

The largest density is recorded for mortars reinforced with Flax fibres (Ka000206-221001, 1816kg/m³) whereas the lowest density is achieved with the addition of Pine Needles (Ka000205-221001; 1618kg/m³) which is an 11%-difference for mortar made with Yellow Sand whereas mortars made with Grey Sand have much lower density but similar or higher than Reference Mortar 1.

The denser mortars are made with thinner and lighter fibres (flax and wool) since they also have a higher shrinkage so probably less porosity. Mortars made with long straws or saturated chaff also have a high density, as straws are probably crushed during application and therefore they occupy less volume, giving way for more heavy materials. In the same way, as the amount of fibres was determined by non-compressed volume, mortars reinforced by stiff fibres (Ka000104-221001, Ka000207-221001) have a lower number of fibres and therefore have a higher density. On the other hand, using water-absorbing and light fibres such as pine needles and chaff makes a lighter mortar as the weight of fibre per volume is higher, so more fibres are present in the samples, thus lowering the density; which confirms the results of Jové-Sandoval et al. (2018).

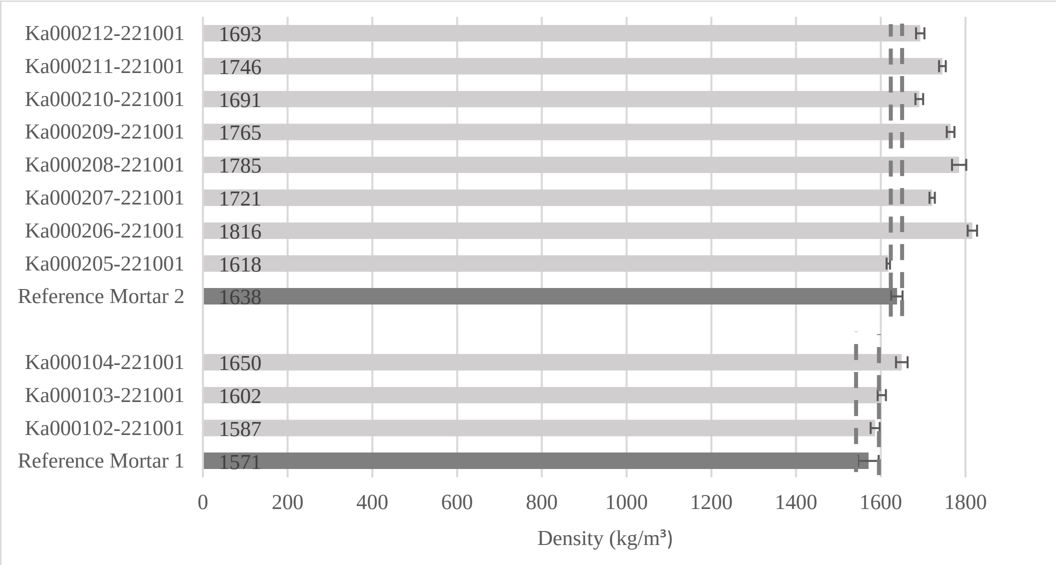

Figure 6-18: Density of earth mortars made with alternative fibres

6.2.2 Mechanical properties of earth mortar reinforced with alternative fibres

The mechanical properties of mortars made with alternative fibres are presented in this section. The impacts of these fibres on the flexural strength and compressive strength are discussed by comparing the obtained results with the values of the reference mortars and the data given by the literature.

Table 6-9: Mechanical properties of earth mortars modified with alternatives fibres

Mortar Name	Sand type	Density (kg/m³)	Flexural strength (MPa)	*Standard dev.*	Difference with the Reference Mortar (%)	Compressive Strength (MPa)	*Standard dev.*	Difference with the Reference Mortar (%)
Reference Mortar 1	**Chaff**	**1571**	**0.77**	***0.12***		**1.34**	***0.12***	
Ka000102-221001	48h Saturated fibres	1587	0.93	*0.07*	20.4	1.58	*0.10*	17.7
Ka000103-221001	2m Saturated fibres	1602	0.93	*0.02*	20.5	1.59	*0.04*	18.8
Ka000104-221001	Plastic fibres	1650	1.32	*0.02*	71.9	1.57	*0.19*	16.9
Reference Mortar 2	**Chaff**	**1638**	**0.88**	***0.14***		**1.95**	***0.15***	
Ka000205-221001	Pine needles	1618	0.75	0.09	-15.0	1.52	0.08	-22.1
Ka000206-221001	Flax fibres	1816	1.60	0.18	81.0	2.65	0.08	36.0
Ka000207-221001	Cow hair	1721	1.23	0.28	39.4	1.81	0.13	-7.1
Ka000208-221001	Long sheep wool	1785	1.20	0.07	35.5	2.13	0.19	9.6
Ka000209-221001	Short sheep wool	1765	1.13	0.05	27.4	2.07	0.11	6.5
Ka000210-221001	Washed straw	1691	1.07	0.10	21.4	1.81	0.06	-7.0
Ka000211-221001	Long straw	1746	1.07	0.01	20.6	1.65	0.10	-15.1
Ka000212-221001	Short washed straw	1693	1.05	0.09	18.9	1.66	0.11	-14.5

6.2.2.1 Flexural strength

The average flexural strength of earth mortars prepared with alternative fibres is presented in Table 6-9.

The higher flexural strength is achieved by mortars reinforced with Flax fibres (Ka000206-221001; 1.60 MPa) whereas the lowest strength is recorded on mortars reinforced with Pine Needles (Ka000205-221001; 0.75 MPa) for mortars made with Yellow Sand. For mortars made with Grey Sand, the highest flexural strength is found for mortars reinforced with plastic fibres (Ka000104-221001; 1.32 MPa). All other mortars have similar strengths to the Reference Mortars and therefore the impact of fibres on the flexural strength seems limited. However, when the range of flexural strengths, especially for mortars made with Yellow Sand is taken into account, it is a large range (0.81 MPa) larger than the range of strength for mortars reinforced with alternative sands (0.68 MPa) and more importantly, the average strength is higher (1.12 MPa instead of 0.84 MPa). Therefore, it can be told that the type of fibre used has a large impact on flexural strength.

The low strength reached by mortars reinforced by pine needles reinforced mortars might be due to their high water absorption and swelling behaviour which create a lower bond with the matrix, similar to some pine needles tested by Jove-Sandoval et al. (2018) and Sharma et al (2015). Moreover, pine needles have a brittle behaviour which also decreases the flexural strength of mortars according to Olacia et al. (2019). The high strength achieved with flax fibres might be due to their higher tensile strength compared to other fibres and their low water absorption, which prevents higher shrinkages while drying and enhances the cohesion within the matrix (Onuaguluchi & Banthia, 2016)

Interestingly, mortars reinforced with wool have no high strength despite similar high strength and low water absorption with flax fibres. This is probably due to the lack of homogeneity in the distribution of fibres in the specimens (Araya-Letelier et al., 2021). According to Danso et al. (2017), this problem occurs due to the difficulty in separating the wool fibres as well as their higher water absorption and probably higher expansion, which creates a weaker bond with the matrix.

6.2.2.2 Compressive strength

The average compressive strength of earth mortars prepared with alternative fibres is presented in Table 6-9.

The average compressive strength of mortars reinforced with alternative fibres varies from 1.52 MPa (Ka000205-221001) and 2.65 MPa (Ka000206-221001) for mortars reinforced with Pine Needles and Flax respectively. Mortars based on Reference Mortar 2 have an average compressive strength of 1.9 MPa similar to Reference Mortar 2 whereas the mortars made with Grey Sand have a similar strength of around 1.6 MPa, higher than the one of Reference Mortar 1 (1.34 MPa). Similarly to flexural strength, the range of strength of mortars modified with alternative fibres is similar (1.13 MPa instead of 1.08 MPa) and the average strength is higher (1.82 MPa instead of 1.38 MPa) than the one for mortars reinforced with alternative sands, showing the higher impact of fibres on strength

The usage of pine needles reduces the compressive strength of mortar by 20% compared to the mortar made with conventional fibres, which is similar to the results reported by José-Sandoval et al. (2018) for brittle and low-tensile strength pine needles.

The high compressive strength of mortars made with long and thin fibres (Wool and Flax) confirms the results of Lima et al. (Lima & Faria, 2016), who used cattail fibres and barley straw; Olacia et al. (2019) who used seagrass and straw; or Ouedraogo (2017, 2019) who used fonio (a type of straw) and kenaf fibres. However, not only the thinness is important but also the swelling of the fibres as results show a lower strength for mortars reinforced with wool, because of large water absorption and the creation of a gap between the matrix and the fibres as shown by Rivera-Gomes et al. (2014). All mortars made with different types of chaff have a similar compressive strength between 1.65 MPa and 1.81 MPa which is probably due to the usage of the same fibres in different lengths. Similar results have been reported by Navarro et al. (2015) or Olacia et al. (2019) and Ouedraogo (2019) who measured the compressive strength of mortars with different fibre lengths. Moreover, since these chaffs are washed, the dust that is probably used to reduce the porosity is not present anymore and therefore the strength is lower.

Using long straw (Ka000211-221001), which can be crushed under compression, also leads to a lower compressive strength compared to the Reference Mortar 2. On the contrary, using saturated fibres seems to increase the strength, as the fibres are probably more flexible during the application and therefore might bind better to the matrix.

6.2.2.3 Correlation between flexural strength, compressive strength and density

Figure 6-19 presents the correlation between flexural strength and compressive strength. On the contrary of what is seen for mortars modified with alternative sand, there is only a weak correlation between compressive strength and flexural strength. This weak correlation is due to the mortar Ka000104-221001 which has a very different behaviour than other mortars in compression and flexion. As it has very high flexural strength but average compressive strength. When this mortar is discarded, the R^2 of the relation in Figure 6-19 is 0.76 and the relation between compressive strength and flexural strength is similar to the one with alternative sands. The difference is the equation might be due on the impact of fibres which is higher for flexural strength than for compressive strength. For mortars reinforced with alternative fibres – except saturated straw – the increase in flexural strength is higher than the increase in compressive strength, with a 20% to 45% difference of increase – an increase of flexural strength minus increase of compressive strength – for sheep or flax respectively (Table 6-9) or even a lower decrease of strength in the case of pine needles reinforced mortar.

Opposingly to the findings of section 6.1.2.3, the replacement of chaff, has a large impact on the range of densities – in opposite to the replacement of Grey Sand by alternative sands (section 6.1.1.2) – and the range of strengths is large, the correlation between strength and density becomes effective and relevant as presented in Figure 6-20. Moreover, these correlations allow understanding that some mortars (Ka000206-22101 or Ka000104-22101 for example) are outliers, as their strength is not related to their density and therefore, their fibres have even a large impact on their strength, especially flexural strength.

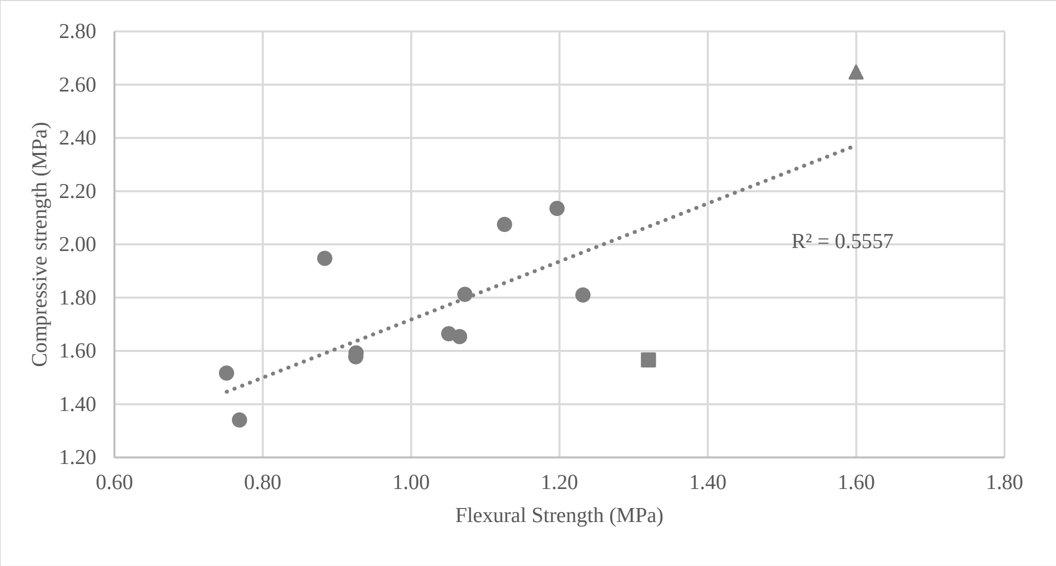

Figure 6-19: Relation between flexural strength and compressive strength of earth mortars reinforced with alternative fibres. The value marked by a triangle represents the mortar Ka000206-221001 and the value marked by a square represents the mortar Ka000103-2210001.

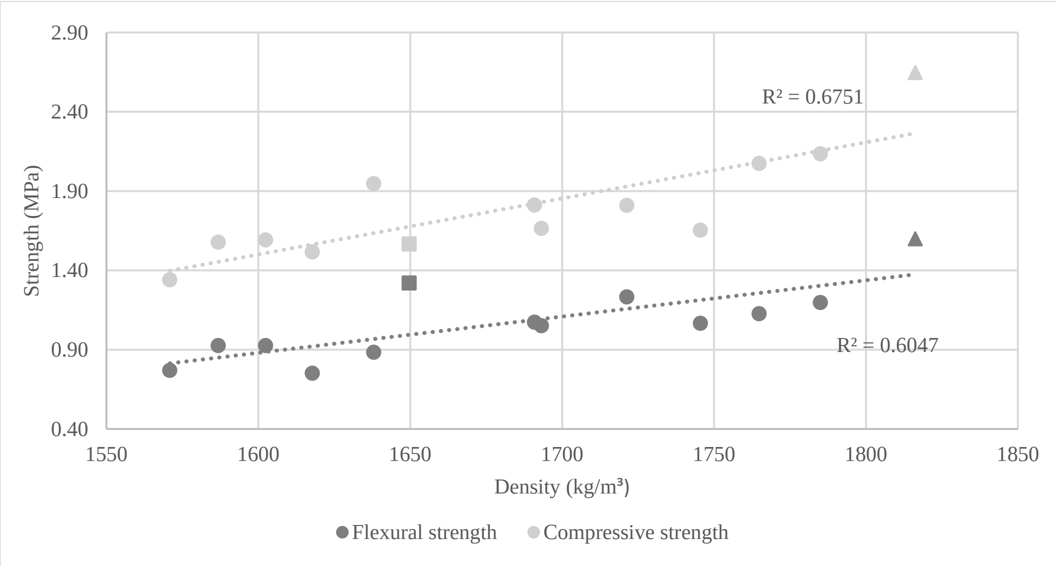

Figure 6-20: Relation between mechanical strength and density of earth mortars reinforced with alternative fibres. The values marked by a triangle represent the mortar Ka000206-221001 and the values marked by a square represent the mortar Ka000103-2210001.

6.2.3 Surface properties of earth mortars reinforced with alternative fibres

The surface water absorption and the surface cohesion of mortars reinforced with alternative fibres are presented in this section. The impact of each fibre on the surface properties is then discussed and compared with the literature. The properties of the earth mortars and their comparison with Reference Mortars 1 and 2 are shown in Table 6-10 and Figure 6-21 to Figure 6-23.

Table 6-10: Surface properties of earth mortars reinforced with alternative fibres

Mortar Name	Fibre type	Density (kg/m²)	Surface water absorption (g/m²·s) for 90 s.	Difference with the Reference Mortar (%)	Peeling test Material loss (µg/cm²)	*standard dev.*	Difference with the Reference Mortar (%)
Reference Mortar 1	**Chaff**	**1571**	**26.2**		**2214**	**1260**	
Ka000102-221001	48h Saturated fibres	1587	31.2	19	1389	157	-37
Ka000103-221001	2m Saturated fibres	1602	26.6	2	1917	568	-13
Ka000104-221001	Plastic fibres	1650	30.7	17	1454	206	-34
Reference Mortar 2	**Chaff**	**1638**	**17.3**		**1192**	**404**	
Ka000205-221001	Pine needles	1618	22.0	27	972	0	-18
Ka000206-221001	Flax fibres	1816	11.7	-32	343	170	-71
Ka000207-221001	Cow hair	1721	19.8	14	528	181	-56
Ka000208-221001	Long sheep wool	1785	16.6	-4	1083	339	-9
Ka000209-221001	Short sheep wool	1765	15.2	-12	713	305	-40
Ka000210-221001	Washed straw	1691	17.7	2	991	274	-17
Ka000211-221001	Long straw	1746	15.0	-13	1398	378	17
Ka000212-221001	Short washed straw	1693	18.6	8	1417	422	19

6.2.3.1 Surface water absorption

The surface absorption of mortars made with Grey Sand varies from 26.6 g/m²·s (Ka000103-221001) to 31.2 g/m²·s (Ka000102-221001) whereas the absorption of mortars made with Yellow Sand varies from 11.7 g/m²·s (Ka000206-221001) to 22.0 g/m²·s (Ka000205-22101). When compared to their reference mortars, it can be seen that there is a low difference in water absorption and that the value of water absorption of most mortars is comprised of the standard deviation of the Reference Mortar. Moreover, as shown in Figure 6-22 and section 5.2.3, the density impacts the water absorption as it seems that the amount of water absorbed decreases with the increase of density. Two exceptions are mortar Ka000104-221001 – whose surface is full of visible cracks around the plastic fibres and therefore has higher absorption and Ka000102-221001 which is an outlier as the same fibres have been used as in Ka000101-221001 and therefore the absorption should be similar. These mortars have not been included in Figure 6-22.

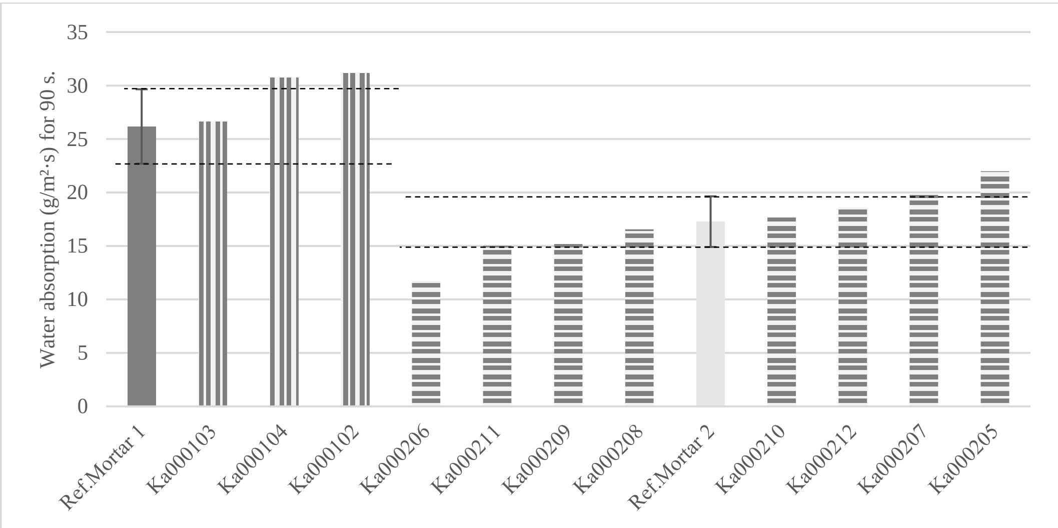

Figure 6-21: Impact of fibres type on the water surface absorption of earth mortars reinforced with alternative fibres

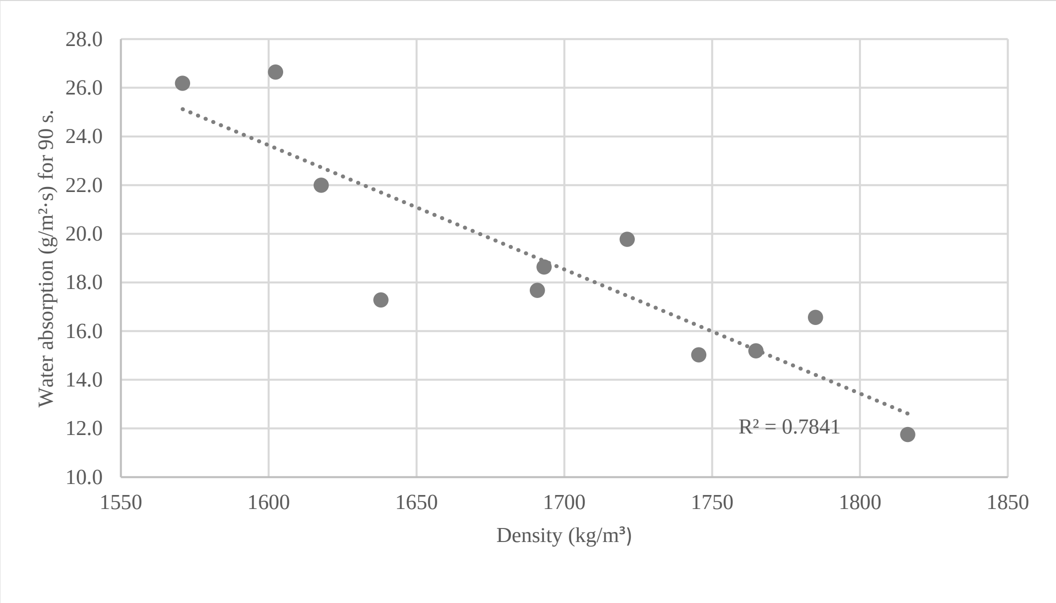

Figure 6-22: Impact of the density on the surface water absorption of fibres.

6.2.3.2 Surface Cohesion

The amount of material detached from earth mortars made with Grey Sand varies between 1389 µg/cm² (Ka000102-221001) and 1917 µg/cm² (Ka000103-221001), less than the average amount of material detached from the Reference Mortar 1 (2214 µg/cm²). The amount of material detached from mortars made with Yellow Sand varies from 343 µg/cm² (Ka000206-221001) and 1417 µg/cm² (Ka000205-221001). Except for Reference Mortar 1 and Ka000103-221001, the variation of results of each mortar is low but the impact of fibres on the surface cohesion is low except for specific fibres such as flax (Ka000206-221001), cow hair (Ka000207-221001) who reduces the material loss probably due to their bond with the matrix.

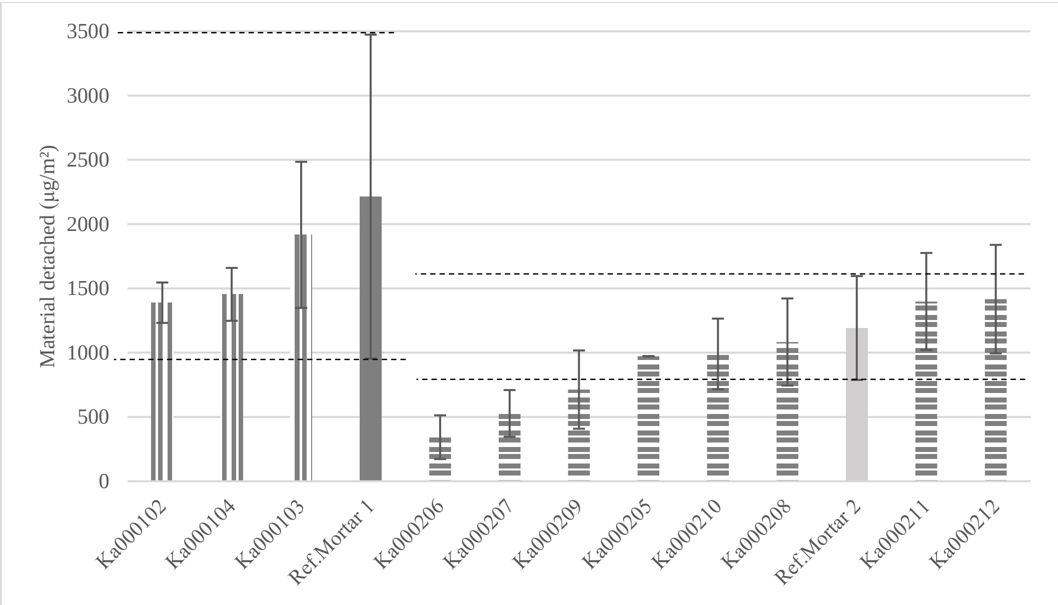

Figure 6-23: Impact of fibres type on the surface of earth mortars reinforced with alternative fibres

6.2.4 Durability properties of earth mortars reinforced with alternative fibres

The durability properties of earth mortars reinforced with alternative fibres are presented in this section. In the first part, the impact of these fibres on the humid strength will be explained and discussed in regard to the results of previous sections, and then the abrasion resistance and erosion resistance will be compared with the resistance of the Reference Mortars 1 and 2 and discussed in regard to the literature.

Table 6-11: Durability properties of earth mortars reinforced with alternative fibres

Mortar Name	Humidity level (weight increase in %)	Humid flexural strength (MPa)	Loss in strength (%)	Humid compressive strength (MPa)	Loss in strength (%)	Abrasion resistance (DIN18947) Material loss (g)	Abrasion resistance (French rules) Abrasion Coefficient (cm²/g)	Erosion resistance Hole depth (mm)	Erosion resistance Hole diameter (mm)
Reference Mortar 1	**0.6-1.5**	**0.36**	**-53**	**0.76**	**-43**	**8.6**	**0.60**	**8**	**22**
Ka000102-221001	1.4%	0.37	-60	1.04	-34	7.4	0.56	6	23
Ka000103-221001	1.4%	0.46	-51	0.96	-40	5.5	0.72	7	20
Ka000104-221001	1.7%	0.43	-68	0.89	-43	5.8	0.84	11.5	23
Reference Mortar 2	**0.9**	**0.61**	**-28**	**1.18**	**-37**	**2.6**	**1.20**	**6**	**25**
Ka000205-221001	1.1%	0.32	-58	0.95	-37	3.1	1.14	6.5	20
Ka000206-221001	1.0%	0.77	-52	1.66	-37	1.2	1.89	4.5	12
Ka000207-221001	1.0%	0.86	-30	0.88	-52	4.3	1.15	11	32
Ka000208-221001	1.0%	0.52	-57	1.31	-39	2.6	1.68	8	22
Ka000209-221001	1.0%	0.50	-56	1.21	-42	2.4	1.34	7.5	32
Ka000210-221001	1.0%	0.52	-52	1.14	-37	2.5	1.85	5.5	23
Ka000211-221001	1.0%	0.39	-64	1.00	-39	2.9	1.54	6	23
Ka000212-221001	0.9%	0.45	-57	1.04	-37	3.4	0.99	0.3	38

6.2.4.1 Humid mechanical strength

The humid mechanical strength of earth mortars is presented in Table 6-11 and Figure 6-24.

The flexural strength varies from 0.32 MPa (Ka000205-221001, 1.1% of humidity, 58% loss of strength) to 0.86 MPa (Ka000207-221001; 1.0% of humidity, 30% loss of strength). The compressive strength varies from 0.88 MPa (Ka000207-221001, 1.0% of humidity, 52% loss of strength) to 1.66 MPa (Ka000206-221001, 1.0% of humidity, 37% loss of strength). Due to the humidity amount in samples, except for Reference Mortar 2, Ka000206-221001 and Ka000207-221001, the flexural strength is below 0.55 MPa and the average compressive strength is about 1 MPa independantly of the sand and fibres, similarly to the results of the section 6.1.4.1.

The amount of humidity absorbed by the samples is similar in all cases to the anount of humidity absorbed by the reference mortar, therefore, it seems to be no impact of the type of fibres on the humidity absorption.

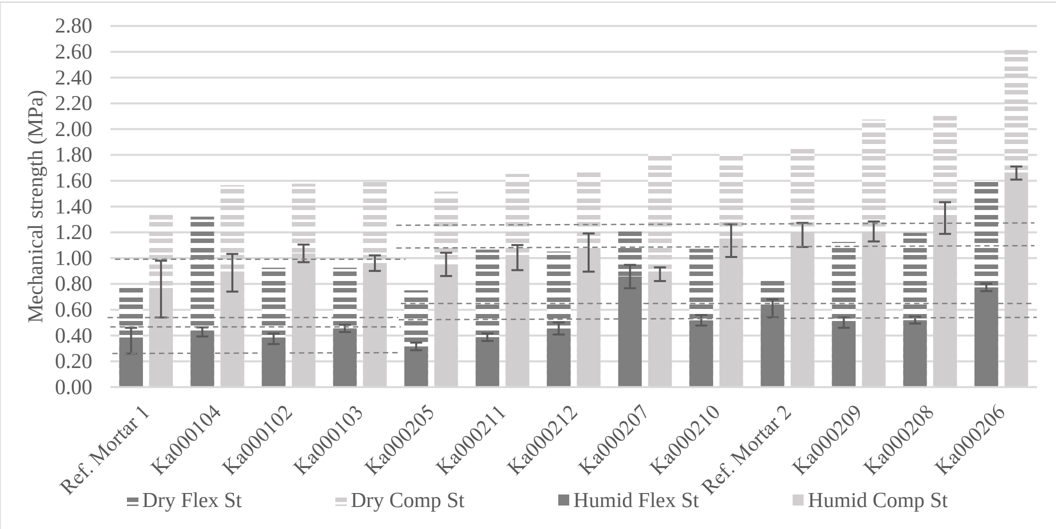

Figure 6-24: Mechanical strength of humid and dry earth mortars modified with alternative fibres. The dashed lines show the strength range of the Reference mortars 1 and 2 for comparison.

The average loss of strength is more than 50% except for Ka000207-221001 and Reference Mortar 2 which explain their high flexural strength whereas the high flexural strength of Ka000206-221001 is due to its high dry strength. For compressive strength, the average loss of strength is lower than 40% - but again most of the mortar experienced a similar loss – showing the lesser impact of humidity on compressive strength. Therefore, it can be summarized that despite alternative fibres having a large impact on the dry strength, they don’t have an impact on the loss of strength of the mortars, their humid strength being directly related to their dry strength.

6.2.4.2 Resistance to water by immersion

The resistance to immersion has been tested by partly plunging the mortar in water and determining the time necessary for the disaggregation of the immersed part. The results of the test are given in Table 6-11.

The resistance to immersion varies between 2 min (Ka000102-221001) and 10 min (Ka000103-221001) for mortar based on Reference Mortar 1 and between 5 min (Ka000207-221001) and 50 min (Ka000206-221001) for mortars based on reference Mortar 2, all values lower than the value of the respective reference mortar except for Ka000206-221001. The lowest values are for the mortars made with stiff fibres (Ka000104-221001 and Ka000207-221001) which induced a high amount of cracks and created weakness and an entry point for the water whereas the only mortar that resist for more than 40 minutes – the threshold to pass the test according to disused Turkish Standard (TS 2514, 1977) – is made with thin and non-absorbing fibres.

6.2.4.3 Abrasion resistance

The abrasion resistance has been tested according to German Standards (DIN18947) and French professional rules (Regles Pro). The results of the experiments are given in Table 6-11 and Figure 6-25. For both tests, the mortar with the lowest resistance is Reference Mortar 1 followed by mortar Ka000102-221001. The mortar with the highest resistance is Ka000206-221001 for both DIN18947 and Regles Pro tests. Figure 6-26 presents the impact of the density on the abrasion resistance of mortars. There seems to be a correlation between the density and the abrasion resistance as seen for other types of mortars (sections 5.2.4, 5.3.4, 5.4.4 and 6.1.4.2) however, this correlation is weak and not existing if mortars made only with 1 type of sand are accounted for. Therefore, the type of fibres seems also to play a role as all fibres used with Yellow Sand except cow hair (Ka000207-221001) and flax (Ka000206-221001) have a similar resistance (between 2.5g and 3.1g lost) whereas Ka000207-221001 lost 4.3g and Ka000206-221001 lost 1.2g. This difference is probably due to the density of fibres and how thin fibres are linked within the matrix and are not easily pulled out by friction contrary to thick and rigid cow hair fibres. Mortars made with pine needles (Ka000205-221001) have also a better resistance compared to their very low density, probably because of the shape of these fibres (Jové-Sandoval et al., 2018) that might prevent a pull-out. Also, the fact that the mortars made with 2-months saturated fibres have better resistance than the identical mortar with similar density made with 48h saturated fibres (5.5 g lost versus 7.4 g) shows the impact of certain types of fibres or treatments.

However, more study needs to be made to determine which type of fibres has a real impact as wool fibres seem to have no impact despite having a similar size and flexibility to flax fibres. According to Giroudon et al. (2019) who studied the impact of lavender straw and barley straw, the difference is mostly coming from the aspect ratio and the roughness of the fibres and rough and thin fibres provide better resistance than smooth and more bulky fibres.

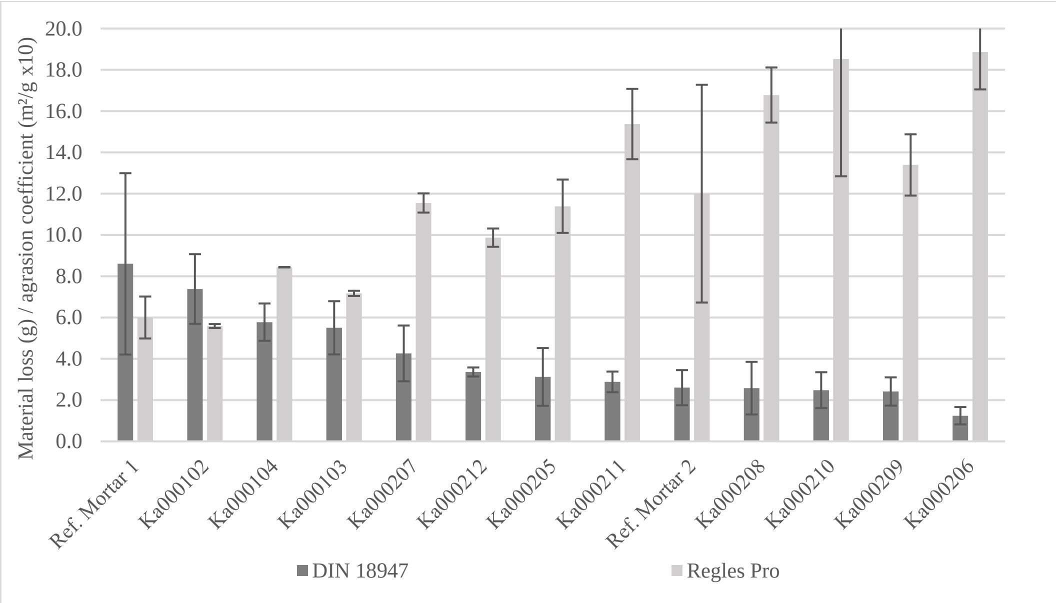

Figure 6-25: Abrasion resistance of mortars reinforced with alternative fibres. For a better understanding, the data of the abrasion coefficient have been multiplied by ten.

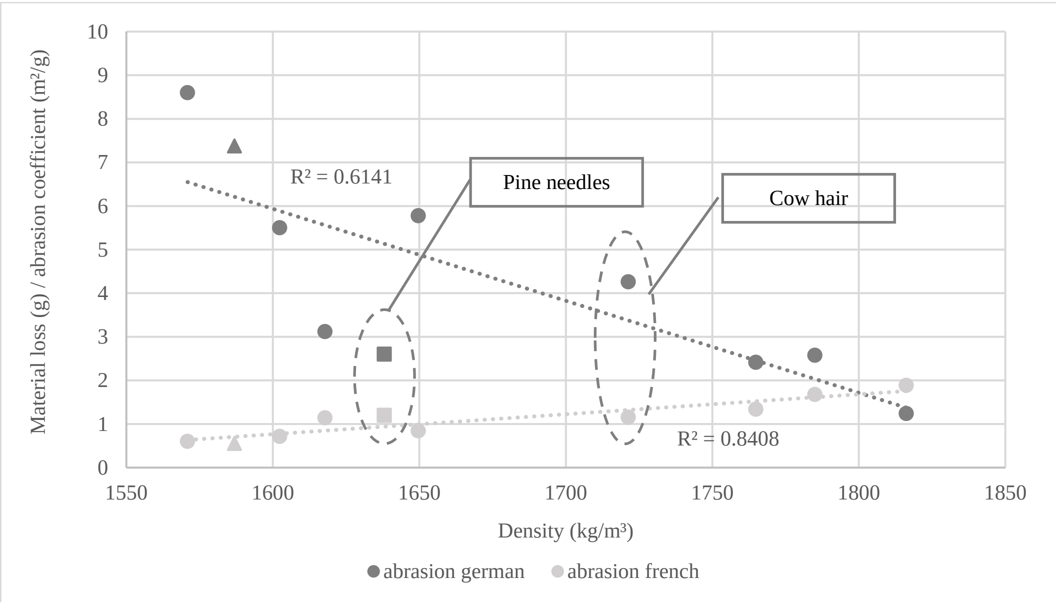

Figure 6-26: Relation between density and resistance to abrasion for earth mortars reinforced with alternative fibres

6.2.4.4 Erosion resistance

The erosion resistance is presented in Table 6-11. The depth of the pith made by the dripping water varies from 0.3 mm (Ka000212-221001) to 11.5 mm (Ka000104-221001). However, the results for Ka000212-221001 should not be considered as they are probably false due to the experiment conditions – the diameter of the pith is very large therefore it might be considered that the drops were not falling on the same place every time. Therefore, the lowest erosion is seen for mortar Ka000206 (4.5 mm).

When the erosion depth is considered in terms of the type of fibres used, it can be seen that the worst erosion occurred for mortars made with thick and rigid fibres which have very low adhesion to the matrix (Ka000104-221001 and Ka000207-221001) but also for mortars reinforced with wool (Ka000208-221001 and Ka000209-221001) – probably again because of the non-homogeneity of the mix – whereas all straw/chaff based fibres have a similar erosion depth (6 mm to 8 mm) independently to the type of sand used to make the mortar which is confirmed by the test on mortars reinforced with alternative sands (section 6.1.4.4).

6.2.5 Hydric properties of mortars reinforced with alternative fibres

The hydric properties of mortars reinforced with alternative fibres are summarized in Table 6-12 as the capillarity coefficient and the drying behaviour. Results for both properties are presented and discussed in the following sections.

Table 6-12: Hydric properties of mortars reinforced with alternative fibres

Mortar Name	Fibre type	Capillarity coefficient (kg/(m²·min^0.5)	*R^2 (-)*	Drying rate (1st phase) (kg/m²/h)	*R^2 (-)*	Drying rate (2nd phase) (kg/m²/h^0.5)	*R^2 (-)*	*Drying Index (-)*
Reference Mortar 1	**Chaff**	1.06		0.13		**1.12**	0.11*	0.26
Ka000102-221001	48h Saturated fibres	1.06	1.00	0.08	0.99	0.92	0.99	0.36
Ka000103-221001	2m Saturated fibres	1.11	1.00	0.10	1.00	1.08	1.00	0.29
Ka000104-221001	Plastic fibres	1.22	1.00	0.08	1.00	1.00	0.99	0.36
Reference Mortar 2	**Chaff**	0.94		0.11		**1.20**	0.08*	0.24
Ka000205-221001	Pine needles	0.96	1.00	0.13	1.00	1.08	1.00	0.25
Ka000206-221001	Flax	0.87	1.00	0.11	0.99	0.93	0.99	0.30
Ka000207-221001	Cow hair	1.26	0.99	0.10	1.00	1.41	0.98	0.27
Ka000208-221001	Long sheep wool	1.18	1.00	0.11	0.99	1.42	0.99	0.24
Ka000209-221001	Short sheep wool	0.91	1.00	0.13	0.99	1.32	0.99	0.20
Ka000210-221001	Washed straw	0.86	1.00	0.13	0.99	1.00	1.00	0.36
Ka000211-221001	Long straw	1.09	1.00	0.12	0.99	1.02	1.00	0.32
Ka000212-221001	Short washed straw	0.91	0.99	0.08	0.99	1.21	0.99	0.23

6.2.5.1 Capillarity absorption

The capillarity absorption is presented in Table 6-12, Figure 6-27 for mortars reinforced with Yellow Sand and straw/chaff fibres and Figure 6-28 for mortars reinforced with alternative fibres.

The lowest capillarity absorption rate is found for mortar Ka000206-221001 (0.87 kg/(m²·min$^{0.5}$)) whereas the highest one is found for Ka000207-221001 (1.26 /(m²·min$^{0.5}$)) which corresponds to the results of the surface water absorption (section 6.2.3.1). However, at the end of the test (after 4h05 and water reaching the upper surface of samples), it can be seen that the maximum amount of water absorbed is very close for most mortars (between 12.3g/m² and 12.9 g/m²) except Ka000207-221001 (14.2 g/m²), Ka000208-221001 (13.5 g/m²) and Ka000211-221001 (13.5 g/m²) which are higher.

From the value of the capillarity coefficient and the results published by Lima & Faria (2017) for oat straw and typha fibres, it can be concluded that the type of fibre used has a large impact on the capillarity coefficient, the fibres probably working as a medium to transport the water inside the mortar and the most water absorbing fibres having a higher CC. However, as some mortars reinforced with fibres with a low water absorption (Ka000104-221001 and Ka000207-221001) but with a large number of cracks due to shrinkage have a high CC, it can also be said that the surface aspect plays a large role in the water absorption. This can also be understood from the curve representing the water absorption as the first segment of the curve which represents the wetting of the sample is higher (Figure 6-28) for these mortars.

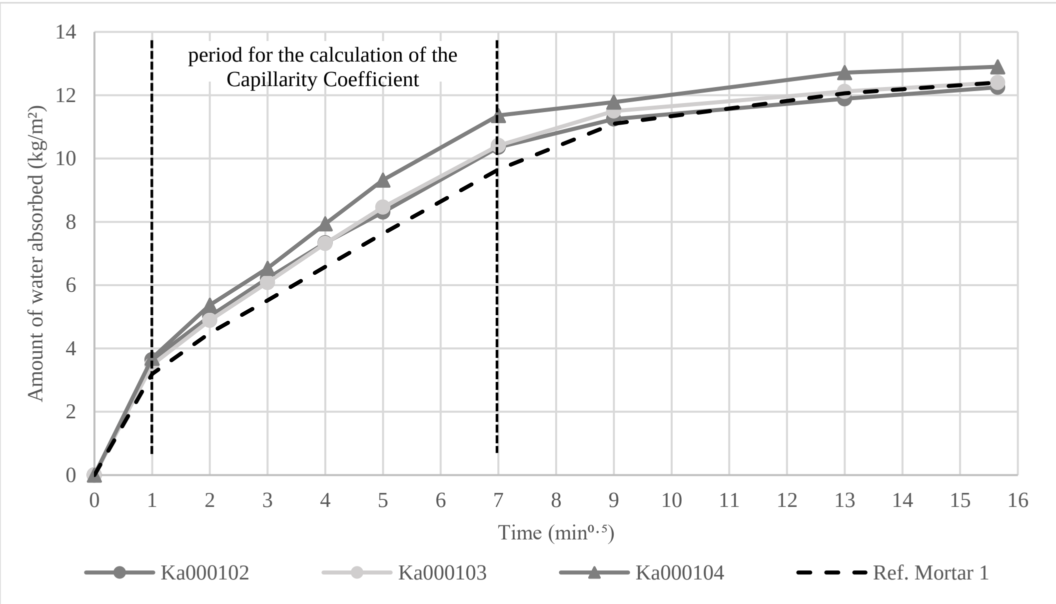

Figure 6-27: Water capillarity absorption of earth mortars based on Reference Mortar 1 and reinforced with alternative fibres.

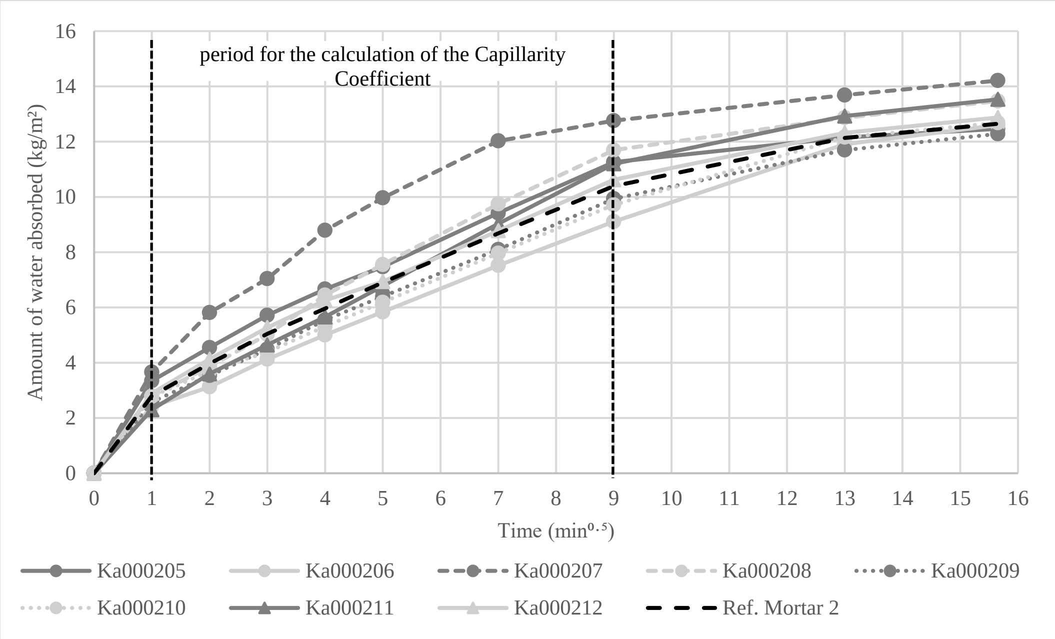

Figure 6-28: Water capillarity absorption of earth mortars based on Reference Mortar 2 and reinforced with alternative fibres.

6.2.5.2 Drying behaviour

The drying behaviour is presented in Table 6-12 with the primary drying rate, the secondary drying rate and the Drying Index.

The primary drying rate varies from 0.08 kg/m²h (Ka000102-221001, Ka000104-221001, Ka000212-221001) to 0.13 kg/m²h (Ka000205-221001, Ka000209-221001, Ka000210-221001) which shows a very slight difference in the first drying phase, and all close to the value of the reference mortars. The secondary drying phase varies from 0.92 kg/m²h^{-1} (Ka000102-221001) to 1.42 kg/m²h^{-1} (Ka0001208-221001) whereas the Reference Mortars 1 and 2 have a drying rate of 1.12 kg/m²h^{-1} and 1.20 kg/m²h^{-1} respectively which shows that some mortars have a much lower and higher drying rate. The drying index is varying from 0.20 (Ka000209-221001) to 0.36 (Ka000102-221001, Ka000104-221001, Ka000210-221001) showing the impact of the type of fibres on the drying, especially when compared to the DI of mortars reinforced with alternative sands which DI only varied from 0.24 to 0.28 (section 6.1.5.2). However, despite this large variety of results, it seems difficult to explain it according to the water absorption of the fibres as some very similar fibres have very different drying rates (e.g. Ka000102-221001 and Reference Mortar 1 or Ka000210-221001 and Ka000212-221001 and Reference Mortar 2). The not-perfect drying conditions might have affected the drying of the mortars and therefore the drying rate.

6.2.6 Hygric properties of earth mortars reinforced with alternative fibres

The hygric properties of mortars are presented in Table 6-13 and the impact of alternative fibres on water vapour permeability, dynamic water vapour absorption and dynamic water vapour desorption are discussed in the following paragraphs.

Table 6-13: Hygric properties of earth mortars reinforced with alternative fibres

Mortar Name	Fibre Type	Water vapour diffusion resistance factor (-)	Equivalent air layer (m)	Water vapour adsorption (12h - g/m²)	Primary adsorption rate - first 3h (g/m²h)	Water vapour desorption (12h - g/m²)	Primary desorption rate - first 3h (g/m²h)	Secondary desorption rate - 12h-48h (g/m²h)
Reference Mortar 1	**Chaff**	**4.1**	**0.16**	**149**	**14.5**	**-**	**-**	**-**
Ka000102-221001	48h Saturated fibres	4.5	0.18	144	14.6	81	10.6	2.5
Ka000103-221001	2m Saturated fibres	4.1	0.16	141	13.9	83	11.5	2.7
Ka000104-221001	Plastic fibres	3.8	0.15	145	14.6	76	10.3	2.5
Reference Mortar 2	**Chaff**	**4.1**	**0.16**	**145**	**14.5**	**84**	**11.1**	**2.9**
Ka000205-221001	Pine needles	4.0	0.16	140	13.9	82	11.3	2.6
Ka000206-221001	Flax	3.9	0.16	150	14.9	88	11.7	2.7
Ka000207-221001	Cow hair	3.8	0.15	161	15.7	79	10.9	2.7
Ka000208-221001	Long sheep wool	4.1	0.17	157	15.4	76	10.5	2.4
Ka000209-221001	Short sheep wool	4.0	0.16	153	15.9	80	11.2	2.6
Ka000210-221001	Washed straw	4.1	0.17	140	14.2	83	10.9	2.3
Ka000211-221001	Long straw	4.2	0.16	142	13.9	84	11.9	2.5
Ka000212-221001	Short washed straw	4.0	0.16	149	14.5	85	12.0	2.7

6.2.6.1 Water vapour permeability

The water vapour diffusion resistance varies from 3.8 (Ka000103-221001 and Ka000207-221001) to 4.5 (Ka000102-221001) which are very low values according to DIN18947. The values are in the same range as the value found for mortars reinforced with alternatives sands (section 6.1.6.1) and in the same range as the reference value which is in line with the conclusion of sections 5.2.6 and 5.3.6 which shows that the water vapour diffusion resistance factor was depending on the amount of clay in the mix. Therefore, as all mortars used here have a similar amount of clay, it seems that the type of fibres has no or only a little impact on the water vapour permeability.

6.2.6.2 Dynamic water vapour absorption and desorption behaviour

The dynamic water absorption and desorption are presented in Table 6-13 and Figure 6-29 and Figure 6-30. Due to problems during the testing period, only 24h of adsorption is displayed on the graphs. To keep it readable, only the values of mortars with the lowest and highest curve have been represented on the graphs. The curves for other mortars can be found in APPENDIX F.

The adsorption at 12 h varies from 141 g/m² (Ka000103 -22101) to 145 g/m² (Ka000104-22101) for mortars based on Reference Mortar 1 and from 140 g/m² (Ka000210-22101, Ka000205-22101) to 161 g/m² (Ka000207-22101) for mortar based on Reference Mortar 2. These values are very close to the value of the reference mortars, respectively 144 g/m² for Reference Mortar 1 and 145 g/m² for Reference Mortar 2. This proximity of value shows that for usage in a building with a daily circle of humidity increase and decrease, the impact of the fibre type will not be important except if animal-based fibres are considered. As can be seen in Figure 6-29 (which shows the mortars with the highest and lowest adsorption rate) the adsorption at 24h is also very similar to the one of the respective reference mortars. However, if mortars are separated by type of fibres (straw/chaff and others, as can be observed in APPENDIX E), it can be seen that mortars reinforced with straw and chaff have the same vapour adsorption behaviour with almost identical curves whereas other mortars -except Ka000104-221001 – have a slightly higher curve.

Similar behaviour can be observed for desorption as shown in Figure 6-30 and Figure F 4 to Figure F 9 in APPENDIX F. Desorption curves of mortars made with straw/chaff fibres are almost identical whereas the ones for alternative fibres are slightly different with slightly lower desorption for animal fibres-based mortars (Ka000207-221001, Ka000208-221001 and Ka000208-221001). Moreover, as in the case of water vapour adsorption, the amount of vapour desorbed after 12h is very close.

Therefore it can be concluded that there is only a low to no impact of the fibres type on the adsorption and desorption rate and this impact is only visible on alternative fibres because of different chemical composition and therefore a different behaviour towards vapour adsorption and desorption. Animal fibres might have a different vapour adsorption/desorption capacity than plant fibres (APPENDIX F) as their main component are different (cellulose and hemicellulose for plant fibre, keratin for animal fibres).

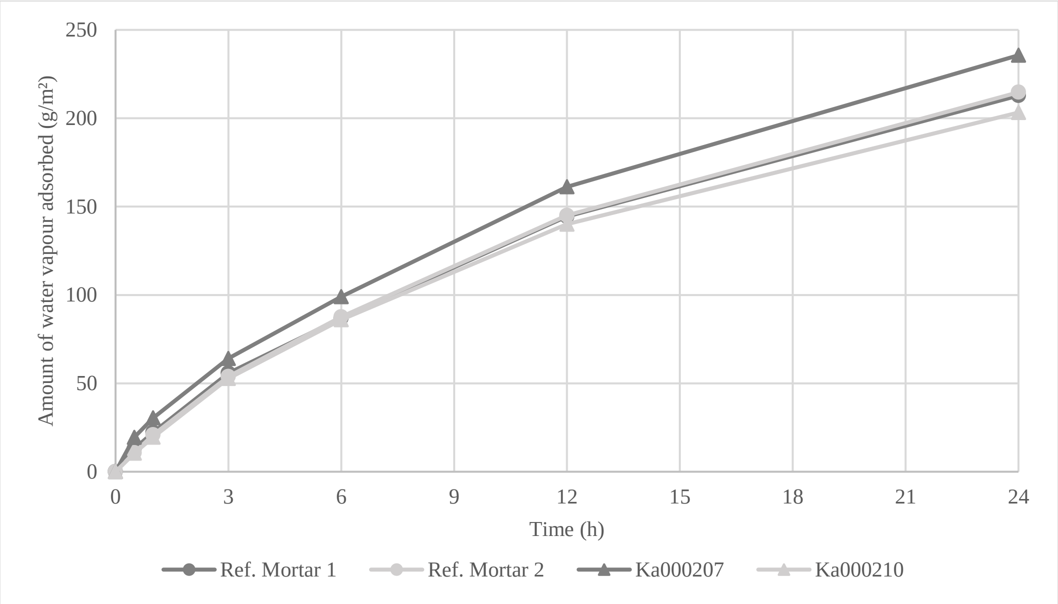

Figure 6-29: Water vapour adsorption of earth mortars reinforced with alternative fibres. Only the top and bottom curves and the curves of the Reference Mortars are shown to increase the readability of the graph as most curves superposed each other.

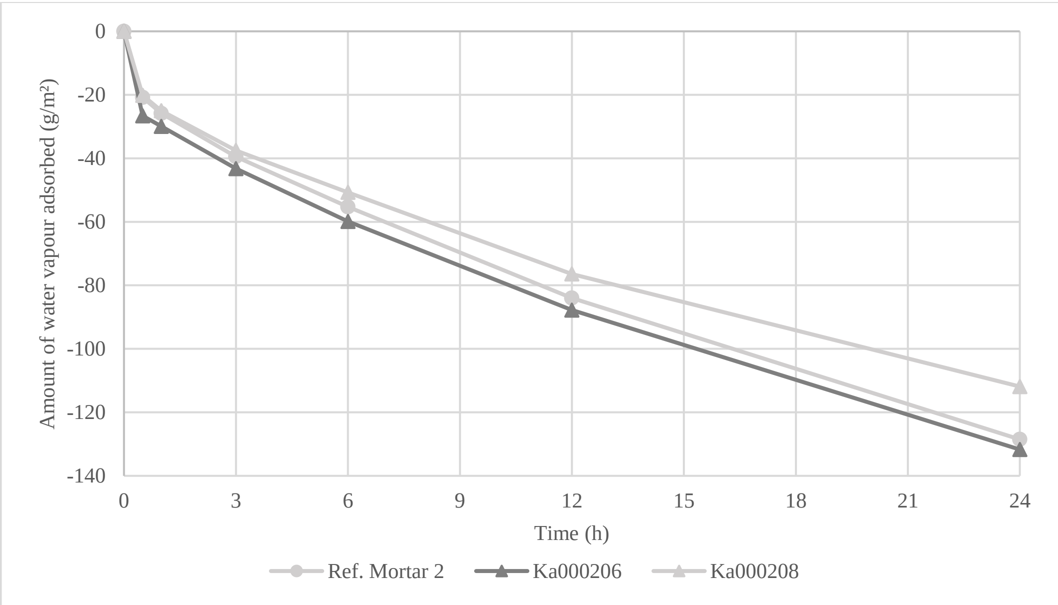

Figure 6-30: Water vapour desorption behaviour of earth mortars reinforced with alternative fibres. Only the top and bottom curves and the curves of the Reference Mortars are shown to increase the readability of the graph as most curves superposed each other.

CHAPTER 7

CHARACTERISTICS OF EARTH MORTARS STABILIZED WITH BIOPOLYMERS

In this chapter, the properties of earth mortars which have been stabilized with biopolymers, i.e, mortars in which an organic material extracted from natural resources have been added to enhance their properties, will be determined and discussed in relation to the literature and the reference mortar properties. The physical properties, mechanical properties, surface properties, durability properties, hydric properties and hygric properties of earth mortars of stabilized earth mortars will be presented. The impact of each polymer will be discussed property by property and related to the literature if existing.

7.1 Physical properties of earth mortars stabilized with biopolymers

The average physical properties of mortars stabilized with natural additives are presented in Table 7-1, Table 7-2 and

Table 7-3 together with the average value of the Reference Mortar 1 and Reference Mortar 2. In order to understand the impact of the additives more clearly, Figure 7-1 to Figure 7-9 presents the difference in shrinkage and density of the stabilized mortars compared with the reference mortar they are related to.

Table 7-1: Physical properties of earth mortars stabilized with natural additives and made with Reference Mortar 1 as a base material

mortar name	Type of additive	Amount of fibres (% weight)	Amount of additive (%wt)	Slump test (cm)”	Amount of water (% of dry mix)	Settling time	Shrinkage (%)	Standard dev.	Average dry density (kg/m^3)	Standard dev.	Difference of shrinkage (%)	Difference of dry density (%)
Reference Mortar 1	**---**	**1.2**	**---**	**16.2-16.8**		**1-2**	**1.8**	**0.4**	**1571**	**24**		
Ka010101-221051	Egg	1.1	0.5	16.6	27	2	1.6	0.3	1534	8	-11	-2
Ka010101-221101	Egg	1.3	1.1	16.8	28	2	2.3	0.4	1566	9	25	0
Ka010101-221151	Egg	1.1	1.6	16.4	28	2	2.0	0.3	1577	9	12	0
Ka020101-221011	D-juice	1.1	0.9	16.4	*27*	2	2.1	0.2	1570	10	15	0
Ka020101-221051	D-juice	1.1	4.6	16.4	*22*	2	2.5	0.4	1589	8	39	1
Ka020101-221101	D-juice	1.1	8.9	16.0	*19*	2	2.4	0.2	1583	14	33	1
Ka040101-221081	Fl paste	1.3	8	16.8	*24*	2	1.4	0.0	1501	1	-20	-4
Ka040101-221161	Fl paste	1.3	15.7	16.8	*16*	2	0.9	0.4	1420	13	-47	-10
Ka040101-221351	Fl paste	1.3	35	16.4	*0*	2	1.3	0.2	1398	9	-26	-11
Ka080101-22121	U. oil	1.2	2.0	16.3	28	2	1.7	0.1	1519	8	-8	-3
Ka080101-22141	U. oil	1.1	4.0	16.5	28	2	1.2	0.3	1508	8	-34	-4
Ka080101-22161	U. oil	1.2	5.9	16.4	28	2	1.7	0.3	1480	10	-5	-6
Ka080101-22181	U. oil	1.1	7.9	16.5	23	2	1.5	0.4	1498	14	-14	-5
Ka100101-221011	L. oil	1.1	1	16.7	29	2	0.9	0.5	1559	8	-52	-1
Ka100101-221021	L. oil	1.1	2	16.7	28	2	1.2	0.2	1553	14	-35	-1
Ka100101-221041	L. oil	1.1	4	16.8	28	2	1.0	0.5	1563	15	-43	-1
Ka100101-221061	L. oil	1.1	6	16.9	28	2	1.1	0.5	1551	6	-41	-1
Ka090101-221301	S-Juice	1.1	30	16.8	0	2	1.9	0.4	1606	5	4	2

The amount of added water written in italic font and recorded for the mortars made with decomposition juice and Flour paste only correspond to the added water, not to the liquid part of the additive. Same comment is valid for other liquid or viscous additives such Molasses or Straw-Juice

Table 7-2: Physical properties of earth mortars stabilized with natural additives and made with Reference Mortar 2 as a base material

Mortar Name	Type of additive	Amount of fibres (% weight)	Amount of additive (%wt)	Slump test (cm)	Amount of water (% of dry mix)	Settling time	Shrinkage (%)	Standard dev.	Average dry density (kg/m³)	Standard dev.	Difference of shrinkage (%)	Difference of dry density (%)
Reference Mortar 2	**---**	**1.0**	**---**	**16.0-17.5**		**0-2**	**2.0**	**0.5**	**1638**	**13**		
Ka070201-221031	Dung	0.9	3	16.5	28	30	2.2	0.3	1631	2	7	0
Ka070201-221061	Dung	0.9	6	16.5	29	30	2.3	0.4	1606	51	14	-2
Ka070201-221111	Dung	0.9	11	16.6	28	30	2.8	0.3	1511	6	37	-8
Ka110201-221011	Mayo	0.9	1	16.4	26	2	1.7	0.4	1637	18	-14	0
Ka110201-221021	Mayo	0.9	2	16.6	26	2	1.3	0.2	1610	13	-34	-2
Ka110201-221031	Mayo	0.9	3	16.4	26	2	1.6	0.4	1613	4	-23	-1
Ka150201-22102	Casein	0.9	2	16.6	30	2	2.9	0.4	1650	37	41	1
Ka150201-22105	Casein	0.9	5	16.5	2	2	2.3	0.4	1685	15	14	3
Ka150201-22110	Casein	0.9	9	16.3	5	2	1.5	0.1	1663	13	-24	2
Ka120201-221061	Dry CD	0.9	6	16.3	27	30	0	0.1	1390	4	-105	-15
Ka130201-221251	HH stalk	0.9	25	16.6	27	2	2.3	0.4	1611	3	12	-2
Ka140201-221201	HH flower	0.9	19	16.6	26	2	1.7	0.3	1650	6	-18	1

Table 7-3 Physical properties of earth mortars stabilized with natural additives and made with Reference Mortar 3 as a base material

Mortar Name	type of additive	amount of fibres (% weight)	amount of additive (%wt)	slump test (cm)	amount of water (% of dry mix)	settling time	shrinkage (%)	standard dev.	average dry density (kg/m³)	standard dev.	Difference in shrinkage (%)	Difference in dry density (%)
Reference Mortar 3	**---**	**---**	**---**			**1-2**	**0.8**	**0.2**	**1712**	**17**		
Ka060100-210021	Mo	0	2	17	n.a.	2	1.2	0.5	1643	12	49	-4
Ka060100-210051	Mo	0	5	15.9	n.a.	2	1.8	0.4	1620	9	128	-5
Ka060100-210151	Mo	0	15	15.8	n.a.	2	2.9	0.2	1631	6	274	-5
Ka060100-210201	Mo	0	20	16.8	n.a.	2	2.8	0.1	1654	5	254	-3

7.1.1 Shrinkage

The shrinkage of mortars stabilized with biopolymers depends on the polymer and its amount. The highest shrinkage is seen for molasses-stabilized mortars (Ka060100-210151; 2.9% or Ka060100-210201; 2.8%) and the smallest for mortars stabilized with old and dry cow-dung (Ka120201-221061; 0%). However, it is important to underline that mortars with Molasses have a higher amount of sand and no fibres as the addition of fibres with Molasses lead to the decomposition of the fibres and very weak and crumbly material. Therefore, the highest shrinkages are seen on mortars stabilized with decomposition juice (Ka020101-221051, 2.5%, Ka020101-221101, 2.4%) for mortars based on Reference Mortar 1 and on mortars stabilized with casein (Ka150201-22102; 2.9%) and dung (Ka070201-221111; 2.8%) for mortars based on Reference Mortar 2. On the other hand, the lowest shrinkage is seen for mortars stabilized with flour paste, linseed oil and mayonnaise.

7.1.2 Density

The density of mortars stabilized with biopolymers is not really impacted by the addition of biopolymers – variations are usually between +1.5% and -1.5%, meaning that they are comprised in the variation of the Reference Mortar. The highest density is measured for mortars stabilized with molasses (Ka060100-210201; 1654 kg/m³; -3.4%) or with fermented juice of straw (Ka090101-221301, 1606 kg/m³; +2.2%) and fermented juice of hay (Ka020101-221012, 1656 kg/m³; +5.4%) for mortars made with Grey Sand and for mortars stabilized with casein (Ka150201-22105; 1685 kg/m³; +2.9%) for mortars made with Yellow Sand. The lowest density is measured for flour paste stabilized mortars (Ka040101-221351; 1398 kg/m³: -11%) for mortars made with Grey Sand and for cow dung stabilized samples (Ka120201-221061; 1390 kg/m³; -8.5%) for mortars made with Yellow Sand. However, as molasses-based mortars have no fibres included in the mix, a higher density is expected and therefore, their density should be compared to the density of the Reference Mortar 3. Therefore, despite their high density, molasses reduce the density of the mortars.

Additives impact density in different manners; either by reducing the shrinkage and therefore reducing the density (e.g. flour paste or oils) or by their action during drying (e.g. molasses). However, they are some specific large variations of density due to the type of additive which by itself and its amount changes the composition of the mix (e.g. cow-dung and its large amount of fibres).

7.1.3 Impact on the physical properties of mortars classified per additive

As can be seen from the literature review, only partial results and often contradictory results are available on the behaviour of earth mortars stabilized by biopolymers. However, below the impact of the different additives used and the comparison with the literature when existing is given.

7.1.3.1 Fermented fibres juice (cellulose)

The usage of fermented fibres is difficult to apprehend as the results are different depending on the type of fermentation but also on the specimens. Their impact is summarized in Figure 7-1. From the results, it seems that fermented fibre juice has an adverse effect on shrinkage (increase of shrinkage with an increasing amount of juice) except in the case of straw-washing water (Ka090101-221301). The impact of fermented fibre juice is negligible on the density of earth mortars as related by Guiheneuf et al. (2019a).

The differences between the fermented fibre juice and the straw washing water are the type and duration of decomposition and the type of fibres. It seems that the long anaerobic decomposition of hay as made during this research has a higher but adverse impact than the aerobic decomposition of straw.

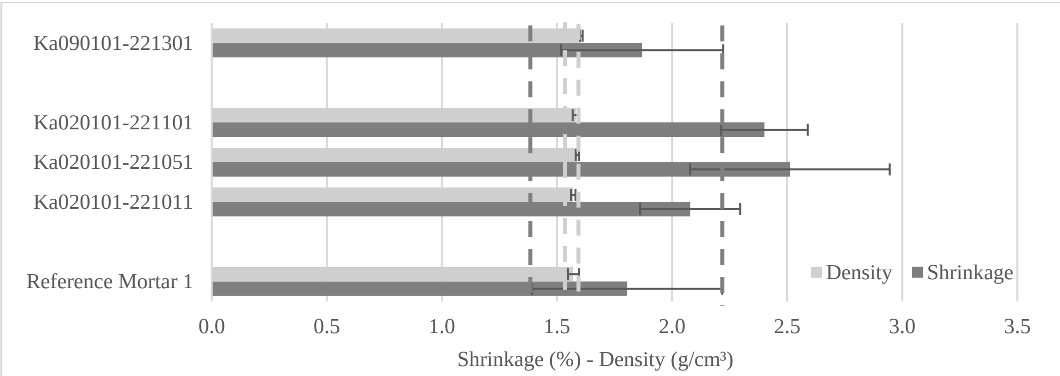

Figure 7-1: Impact of the fermented fibres juice on physical properties of earth mortars

7.1.3.2 Molasses (sugar)

The impact of the addition of molasses is summarized in Figure 7-2. Increasing the amount of molasses increases the shrinkage – until 174% compared to the Reference

Mortar 3 but only 2.9% of maximum shrinkage for 15% molasses – which is just below the 3% limit of the German Standard (DIN18947, 2013).

The increase in shrinkage by the addition of molasses is probably due to the drying behaviour of the molasse itself which is a sugary material and shrinks a lot while drying. Moreover, the drying duration of the earth mortars stabilized with molasses was much longer than with any other additive and for high content of molasses, the surface stayed soft even after 2 months.

The density varies from 1620 kg/m³ for 5% molasses and 1654 kg/m³ for 20% molasses however with a large spread between the specimens. Despite the large difference in shrinkage – 1.2% for 2% molasses and 2.9% for 15% molasses, the density is only slightly impacted with a decrease of 5% compared to the mortar without molasses.

No other author has studied the impact of molasses on the physical properties of earth mortar, however, Pinto et al. (2014) in their study of sugar-stabilized mortar found an increase in density for an increasing amount of sugar.

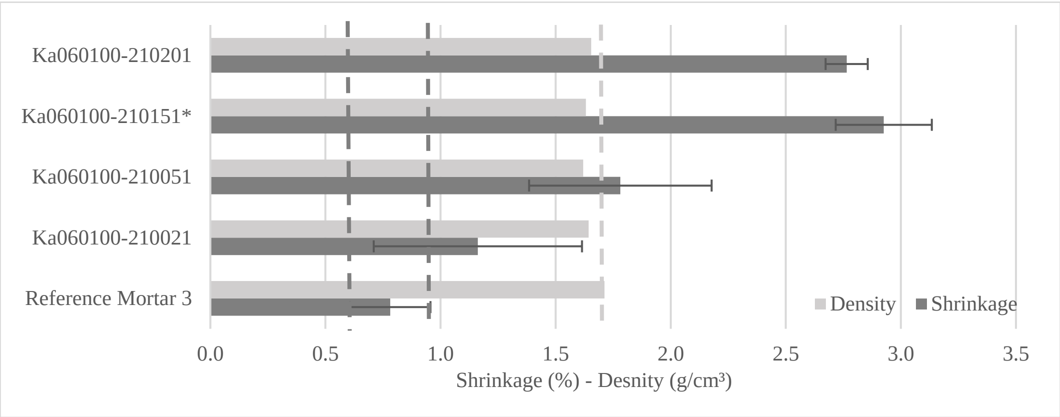

Figure 7-2: Impact of the addition of molasses on the physical properties of earth mortars

7.1.3.3 Flour Paste (starch)

The impact of Flour Paste is summarized in Figure 7-3. The addition of Flour Paste reduces the shrinkage compared to the Reference Mortar and all mortars stabilized with flour paste have a shrinkage varying between 1.2% and 1.4% if the outliers in shrinkage are omitted. The shrinkage is smaller than the 1.8% of the Reference Mortar, in opposition to the literature (Alhaik et al., 2017; Lagouin et al., 2019; Lagouin, Laborel-Préneron, et al., 2021) which shows a slight increase of volumetric shrinkage and an increasing amount of cracks for mortars made with starch. The addition of flour paste also leads to a decrease in density, probably linked to the decrease in shrinkage. This behaviour has also been shown by Tourtelot et al. (2021) which is using commercial wheat starch.

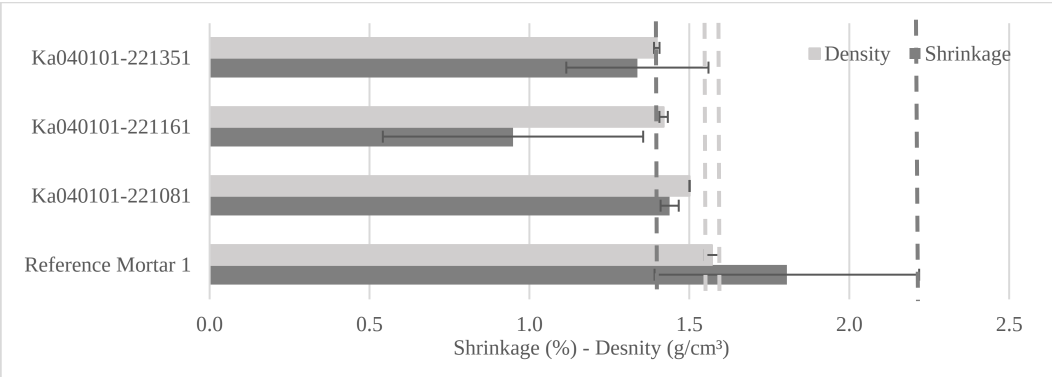

Figure 7-3: Impact of flour paste on the physical properties of earth mortars.
(The impact of the addition of 16% of flour paste is shown on the graph as if the shrinkage was 0.9%, but as it should be taken as 1.2%, its impact is not so high)

7.1.3.4 Hollyhock products (mucilage)

Two types of plant juice based on the hollyhock plant have been tested and the results compared to the Reference Mortar are presented in Figure 7-4. The juice made from the stalk seems to have an adverse impact on the shrinkage whereas the one made from the flowers as it is done traditionally seems to reduce the shrinkage. This is probably because the sticky juice was only extracted from the flower and not from the stalk. The mucilage has therefore a positive impact as reported in the literature for other traditionally used mucilage (Barbeta Solà et al., 2014; Heredia Zavoni et al., 1988; Paul & Changali, 2020) In both cases the density is unchanged.

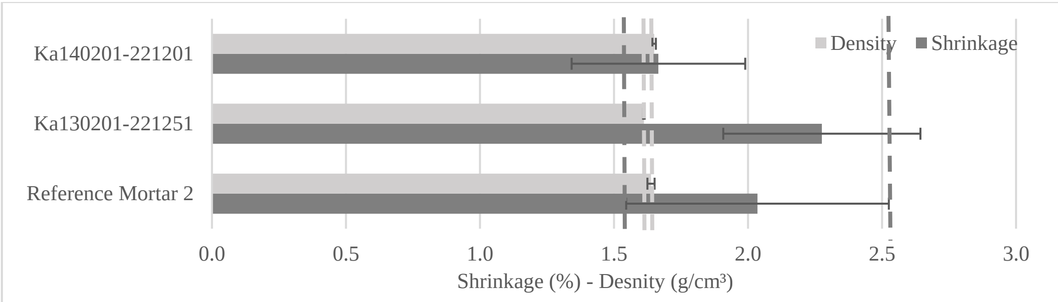

Figure 7-4: Impact of hollyhock flower and stalk juice on the physical properties of earth mortars.

7.1.3.5 Linseed oil and used frying oil

The properties of oil-stabilized mortars are presented in Table 7-1 and the impact of oils is shown in Figure 7-5. The usage of oils reduces the shrinkage of the earth mortar by 30% to 40% for linseed oil (Ka100101-221011 to Ka100101-221061) and 10% to 30% for used frying oil (Ka080101-22121 to Ka080101-22181) independently of the amount of oil used. This behaviour is similar to the one noticed by Colas and Bourges (2013), Brzyski et al. (2020) for a low amount of linseed oil and Gomes-Batitstelle et al. (2020) for castor oil and frying oil. However, Lima et al. (2016) found an increase in shrinkage for a similar amount of linseed oil, probably because the shrinkage of the tested mix was already very low. Similarly to the literature, the density is not impacted by the addition of oil, independently of its amount. The reduction of shrinkage found is probably due to the fact that less water was used to make the mortar as the oil is used as a lubricant, helping the particles to slide and therefore the mix to be homogenised. However, in the case of linseed oil, as it is a very sticky material, there was no reduction in the water amount.

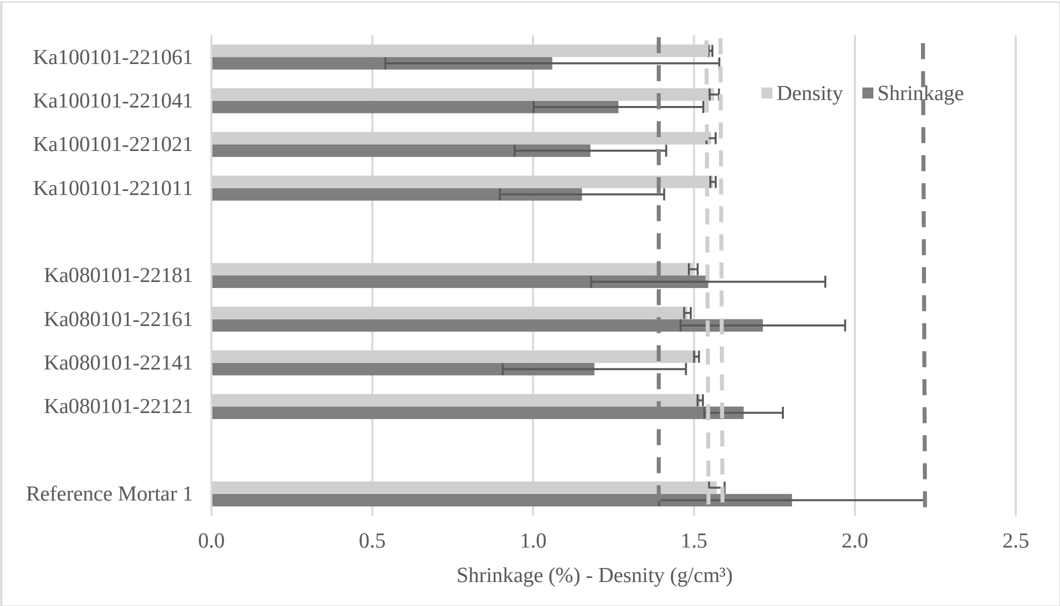

Figure 7-5: Impact of the usage of linseed oil and used frying oil on the physical properties of earth mortars

7.1.3.6 Egg-white (ovalbumine)

The shrinkage of mortars stabilized with egg whites varies from 0.5% (Ka010101-2210051) to 1.3% (Ka010101-221101) but the varşiation of the results of individual specimens is large (Figure 7-6). Therefore, the addition of egg white seems to have only a limited impact on the shrinkage of the earth mortar. An increasing amount of eggs seems to increase slightly the shrinkage, however, it stays in the margin of error determined by the standard deviation of the Reference Mortar. This finding is similar to the one of Colas and Bourges (2013) who used egg white in smaller quantities but also found an increasing shrinkage and Lagouin et al. (2019; 2021) who used powdered ovalbumin.

The results show a density comprised between 1534 kg/m³ (Ka010101-2210051) and 1577 kg/m³ (Ka010101-2210151) which shows a slight increase in density for an increasing amount of egg-white. However, as this increase is very low, in accordance with the literature (Colas & Bourgès, 2013), it can be concluded that the density is not impacted by the addition of egg white.

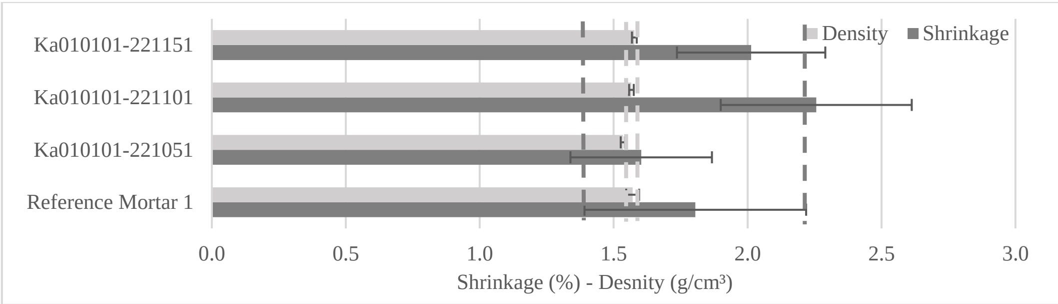

Figure 7-6: Impact of the usage of egg white on the physical properties of earth mortars

7.1.3.7 Casein

Shrinkage and density of casein-stabilized earth mortars are presented in Figure 7-7 and Table 7-1. The shrinkage varies from 1.5% (Ka150201-22110) to 2.9% (Ka150201-22102) and the density varies from 1650 1534 kg/m³ (Ka150201-22102) to 1685 1534 kg/m³ (Ka150201-22105). In accordance with the literature (Lagouin et al., 2019), it seems that the addition of a small amount of casein activated with ammoniac leads to an increase of shrinkage. However, increasing the amount of casein seems to reduce the shrinkage and has no impact on the density. Comparison with the literature is difficult as no sources exist on the subject except documents telling that casein can be/has been used (Vissac et al., 2013, 2016) for reducing shrinkage (Vissac et al., 2013, 2016) without giving any comparison points.

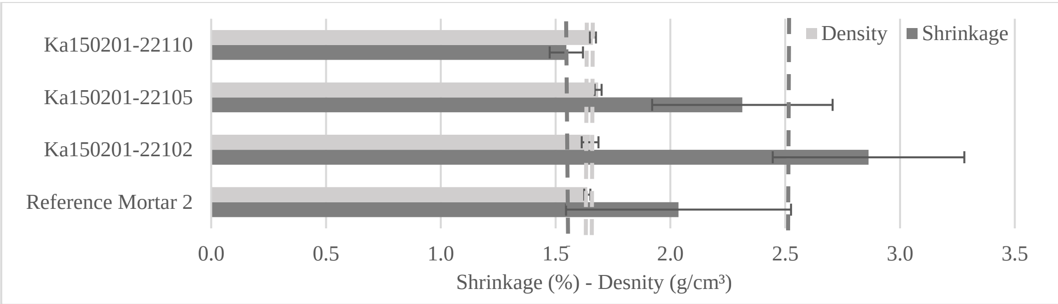

Figure 7-7: Impact of the usage of casein on the physical properties of earth mortars

7.1.3.8 Mayonnaise

The shrinkage of mayonnaise-stabilized mortars varies between 1.3% (Ka110201-221021) and 1.7% (Ka110201-221011). The density of mortars varies from 1610 kg/m³ (Ka110201-221021) to 1637kg/m³ (Ka110201-221011). Figure 7-8 shows the impact of mayonnaise compared with Reference Mortar 2. The addition of mayonnaise seems to have a slight impact on the shrinkage of earth mortars, with an optimum reduction of strength at about 2% of mayonnaise which leads to a shrinkage much lower than the reference shrinkage. A higher amount seems to increase the shrinkage, however, amounts higher than 3% haven't been tested in this work. The density is not impacted by the amount of mayonnaise.

As mayonnaise is mostly constituted from linseed oil and is a very sticky material, probably due to the combination of two materials used as natural glue in painting work, the reduction of shrinkage might be due to the fact that all particles are glued by the additive. However, when more material is added, its own internal strength might also induce shrinkage and therefore increase the shrinkage.

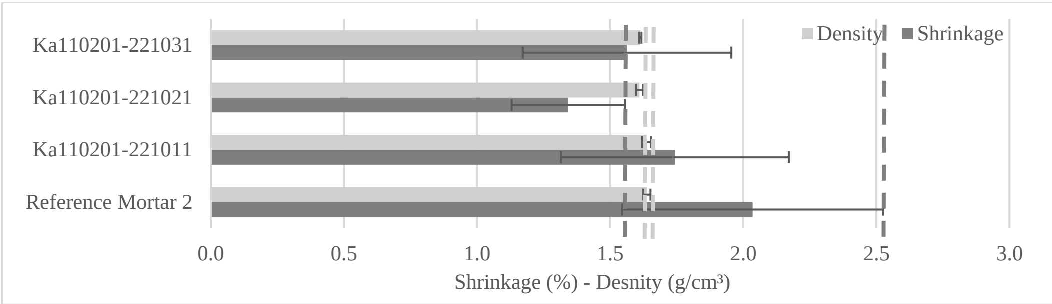

Figure 7-8: Impact of the usage of mayonnaise on the physical properties of earth mortars

7.1.3.9 Cow dung

Figure 7-9 presents the impact of cow dung on the physical properties of earth mortars. More detailed data are presented in Table 7-2. The mortars Ka070201-221031 to Ka070201-221111 presents the impact of adding different amount of fresh cow dung – 3%, 6%, and 11% – with 30 days settling time. The mortar Ka120201-221061 used 6% of dried cow dung.

From these data, it can be concluded that despite the presence of additional fibres, the addition of fresh cow dung increases the shrinkage, especially when the paste settled in humid anaerobic conditions for a long period (mortars Ka070201). Moreover, the shrinkage increases with the addition of more dung. Unexpectedly, despite a large increase in shrinkage (+40%), it seems to be a decrease in density with the addition of more dung, probably due to the higher amount of fibres present in the mortar. Similar behaviour of increased shrinkage is seen while using fermented hay juice, so there might probably be similar process due to the decomposition of fibres.

Conversely, the addition of the same amount of dry dung reduces the shrinkage to none and reduces the density as underlined by Bamogo et al. (2020) and Pachama et al. (2020). This impact might probably be due to the combination of two facts;

- a higher amount of fibres – with a rough surface due to the digestion process undergone in the stomach of the cows (Bamogo et al., 2020) – as the dry dung used doesn't contain any water and therefore there is a better adhesion of the fibres to the matrix as well as a lower amount of dense material (sand, earth)
- no or a low decomposition process while settling as the bacteria of the dung might have been inactivated by the drying process.

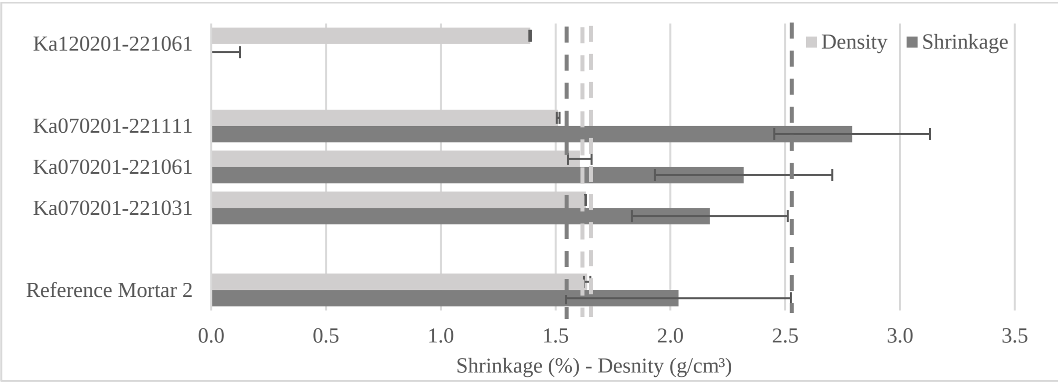

Figure 7-9: Impact of the usage of cow dung on the physical properties of earth mortars.

7.2 Mechanical properties of earth mortars stabilized with biopolymers

This section presents the flexural strength and compressive strength of mortars stabilized with polymers. In the two first parts, the general behaviour of mortars stabilized with polymers is presented and in the third section, the impact of each polymer is reviewed and discussed regarding the literature.

7.2.1 Mechanical strength

The mechanical properties of the mortars stabilized with different natural additives are presented in Table 7-4 for mortars based on Reference Mortar 1, Table 7-5 for mortars based on Reference Mortar 2 and Table 7-6 for the mortars based on Reference Mortar 3

The flexural strength of mortars varies from 0.22 MPa (Ka080101-221031) to 1.29 MPa (Ka020101-221051) for mortars based on Reference Mortar 1, from 0.72 MPa (Ka140201-221201) to 1.07 MPa (Ka050201-22105) for mortars based on Reference Mortar 2 and from 1.61 MPa (Ka060100-210021) to 3.23 MPa (Ka060100-210201) which shows a large variety of results when compared to the values of Reference Mortars (0.77 MPa, 0.88 MPa and 0.60 MPa for Reference Morta 1, 2 and 3 respectively).

The compressive strength varies from 0.33 MPa (Ka080101-221031) to 2.41 MPa (Ka100101-221061) for mortars based on Reference Mortar 1 with also a high strength (2.12 MPa) for mortar Ka020101-221051 which had the highest flexural strength. The flexural strength varies from 1.56 (MPa Ka050201-22110) to 2.69 MPa (Ka110201-221031) for mortar based on Reference Mortar 2 and from 2.48 MPa (Ka060100-210021) to 6.89 MPa (Ka060100-210201) for mortar based on Reference Mortar 3.

From the results, it can be observed that some additives have a large impact – negative e.g. used frying oil (Ka080101) or positive, e.g. linseed oil (Ka100101) – on the strength of earth mortars, whereas others have no impact. Generally, the impacts on the strength are similar for both flexural and compressive strengths and are linked to the density of the samples but some additives such as casein have a different impact on flexural strength and compressive strength.

Figure 7-10 presents the impact of the density on the compressive strength of earth mortars as it has been underlined that there is a correlation between increasing density and increasing strength (section 5.4.2). This is also the case with stabilized mortars, as an increased density means an increased strength. However, the data of some mortars have been taken out of the calculation as they behave in a different manner. Two different trends can be found, which are related to the type of additive.

- Flour paste stabilized mortars present a decreasing compressive strength for an increasing density. Their overall density is lower than the Reference Mortar 1 and as the density decreases with the addition of flour paste, their strength also increases.
- Linseed oil and Mayonnaise additives are two additives based on the usage of linseed oil. Increasing the amount of these additives has no impact or a little impact on the density but it increases the compressive strength and therefore their strength is directly related to the amount of additive used.

In the same way, the same, Flour paste and Mayonnaise have different behaviour than other stabilized mortars when the relation between flexural and compressive strength is accounted for. In Figure 7-11, it can be understood that the only impact of Flour paste is on the flexural strength, as it has a compressive strength similar to the Reference Mortar for all tested amounts of flour paste, but the flexural strength increases for an increasing amount of additive. For the mortars stabilized with Mayonnaise, the opposite is valid. All samples have a slightly increasing flexural strength for an increasing amount of additive but their compressive strength increases largely.

In addition, from Figure 7-10and Figure 7-11 it can also be seen that most stabilized mortars have a similar strength to non-stabilized mortars as most strengths are comprised in the variation margins of Reference Mortar 1 and Reference Mortar 2. It shows that except for specific additives or a specific amount of additives, the addition of polymers has no impact on strength.

Table 7-4: Summary of average mechanical strength of tested earth mortars based on Reference Mortar 1

Mortar name	Type of additive	Amount of additive (%wt)	Average dry density (kg/m³)	Average dry flexural strength (mpa)	*Standard dev.*	Average dry compressive strength (mpa)	*Standard dev.*	Difference of dry flexural strength (%)	Difference of dry compressive strength (%)
Reference Mortar 1	**---**	**---**	**1571**	**0.77**	***0.12***	**1.34**	***0.12***		
Ka010101-221051	Egg	0.5	1534	0.81	*0.11*	1.36	*0.06*	5.2	1.3
Ka010101-221101	Egg	1.1	1566	0.90	*0.04*	1.46	*0.09*	16.9	8.6
Ka010101-221151	Egg	1.6	1577	0.96	*0.10*	1.50	*0.12*	25.3	11.7
Ka020101-221011	D-juice	0.9	1570	0.94	*0.07*	1.52	*0.11*	22.3	13.6
Ka020101-221051	D-juice	4.6	1589	1.29	*0.03*	2.12	*0.09*	67.4	57.9
Ka020101-221101	D-juice	8.9	1583	0.97	*0.06*	1.68	*0.12*	25.8	25.7
Ka040101-221081	Fl paste	8	1501	0.77	*0.07*	1.24	*0.12*	0.0	-7.1
Ka040101-221161	Fl paste	15.7	1420	0.91	*0.02*	1.41	*0.05*	18.4	5.1
Ka040101-221351	Fl paste	35	1398	1.07	*0.03*	1.39	*0.07*	39.5	3.4
Ka080101-22121	U. oil	2.0	1519	0.43	*0.03*	0.66	*0.03*	-44.1	-50.4
Ka080101-22141	U. oil	4.0	1508	0.29	*0.00*	0.43	*0.05*	-61.8	-68.1
Ka080101-22161	U. oil	5.9	1480	0.23	*0.01*	0.33	*0.02*	-69.7	-75.6
Ka080101-22181	U. oil	7.9	1498	0.22	*0.02*	0.33	*0.03*	-71.2	-75.6
Ka100101-221011	linseed oil	1	1559	0.49	*0.02*	1.12	*0.10*	-36.4	-16.1
Ka100101-221021	linseed oil	2	1553	0.66	*0.03*	1.59	*0.11*	-14.2	18.5
Ka100101-221041	linseed oil	4	1563	1.01	*0.10*	2.40	*0.15*	32.0	79.3
Ka100101-221061	linseed oil	6	1551	1.10	*0.08*	2.41	*0.07*	42.6	79.8
Ka090101-221301	straw juice	30	1606	0.97	*0.07*	1.58	*0.08*	26.3	17.6

Table 7-5: Summary of average mechanical strength of tested earth mortars based on Reference Mortar 2

Mortar name	type of additive	amount of additive (%wt.)	average dry density (kg/m³)	average dry flexural strength (MPa)	*standard dev.*	average dry compressive strength (MPa)	*standard dev.*	Difference of dry flexural strength (%)	Difference of dry compressive strength (%)
Reference Mortar 2	**---**	**---**	**0.5**	**0.88**	***0.14***	**1.93**	***0.15***		
Ka070201-221031	Dung	3	1631	0.89	*0.06*	1.81	*0.06*	1	-6
Ka070201-221061	Dung	6	1606	0.87	*0.04*	1.71	*0.14*	-2	-11
Ka070201-221111	Dung	11	1511	0.81	*0.06*	1.58	*0.09*	-8	-18
Ka110201-221011	mayo	1	1637	0.82	*0.02*	1.63	*0.21*	-7	-16
Ka110201-221021	mayo	2	1610	0.85	*0.02*	1.75	*0.07*	-3	-9
Ka110201-221031	mayo	3	1613	0.87	*0.02*	2.69	*0.17*	-1	39
Ka150201-22102	casein	2	1650	1.00	*0.07*	1.78	*0.10*	14	-8
Ka150201-22105	casein	5	1685	1.07	*0.07*	1.87	*0.18*	21	-3
Ka150201-22110	casein	9	1663	0.80	*0.03*	1.56	*0.08*	-9	-19
Ka120201-221061	dry CD	6	1390	0.94	*0.01*	1.91	*0.13*	7	-1
Ka130201-221251	HH stalk	25	1611	0.73	*0.03*	1.74	*0.07*	-17	-10
Ka140201-221201	HH flower	19	1650	0.72	*0.01*	1.99	*0.12*	-18	3

Table 7-6: Summary of average mechanical strength of tested earth mortars based on Reference Mortar 3

Mortar name	Type of additive	Amount of additive (%wt)	Average dry density (kg/m³)	Average dry flexural strength (mpa)	*Standard dev.*	Average dry compressive strength (mpa)	*Standard dev.*	Difference of dry flexural strength (%)	Difference of dry compressive strength (%)
Ref. Mortar 3	**---**	**---**	**1712**	**0.60**	***0.08***	**1.39**	***0.25***		
Ka060100-210021	Molasses	2	1643	1.61	*0.21*	2.48	*0.17*	167	79
Ka060100-210051	Molasses	5	1620	1.70	*0.20*	2.66	*0.21*	181	92
Ka060100-210151	Molasses	15	1631	2.77	*0.15*	5.96	*0.32*	359	330
Ka060100-210201	Molasses	20	1654	3.23	*0.66*	6.89	*0.33*	435	396

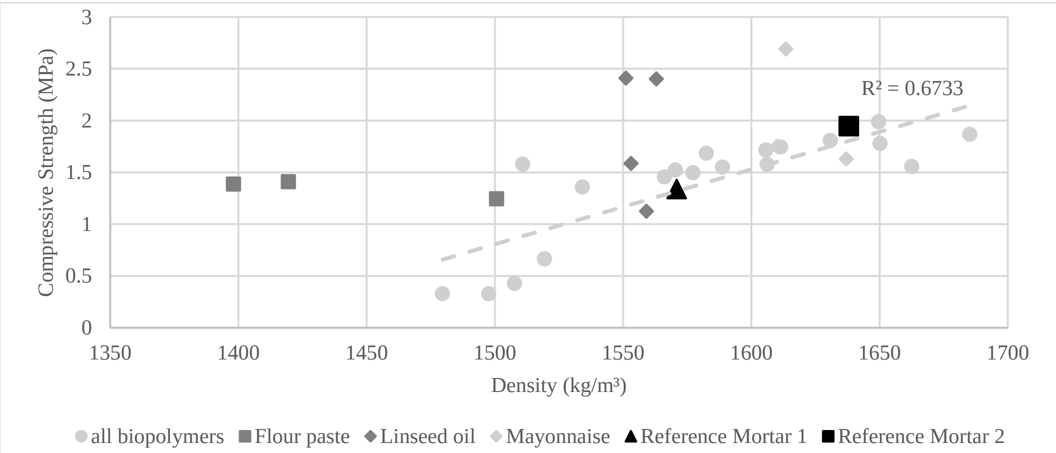

Figure 7-10: Impact of the density on the compressive strength of the stabilized earth mortars. The trendline doesn't account for the mortars stabilized with Flour paste, Linseed oil and Mayonnaise as they have different behaviour.

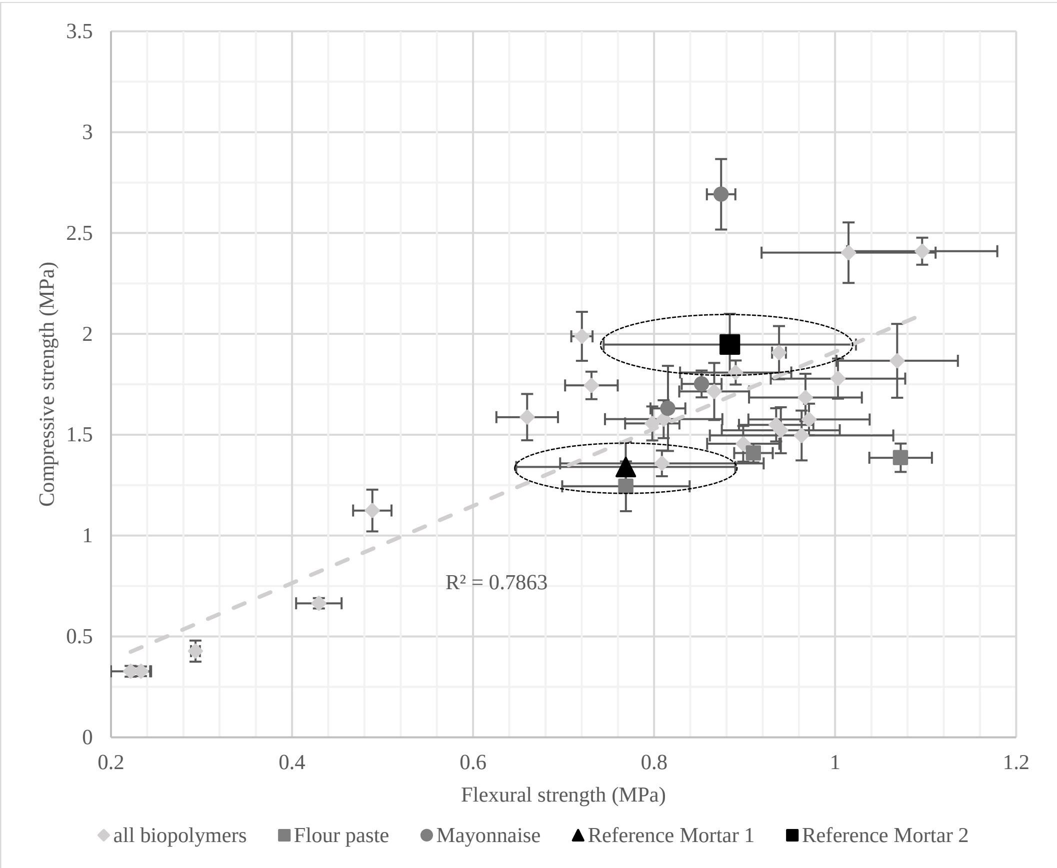

Figure 7-11: Relation between flexural strength and compressive strength of the different earth mortars stabilized with natural additives. The trendline doesn't account for the mortars stabilized with Flour paste and Mayonnaise as they have different behaviour. The dotted lines represent the variation of the value of the reference mortars.

7.2.2 Impact of additives on the mechanical properties of earth mortars classified by additive

This section presents the impact of the tested additives on the flexural strength and compressive strength of earth mortars.

7.2.2.1 Fermented fibres juice (cellulose)

The impact of fermented fibres on mechanical strength is detailed in Table 7-4 and shown in Figure 7-12. The lowest strength for mortars reinforced with fermented hay-juice is found for mortar Ka020101-221011 (0.94 MPa and 1.52 MPa for flexural and compressive strength respectively) and the highest strength is found for mortar Ka020101-221051 (1.29 MPa; 2.12 MPa) both higher than the strength of the Reference Mortar 1. The strength of mortar reinforced with straw washing water is also higher than Reference Mortar 1. Therefore, the addition of fermented hay juice and the addition of fermented straw juice (Ka090101-221301) increases the mechanical strength with an optimum of 5% of fermented juice. Similar findings have been described by Guiheneuf et al. (2019a) however the increase in compressive strength was less significant probably because the optimum amount was not reached.

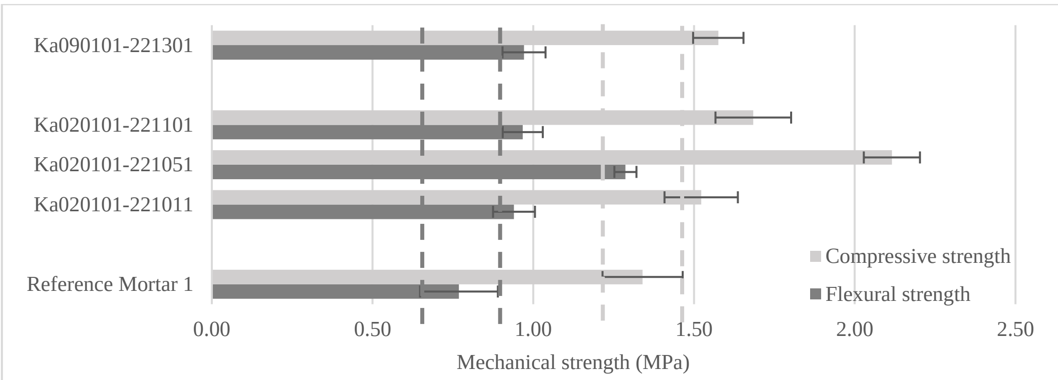

Figure 7-12: Impact of the addition of fermented fibres juice on mechanical properties of earth mortars

7.2.2.2 Molasses (sugar)

The impact of molasses on mechanical strength is detailed in Table 7-4 and Figure 7-13. The flexural strength of mortar stabilized with molasses varies from 1.61 MPa

(+167%) to 3.23 MPa (+435%) which means an increase of 124% between mortar stabilized with 2% of molasses and mortar stabilized with 20%. The same trend is seen for the compressive strength, with a maximum compressive strength of 6.89 MPa (+396%) for 20% of added molasses. This behaviour was expected as it was reported by Vilane (2010) who studied mud bricks stabilized with different amounts of molasses and found similar values for an earth containing about 15% of fines. On the opposite, Rodrigez Cuervo (2020) and Pinto et al. (2014) who studied the impact of sugarcane molasses and domestic sugar on different types of very clayey soil comes out with a decrease in strength of increasing molasses or sugar content. The usage of sugarcane molasses instead of sugar beet molasses as in this study and their difference in composition might explain the very different behaviour.

The large increase in strength seen might be caused by a chemical reaction between the ashes and the clay or the glucose as described by (Pinto et al., 2014).

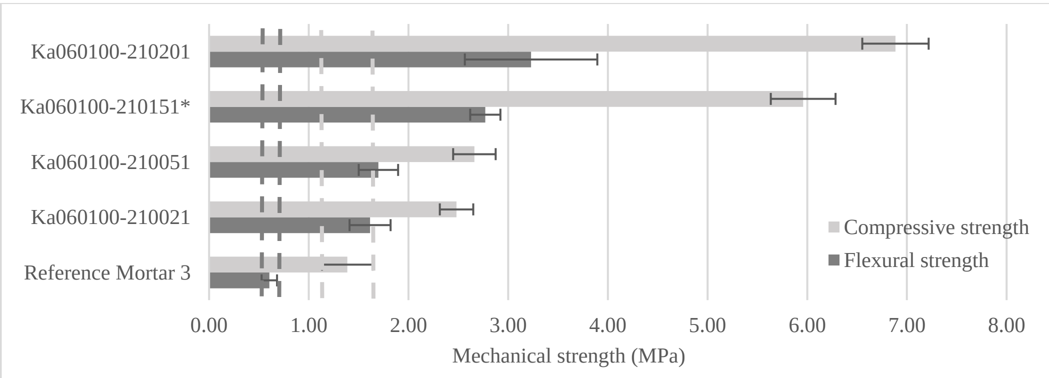

Figure 7-13: Impact of the addition of molasses on the mechanical properties of earth mortars

7.2.2.3 Flour paste (starch)

The impact of the flour paste on mechanical strength is detailed in Table 7-4 and Figure 7-14. The flexural strength of mortars stabilized with flour paste varies from 0.77MPa – similar to the Reference Mortar 1 – and 1.07 MPa for 35% of added flour paste which means an increase of 40% of flexural strength compared to non-stabilized mortar. On the other hand, flour paste seems to have no impact on the compressive strength with strengths varying between 1.24 MPa (Ka040101-221081) and 1.41 MPa (Ka040101-221081) similar to the average strength of the Reference Mortar 1 (1.34 MPa). An increase in flexural strength with the addition of starch has been underlined by Alhaik et al (2017, 2015) however, the authors also noticed an increase in compressive strength which is not the case in this study. This might be due to the fact that the amount of starch used is low despite a high amount of flour paste used, as in the different studies, commercial powdered – and therefore concentrated – starch is used. The impact of the amount of starch used in relation to the amount of clay is also underlined by Lagouin et al. (2021) as the authors would not observe any strength difference while using lower amounts than others (Tourtelot et al., 2021).

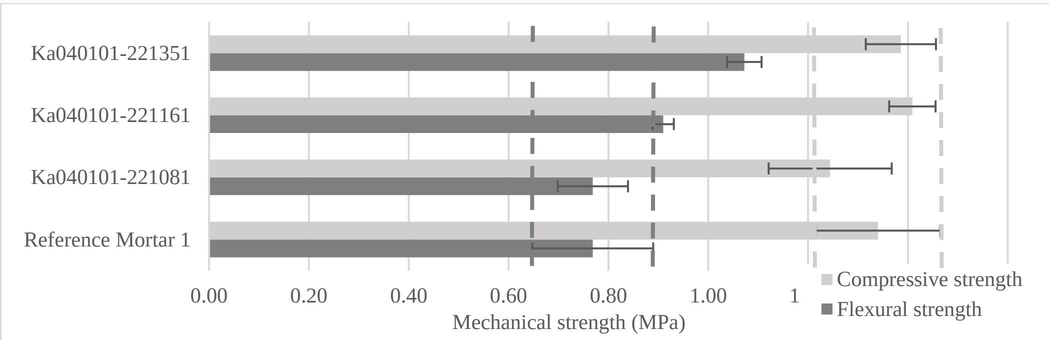

Figure 7-14: Impact of the addition of flour paste on the mechanical properties of earth mortars.

7.2.2.4 Hollyhock products (mucilage)

The impact of hollyhock mucilage on mechanical strength is detailed in Table 7-4. Usage of hollyhock mucilage leads to a decrease in flexural strength for both types but a decrease in compressive strength for the stalk juice and a conservation of the compressive strength of the flower juice.

7.2.2.5 Linseed oil and used frying oil

The impact of oils on mechanical strength is detailed in Table 7-4 and Figure 7-15. As for the physical properties, two different types of behaviour can be observed in mechanical strength.

For mortars stabilized with used frying oil, the flexural strength varies between 0.43 MPa and 0.22 MPa for the mortars with 2% and 8 % of oil respectively and the compressive strength varies between 0.66 MPa and 0.33 MPa for the same amounts of oils. There is a constant loss of strength with an increasing amount of oil in the mortar as has been observed by Gomes Battistelle et al. (2020). The impact of used frying oil is remarkable as it creates a crumbly material, probably preventing the clay particles to bind the other particles while not having the potential of drying oil to create a strong and coherent matrix.

The flexural strength of mortars made with linseed oil increases from 0.49 MPa to 1.10 MPa for 1% and 6% of linseed oil respectively and the compressive strength increases from 1.12 MPa to 2.41 MPa for the same amount of oil. The addition of a small amount of oil – less than 2% - has an adverse effect on the mechanical strength of the mortar, whereas a higher amount leads to a higher strength. This increase in compressive strength has been underlined by Lima et al. (2016) and Guiheneuf et al. (2019a; 2018) for a similar amount of linseed oil. Brzyski et al. (2020) found an increase in flexural strength but a decrease in compressive strength for a low amount of linseed oil varnish as did Tourtelot et al. (2021) for mortars with 1% of linseed oil. The same authors also show that stabilized specimens were having a larger deformation before breaking which was not possible to measure in this work but can explain the better behaviour under flexural strength.

The results of the present study with an amount of linseed related to the amount of clay correspond to the literature showing that there is a minimum ratio of clay/linseed oil necessary for the additive to have an impact on compressive strength (Table 7-7). This minimum ratio seems to be above 0.14.

Table 7-7: Impact of the amount of linseed oil/clay ratio on the strength of earth mortars.

	Clay amount	LO amount	Ratio LO/clay	Impact on flexural strength	Impact on compressive strength
This study	14	1	0.07	-	-
This study	14	2	0.14	-	+
This study	14	4	0.28	+	+
This study	14	6	0.42	+	+
(Tourtelot et al., 2021)	7	1	0.14	n.a.	-
(Guihéneuf et al., 2020)	17	1	0.05	n.a.	=
(Guihéneuf et al., 2020)	17	2	0.10	n.a.	=
(Brzyski & Grudzińska, 2020)	25	1	0.04	+	-
(Brzyski & Grudzińska, 2020)	25	2	0.08	+	-
(Brzyski & Grudzińska, 2020)	25	3	0.12	+	-

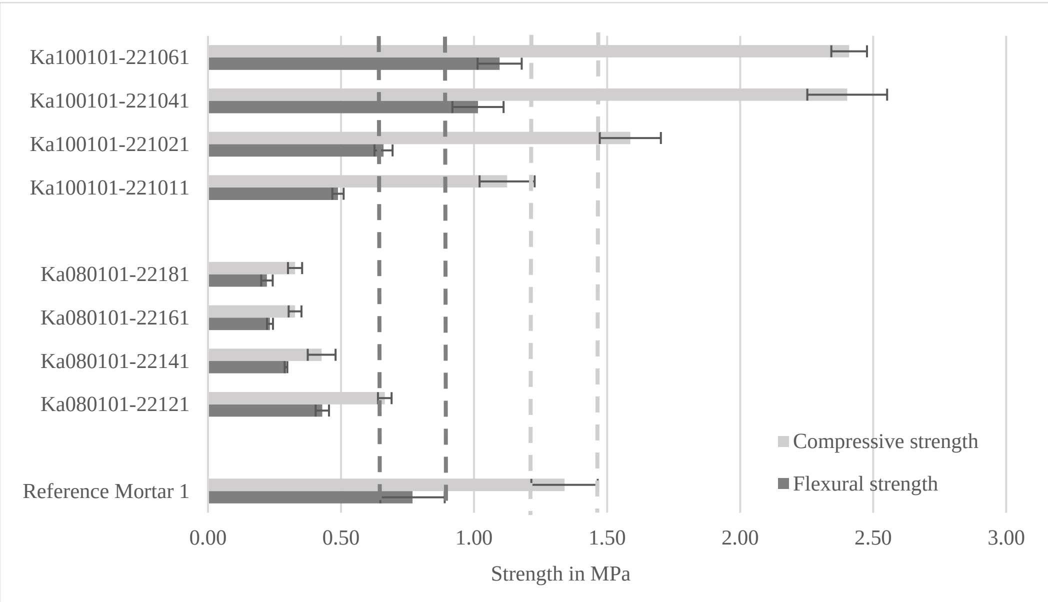

Figure 7-15: Impact of the addition of linseed oil and used frying oil on the mechanical properties of earth mortars. The standard deviation of the reference mortar is represented by the dashed lines.

7.2.2.6 Egg-white (ovalbumine)

The impact of egg white on mechanical strength is detailed in Table 7-4 and Figure 7-16. The lowest average mechanical strength is recorded for mortar Ka010101-221051 (0.5% by weight of dry mix) with a flexural strength of 0.81 MPa and a compressive strength of 1.36 MPa and the highest mechanical strength is recorded for Ka010101-221151 (1.5% by weight of dry mix) with a flexural strength of 0.96 MPa and a compressive strength of 1.50 MPa. For the range of additive used, the results show a constant increase in strength with an increasing amount of egg white.

The results are conformed to the literature as Lagouin et al. (2021) for earth plasters and Ouedraogo (2019; 2021) for compressed earth blocks reported also an increase in strength with the addition of ovalbumin – which is the main polymer contained in egg-white with compressive strength even higher than the one achieved with Portland cement, however, probably due to the low amount of egg white used (i,e. low amount of ovalbumin), the increase of strength is not as important as reported in the cited articles. The maximum increase in the present study is 25% and 12% for flexural strength and compressive strength respectively, whereas, the literature reports a 50% increase in compressive strength for 1% of ovalbumin (Lagouin, Laborel-Préneron, et al., 2021).

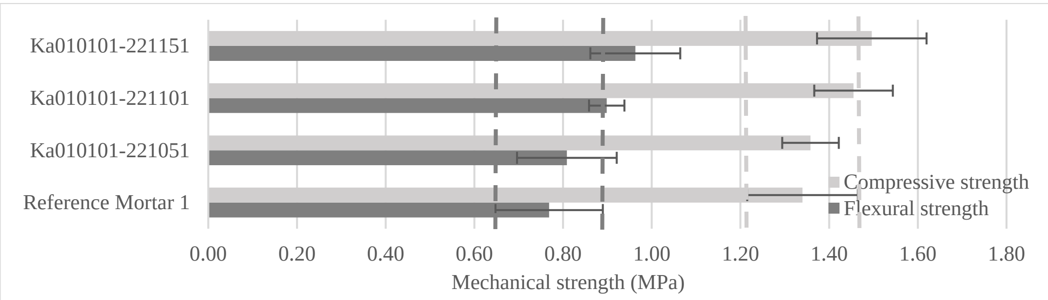

Figure 7-16: Impact of the addition of egg white on the mechanical properties of earth mortars. The standard deviation of the reference mortar is represented by the dashed lines.

7.2.2.7 Casein

The impact of casein on mechanical strength is detailed in Table 7-5 and Figure 7-17. The lowest strengths are measured for mortars stabilized with 10% of casein (Ka150201-22110) with an average flexural strength of 0.80 MPa and average compressive strength of 1.56 MPa, both lower than the reference mortar strength. The maximum strengths are measured for mortar Ka150201-22105 (5% casein) with a flexural strength of 1.07 MPa and compressive strength of 1.87 MPa, lower than the Reference Mortar 2. It seems that the addition of casein reaches an optimum with 5% of the dry mix but this optimum is only a low improvement of the flexural strength (+20%) and the conservation of the compressive strength (-3%).

These results are different from the ones in the literature as according to the ratio of clay/casein, it has been found a large increase or decrease in compressive strength (Guihéneuf et al., 2019a; Tourtelot et al., 2021). The difference between this study and the literature – in addition to a different amount – is the usage of homemade casein directly extracted from milk which is different from commercial ones used by author authors. Therefore, generalization of the impact of casein is difficult to assess. Moreover, Ouedraogo (2019) also states that the impact of casein is very dependent on the type of clay used.

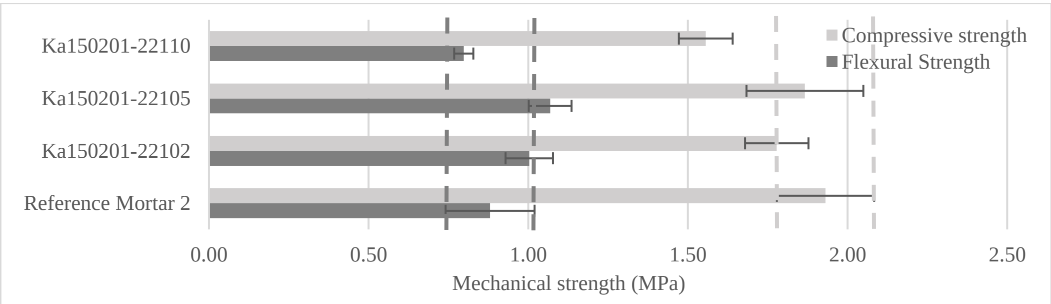

Figure 7-17: Impact of the addition of casein on the mechanical properties of earth mortars

7.2.2.8 Mayonnaise

The impact of mayonnaise on mechanical strength is detailed in Table 7-5 and Figure 7-18. The lowest strengths are recorded for the mortar Ka110201-221011 (1% of mayonnaise) with a flexural strength of 0.82 MPa and compressive strength of 1.63 MPa. The highest strengths are recorded for the mortar Ka110201-221031 (3% of additive) with a flexural strength of 0.87 MPa and compressive strength of 2.69 MPa. These results show that the addition of mayonnaise has almost no impact on the flexural strength as the variations of strength are inside the limits of the standard deviation of the Reference Mortar 2 and the limits of the stabilized mortars also. Conversely, the addition of mayonnaise seems to increase the compressive strength for a high amount – which correspond to the amount described by Rijven (2009) – but the addition of a low amount seems to have no impact on the strength.

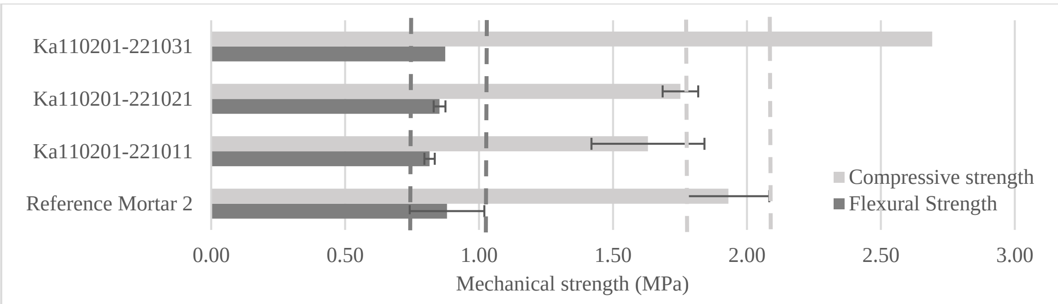

Figure 7-18: Impact of the addition of mayonnaise on the mechanical properties of earth mortars

7.2.2.9 Cow dung

The impact of cow dung on mechanical strength is detailed in Table 7-5 as well as shown in Figure 7-19.

The lowest strength is determined in mortars with the highest amount of fresh cow dung (Ka070201-221111) whereas the highest strength is determined for mortars with 3% of cow dung (Ka070201-221031). Moreover, it can be observed that the addition of fresh cow dung decreases the strength of the mortars. On the opposite, when 6% of dry cow dung is used (similar amount used for Ka070201-221061), it can be observed that the strength is very similar to the strength of the Reference Mortar 2, with a very slight increase of flexural strength and a slight decrease of compressive strength.

Fresh cow dung has been tested for compressed earth bricks by Katale and Kamara (2014) who reported a similar loss of strength for amounts of dung larger than 10%. Other literature on cow dung only focused on dried dung for earth mortars with a large amount of clay – above 35% - except the article from Vilane (2010) who used earth with 10% of clay. As explained by Millogo et al. (2016) and Bamogo et al. (2020), the increase in strength in mortar stabilized with cow dung is due to the reaction between the dung and the kaolin in an alkali solution. Therefore, because of the low amount of clay used in the reference mortar in this study – close to the amount used by Vilane – it is possible that the reaction is not developing, preventing any strength improvement. Moreover, as the content of the dung depends on the cow fodder, it is difficult to reflect the results of one study to another.

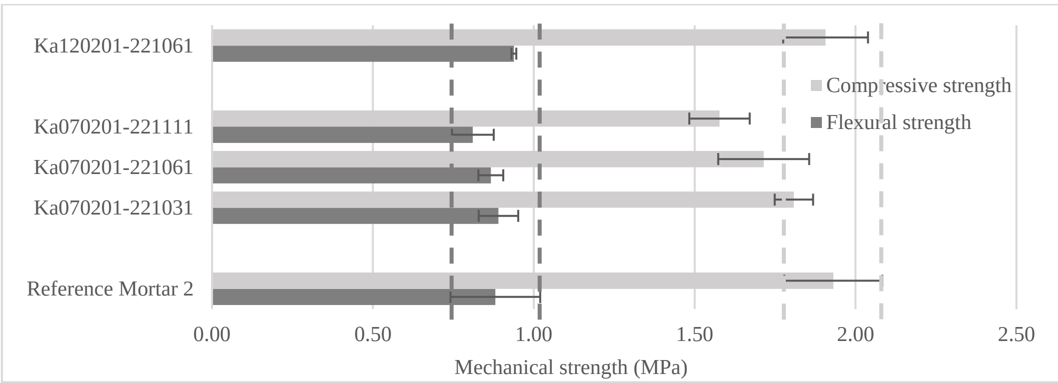

Figure 7-19: Impact of the addition of fresh and dry cow dung on the mechanical properties of earth mortars.

7.3 Surface properties of earth mortars stabilized with biopolymers

The surface properties of stabilized earth mortars are presented in Table 7-8 to Table 7-10, depending on the reference mortar they are based on the impact of the stabilizer is shown in Figure 7-20 and Figure 7-21 by plotting the properties of the reference mortars and the deviation of the values together with the average value and standard variation of the stabilized mortars.

The general surface properties of stabilized earth mortars are first presented and discussed then the impact of each stabilizer and its amount on the surface properties of earth mortars is determined. In this discussion, no reference to previous work is given as no other authors worked with similar materials and did similar tests on them.

7.3.1 Surface water absorption

The surface water absorption of stabilized earth mortars varies from 0.1 g/m²·s (Ka080101-22181; -100%) to 27.7 g/m²·s (Ka070101-441061, +6%) for mortars made with Grey Sand, from 1.0 g/m²·s (Ka110201-221011; -94%) to 17.3 g/m²·s (Ka020201-221054; no change) for mortars made with Yellow Sand and from 1.0 g/m²·s (Ka060100-210201; -96%) to 16 g/m²·s (Ka060100-210021; 45%) for mortars without fibres and only 5 mortars present an increase or a very low decrease (inferior to 5%) that would mean that the change is not significant.

Another general comment is that the water absorption decreases with an increasing amount of stabilizer for almost all tested stabilizers and the mortars presenting no significant changes are made with a low content of stabilizer. Therefore, it can be concluded that the addition of a sufficient amount of the tested stabilizer increases the water resistance of the surface of the samples when water is applied for a short period.

7.3.2 Surface cohesion

The surface cohesion as determined with the peeling test shows amount of material loss varying from 542 μg/cm² (Ka100101-221061; -76%) to 4722 μg/cm² (Ka080101-22141; +114) for mortars reinforced with Grey Sand, from 375 μg/cm² (Ka150201-22102; -69) to 4964 μg/cm² (Ka020201-221052; +294) for mortars reinforced with Yellow Sand and from 167 μg/cm² (Ka060100-210201; -74%) to 620 μg/cm² (Ka060100-210021; 3%). The range of variation shows a very different impact of stabilizers in terms of surface cohesion with some stabilizers almost suppressing any loss of material – e.g. molasses or mayonnaise – whereas on the opposite other stabilizers will decrease the surface cohesion and produce very unstable mortars – used oil mostly, as the high value found for mortar Ka020201-221052 might not be representative of the mortar's behaviour – or have no impact on the surface cohesion.

Table 7-8: Surface properties of stabilized earth mortars reinforced with Grey Sand

Mortar Name	Additive type	Density (kg/m²)	Surface water absorption (g/m²·s) for 90 s.	*Change to reference (%)*	Peeling test Material loss (µg/cm²)	*standard dev.*	*Change to reference (%)*
Reference Mortar 1	**Chaff**	**1571**	**26.2**		**2214**	***1260***	
Ka010101-221051	Egg	1534	25.4	*-3*	1963	*454*	*-11*
Ka010101-221101	Egg	1566	22.5	*-14*	1657	*289*	*-25*
Ka010101-221151	Egg	1577	22.6	*-14*	1722	*240*	*-22*
Ka020101-221011	D-juice	1570	24.2	*-8*	2352	*1230*	*6*
Ka020101-221051	D-juice	1589	19.8	*-25*	1311	*237*	*-41*
Ka020101-221101	D-juice	1583	19.6	*-25*	1269	*330*	*-43*
Ka040101-221081	Fl paste	1501	19.7	*-25*	1704	*378*	*-23*
Ka040101-221161	Fl paste	1420	19.0	*-27*	1481	*310*	*-33*
Ka040101-221351	Fl paste	1398	15.0	*-43*	1019	*381*	*-54*
Ka080101-22121	U. oil	1519	25.4	*-3*	3880	*2910*	*75*
Ka080101-22141	U. oil	1508	10.0	*-62*	4722	*834*	*113*
Ka080101-22161	U. oil	1480	0.7	*-97*	3565	*1262*	*61*
Ka080101-22181	U. oil	1498	0.1	*-100*	3167	*1660*	*43*
Ka100101-221011	Linseed oil	1559	5.9	*-77*	1306	*865*	*-41*
Ka100101-221021	Linseed oil	1553	3.5	*-87*	759	*277*	*-66*
Ka100101-221041	Linseed oil	1563	1.2	*-95*	787	*266*	*-64*
Ka100101-221061	Linseed oil	1551	0.9	*-97*	542	*292*	*-76*
Ka090101-221301	Straw juice	1606	24.4	*-7*	2000	*1024*	*-10*

Table 7-9: Surface properties of stabilized earth mortars reinforced with Yellow Sand

Mortar Name	Additive type	Density (kg/m²)	Surface water absorption (g/m²·s) for 90 s.	Change to reference (%)	Peeling test Material loss (µg/cm²)	*standard dev.*	*Change to reference (%)*
Ref. Mortar 2	**---**	1638	17.3		1192	404	
Ka070201-221031	Dung	1631	17.3	0	889		-25
Ka070201-221061	Dung	1606	11.5	-33	750		-37
Ka070201-221111	Dung	1511	13.7	-21	2500		110
Ka110201-221011	Mayo	1637	11.6	-33	1361	306	14
Ka110201-221021	Mayo	1610	1.5	-92	986	236	-17
Ka110201-221031	Mayo	1613	1.0	-94	556	139	-53
Ka150201-22102	Casein	1650	n.a.	n.a.	375	42	-69
Ka150201-22105	Casein	1685	11.3	-35	972	333	-18
Ka150201-22110	Casein	1663	11.6	-33	486	69	-59
Ka120201-221061	Dry CD	1390	15.6	-10	806	300	-32
Ka130201-221251	HH stalk	1611	17.1	-1	986	319	-17
Ka140201-221201	HH flower	1650	14.3	-17	1014	431	-15

Table 7-10: Surface properties of stabilized earth mortars reinforced with Sand 3

Mortar Name	Additive type	Density (kg/m²)	Surface water absorption (g/m²·s) for 90 s.	Change to reference (%)	Peeling test Material loss (µg/cm²)	*standard dev.*	*Change to reference (%)*
Ref. Mortar 3	---	1712	29.3		639	135	
Ka060100-210021	Molasses	1643	16.0	-45	620	272	-3
Ka060100-210051	Molasses	1620	4.5	-85	602	284	-6
Ka060100-210151	Molasses	1631	3.3	-89	361	208	-43
Ka060100-210201	Molasses	1654	1.0	-96	167	126	-74

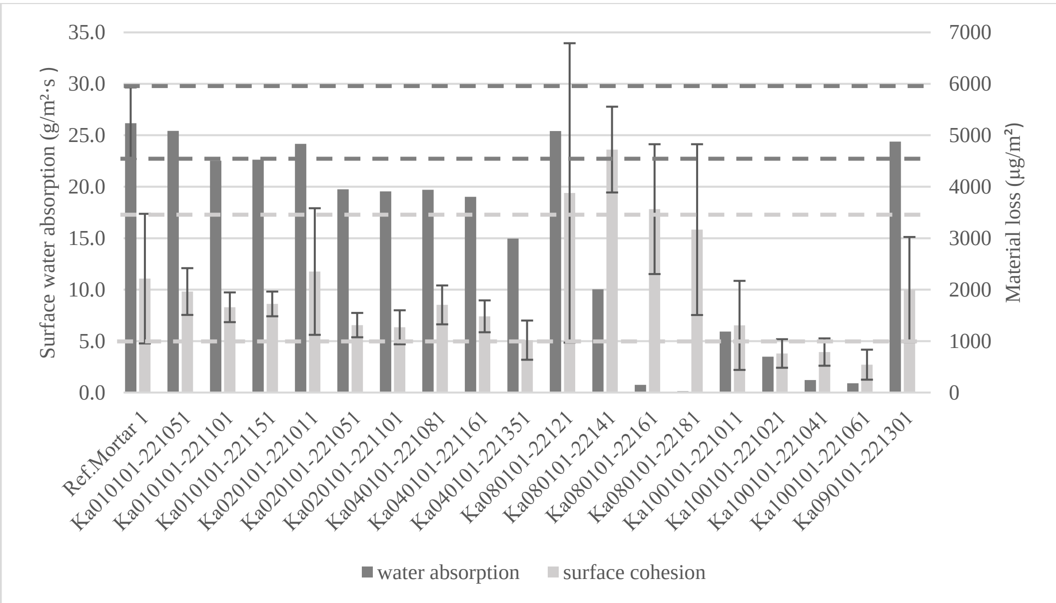

Figure 7-20: Impact of the stabilizers on the surface properties of earth mortars based on Reference Mortar 1

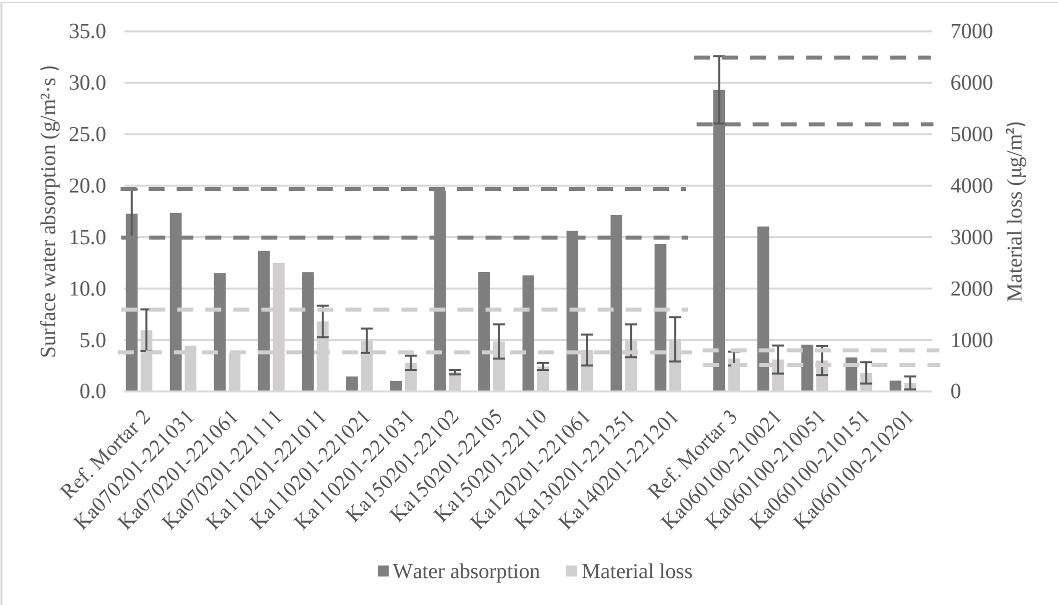

Figure 7-21: Impact of the stabilizers on the surface properties of earth mortars based on Reference Mortar 2 (left part of the graph) and on Reference Mortar 3 (right part of the graph)

7.3.3 Impact of stabilizer on surface properties

In this section, the impacts of the different stabilizers tested which have an impact on the surface property are discussed regarding the test results and the existing literature.

7.3.3.1 Fermented fibres (cellulose)

The surface properties of mortars stabilized with fermented fibres are shown in Table 7-8 and the impact of the fermented fibres as a change compared to the reference mortar is shown in Figure 7-22.

The surface water absorption of mortars stabilized with fermented hay juice varies from 19.6 g/m²·s (Ka020101-221101) to 24.2 g/m²·s (Ka020101-221011) and the material loss varies from 2352 µg/cm² to 1259 µg/cm² for the same samples, therefore showing a decrease in water absorption and an increase in surface resistance for an increasing amount of stabilizer. However, the increase in surface resistance is low compared to the variation of results found for the different specimens tested and for Reference Mortar 1 (Figure 7-20)

The impact of the washing water of straw (mortar Ka090101-221301) seems negligible as the water absorption and the material loss are reduced in average value but the decrease is low and inside the variations of the Reference Mortar 1 (Figure 7-20).

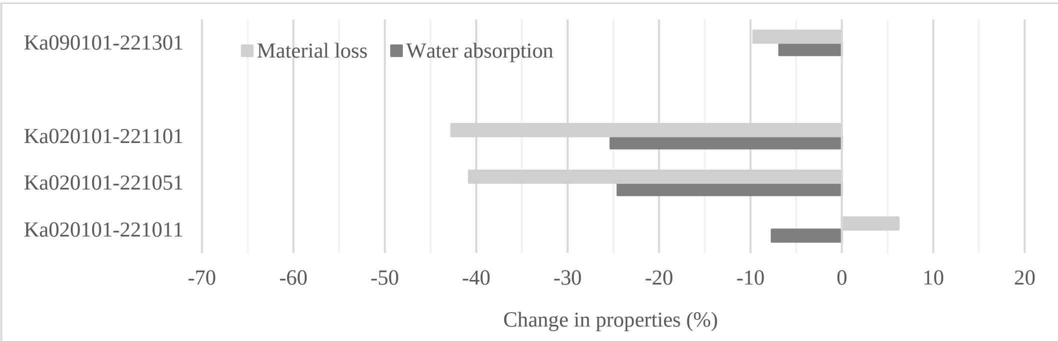

Figure 7-22: Impact of the addition of fermented fibres on the surface properties of earth mortar

7.3.3.2 Molasses (sugar)

The surface properties of mortars stabilized with molasses are shown in Table 7-10 and the impact of the molasses as a change compared to the reference mortar is shown in Figure 7-23.

The surface water absorption of mortars stabilized with molasses varies from 1.0 $g/m^2 \cdot s$ (Ka060100-210201) to 16.0 $g/m^2 \cdot s$ (Ka060100-210021) and the material loss varies from 167 $\mu g/cm^2$ to 620 $\mu g/cm^2$ for the same samples, therefore showing a decrease in water absorption and an increase in surface resistance for an increasing amount of stabilizer. The increase in molasses amount prevents almost any water absorption for samples stabilized with 20% of molasses (Ka060100-210201) whereas a low amount of molasses (2%) already reduces the water absorption by almost 50%. The impact of molasses on the material cohesion is not as important as more than 15% of molasses is needed to find a significant change in the material loss – i.e. a change lower than the possible variation of Reference Mortar 3 (Figure 7-21).

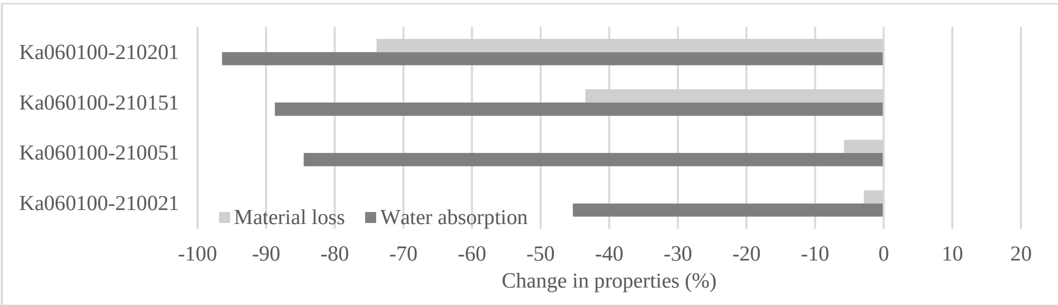

Figure 7-23: Impact of the addition of molasses on the surface properties of earth mortars

7.3.3.3 Flour paste (starch)

The surface properties of mortars stabilized with flour paste are shown in Table 7-8 and the impact of the flour paste as a change compared to Reference Mortar 1 is shown in Figure 7-24.

Figure 7-24 shows a decreasing amount of water absorption and material loss for an increasing amount of flour paste. A small amount of flour paste such as 8% (Ka040101-221081) already shows an improvement of the surface properties of more than 20% whereas the loss of material decreases by more than 50% for the addition of 35% of flour paste. Since the flour paste is mostly constituted of water, even 35% of flour paste is a small amount of flour and even less starch. Then working directly with starch would increase the cohesion of the mortar and prevent water absorption even more. The works of Colas & Bourges (2013) and Ouedraogo et al. (2019) suggest the same conclusion as they studied respectively the impact of flour paste as surface protection of plaster and wheat starch as an additive for compressed earth block. Both authors found a large decrease in the water absorption of the sample tested, either following a similar method of contact with a sponge or by immersing a specimen in water.

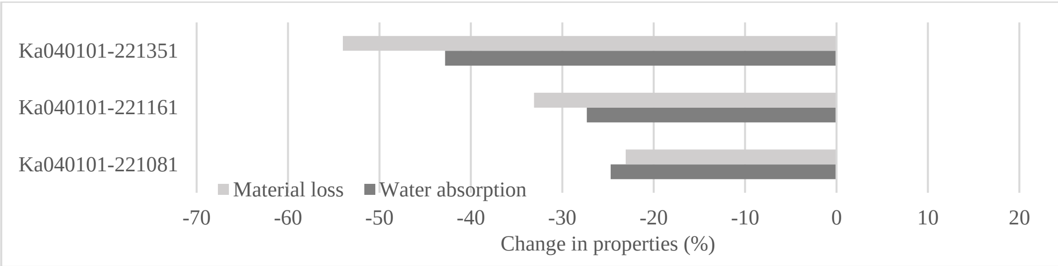

Figure 7-24: Impact of the addition of flour paste on the surface properties of earth mortars

7.3.3.4 Linseed oil and used oil

The surface properties of mortars stabilized with oils are shown in Table 7-8 and the impact of the oils as a change compared to the reference mortar is shown in Figure 7-25.

The water absorption of samples stabilized with oil is strongly impacted by oils, as both types of mortars have a very large decrease in water absorption – more than 60% – except for mortar with 2 % used oil. Therefore the addition of oils – which probably creates a hydrophobic film around the clay particles Guiheneuf et al. (2020) – prevents the water to enter the mortar.

On the other hand, the type of oil is important in terms of cohesion. The usage of used frying oil – which is a non-drying oil – has an adverse impact on the cohesion with samples even losing more materials than the Reference Mortar 1 whereas the mortars stabilized with linseed oil see an increase in cohesion even with 1% of oil added (Ka100101-221011). Therefore, it is important to use an oil which has drying properties to increase the cohesion of the mortar.

Similar results have been found by Colas & Bourges (2013) on plasters stabilized with linseed oil. The addition of even a small amount of oil decreases both the water absorption and the material loss in similar tests. However, according to the author, the increase in cohesion is not a permanent effect as after several applications of the band – during the test – on the same surface, the cohesion is loosened and more material is lost, however, still less than the reference mortar.

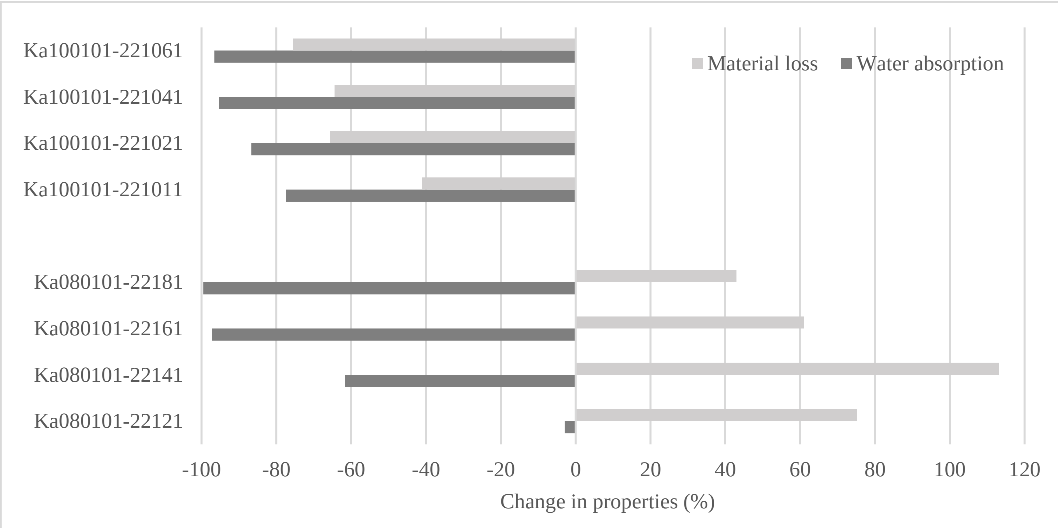

Figure 7-25: Impact of the addition of used frying oil and linseed oil on the surface properties of earth mortars

7.3.3.5 Egg white (ovalbumine)

The surface properties of mortars stabilized with egg white are shown in Table 7-8 and the impact of the egg white as a change compared to the reference mortar is shown in Figure 7-26.

The surface water absorption varies between 22.6 g/m²·s (Ka010101-221151) and 25.4 g/m²·s (Ka010101-221051) and the material loss varies between 1657 μg/cm² (Ka010101-221101) and 1963 μg/cm² (Ka010101-221051). The addition of egg white in the mortar only slightly reduces the water absorption – about a 12% reduction for 1% and 1.5% of egg white. This result was expected and is similar to the one of Colas & Bourges (2013) who tested the addition of 1 egg white for 5L of fresh mortar which is equivalent to mortar Ka010101-221051. However, because probably a different type of earth (Kim & Oh, 2019), a higher quantity of egg white was necessary to achieve results. The addition of egg white also increases the cohesion of the mortar, but only slightly compared to other tested stabilizers.

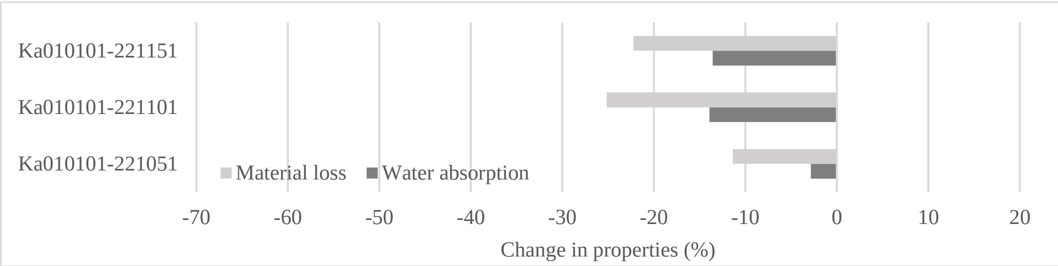

Figure 7-26: Impact of the addition of egg whites on the surface properties of earth mortars

7.3.3.6 Casein

The surface properties of mortars stabilized with casein are presented in Table 7-9 and the impact of the casein as a change compared to the reference mortar is shown in Figure 7-27.

There seem not to be a clear impact of casein on the surface properties of earth mortar, however, the addition of casein in small quantity seems to increase the water absorption whereas a higher quantity decreases it. Similar results have been found by Guiheneuf et al. (2019) on the increase of capillarity absorption.

Opposingly, the surface cohesion is improved by the addition of casein which is often the reason declared for its usage (Vissac et al., 2013). However, it seems that the usage of a high quantity of casein decreases the cohesion however, in the quantity tested it is still higher than Reference Mortar 2.

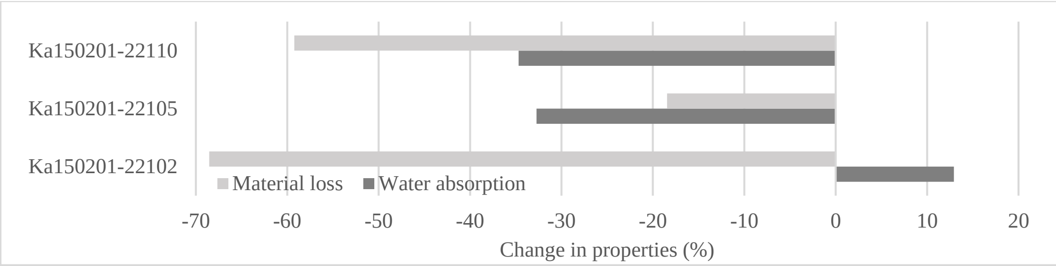

Figure 7-27: Impact of the addition of casein on the surface properties of earth mortars

7.3.3.7 Mayonnaise

The surface properties of mortars stabilized with mayonnaise are shown in Table 7-9 and the impact of the mayonnaise as a change compared to the reference mortar is shown in Figure 7-28.

The water surface absorption of mayonnaise-reinforced mortars varies from 11.6 to 1.0 for Ka110201-221011 and Ka110201-221031 respectively which are lower amounts than the absorption by the Reference Mortar 2. The addition of mayonnaise almost totally prevents the absorption of water. The addition of mayonnaise enhances the surface cohesion of the mortar, with a reduction of 50% of the weight loss despite a low amount of stabilizer used (maximum 3% for Ka110201-221031) but a very low amount of additive (less than 2 %) seems to lower the surface cohesion.

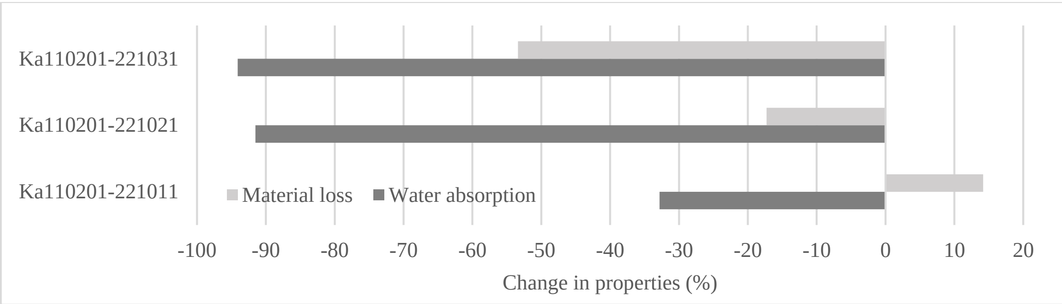

Figure 7-28: Impact of the addition of mayonnaise on the surface properties of earth mortars

7.3.3.8 Cow dung

The surface properties of mortars stabilized with cow dung are summarized in Table 7-9 and the impact of the cow dung as a change compared to the reference mortar is shown in Figure 7-29.

The cow dung has been used fresh (Ka070201) and dried (Ka120201). Despite these different possibilities, no clear impact on the surface properties is seen. Some mortars seem to have a lower water absorption and others have not been impacted, some mortars have an increased resistance to the peeling test but one has a very low resistance. Therefore, more testing needs to be done to determine the impact of cow dung on the surface properties.

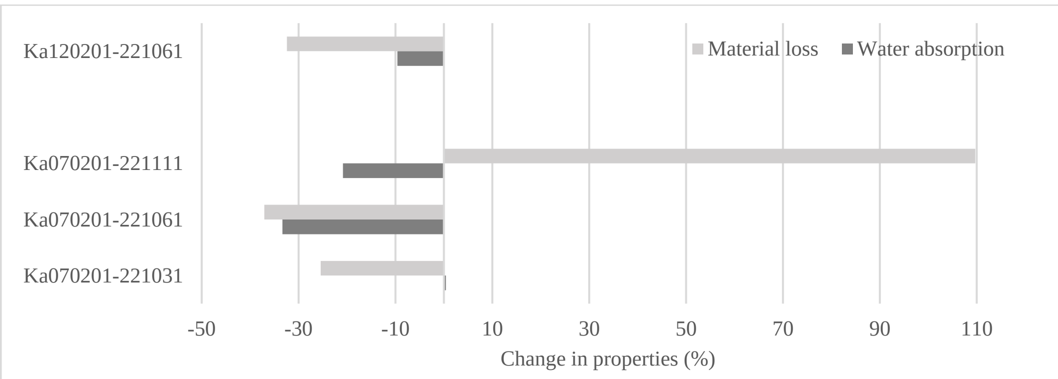

Figure 7-29: Impact of the addition of cow dung on the surface properties of earth mortars

7.4 Durability properties of earth mortars stabilized with biopolymers

The durability properties of stabilized earth mortars are summarized in Table 7-11 to Table 7-13 depending on the reference mortar they are derived from. The results are presented in the following sections and the impacts of the different stabilizers on each durability property are discussed one by one in the same section.

Table 7-11: Durability properties of stabilized earth mortars made with Grey Sand

Mortar Name	Humidity level (weight increase in %)	Humid flexural strength (MPa)	Loss in strength (%)	Humid compressive strength (MPa)	Loss in strength (%)	Resistance to immersion (min)	Abrasion resistance (DIN18947) Material loss (g)	Abrasion resistance (French rules) Abrasion Coefficient (cm²/g)	Erosion resistance Hole depth (mm)	Erosion resistance Hole diameter (mm)
Reference Mortar 1	**0.6 1.5**	**0.36**	**-53**	**0.76**	**-43**	**14**	**8.6**	**0.60**	**8**	**22**
Ka010101-221051	1.4%	0.50	-44	0.80	-45	16	6.7	0.9	8	22
Ka010101-221101	1.6%	0.56	-42	0.89	-40	30	5.4	0.9	5	25
Ka010101-221151	0.8%	0.24	-68	0.60	-50	50	10.9	0.5	1	12
Ka020101-221011	1.1%	0.61	-35	0.97	-36	7	6.9	na	8	20
Ka020101-221051	1.4%	0.48	-49	0.92	-41	7	5.1	1.6	7	25
Ka020101-221101	1.2%	0.51	-47	1.12	-33	9	5.4	1.2	9	20
Ka040101-221081	1.6%	0.40	-48	0.83	-33	6	4.3	1.4	6	45
Ka040101-221161	1.0%	0.41	-55	0.82	-42	16	3.1	1.6	5	25
Ka040101-221351	1.5%	0.38	-64	0.81	-42	83	0.5	5.3	1	25
Ka080101-22121	0.9%	0.07	-84	0.36	-46	1440	11.5	0.4	5	25
Ka080101-22141	0.9%	0.13	-55	0.32	-25	2880	6.4	0.6	0	0
Ka080101-22161	0.9%	0.21	-8	0.36	10	1340	2.6	1.4	0	0
Ka080101-22181	0.7%	0.21	-4	0.40	21	68	2.8	3.5	0	0
Ka100101-221011	0.6%	0.33	-32	0.51	-55	1440	2.4	0.9	0	0
Ka100101-221021	0.8%	0.40	-40	0.87	-45	2880	1.1	4.7	0	5
Ka100101-221041	1.0%	0.65	-36	1.41	-41	2880	0.0	30.7	0	0
Ka100101-221061	0.9%	0.61	-45	1.39	-42	2880	0.0	30.2	0	7.5
Ka090101-221301	1.7%	0.42	-57	0.84	-47	11	9.1	0.9	8	25

Table 7-12: Durability properties of stabilized earth mortars made with Yellow Sand

Mortar Name	Humidity level (weight increase in %)	Humid flexural strength (MPa)	Loss in strength (weight increase in %)	Humid compressive strength (MPa)	Loss in strength (%)	Resistance to immersion (min)	Abrasion resistance (DIN18947) Material loss (g)	Abrasion resistance (French rules) Abrasion Coefficient (cm²/g)	Erosion resistance Hole depth (mm)	Erosion resistance Hole diameter (mm)
Reference Mortar 2	**0.9%**	**0.61**	**-28**	**1.18**	**-37**	**24**	**2.6**	**1.20**	**6**	**25**
Ka070201-221031	0.8%	0.67	-25	1.36	-25	44	1.1	1.0	5	17
Ka070201-221061	0.8%	0.50	-43	1.29	-25	94	1.2	1.3	1	5
Ka070201-221111	0.6%	0.31	-62	0.83	-47	120	1.6	1.0	2	11
Ka110201-221011	0.8%	0.34	-58	0.83	-49	2880	1.1	2.2	0	0
Ka110201-221021	0.8%	0.41	-52	0.78	-55	2880	0.2	6.7	0	0
Ka110201-221031	0.9%	0.53	-39	1.35	-50	2880	0.1	43.4	0	0
Ka150201-22102	1.0%	0.70	-30	1.16	-35	132	2.5	1.2	5	32
Ka150201-22105	1.0%	0.61	-43	1.52	-18	120	1.1	2.6	5	24
Ka150201-22110	0.7%	0.57	-29	1.47	-6	141	0.7	2.8	4	28
Ka120201-221061	0.8%	0.57	-39	1.36	-29	130	1.7	1.3	4	17
Ka130201-221251	0.9%	0.41	-43	0.89	-49	22	3.0	0.9	6	22
Ka140201-221201	1.1%	0.56	-22	1.12	-44	28	2.5	1.1	6	30

Table 7-13: Durability properties of stabilized earth mortars made without fibres

Mortar Name	Humidity level (weight increase in %)	Humid flexural strength (MPa)	Loss in strength (%)	Humid compressive strength (MPa)	Loss in strength (%)	Resistance to immersion (min)	Abrasion resistance Material loss (g)	Abrasion resistance Abrasion Coefficient (cm²/g)	Erosion resistance Hole depth (mm)	Erosion resistance Hole diameter (mm)
Reference Mortar 3	**0.9%**	**0.22**	**-61**	**0.45**	**-67**	**4**	**10**	**0.3**	**8**	**25**
Ka060100-210021	1.0%	0.53	-67	0.97	-61	23	0.5	8.3	6	27
Ka060100-210051	0.8%	0.55	-68	0.81	-70	150	0.2	43.7	3	10
Ka060100-210151	0.8%	0.50	-82	1.29	-78	2880	0.1	85.3	3	20
Ka060100-210201	4.5%	0.01	-100	0.17	-98	1178	0.0	102.2	8	15

7.4.1 Humid mechanical strength of earth mortars stabilized with biopolymers

The humid mechanical strength of stabilized earth mortars is summarized in Table 7-11 to Table 7-13 depending on the reference mortar the mix is based on. The humid strength is given together with the amount of water vapour absorbed in % and the loss of strength compared to dry strength.

For stabilized Reference Mortar 1 the highest humid flexural strength is tested on Ka100101-221041 (0.65 MPa; 36% loss of strength) and the lowest is tested on Ka0801010-221021 (0.07MPa; 84% loss of strength), whereas for stabilized Reference Mortar 2, the lowest humid flexural strength is 0.31 MPa (Ka070210-211111; 62% loss of strength) and the highest is 0.91 MPa (Ka020201-221054; 15% loss of strength) and for Reference Mortar 3 the lowest strength is 0.02 MPa (Ka060100-210201; 99% loss of strength; only one specimen tested) and the highest is 0.55 MPa (Ka060100-210051; 67% loss of strength). The amount of water absorbed varies between 0.7% to 2% of specimen weight increase, independently of the reference mortar, except for mortar Ka060100-210201 which has a 4.5% weight increase. From the comparison of stabilized mortars with reference mortars, it can be understood that some stabilizers such as fermented juice (mortars starting with Ka02), linseed oil (Ka10) and casein (Ka15) lead to a slightly higher humid mechanical strength than the reference mortar, whereas some other such as used frying oil (Ka08) lead to a very lower strength. However, when the mortars are compared between themselves to determine the impact of the stabilizer on the loss of strength, it seems that used frying oil (Ka08) and to certain point casein (Ka15) and fermented juice (Ka02) lead to lower loss of strength whereas mayonnaise (Ka11) and especially molasses (Ka06) lead to a higher loss of strength.

7.4.1.1 Impact of fermented fibres

The impact of fermented fibres on the humid strength of earth mortars is presented in Figure 7-30 and the results of the compressive and flexural tests are presented in Table 7-11. From these results, it can be observed that independently of the amount of fermented fibre juice used, the amount of water vapour absorbed after 3 weeks in a humid environment is comprised between 1.1% and 1.3% except when only washing water is used (Ka090101-221301). The strength loss for flexural strength varies from 35% to 49% again except for Ka090101-221301 which has a strength loss of 57% and it varies from 33% to 41% for compressive strength with a higher loss (47%) for Ka090101-221301. As the average loss for Reference Mortar 1 is 54% for flexural strength and 44% for compressive strength (Figure 7-30), for a similar amount of humidity absorbed, therefore, it can be concluded that fermented fibre juice not only increases the humid strength as it increases the dry strength (section 7.2.2.1) but also lower the strength loss.

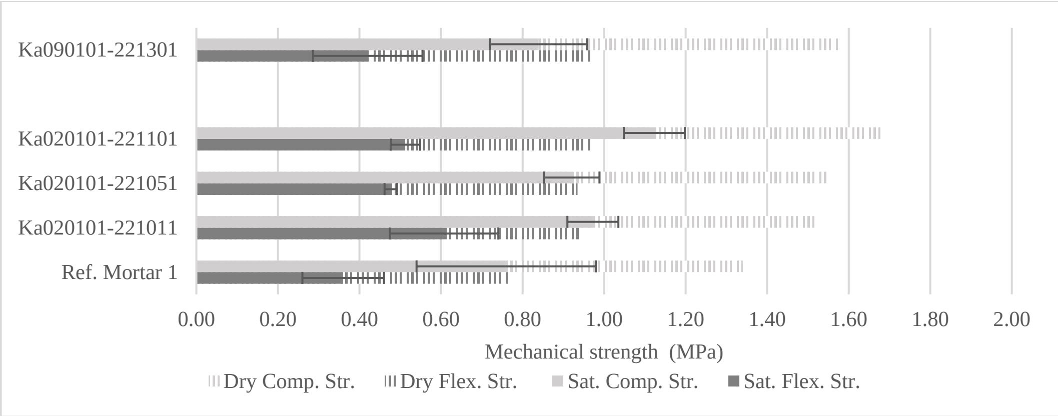

Figure 7-30: Impact of fermented fibres on the humid mechanical strength of earth mortars

7.4.1.2 Impact of molasses

The impact of molasses on the humid strength of earth mortars is presented in Figure 7-31 and the results of the compressive and flexural tests are summarized in Table 7-13. From the results, it can be seen that samples reinforced with molasses absorbed a similar amount of water vapour with the Reference Mortar 3 – except for Ka060100-210201 which absorbed 4.5% - and have flexural strength and compressive strength higher than Reference Mortar 3 – except for Ka060100-210201. However, the loss of strength is very high, as the absorption of water vapour leads to an 80% loss of strength and even 99% loss of strength for Ka060100-210201 which was even difficult to test due to its sticky surface and the softness of the specimens. Additionally, mould growth was visible on the surface of the samples. Therefore, it can be concluded that the addition of molasses has an adverse impact on the strength of mortar in humid conditions despite keeping a higher strength than the reference mortar even with a low amount of molasses.

Vilane (2010) reported the testing of water-saturated earth blocks for compressive strength and stated that the saturated strength of blocks was still higher than other earth blocks except for cement reinforced blocks, but it also showed that the higher the amount of molasses, the higher the loss of strength between the saturated and non-saturated strength. However, the remaining strength was still high compared to the one found it this experiment for a higher amount of water absorbed. This difference might come from the type of molasses (sugarcane instead of beetroot) the type an amount of clay from the earth and the amount of ashes present in the molasses.

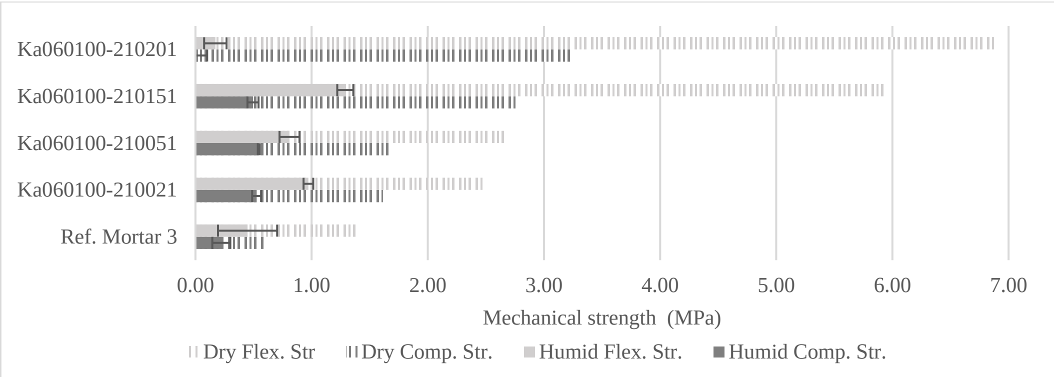

Figure 7-31: Impact of molasses on the humid mechanical strength of earth mortars

7.4.1.3 Impact of linseed oil and used frying oil

The impact of oils on the humid strength of earth mortars is presented in Figure 7-32 and the results of the compressive and flexural tests are summarized in Table 7-11. Two different behaviour can be seen in Figure 7-32 with mortars stabilized with used frying oil and mortars stabilized with linseed oil having different strengths and loss of strength despite similar amounts of absorbed water vapour – between 0.7% and 1%.

Mortars stabilized with used frying oil (Ka08 series) have lower humid strength than the reference mortar, however, the strength is increasing with an increasing amount of oil. Moreover, mortars with a high amount of oil (6% and 8%) have also a higher humid strength than dry strength but the spread of results is very large and therefore the homogeneity of the mortars and the veracity of the results can be questioned. However, it seems that oil prevents the loss of strength in humid conditions.

On the other hand, mortars reinforced with linseed oil (Ka10 series) have a similar or higher strength than Reference Mortar 1 – except for Ka100101-221011 – but their loss of strength – especially flexural strength – is slightly lower than the loss of strength of Reference Mortar 1 – between 32% and 45% for flexural strength and 41% and 55% for compressive strength whereas Reference Mortar 1 has an average loss of 54% for flexural strength and 44% for compressive strength (Figure 7-32). Therefore, it can be concluded that linseed oil partly prevents losses in flexural strength but has no impact on the loss prevention for compressive strength despite a strength value being much higher due to the presence of the additive and the higher dry strength.

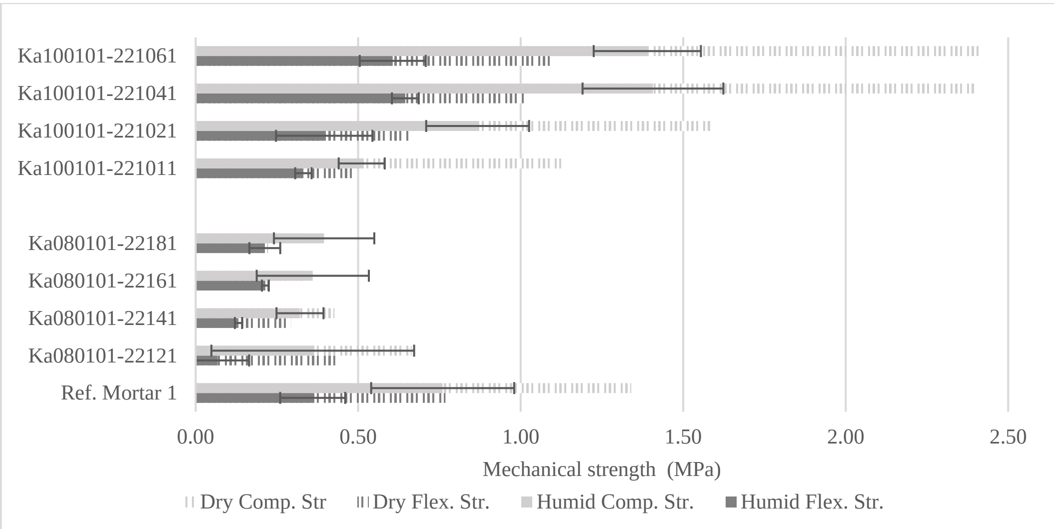

Figure 7-32: Impact of linseed oil and used frying oil on the humid mechanical strength of earth mortars

7.4.1.4 Impact of casein

The impact of casein on the humid strength of earth mortars is presented in Figure 7-33 and the results of the compressive and flexural tests are summarized in Table 7-12.

The humidity amount of mortars after 3 weeks of exposure to humidity is similar to the Reference Mortar 2 – 0.7% to 1.0% – for similar humid flexural strength and higher loss of flexural strength. However, the humid compressive strength is much higher than the one of Reference Mortar 2 – until 1.52 MPa instead of 1.18 MPa, due to a very lower loss of strength with a high amount of casein (Ka150201-22110, 6% loss, Ka150201-22105, 18% loss). Therefore, it seems that the casein reduces the strength loss for compressive strength only with increasing amount of casein probably due to the casein micelles which are hydrophobic and therefore create a strong skeleton around the clay particles.

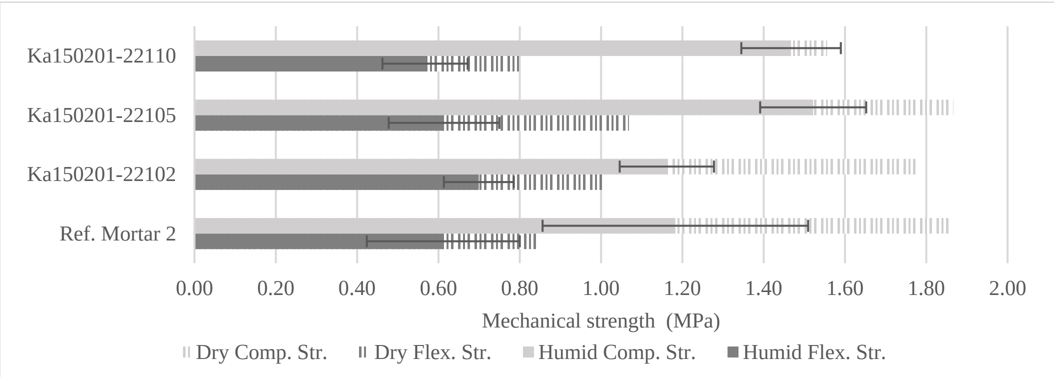

Figure 7-33: Impact of casein on the humid mechanical strength of earth mortars

7.4.1.5 Impact of mayonnaise

The impact of mayonnaise on the humid strength of earth mortars is presented in Figure 7-34 and the results of the compressive and flexural tests are presented in Table 7-12.

The flexural strength is varying from 0.34 MPa to 0.53 MPa (for 1% and 3% of mayonnaise respectively) whereas the compressive strength varies from 0.78 MPa to 1.35 MPa for the same mortars which are lower values than the values of Reference Mortar 2 except for the compressive strength of Ka010201-221031 which is similar. Moreover, despite a lower abosrption of humidity – only 0.9% weight increase – the loss of strength of the mortars while humid is higher – around 50% loss of strength for both flexural and compressive instead of 19% or 32% respectively for Reference Mortar 2. Therefore it can be concluded that mayonnaise has an adverse impact on humid mechanical strength.

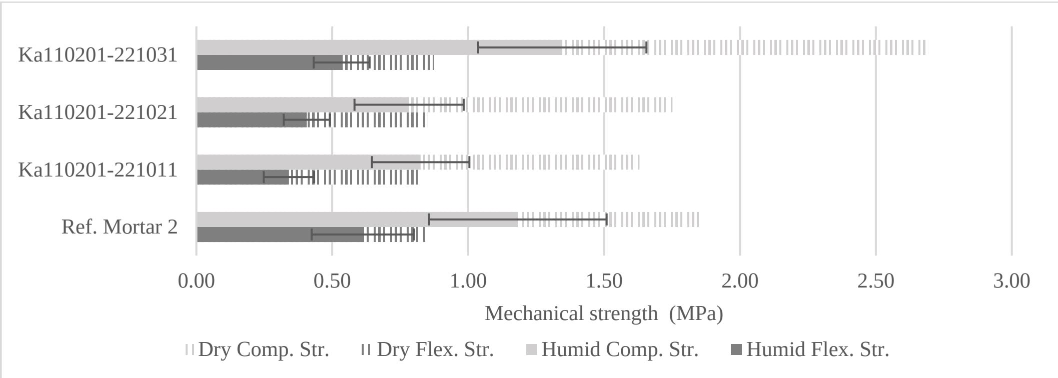

Figure 7-34: Impact of mayonnaise on the humid mechanical strength of earth mortars

7.4.1.6 Impact of cow dung

The impact of cow dung on the humid strength of earth mortars is presented in Figure 7-35 and the results of the compressive and flexural tests are presented in Table 7-12.

The flexural strength varies from 0.67 MPa to 0.31 MPa for an increasing amount of fresh cow dung (samples Ka07) and is 0.57 MPa for the addition of 6% of dry dung. The compressive strength varies from 1.36 MPa to 0.83 MPa for an increasing amount of fresh dung and is 1.36 MPa for 6% of dry dung. Therefore it can be understood that despite a slight improvement in strength and a lower loss of strength for a small amount of dung (between 3% and 6%), the addition of cow dung decreases the flexural strength of mortars and has no impact on the compressive strength. Similar results for the compressive strength of cow-dung stabilized adobe have been found by Vilane (2010)

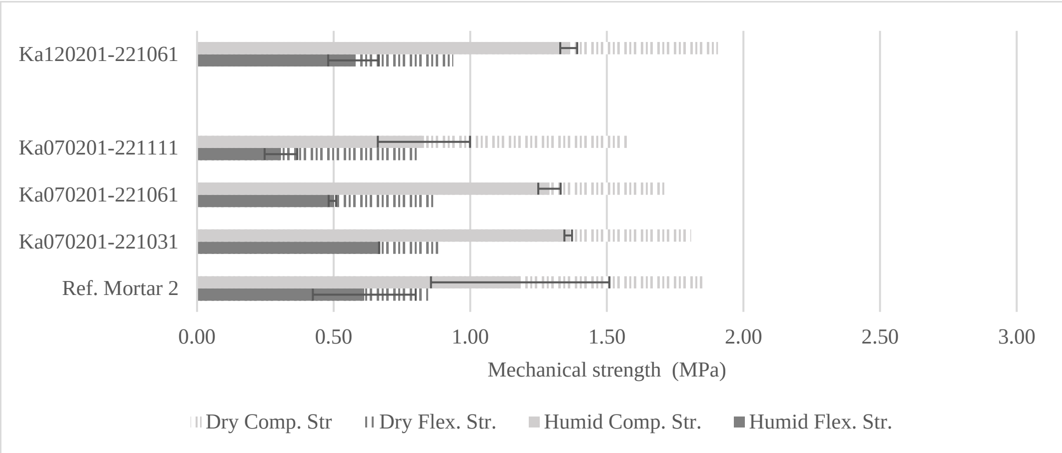

Figure 7-35: Impact of cow dung on the humid mechanical strength of earth mortars

7.4.2 Resistance to immersion in water of earth mortars stabilized with biopolymers

The resistance to immersion in water of stabilized mortars is presented in Table 7-11 to Table 7-13 and compared with the Reference Mortar in Figure 7-36 and Figure 7-37. The results are given with a logarithmic scale in order to present the diversity of values. Maximum values are 2880 min for any specimen as it is the total duration of the test. A very large variation of resistance is found with samples being destroyed in 4 min (Ka020101-221012; -221052 and 221102) whereas some others can hold at least 28880 min. i.e. the total duration of the test (Ka080101-221041 or Ka100101-221041; -221061 or Ka060100-210051). As a general comment, it can be seen from the comparison with the reference mortar that decomposition juice and other cellulosic juices have no impact or an adverse impact on the water resistance whereas other tested stabilizers improve the water resistance of mortars.

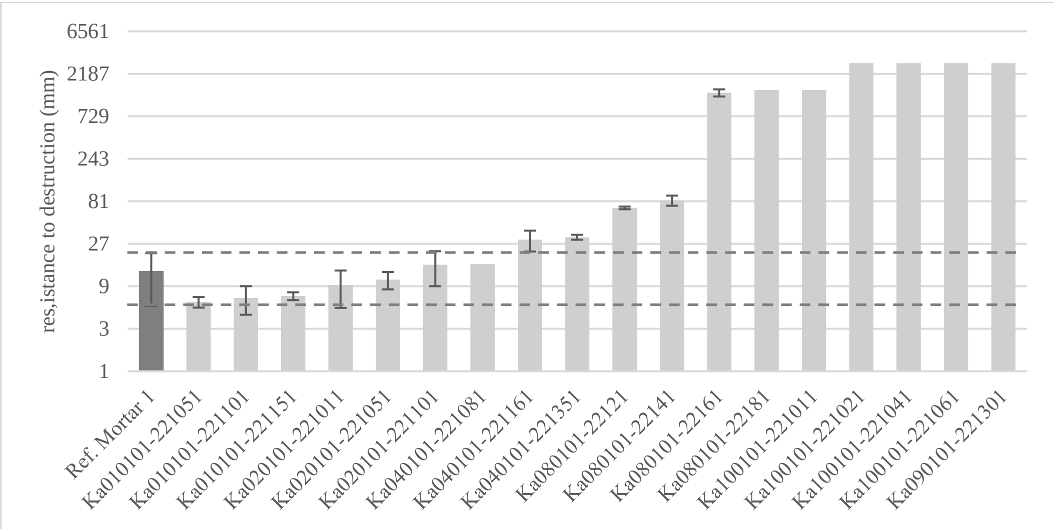

Figure 7-36: Immersion resistance of stabilized earth mortars based on Reference Mortar 1.

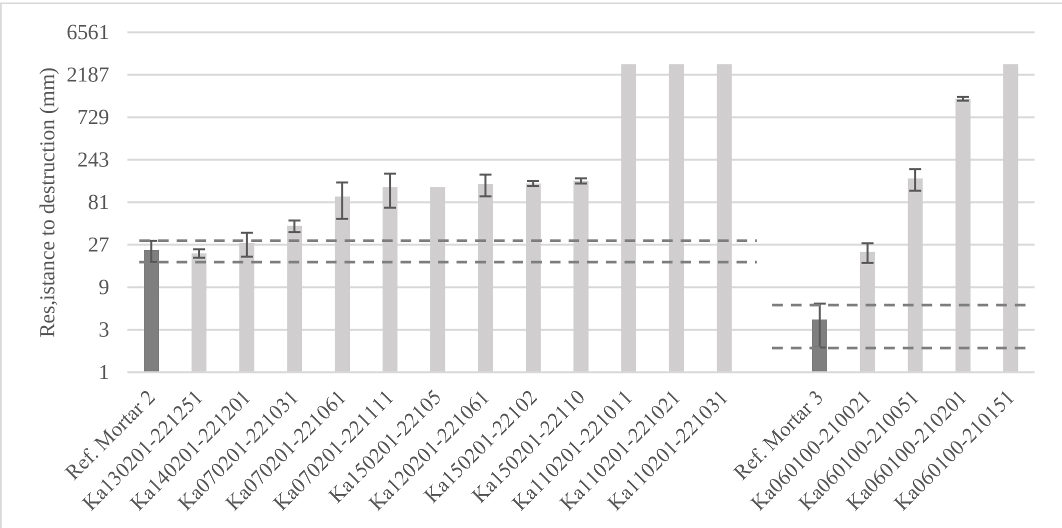

Figure 7-37: Immersion resistance of stabilized earth mortars based on Reference Mortar 2 (left) and Reference Mortar 3 (right)

7.4.2.1 Impact of fermented fibres

The resistance to immersion in water of mortars stabilized with fermented fibres juice (Ka02 series) varies between 7 and 9 min with a maximum resistance of 15 min on one of the specimens of Ka020101-221101 which shows a much lower resistance than Reference Mortar 1 (Table 7-11 and Figure 7-36). However, it was shown in section 0 that mortars stabilized with fermented fibres had a lower surface absorption than Reference Mortar 1. Therefore, fermented fibre juice might reduce the capillarity through the presence of smaller fibres or particles, but the additive doesn’t create any new binding properties able to resist water.

7.4.2.2 Impact of egg white

The resistance of egg white stabilized mortars to immersion in water varies from 16 min (Ka010101-221051) to 32 min (Ka010101-221101) and the resistance of Ka010101-221151 is 30 min but with a larger spread of results whereas the resistance of Reference Mortar 1 is 13 min (Table 7-11 and Figure 7-36). As stated in section 0, egg whites reduce the absorption of water, but here it is also clear that they have a cohesive impact in presence of water preventing the immediate destruction of the samples. However, their impact is limited –contrary to what is shown and stated by Anger et al. (2012) – and their presence alone in the quantity tested is not sufficient to stabilize the mortar. Moreover, a higher amount of egg white as tested with Ka010101-221151 doesn’t improve further the water resistance.

7.4.2.3 Impact of oils

The resistance earth mortars stabilized with oils varies from 68 min for Ka080101-221081 to 2880 min for Ka080101-221041;-221061, Ka 100101-221021, -221041 and -221,061 (Table 7-11 and Figure 7-36). These results concord with the results given in section 0 that shows that the mortars stabilized with oil absorb almost no water.

However, despite a very low absorption of water as also shown in section 7.5.1, mortars with a low amount or high amount of used frying oil will still be damaged by the water, showing that the used frying oil is only coating the clay molecules as stated by Guiheneuf et al. (2020) whereas mortars made with linseed oil – which is a drying oil – absorb more water by capillarity than used frying oil based mortars but will have a longer resistance to immersion independently of the amount of oil, showing that the oil also acts as a binder while drying. Similar results were found by Brzyski & Grudzińska (2020) using linseed oil-based varnish.

7.4.2.4 Impact of mayonnaise

All mortars stabilized with mayonnaise have a resistance to the immersion of 2880 min (Table 7-12 and Figure 7-37) which shows that these mortars are resistant to water even with a very low amount of additive. However, as shown in section 7.3.3.7 and section 7.5.1.4 using a low amount of mayonnaise only has a low impact on the amount of water absorbed compared to the reference but, even for the large possible amount of water absorbed, it has no impact on the resistance to immersion. This is probably due to the usage of two stabilizers with hydrophobic and binding properties, linseed oil and yolk. This result was expected due to the traditional binding and hardening properties attributed to the mix of linseed oil and yolk in painting.

7.4.2.5 Impact of molasses

The water resistance of molasses-stabilized earth mortars varies between 23 min (Ka060100-210021) to 2880 min (Ka060100-210151) (Table 7-13) which is much higher than the 4 min resistance of Reference Mortar 3 and an increase of more than 120 times between 2% molasses and 15% molasses but an increase of 60 times between 2% molasses and 20% molasses.

However, these results contradict the results from section 0 which shows a decrease in the water absorption with an increasing amount of molasses. Moreover, as the samples get saturated by water, the material softened and the water takes a darker colour as if the molasses was diluted in water. Therefore, it can be assumed, that the molasses prevents the surface water absorption by coating the mortar particles but as molasses is material dissolvable in water, after a long stay in the water, its impact is reduced, especially when the ratio of clay/molasses is reduced. There is a possibility that the amount of molasses might be too high compared to the amount of clay and therefore, prone to dissolution or that the specimens were not fully dried when tested as the samples with 15% and 20% molasses had a very long drying time before obtaining a hard surface. The core itself of the sample might not have been fully dried which might also explain why the mechanical strength of Ka060100-210151 and -210201 are similar (section 7.2.2).

7.4.3 Resistance to abrasion of earth mortars stabilized with biopolymers

The resistance to abrasion of stabilized earth mortars has been determined with two methods, the german method (DIN 18947) and the French method (French professional rules) and is presented in Table 7-11 to Table 7-13 and compared to the reference mortars in Figure 7-38 and Figure 7-39.

The lowest resistance to abrasion is determined for mortar Ka080101-221021 and the highest for mortar Ka060100-210201, independently of the reference mortar. From Figure 7-38 and Figure 7-39 and the comparison with the reference mortars, it can be understood that most stabilizers don’t have a large impact on the abrasion resistance – egg-white, fermented fibres, flour paste only decrease the material loss by 50% which is not a lot compared to the spread of results for Reference Mortar 1 (+/- 30%) – but some create a very high resistance such as linseed oil (Ka10), mayonnaise (Ka11) and molasses (Ka06) which present almost no loss of material for an optimum amount of stabilizer, whereas the impact of other is depending on the amount of stabilizer.

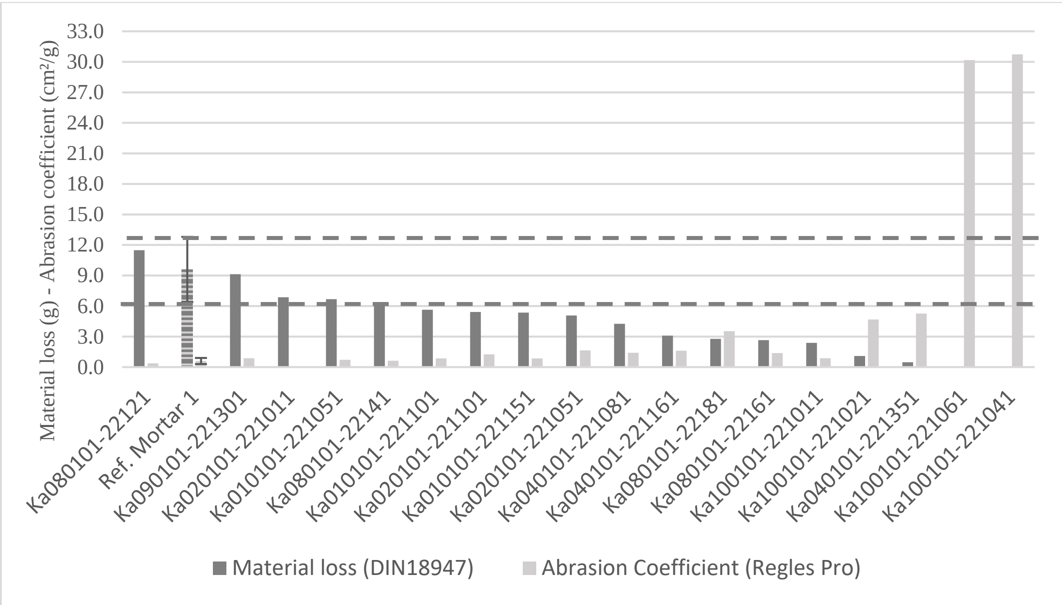

Figure 7-38: Abrasion resistance earth mortars based on Reference Mortar 1

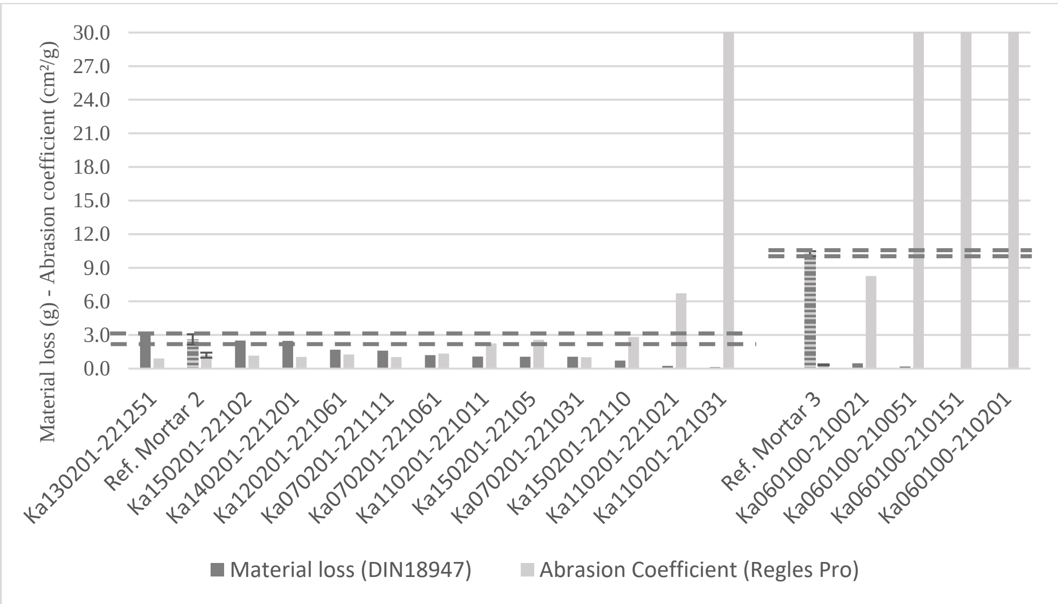

Figure 7-39: Abrasion resistance earth mortars based on Reference Mortar 2 (left) and Reference Mortar 3 (right)

7.4.3.1 Impact of fermented fibres

The abrasion resistance of earth mortars stabilized with cellulose-based additive – i.e fermented fibre juice and straw washing water – is presented in Table 7-11 and Figure 7-38.

The material loss on samples tested according to German Standard varies from 5.1 g (Ka020101-221051) and 9.1 g (Ka090101-221301), all lower than the Reference Mortar 1 (9.6 g +/- 2.8 g) whereas the abrasion coefficient tested according to the French Rules varies between 0.9 cm²/g and 1.6 cm²/g for the same samples, higher than Reference Mortar 1 (0.6 +/-0.3).

The abrasion resistance of the mortar stabilized with washing water of straw (Ka090101-221301) is similar to the Reference Mortar 1 values, which show that there is no impact of the straw washing water on the abrasion resistance. Optimum resistance is found for both tests for the mortar stabilized with fermented fibre juice with 50% additives (Ka020101-221051). However, the difference in values is low and the mortars have a much lower resistance than Reference Mortar 1. Moreover, according to French Rule, the mortar is not suitable to be a plaster as the depth of the depression created by the brush is higher than 2 mm.

7.4.3.2 Impact of molasses

The abrasion resistance of earth mortars' stabilized with molasses is presented in Table 7-13 and Figure 7-39.

The material loss varies from 0.5 g (Ka060100-210021) to 0.0 g (Ka060100-210201) whereas the abrasion coefficient varies from 8.3 cm²/g to 102.2 cm²/g which are values showing a large increase in resistance compared to Reference Mortar 3 (10 g; 0.3 cm²/g).

Higher abrasion resistance was expected as a higher surface cohesion was found (section0), however, the results show that molasses creates a very high resistance for a low amount of molasses (Ka060100-210051 - 0.0 g; 43.7 cm²/g), even when compared to other mortars with high resistance - Ka100101-221061 (0.0g; 30.2 cm²/g) or Ka110101-221021 (0.0g; 43.4 cm²/g). Therefore, it seems that the low amount of glucose contained in molasses is fully playing its role of glue, preventing any particle to separate from the sample by binding them together.

7.4.3.3 Impact of flour paste

The abrasion resistance of earth mortars stabilized with flour paste is presented in Table 7-11 and Figure 7-38.

The material loss varies between 4.5 g (Ka040101-221081) and 0.5 g (Ka040101-221351) and the coefficient resistance varies between 1.4 cm²/g and 5.3 cm²/g for the same mortars. Therefore, it is clear that the addition of an increasing amount of flour paste increases the resistance to erosion, which is supported by the results of the surface cohesion test. The addition of starch increases the cohesion of the mortar through its binding properties. However, despite a much better resistance than Reference Mortar 1 and almost no loss of material for the sample Ka040101-221351, the depth of the depression is 2 mm or more, and therefore, the mortar could not be used as a plaster according to the French Rules.

7.4.3.4 Impact of linseed oil and used frying oil

The abrasion resistance of earth mortars stabilized with linseed oil and used frying oil is presented in Table 7-11 and Figure 7-38.

For used frying oil, the material loss determined according to the German Standard (DIN18947) varies from 2.8 g (Ka080101-221081) to 11.5 g (Ka080101-221021) and the abrasion coefficient varies from 0.4 cm²/g to 3.5 cm²/g for the same mortars. For linseed oil, the values show a higher resistance – with a largest material loss (2.4

g) and lowest abrasion coefficient (0.9 cm²/g) for the mortar with only 1% of linseed oil (Ka100101-221011).

These values show that the usage of oil enhances cohesion compared to Reference Mortar 1 but in a much lesser way with used frying oil than with linseed oil. The relatively good behaviour of mortars stabilized with used frying oil is unexpected, as the surface cohesion test – and the delicate handling of specimens of mortars stabilized with used frying oil due to dusting – shows that used frying oil is losing a large amount of material from surface abrasion. However, it seems that similarly to linseed oil, the internal cohesion is reinforced compared to Reference Mortar 1 even if this increase of resistance is not sufficient to be used as plaster according to French Rules. On the other hand, usage of linseed oil even in small quantities (2% - Ka100101-221021) is enough to reduce the depth of the depression below 2 mm, but increasing the amount of linseed oil above 6% seems to have no further impact on the abrasion resistance. These results contradict the study of Colas and Bourges (2013) who haven't seen any impact of using linseed on abrasion resistance. However, the experimental set-up was not designed for earth material and was probably too destructive to find any difference.

7.4.3.5 Impact of egg-whites

The abrasion resistance of earth mortars stabilized with egg whites is presented in Table 7-11 and Figure 7-38.

The material loss determined according to German Standard varies from 5.4 g (Ka010101-221151) and 6.7 g (Ka010101-221051) whereas the abrasion coefficient varies from 0.7 cm²/g to 0.9 cm²/g for the same mortars. These values show a higher resistance to abrasion than Reference Mortar 1 (9.6 g; 0.6 cm²/g), but as shown by Colas and Bourges (2013), using egg whites is not enough to increase abrasion resistance above the threshold necessary for usage in construction. Moreover, adding more egg white has a negative impact on abrasion resistance.

7.4.3.6 Impact of casein

The abrasion resistance of earth mortars stabilized casein is presented in Table 7-12 and Figure 7-39.

The material loss determined according to German Standard varies from 0.7 g (Ka150201-221101) and 2.5 g (Ka150201-221021) whereas the abrasion coefficient varies from 2.8 cm²/g to 1.2 cm²/g for the same mortars. These values are much lower than the ones of the Reference Mortar 2 and show increased resistance to abrasion with an increasing amount of casein. Similar results were expected because of the traditional usage of casein in plaster to prevent dusting (Vissac et al., 2016) but the amounts of casein tested here are not sufficient to prevent abrasion according to French Rules and, as seen in section 0, the improvement of the surface cohesion with casein is not consequent.

7.4.3.7 Impact of mayonnaise

The abrasion resistance of earth mortars stabilized mayonnaise is presented in Table 7-12 and Figure 7-39.

The material loss determined according to German Standard varies from 0.1 g (Ka110201-221031) and 1.1 g (Ka110201-221011) whereas the abrasion coefficient varies from 43.4 cm²/g to 2.2 cm²/g for the same mortars. These results show that using mayonnaise, independently of the quantity increases the abrasion resistance. Moreover, increasing the amount of mayonniase tend to increase the resistance to abrasion as found also section 7.3.3.7. However, amount higher than 3% have not been tested and therefore it is not possible to determine if this inncrease will continue.

7.4.4 Resistance to erosion of earth mortars stabilized with biopolymers

The resistance of stabilized earth mortars to erosion has been determined by measuring the diameter of a hole made by constant dripping. The results are reported in Table 7-11 to Table 7-13 and Figure 7-40 and Figure 7-41.

The highest erosion is measured on mortar Ka020101-22101 (9 mm) and the lowest erosion is measured on mortars Ka070101-441063, and mortars stabilized with used frying oil (Ka08), linseed oil (Ka10) and mayonnaise (Ka11) which present no trace of erosion. When the erosion of stabilized mortars is compared with reference mortars, it is seen that no stabilizer has an adverse impact on erosion and except fermented juices and other mucilage (Ka02, Ka09, Ka13 and Ka14) all types of stabilizers if enough concentrated improve the erosion resistance.

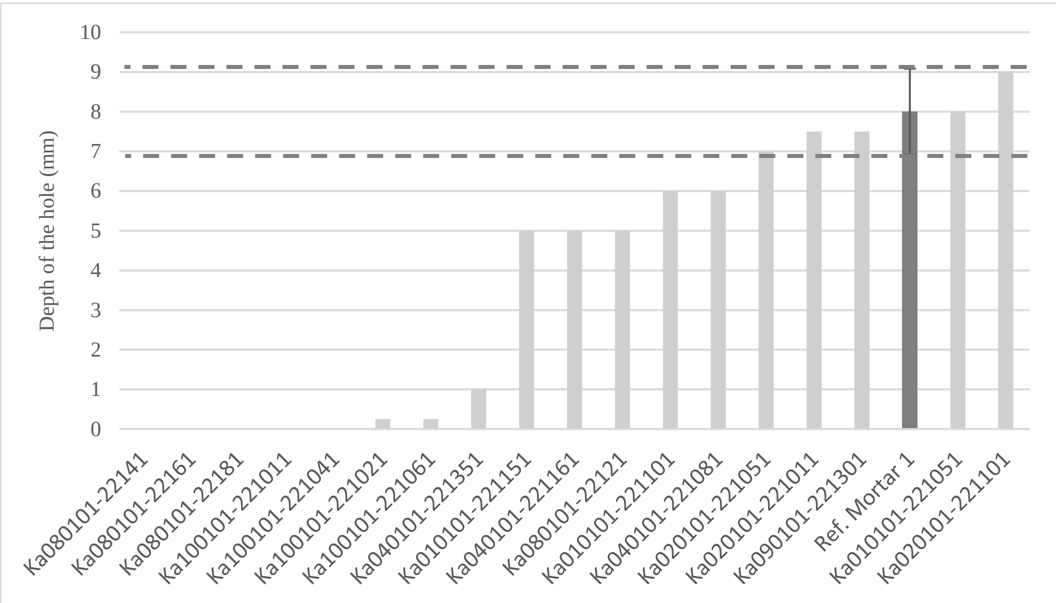

Figure 7-40: Impact of stabilizer on the erosion resistance of mortars based on Reference Mortar 1

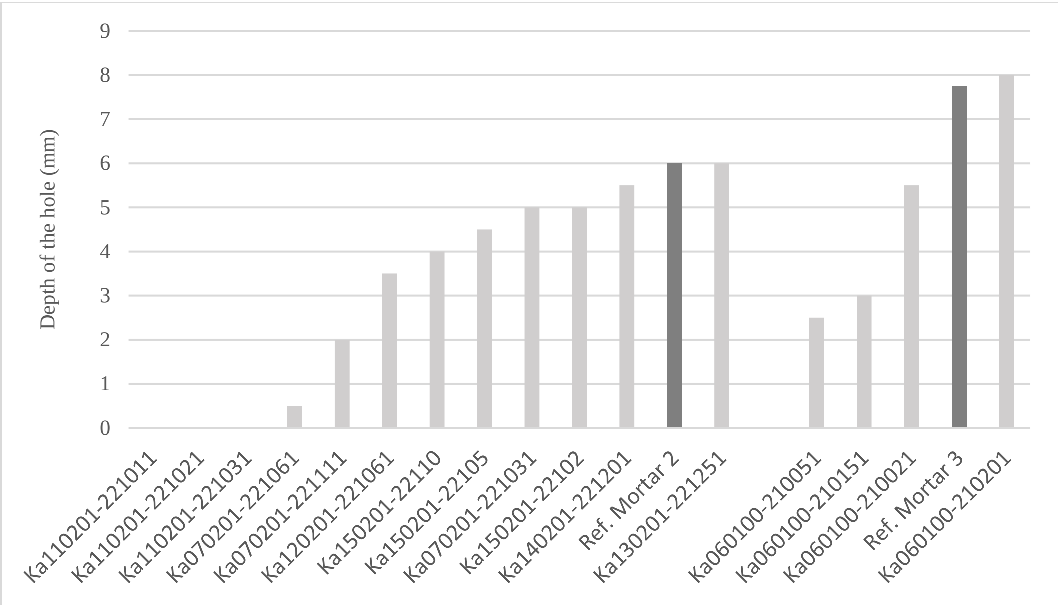

Figure 7-41: Impact of stabilizer on the erosion resistance of mortars based on Reference Mortar 2 (left) and Reference Mortar 3 (right).

7.4.4.1 Impact of egg-whites

The results of the drip test for egg-white stabilized mortars are presented in Table 7-11 and Figure 7-40.

The pith depth measured on egg-white stabilized specimens submitted to drip test varies from 5 mm (Ka010101-221151) to 8 mm (Ka010101-221051) similar to non-stabilized mortars. Therefore, the addition of egg whites increases the resistance to erosion but not very effectively as even the mortar prone to the least erosion fails the test according to the New Zealand Standard adapted by Giroudon et al. (2019) as its erosion pith is deeper than 5 mm.

7.4.4.2 Impact of molasses

The results of the drip test for egg-white stabilized mortars are presented in Table 7-13 and Figure 7-41.

The pith depth varies from 2.5 mm (Ka060100-210051) to 8 mm (Ka060100-210201) with a decreasing depth with the addition of more molasses until reaching the lowest value (15%). An increasing amount of molasses – more than 15% – reduces the erosion resistance, probably because its water absorption is high and therefore the mortar surface is softened by the water. However, despite the poor performance of samples with high amounts of molasses, samples with lower amounts pass the test for mud bricks with a pith depth lesser than 5 mm. A similar increase in erosion resistance is shown by Pinto et al. (2014) on sugar-stabilized mortars. According to the authors, the good resistance to erosion of molasses-stabilized mortars is probably due to their sugar contact on the creation of clay clusters which are a larger size than typical clay particles and therefore have probably a higher cohesion

7.4.4.3 Impact of flour paste

The results of the drip test for flour-paste stabilized mortars are presented in Table 7-11 and Figure 7-40.

The depth of the pith made by the dripping drops varies from 1 mm (Ka040101-221351) to 6 mm (Ka040101-221061) lower than the value of Reference Mortar 1 (8 +/-1 mm) showing a high positive impact of the addition of flour paste even for the lowest quantity of additive tested. Mortars pass the threshold of the drip test with 12% of flour-paste. This good resistance of flour-paste stabilized mortars is probably due to a combination of low surface water absorption and a good cohesion of the mortar when placed in water with starch preventing a too-fast separation of the mortar particles. Similar results have been found by Braun (2017b) who tested the impact of rye flour paste. The authors also underlined that this high impact is due to the fermentation of the starch that creates lactic acid “*which forms salts (lactates) with the constituents of the loam with a sealing effect on the surface of the bricks”.*

7.4.4.4 Impact of linseed oil and used frying oil

The results of the drip test for oil-stabilized mortars are presented in Table 7-11 and Figure 7-40.

No pith depth could be measured on most of the samples stabilized with oil except on samples with 2% of used frying oil (5mm depth) however, the mark of repetitive falling of drop was visible as a decolouration of the mortar even if no material was washed away in a measurable manner. Therefore, in the same way, that oils prevent the destruction of samples immersed in water, it also prevents failure by erosion, preventing the loss of cohesion of the mortar by preventing any absorption of water.

7.4.4.5 Impact of casein

The results of the drip test for casein-stabilized mortars are presented in Table 7-12 and Figure 7-41.

The depth of the pith made by the dripping of water on casein-stabilized mortars varies between 4 mm (Ka150101-221101) and 5 mm (Ka150201-221021) lower than the values of Reference Mortar 2 (6 +/-0 mm). Therefore the addition of casein increases slightly the erosion resistance, however, it doesn't seem that a larger amount of casein impacts further the resistance, as there is only a 1 mm difference between the highest and lowest value. This is especially true, as already commented on other properties for mortars with 2% and 3% of casein, as the depth of the pith is respectively 4.5 mm and 5 mm but the diameter is 24 mm and 28 mm, showing a similar material loss of material.

7.4.4.6 Impact of mayonnaise

The results of the drip test for mayonnaise stabilized mortars are presented in Table 7-12 and Figure 7-41.

After the dripping of 500 mL of water, no depression and dripping mark were visible on any of the sample and therefore it can be determined that the addition of mayonnaise improves the water resistance and erosion resistance of earth mortars. This resistance is probably achieved by preventing the penetration of water in the samples as it can be undersod by their low capillarity coefficient (section 7.5.1.4) and their low surface absorption (section 7.3.3.7).

7.5 Hydric properties of earth mortars stabilized with biopolymers

The hydric properties of earth mortars are presented in the following sections. In each section, firstly general results and trends are introduced and then in the second part the results for each type of additive are discussed. The hydric properties of earth mortars are summarized in Table 7-14 to Table 7-16.

Table 7-14: Hydric properties of stabilized earth mortars based on Reference Mortar 1

Mortar Name	Type of additive	Capillarity coefficient (kg/(m²·min^0.5)	R^2 (-)	Drying rate (1st phase) (kg/m²/h)	R^2 (-)	Drying rate (2nd phase) (kg/m²/h$^{0.5}$)	R^2 (-)	Drying Index (-)
Reference Mortar 1	**---**	**1.04**	**1.00**	**0.08**	**0.96**	**1.12**	**1.00**	**0.26**
Ka010101-221051	Egg	1.02	1.00	0.07	0.97	1.30	1.00	0.20
Ka010101-221101	Egg	1.09	1.00	0.08	0.96	1.13	1.00	0.28
Ka010101-221151	Egg	1.06	1.00	0.07	0.97	1.15	1.00	0.29
Ka020101-221011	D-juice	0.80	0.99	0.06	0.97	1.10	0.99	0.26
Ka020101-221051	D-juice	0.97	1.00	0.06	0.97	1.17	1.00	0.26
Ka020101-221101	D-juice	0.99	0.99	0.07	0.95	1.26	1.00	0.26
Ka040101-221081	Fl paste	1.05	0.99	0.09	0.96	1.42	1.00	0.24
Ka040101-221161	Fl paste	1.01	0.98	0.07	0.97	1.39	0.99	0.27
Ka040101-221351	Fl paste	1.18	0.99	0.10	0.96	1.31	0.99	0.29
Ka080101-22121	U. oil	0.55	0.99	0.07	0.81	0.47	0.99	0.31
Ka080101-22141	U. oil	0.11	0.95	0.05	0.92	0.29	0.99	0.33
Ka080101-22161	U. oil	0.61	1.00	0.05	0.99	0.62	1.00	0.41
Ka080101-22181	U. oil	0.44	1.00	0.03	0.82	0.39	0.99	0.53
Ka100101-221011	Linseed oil	0.13	0.98	0.04	0.99	0.30	0.99	0.23
Ka100101-221021	Linseed oil	0.16	0.97	0.03	0.99	0.22	1.00	0.30
Ka100101-221041	Linseed oil	0.14	0.98	0.05	0.96	0.15	0.99	0.22
Ka100101-221061	Linseed oil	0.15	0.95	0.04	1.00	0.15	0.98	0.20
Ka090101-221301	Straw juice	0.91	1.00	0.08	0.95	1.33	0.99	0.22

Table 7-15: Hydric properties of stabilized earth mortars based on Reference Mortar 2

Mortar name	Type of additive	Capillarity coefficient (kg/(m²·min^0.5)	R^2 (-)	Drying rate (1st phase) (kg/m²/h)	R^2 (-)	Drying rate (2nd phase) (kg/m²/h$^{0.5}$)	R^2 (-)	Drying Index (-)
Reference Mortar 2	**---**	**0.94**	**1.00**	**0.08**	**0.98**	**1.21**	**0.99**	**0.24**
Ka070201-221031	Dung	0.80	1.00	0.08	0.98	1.17	1.00	0.23
Ka070201-221061	Dung	0.99	1.00	0.08	0.95	1.16	0.99	0.24
Ka070201-221111	Dung	1.06	1.00	0.08	0.99	1.17	0.99	0.26
Ka110201-221011	Mayonnaise	0.35	0.99	0.05	0.99	0.57	1.00	0.31
Ka110201-221021	Mayonnaise	0.20	0.99	0.03	0.94	0.28	1.00	0.40
Ka110201-221031	Mayonnaise	0.15	0.94	0.03	0.99	0.20	0.98	0.42
Ka150201-22102	Casein	1.04	1.00	0.09	1.00	1.34	1.00	0.25
Ka150201-22105	Casein	1.03	1.00	0.08	0.99	1.11	0.98	0.34
Ka150201-22110	Casein	1.04	1.00	0.10	0.94	1.00	0.99	0.36
Ka120201-221061	Dry CD	0.91	1.00	0.09	0.86	1.15	1.00	0.21
Ka130201-221251	HH stalk	1.04	1.00	0.06	0.99	1.11	1.00	0.26
Ka140201-221201	HH flower	0.78	1.00	0.08	0.98	1.09	1.00	0.24

Table 7-16: Hydric properties of stabilized earth mortars based on Reference Mortar 3

Mortar Name	Type of additive	Capillarity coefficient (kg/(m²·min^0.5)	R^2 (-)	Drying rate (1st phase) (kg/m²/h)	R^2 (-)	Drying rate (2nd phase) (kg/m²/h$^{0.5}$)	R^2 (-)	Drying Index (-)
Reference Mortar 3	**---**	**0.99**	**1.00**	**0.12**	**0.84**	**1.10**	**0.99**	**0.26**
Ka060100-210021	Mo	0.39	1.00	0.05	0.99	0.84	1.00	0.25
Ka060100-210051	Mo	0.14	0.99	0.02	0.96	0.67	0.96	0.16
Ka060100-210151	Mo	0.07	0.91	0.03	0.96	0.25	0.84	0.07
Ka060100-210201	Mo	0.24	0.94	0.04	0.89	0.37	0.92	0.19

7.5.1 Capillarity water adsorption of earth mortars stabilized with biopolymers

The results of the tests for capillarity absorption are summarized in Table 7-16 to Table 7-15 as the Capillarity adsorption Coefficient (CC) and the water adsorption curves of the stabilized mortars are shown in Figure 7-42 to Figure 7-45 in the following sections.

The CC varies from 0.13 kg/(m²·min$^{0.5}$) for mortar Ka100101-221011 (1% linseed oil) to 1.18 kg/(m²·min$^{0.5}$) for mortar Ka040101-221351 for stabilized Reference Mortars 1 with most mortars having CC values much lower than the Reference Mortar 1 (1.04 kg/(m²·min$^{0.5}$)) except mortars stabilized with flour paste or egg whites. The capillarity coefficient varies from 0.15 kg/(m²·min$^{0.5}$) for mortar Ka110201-221011 (1% mayonnaise) to 1.06 kg/(m²·min$^{0.5}$) for mortar Ka070201-221111 (11% of fresh cow dung) for mortars based on Reference Mortar 2. Minimum values are lower than the one of the Reference Mortar 2 (0.94 kg/(m²·min$^{0.5}$)) and maximum values are very close to it. Therefore, in accordance with the surface absorption test results, it is understood that the type of additive used has an important impact on water absorption. Additives such as linseed oil (Ka10 series), used oil (Ka08 series), mayonnaise (Ka11 series), molasses (Ka06 series) and in a lesser manner fermented hay juice, washing water of straw and hollyhock flower juice reduces the water absorption whereas cow-dung and to a certain extend flour paste increase the water absorption. The impact of other additives is low and probably null as their capillarity coefficient value is close to the non-stabilized mortar.

7.5.1.1 Impact of fermented fibres and cellulosic additives

The impact of cellulose and plant mucilage on water absorption has been determined with three additives – i.e., fermented fibre juice, straw washing water and hollyhock products. From the results given in Table 7-14 and Table 7-15, it is seen that fermented fibres juices (Ka02 series) and straw washing water (Ka090101-221301) slightly reduce the water absorption – CC values varying between 0.80 kg/(m²·min$^{0.5}$) and 0.99 kg/(m²·min$^{0.5}$) for Ka020101-221011 and -221101 respectively, lower than Reference Mortar 1 values. Guihéneuf et al. (2019a) report a similar reduction of water absorption for mortars stabilized with hay and straw washing water. However, the impact of the reduction seems also to be dependent on the type of clay used.

Maceration juice of stems leads to no change in water absorption whereas the addition of maceration juice of hollyhock flowers reduces the water absorption, despite the juice not having the desired consistency due to the preparation. Therefore, it is very probable that the hollyhock flowers mucilage reduces the absorption of water as its traditional usage in Turkey for creating a plant-based glue has been reported

7.5.1.2 Impact of molasses

The capillarity absorption of molasses-stabilized earth mortars is given in Table 7-16 and its absorption behaviour is compared with Reference Mortar 3 in Figure 7-42. The capillarity coefficient varies from 0.07 kg/(m²·min$^{0.5}$) (Ka060100-210151) to 0.39 kg/(m²·min$^{0.5}$) (mortar Ka060100-210021) whereas Reference Mortar 3 has a CC of 0.99 kg/(m²·min$^{0.5}$). These results show a decrease in absorption with an increase in additive amount, similar to the results given by Pinto et al (2014). However, the addition of a very high amount of molasses (20%) seems to increase the water absorption compared to using only 15% of molasses. Figure 7-42 explains this behaviour clearly, with mortar Ka060100-210151 having an almost flat curve whereas Ka060100-210051 and Ka060100-210201 have a similar slope at the beginning with Ka060100-210201 absorbing few water in total.

Therefore, as explained in previous sections, a high amount of molasses has an adverse impact which might be due to its long drying time or the weak bond of the additive with the clay, as the amount of clay is not sufficient in comparison with the amount of sugar and therefore clusters of clay particles which stabilize the mortars could not be fully produced and free sugar sensitive to water leads to a less water resistant material. However, the total amount of water adsorbed is still lower than other mortar, which means that even if not optimum 20% of molasses prevents capillarity adsorption.

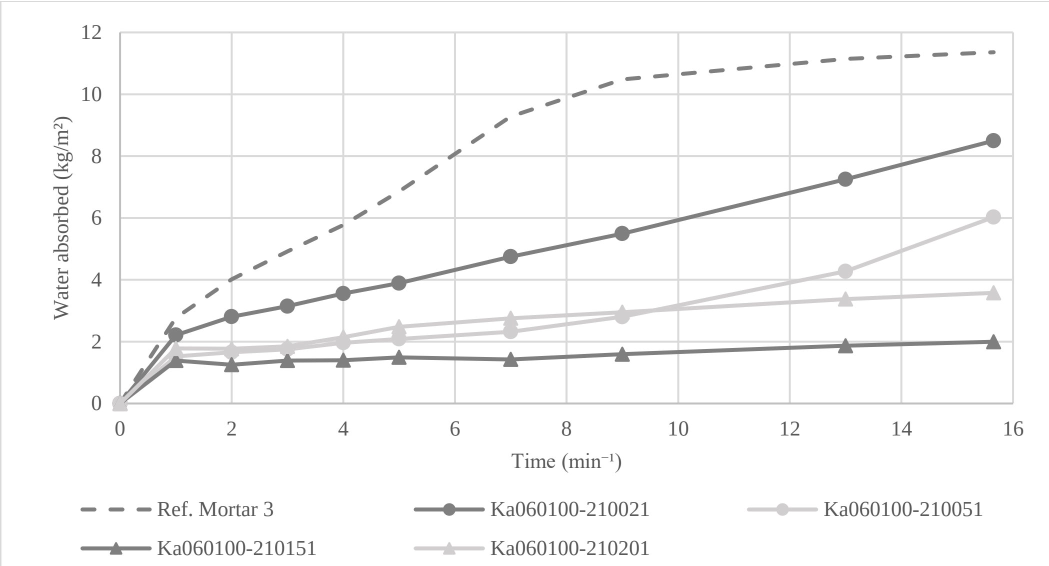

Figure 7-42: Impact of molasses on the water capillarity adsorption of earth mortars based on Reference Mortar 3

7.5.1.3 Impact of used frying oil and linseed oil on the water capillarity absorption of earth mortars

The capillarity coefficient (CC) of used frying oil stabilized earth mortars is summarized in Table 7-14 and the absorption behaviour of the mortars is presented in Figure 7-43.

The CC varies between 0.11 kg/(m²·min$^{0.5}$) and 0.61 kg/(m²·min$^{0.5}$) for 4% and 6% of oil respectively whereas the other values of CC are 0.44 kg/(m²·min$^{0.5}$) and 0.55 kg/(m²·min$^{0.5}$). For linseed oil stabilized mortars, the values vary between 0.13 kg/(m²·min$^{0.5}$) and 0.16 kg/(m²·min$^{0.5}$). All these values are very lower than the value of Reference Mortar 1 (1.04 +/- 0.11 kg/(m²·min$^{0.5}$)) showing the high impact of oil on water absorption and confirming the results of the surface water absorption and water resistance of the mortars.

However, two different behaviour can be determined for used frying oil and linseed oil. It seems that the amount of linseed oil added has no impact on the amount of water absorbed since all samples have a similar CC and, when absorption behaviour is observed (Figure 7-43), the amount of water absorbed after the 4th minute – surface absorption and absorption by the filter paper placed below the sample – is the same (1.5 kg/m² to 1.7 kg/m²). After this primary absorption, the continuous absorption represented by the CC is very low. This very low water absorption is similar to the one found by Braun (2017a), and Guihéneuf et al. (2019a) but Navarro et al. (2015) found that linseed oil has no impact on the on-site water absorption and Lima & Faria (2017) even show an increase in the CC despite a decrease in the total amount of water absorbed. For samples stabilized with used frying oil, similar behaviour is observed for 2% and 4% addition of oil, but above this maximum, the total absorption increases (Figure 7-43).

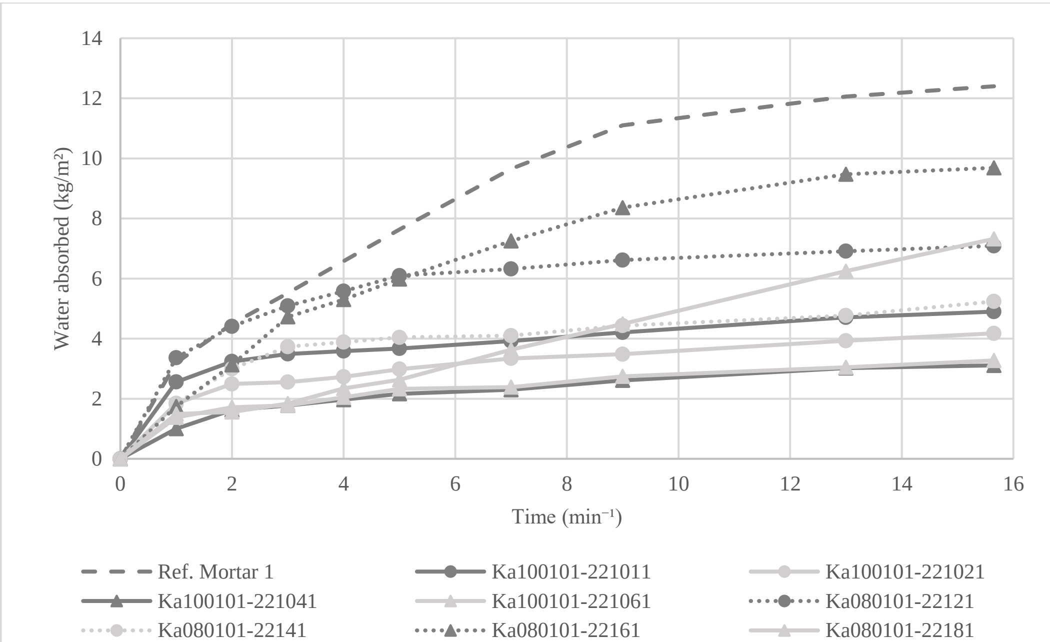

Figure 7-43: Impact of linseed oil on the capillarity water adsorption of earth mortars based on Reference Mortar 1

7.5.1.4 Impact of mayonnaise on the water capillarity absorption of earth mortars

The capillarity coefficient (CC) of mayonnaise-stabilized earth mortars is summarized in Table 7-15. The CC varies from 0.15 kg/(m²·min$^{0.5}$) to 0.35 kg/(m²·min$^{0.5}$), with a decreasing CC for an increasing amount of mayonnaise, and moreover, for any amount of mayonnaise tested, the CC is lower than the one of Reference Mortar 2. The absorption behaviour (Figure 7-44) is also close to the one described for oil-stabilised mortars – with a large increase at the beginning corresponding to the wetting of the filter paper and then a slow but constant increase – in opposition to the increase of non-stabilized mortars or mortars stabilized with cellulose-based additives which show a constant increase until reaching a step which corresponds to the water reaching the top of the sample. Therefore, it can be understood that the addition of mayonnaise prevents water absorption by preventing the water to reach the clay particles.

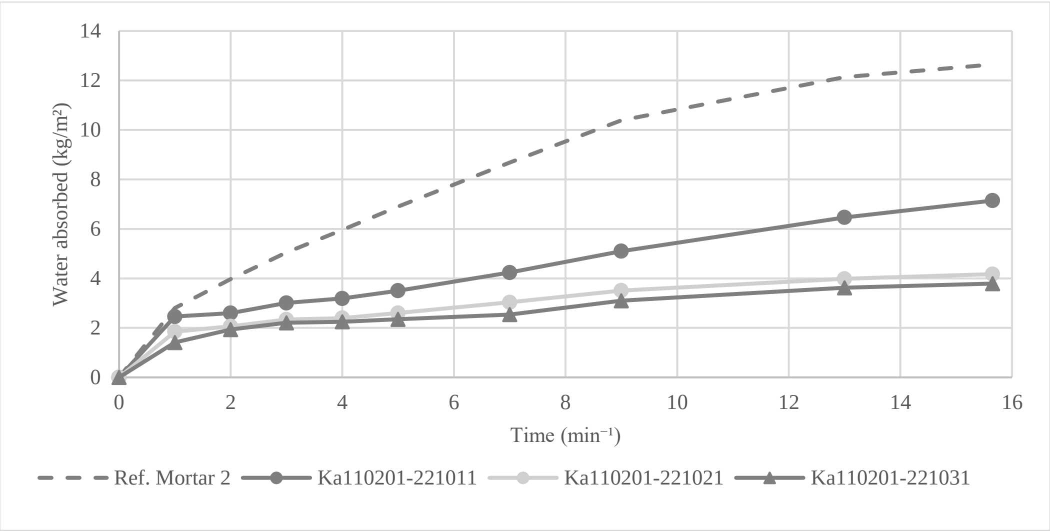

Figure 7-44: Impact molasses on the capillarity water absorption of earth mortars based on Reference Mortar 2.

7.5.1.5 Impact of eggwhites on the water capillarity absorption of earth mortars

The CC of egg whites stabilized mortars is summarized in Table 7-14 and the absorption behaviour of the mortars is shown in Figure 7-45.

The CC varies from 1.02 kg/(m²·min$^{0.5}$) (Ka010101-2210051) to 1.06 kg/(m²·min$^{0.5}$) (Ka010101-2210151), all very close values from the CC of the Reference Mortar 1 (1.04 kg/(m²·min$^{0.5}$)). When the absorption curves are compared (Figure 7-45), higher total adsorption is seen, which is due only to the primary adsorption of the filter paper and the surface adsorption of the mortar. Therefore, despite an increase in the amount of eggwhite in the mortar, there is no impact on the water adsorption which contradicts the results of section 7.3.3.5 and the results of Colas & Bourges (2013).

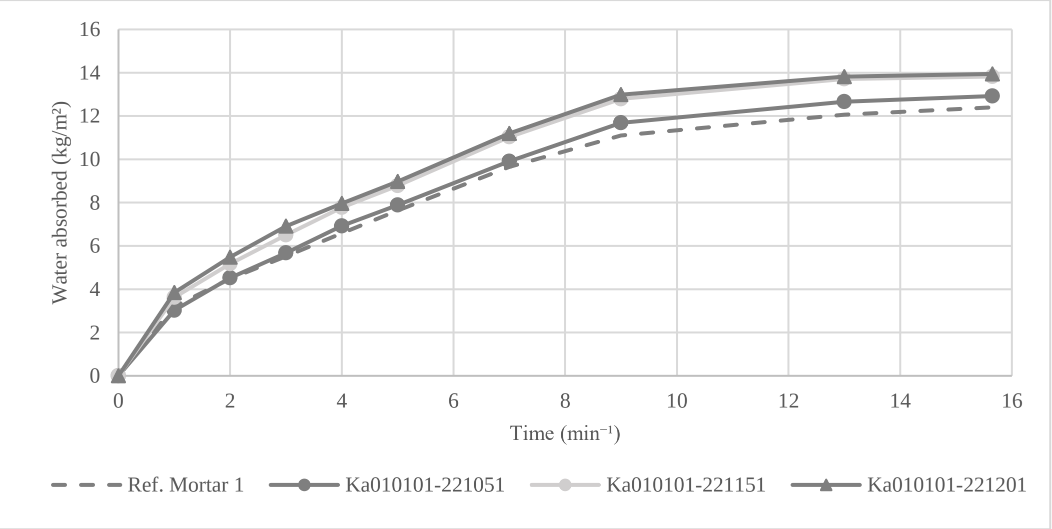

Figure 7-45: Impact of eggwhites on the capillarity water absorption of earth mortars based on Reference Mortar 1.

7.5.2 Drying behaviour of stabilized earth mortars

The drying behaviour of stabilized earth mortars is presented in Table 7-16 to Table 7-15 and some representative drying curves are shown in Figure 7-46. The drying behaviour is defined by the primary Drying Rate (pDR), the secondary Drying Rate (sDR) and the Drying Index which represent the ease of achieving complete drying.

Figure 7-46 shows the drying behaviour of four selected and representative mortars based on Reference Mortar 2. This selection shows that most mortars – independently of the amount of water absorbed – reach a complete drying after 360h (15 days) which is correlated by the similarity of DI in Table 7-16 to Table 7-15. Some stabilizers such as casein in high concentration (Ka150201-22105) have a lower drying rate delaying the complete drying for a few days more whereas others such as mayonnaise stabilized mortar (Ka110201-221021) only achieve full drying due to their very low water absorption. Only some mortars have a higher drying rate leading to a faster loss of water (Ka120201-221061) however, complete drying is achieved at the same time.

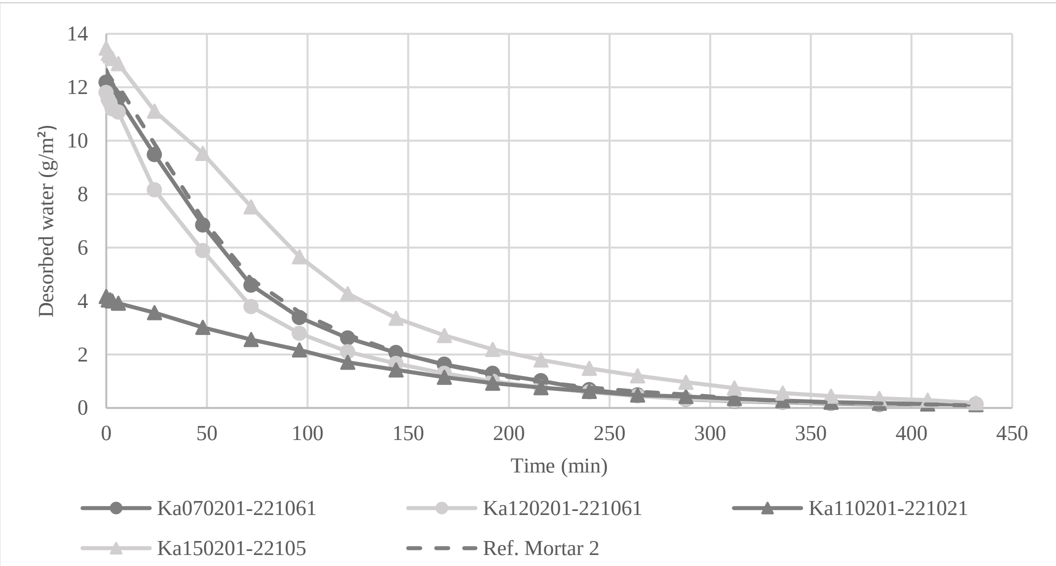

Figure 7-46: Impact of some selected stabilizers on the drying behaviour of earth mortars.

For stabilized mortars based on Reference Mortar 1, the pDR varies from 0.03 kg/m²h (Ka080101-221081 and Ka100101-221021) to 0.10 kg/m²h (Ka040101-221351) and the sDR varies from 0.15 kg/m^2h^{-1} (Ka100101-221041 and -221061) to 1.42 kg/m^2h^{-1} (Ka040101-221081) whereas Reference Mortar 1 has a pDR of 0.08 +/-0.02 kg/m²h and a sDR of 1.12 +/- 0.11 kg/m^2h^{-1}, showing that mortars stabilized with oils have a low drying rate and need a longer time to evacuate the water stored whereas flour-paste stabilized mortars have a much faster drying rate. However, when the Drying Index is considered after 360 h (15 days), the difference in drying ease is not very significant as most of the values are comprised into the deviation of Reference Mortar 1 except for used frying oil stabilized plasters (Ka080101-221061 and -221081) which couldn't achieve a proper drying during the experiment duration and mortars Ka010101-221051 and Ka090101-221301 in which the amount of additive seems to improve the drying behaviour on the long term.

For stabilized mortars based on Reference Mortars 2, the pDR varies from 0.03 kg/m²h (Ka110201-221011 and -221021) to 0.10 kg/m²h (Ka150201-22110) whereas the sDR varies from 0.20 kg/m^2h^{-1} (Ka110201-221011) to 1.34 kg/m^2h^{-1} (Ka150201-22102) but most of the values are similar to the values of Reference Mortar 2 (0.08 +/-0.02 kg/m²h and 1.21 +/0.08 kg/m^2h^{-1} for pDR and sDR respectively). These values show that except for Ka150201-22102, mortars stabilized with casein and mayonnaise have a lower secondary drying rate and therefore need more time to expulse the water trapped inside the mortar. These values are confirmed by the DI of these mortars which varies from 0.34 to 0.42, much higher than the DI of Reference Mortar 2 (0.24 +/- 0.03).

When stabilized mortars based on Reference Mortar 3 are observed, it can be seen that both their pDR and sDR are lower than the ones of Reference Mortar 3 showing that the drying of molasses-stabilized mortars is difficult to achieve. However, due to the low amount of water absorbed, the total drying is faster than Reference Mortar 3.

7.6 Hygric properties of earth mortars stabilized with biopolymers

The hygric properties of earth mortars are presented in the following sections. In each section, firstly general results and trends are introduced and then in the second part, the results for each type of additive are discussed. The hydric properties of earth mortars are summarized in Table 7-17 to Table 7-19.

Table 7-17: Hygric properties of stabilized earth mortars based on Reference Mortar 3.

“	type of additive	Water vapour diffusion resistance factor (-)	Equivalent air layer (m)	Water vapour adsorption (12h - g/m²)	Primary adsorption rate - first 3h (g/m²h)	Secondary adsorption rate - 12h-48h (g/m²h)	Water vapour desorption (12h - g/m²)	Primary desorption rate - first 3h (g/m²h)	Secondary desorption rate - 12h-48h (g/m²h)
Reference Mortar 3	**---**	**5.0**	**0.2**	**119**	**11.6**	**5.6**	**117**	**14.5**	**3.3**
Ka060100-210021	Mo	5.6	0.22	155	15.2	3.5	92	15.7	1.9
Ka060100-210051	Mo	7.4	0.30	152	14.5	4.0	106	17.8	2.2
Ka060100-210151	Mo	8.9	0.38	166	16.4	5.1	94	15.9	1.8
Ka060100-210201	Mo	10.0	0.40	186	18.7	5.6	119	19.6	2.1

Table 7-18: Hygric properties of stabilized earth mortars based on Reference Mortar 1.

Mortar Name	Type of additive	Water vapour diffusion resistance factor (-)	Equivalent air layer (m)	Water vapour adsorption (12h - g/m²)	Primary adsorption rate - first 3h (g/m²h)	Secondary adsorption rate - 12h-48h (g/m²h)	Water vapour desorption (12h - g/m²)	Primary desorption rate - first 3h (g/m²h)	Secondary desorption rate - 12h-48h (g/m²h)
Reference Mortar 1	**---**	**4.1**	**0.2**	**149**	**14.5**	**5.7**	**101**	**13.8**	**3.4**
Reference Mortar 1C	**---**	**4.1**	**0.2**	**123**	**12.6**	**6.3**	**132**	**20.0**	**4.6**
Ka020101-221011	D-juice	4.8	0.19	169	17.0	8.3	129	22.1	5.5
Ka020101-221051	D-juice	4.3	0.17	148	14.1	7.1	102	17.8	5.0
Ka020101-221101	D-juice	4.6	0.18	152	14.9	7.1	115	19.2	5.0
Ka040101-221081	Fl paste	4.6	0.17	136	12.9	6.8	104	15.7	4.4
Ka040101-221161	Fl paste	4.5	0.19	143	13.6	7.2	101	16.7	4.8
Ka040101-221351	Fl paste	5.3	0.20	131	12.8	7.0	100	17.1	4.7
Reference Mortar 1D	**---**	**4.1**	**0.2**	**174**	**17.3**	**4.7**	**105**	**16.6**	**3.1**
Ka010101-221051	Egg	4.6	0.18	184	19.4	4.4	114	18.3	2.7
Ka010101-221101	Egg	4.8	0.18	179	18.6	4.4	107	17.9	2.6
Ka010101-221151	Egg	5.4	0.20	190	19.9	4.8	111	18.0	2.6
Ka080101-22121	U. oil	6.9	0.27	155	16.5	3.2	95	15.0	2.0
Ka080101-22141	U. oil	6.2	0.24	148	16.0	3.2	92	15.0	1.8
Ka080101-22161	U. oil	7.1	0.27	146	15.8	3.1	86	13.6	1.9
Ka080101-22181	U. oil	7.3	0.29	145	15.8	3.2	86	14.5	1.8
Ka100101-221011	Linseed oil	4.8	0.20	157	17.6	4.2	106	17.2	2.3
Ka100101-221021	Linseed oil	5.2	0.21	157	17.1	4.1	110	17.7	2.3
Ka100101-221041	Linseed oil	6.5	0.26	140	15.4	3.4	86	15.1	1.9
Ka100101-221061	Linseed oil	6.4	0.25	156	16.8	4.0	91	15.4	2.0
Ka090101-221301	Straw juice	4.6	0.18	181	19.1	4.6	112	17.6	2.5

Because of experimental conditions which could be changing for the vapour sorption test, the values of the reference mortar tested in the same batch as the stabilized mortar is given in the Table with the mortar name followed by a letter

Table 7-19: Hygric properties of stabilized earth mortars based on Reference Mortar 2.

Mortar Name	Type of additive	Water vapour diffusion resistance factor (-)	Equivalent air layer (m)	Water vapour adsorption (12h - g/m²)	Primary adsorption rate - first 3h (g/m²h)	Secondary adsorption rate - 12h-48h (g/m²h)	Water vapour desorption (12h - g/m²)	Primary desorption rate - first 3h (g/m²h)	Secondary desorption rate - 12h-48h (g/m²h)
Reference Mortar 2	**---**	**4.4**	**0.2**	**145**	**14.5**	**n.a.**	**84**	**11.1**	**2.9**
Reference Mortar 2B	**---**	**4.4**	**0.2**	**186**	**14.0**	**6.3**	**114**	**33.1**	**3.4**
Ka150201-22102	casein	5.7	0.22	169	16.6	5.7	115	15.3	3.1
Ka150201-22105	casein	6.0	0.23	186	18.0	6.6	114	15.3	3.2
Ka150201-22110	casein	6.2	0.25	202	20.0	7.1	116	14.7	3.6
Ka130201-221251	HH stalk	5.9	0.23	192	19.3	6.4	110	13.5	3.5
Ka140201-221201	HH flower	6.1	0.24	209	20.3	7.1	122	16.4	4.1
Reference Mortar 2C	**---**	**4.4**	**0.2**	**197**	**18.4**	**7.0**	**122**	**35.6**	**3.8**
Ka070201-221031	Dung	6.5	0.25	188	17.7	4.8	117	18.4	3.0
Ka070201-221061	Dung	6.3	0.23	188	17.6	4.8	117	18.0	3.1
Ka070201-221111	Dung	5.8	0.22	187	17.2	5.1	124	18.3	3.3
Ka110201-221011	mayo	5.5	0.21	161	18.3	4.3	106	16.8	2.3
Ka110201-221021	mayo	5.1	0.20	149	16.9	3.6	96	15.7	2.0
Ka110201-221031	mayo	7.0	0.27	144	16.1	3.4	91	14.8	2.0
Ka120201-221061	dry CD	6.4	0.25	189	20.4	4.9	130	19.8	3.0

Because of experimental conditions which could be changing for the vapour sorption test, the values of the reference mortar tested in the same batch as the stabilized mortar is given in the Table with the mortar name followed by a letter

7.6.1 Water vapour permeability of stabilized earth mortars

The water vapour diffusion resistance (μ) and the equivalent air layer thickness are presented in Table 7-17 to Table 7-19.

For mortars based on Reference Mortar 1, the coefficient μ varies from 4.3 (Ka020101-221051) to 7.3 (Ka080101-221081) with the reference μ being 4.1 +/- 0.4 and an average μ of 5.3 whereas for mortars based on Reference Mortar 2, the lowest μ is 5.1 (Ka110201-221021) and the highest is 7.0 (Ka110201-221011) both much higher than the μ-value of Reference Mortar 2.

Despite the usage of additives considered as preventing water vapour absorption – linseed oil, used frying oil or mayonnaise (Lima, Silva, et al., 2016; Minke, 2011; Straube, 2000) – the water vapour diffusion resistance is very low and below usual values for these type of mortars. However, despite the difference being low, there is a difference between some stabilized and non-stabilized mortars. Usage of eggwhite, flour paste, cow dung, oils, mayonnaise, casein and plant juice seems to have an impact on the water vapour absorption resistance whereas the usage of cellulose-based additives has no impact on it. These impacts are described for each stabilizer in section 7.6.4.

7.6.2 Water vapour adsorption of stabilized mortars

The water vapour adsorption of stabilized earth mortars is presented in Table 7-17 to Table 7-19 together with the average values of the Reference Mortar it has been tested with (marked with a capital letter). The adsorption after 12h - as described in DIN18947 – and the primary and secondary adsorption rates are given in this table. However, for a better understanding of these values, they need always to be compared with the Reference Mortar with which they have been tested as the testing conditions varied for every batch tested.

From the general results, it can be seen that the adsorption at 12h varies from 131 g/m² for mortar Ka040101-221351 (stabilized with flour paste) to 190 g/m² for mortar Ka010101-221201 (stabilized with egg-white) for mortars based on Reference Mortar 1 whereas the adsorption at 12h varies from 144 g/m² Ka110201-221011 (reinforced with mayonnaise) to 209 g/m² for mortar Ka140201-221201 (reinforced with hollyhock flowers stalks) for mortars based on Reference Mortar 2 and 152 g/m² to 156 g/m² for mortars based on Reference Mortar 3.

These results show a large variation in the amount of vapour absorbed after 12h which depends upon the type of additive used. According to the comparison with the relevant reference mortar, additives such as molasses, oils and mayonnaise decrease the water vapour adsorption whereas additives such as eggwhite, flour paste and hay juice seem to increase the adsorption. Other additives seem to have no or very low impact as their values are comprised in between the deviation of Reference Mortars.

7.6.3 Water vapour desorption of stabilized mortars

The water vapour desorption of stabilized earth mortars is presented in Table 7-17 to Table 7-19 together with the average values of the Reference Mortar it has been tested with (marked with a capital letter). The desorption after 12h and the primary and secondary desorption rates are given in this table. However, for a better understanding of these values, they need always to be compared with the Reference Mortar with which they have been tested as the testing conditions varied for every batch tested.

The amount of vapour desorbed after 12h varies from 100 g/m² (Ka040101-221351) to 129 g/m² (Ka020101-221011) for mortars tested with Reference Mortar 1C, all values lower than the desorption of the Reference Mortar 1C (132 g/m²). Similarly, the desorption rate is lower than the one of the Reference Mortar 1C. For mortars tested with Reference Mortar 1D, the desorption at 12 h varies from 86 g/m² (Ka080101-221061, -221081 and Ka100101-221041) to 114 g/m² (Ka010101-

221051) with mortars stabilized with oils having a low desorption and desorption rate – especially secondary desorption, varying between 1.8 g/m²h and 2.3 g/m²h whereas the rate of Reference Mortar 1D is 3.1 g/m²h – and mortars stabilized with eggs and straw juice having a slightly higher amount of desorbed water after 12h.

For mortars based on Reference Mortar 2, the amount of desorbed water varies between 110 g/m² (Ka130201-221251) and 122 g/m² (Ka140201-221201) similar to the value of the Reference Mortar 2B and from 91 g/m² (Ka110201-221031) to 130 g/m² (Ka120201-221061) whereas Reference Mortar 2C has a desorption of 121.5 g/m² after 12h which shows that mayonnaise lowers the desorption whereas other additives have only a little impact.

Therefore, as a general conclusion, it can be assumed that additives such as molasses, mayonnaise and oils have a high impact in reducing the desorption of vapour whereas other additives have no or little impact on the desorption.

7.6.4 Impact of additives on the hygric properties of stabilized earth mortars

This section presents the impacts of the additive on the hygric properties of earth mortars presented additive by additive. Because experiments have been done on only one specimen for each mortar (except reference mortars which are an average of the value for 3 different mortars of similar composition), the values found are not very precise and could be slightly different if more specimens were tested – as it can be seen in section 5.4.6 in which several mortars with similar composition are tested and different values are found.

7.6.4.1 Impact of fermented fibres and cellulosic additives on the hygric properties of stabilized earth mortars

The water vapour diffusion resistance (μ) of mortars stabilized with fermented fibres, straw washing water and mucilages, varies from 4.3 (Ka020101-221051) to 4.8 (Ka020101-221011) for mortars based on Reference Mortar 1 and 5.9 (Ka130201-221251) and 6.1 (Ka140201-221201) for mortars based on Reference Mortar 2. These values are similar to the μ-values of the reference mortars tested in the same conditions. In addition, the adsorption and desorption values at 12h are also very similar for stabilized mortars and non-stabilized mortars with the exception of mortar Ka140201-221201 which seems to adsorb and desorb water vapour faster. However, when its behaviour is compared with the range of Reference Mortar 2, the adsorption and desorption are only slightly higher than Reference Mortar 2 with the highest adsorption and desorption at 12h. Therefore, it can be concluded that the addition of fermented fibres and cellulosic additives as tested has no impact on the hygric properties of earth mortars.

7.6.4.2 Impact of egg whites on the hygric properties of stabilized earth mortars

The water vapour diffusion resistance (μ) of mortars stabilized with eggwhites varies from 4.6 to 5.4 for an increasing amount of eggwhites, with all values higher than the reference mortar tested in the same batch (Ka000101-2210006 – 4.4). This increase of resistance compared to a non-stabilized mortar is similar to the one demonstrated by Colas & Bourges (2013) even if the authors found higher μ-values for both the non-stabilized mortars and the stabilized mortar. However, the authors underlined that the variation of results is very large and therefore it is difficult to conclude on the real impact of the addition of egg whites.

The water vapour adsorption opposingly shows a different behaviour with samples made with egg-white absorbing an increasing amount of vapour with an increasing amount of stabilizer. However, the difference is not very high from 174 g/m² for Reference Mortar 1 tested in the same batch to 190 g/m² for Ka010101-221201 which is also the highest value for water adsorption at 12h. In the case of water vapour desorption, an opposite behaviour is seen with stabilized mortars releasing the trapped vapour at a faster rate during the first 3h, but then desorbing less water than the reference mortar after 48h. Similar behaviour has been underlined by Ouedraogo et al. (2021) on the moisture buffer value of compressed earth bricks stabilized with ovalbumin.

7.6.4.3 Impact of flour paste on the hygric properties of stabilized earth mortars

The water vapour diffusion resistance (μ) of mortars stabilized varies from 4.6 (Ka040101-221081) to 5.3 (Ka040101-221351) for an increasing amount of flour paste. These values are all higher than the reference mortar 1 tested in similar conditions (Ka000101-2210006 – 4.4) and similar to the values of the mortar stabilized with egg whites. Colas and Bourges (2013) have tested a coating of flour paste and found that it slightly increases the μ-value of the reference mortar however, no experiments have been made with flour paste as an additive but it would probably behave similarly as shown above.

Similarly to the addition of egg whites, the addition to flour paste also seems to increase the adsorption of vapour compared to the Reference Mortar 1 tested in similar conditions with adsorption at 12h varying from 131 g/m² to 143 g/m² higher than the 123 g/m² of Reference Mortar 1C. However, the desorption follows a different pattern, with a much lower amount of desorbed vapour at 12h than the reference mortar. Moreover, the total amount of vapour desorbed is also lower than the vapour desorbed by Reference Mortar 1C. Therefore, it can be concluded that the flour paste increases the adsorption rate and amount of vapour adsorbed but decreases its desorption as Figure 7-47 shows it.

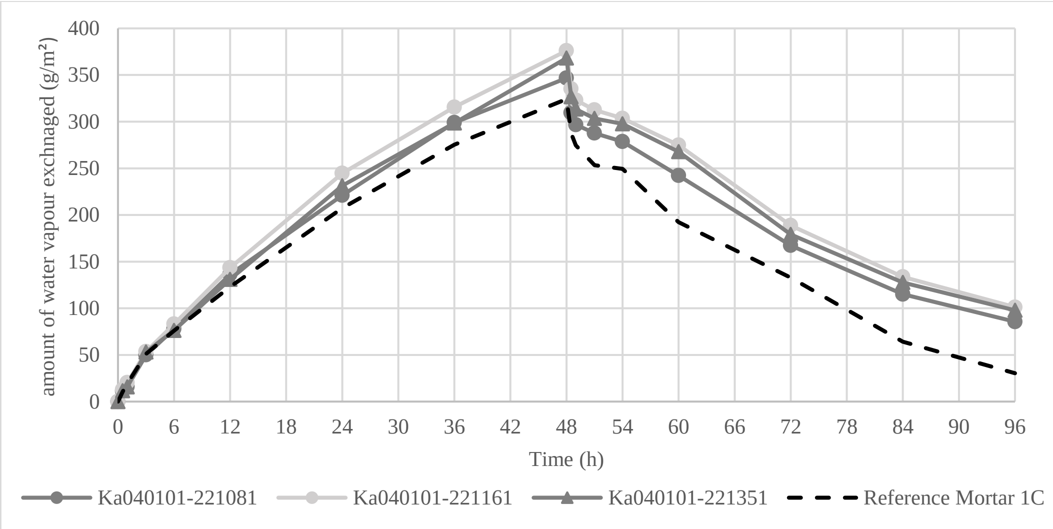

Figure 7-47: Impact of the flour paste on the water vapour adsorption and desorption behaviour of earth mortars.

7.6.4.4 Impact of casein on the hygric properties of stabilized earth mortars

The water vapour diffusion resistance (μ) of casein stabilized mortars varies from 5.7 (Ka150201-22102) to 6.2 (Ka150201-22110) for an increasing amount of casein, values similar to Reference Mortar 2 tested in the same batch (μ-value = 6.3).

When mortars are tested for vapour absorption and desorption, the addition of more casein increases the vapour absorption with 169 g/m² for mortars Ka150201-22102 and 202 g/m²for mortar Ka150201-22110. In opposition to the findings of Minke (2012), it shows that the adsorption of vapour is impacted by the amount of casein, but not reduced except for a small amount of casein. On the other hand, a high amount of casein increases the adsorption of water vapour as shown in Figure 7-48. However, it should be noted that the preparation, activation and usage of casein were different from the one tested by Minke (2012) and all these parameters could have affected the results.

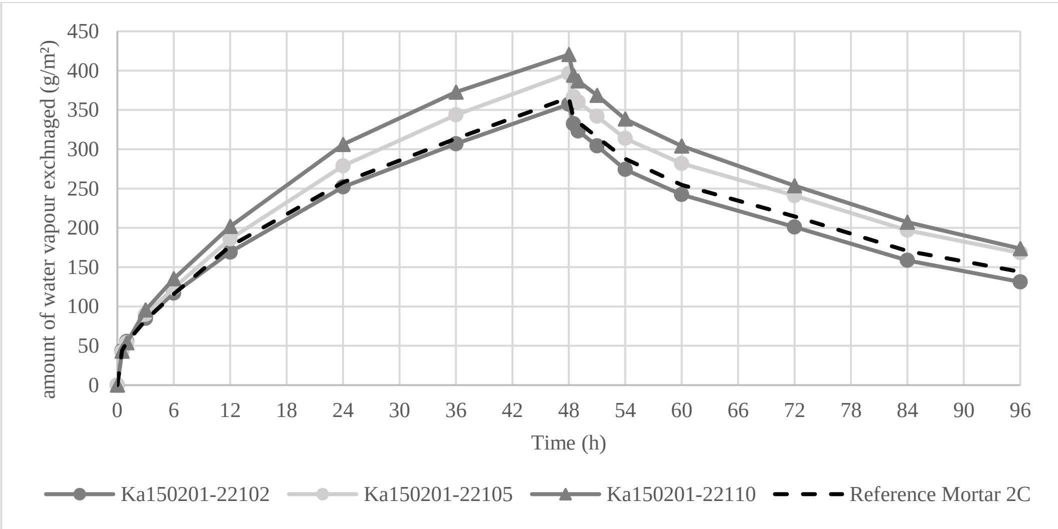

Figure 7-48: Impact of casein on the water vapour adsorption and desorption behaviour of earth mortars

7.6.4.5 Impact of linseed oil and used frying oil on the hygric properties of stabilized earth mortars

The water vapour diffusion resistance (μ) of linseed oil stabilized mortars varies from 4.8 (Ka100101-221011) to 6.5 (Ka100101-221041) for an increasing amount of linseed oil, however, mortars with 6% of linseed oil have a similar μ-value than the mortar with 4% of linseed oil. These values are higher 26% to 70% higher than the values of the Reference Mortar 1 tested in the same batch (μ-value = 3.8). The μ-value for used frying oil reinforced mortar are higher than the one for linseed oil reinforced mortars – 6.9 to 7.3 – but show an increase of the μ-value of 57% to 66% compared to the Reference Mortar 1 for 2% to 8% of oil. Despite the μ-value of oil-stabilized mortars being low compared to the literature and still within the limits given by Röhlen and Ziegert (2014), due to the high increase of their μ-values, it is clear that oil prevents the vapour adsorption of stabilized earth mortars. The impact of the addition of linseed oil on water vapour permeability has also been tested by Colas and Bourges (2013), Lima & Faria (2017) and Guiheneuf et al., (2020) and the authors show that it reduces the vapour permeability of mortars in similar proportions. Minke (2012), Karozou & Stefanidou (2018) and Gomes Battistelle et al. (2020) have tested the addition of linseed oil, used frying oil and other oils as a coating and show a similar reduction of the permeability.

The amount of water vapour adsorbed and desorbed is also impacted by oils used as an additive in earth mortars as can be seen in Figure 7-49 with some representative mortars. From these graphs and the value of water vapour adsorbed after 12h – around 155 g/m² for linseed reinforced mortars and between 145 g/m² and 155 g/m² for used frying oil reinforced mortars – it seems that the amount of additive used in the mortar only has a low impact on the amount of vapour adsorbed and even a low amount reduces the vapour adsorption however not in very high proportion. For desorption, a higher amount of oil means a longer drying and loss of stored vapour as it takes more time for the mortars to lose the lowest amount of water they absorbed. These results are similar to the drying behaviour found in section 7.5.1.3.

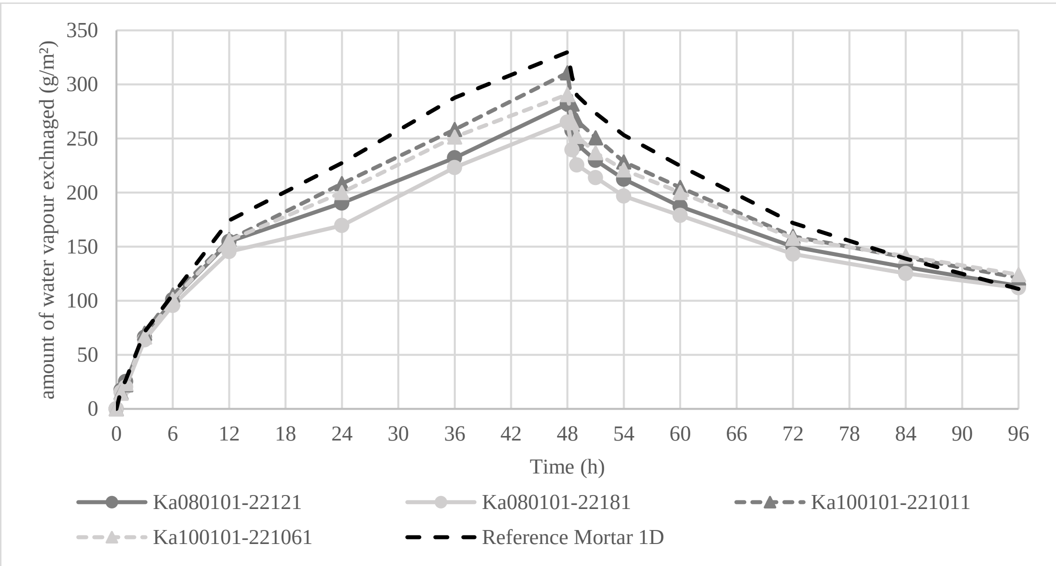

Figure 7-49: Impact of oils on the water vapour adsorption and desorption behaviour of earth mortars. Only 2 mortars of each type (lowest and highest values) have been shown for a better understanding of the graph.

7.6.4.6 Impact of mayonnaise on the hygric properties of stabilized earth mortars

The water vapour diffusion resistance (μ) of mayonnaise stabilized mortars varies from 5.1 (Ka110201-221011) to 7.0 (Ka110201-221031) with the highest μ-value for the highest amount of additive, and with all values showing an increase of at least 27% from the reference mortar tested in same conditions. These values show that the addition of mayonnaise reduces the transfer of water vapour through the material in a similar way to oils or casein.

The amount of water vapour adsorbed after 12h varies from 144 g/m² to 169 g/m² depending on the amount of mayonnaise, lower than the 186 g/m² adsorbed by Reference Mortar 2. The desorption after 12h is also lower than the one of Reference Mortar 2 and therefore the total amount of water vapour exchanged with the environment is low. This behaviour can be seen in Figure 7-50 with a clear slowing of the adsorption after 12h and a clear slowing of the desorption after 72h (24h in a dry environment). This behaviour is somehow similar to the one found for oils stabilized mortars, even if the values are not possible to compare due to different base mortars. However, the in case of mayonnaise, it seems that the addition of more mayonnaise decreases its adsorption capacity whereas the addition of more oil is not very impacting the values.

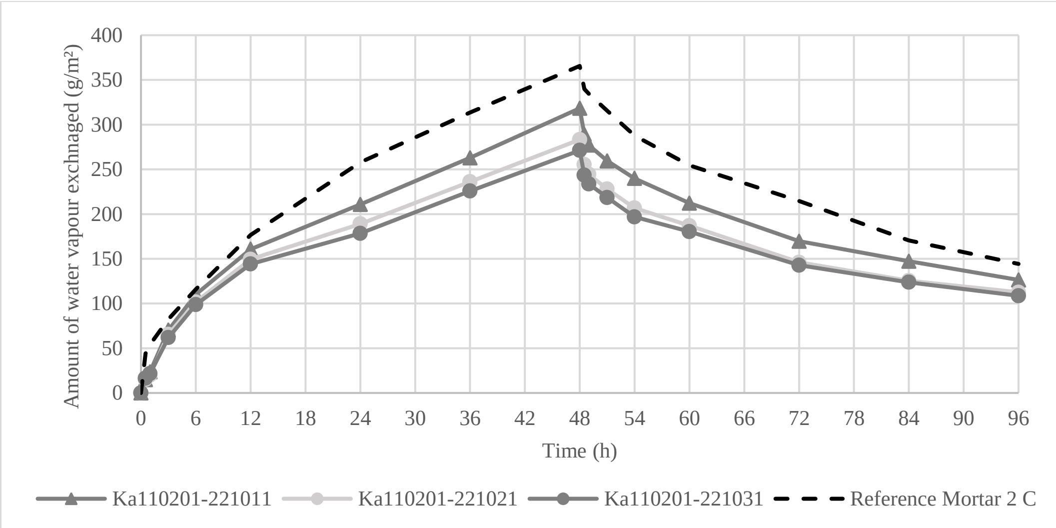

Figure 7-50: Impact of mayonnaise on the water vapour adsorption and desorption behaviour of earth mortars.

7.6.4.7 Impact of molasses on the hygric properties of stabilized earth mortars

The water vapour diffusion resistance (μ) of molasses-stabilized mortars varies from 5.6 (Ka060100-210021) to 10.0 (Ka060100-210201) which corresponds to an increase between 35% and 104% from the μ-value of Reference Mortar 3 tested in the same conditions. Therefore, it can be said that despite a μ-value that is still in the range of vapour resistance of earthen mortars as defined by Röhlen and Ziegert (2014) the addition of molasses highly modify the transfer of vapour through the material. Moreover, the fact that only the samples containing 15% and 20% of molasses have experienced the formation of moulds shows that the additive not only prevents the transfer of water vapour but also is prone to biological growth if exposed to a large amount of humidity during a long period (during the experiment, the samples were exposed to 85% RH to 95% RH during 2 months).

The adsorption of molasses-reinforced mortars at 12 h varies between 152g/m² and 186 g/m² higher than the 119 g/m² found for Reference Mortar 3 in the same conditions. Moreover, despite a slow-down in the adsorption after 12 h, the total adsorption of the stabilized mortars for any amount is still higher than the non-stabilized mortar. On the opposite, the desorption is slower for the stabilized mortars than for Reference Mortar 3. (Figure 7-51) This behaviour is probably due to the reaction of the water with the sugar which is a material very sensitive to water. Sugar will adsorb the water vapour and release it with more difficulty than clay, therefore for samples with a large amount of molasses, the drying period is longer.

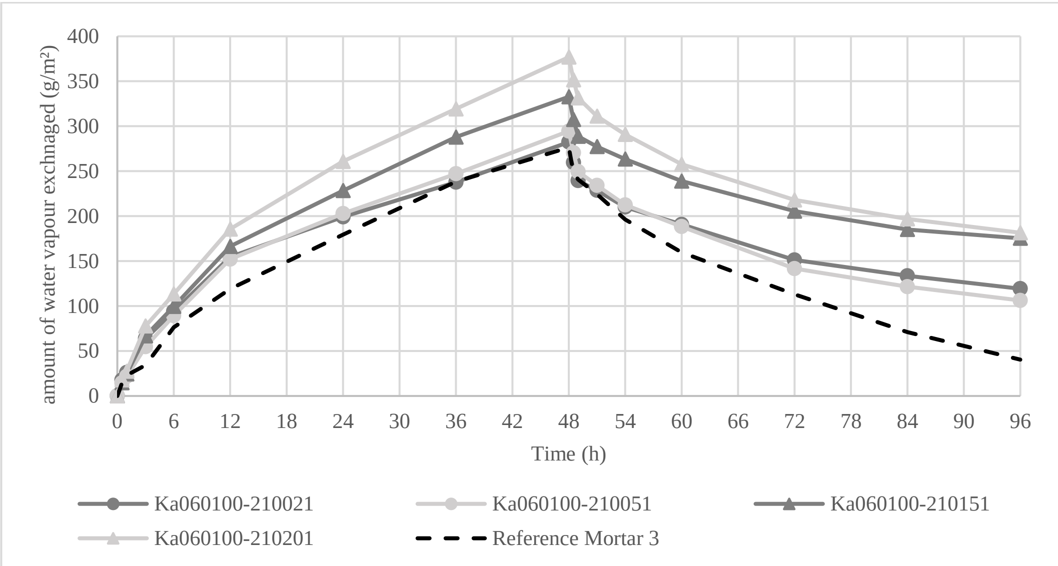

Figure 7-51: Impact of molasses on the water vapour adsorption and desorption behaviour of earth mortars.

7.6.4.8 Impact of cow dung on the hygric properties of stabilized earth mortars

The water vapour diffusion resistance (μ) of cow-dung stabilized mortars varies from 5.8 (Ka070201-221111) to 6.5 (Ka070201-221031), which shows a decreasing resistance with an increasing amount of cow-dung. However, the difference between the values is not large and these values are close to the ones of Reference Mortar 3 tested in the same batch (Ka000201-2210014, μ-value = 6.3). Therefore, it can be considered that the addition of cow dung has no or only a little impact on the vapour resistance of mortars. A similar low impact is found for the adsorption and desorption of water vapour with values of cow-dung stabilized mortar very similar to the ones of non-stabilized mortars (adsorption after varies between 187 g/m² and 188 g/m² whereas the Reference Mortar 2 has adsorption of 186 g/m²). This similarity of value is presented Figure 7-52 on which the low difference between the value of the stabilized and non-stabilized mortar can be obaserved.

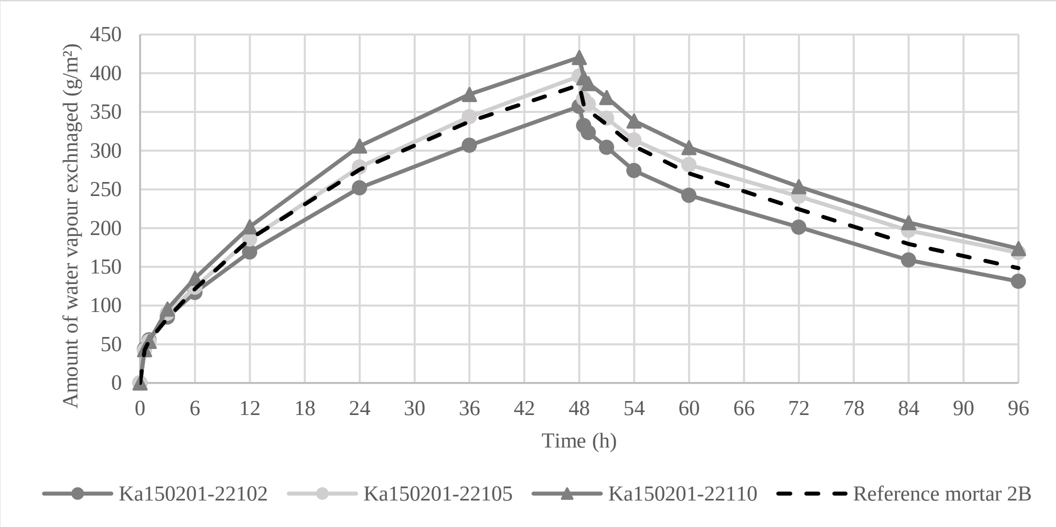

Figure 7-52: Impact of cow dung on the water vapour adsorption and desorption behaviour of earth mortars.

CHAPTER 8

CONCLUSION

This work aimed to study the impact of local and natural additives on the properties of earth mortars aimed for plastering purposes. For this purpose, some abundant agricultural wastes and easy-to-find materials – which were considered promising according to the findings of the literature survey – were integrated into a mortar made from local earth, sands and fibres. The impact of the addition of different amounts of sand and fibres was presented in CHAPTER 5 together with the properties of a reference mortar with optimum properties. The impact on the mortar properties of the replacement of the selected sand and fibres with alternative material was analysed in CHAPTER 6 and the impact of the stabilization with natural additives of the reference mortar was presented in CHAPTER 7. Finally, this chapter concludes the dissertation with a summary of the different impacts of the modification of earth mortar on their many properties and outlines the possibilities for the usage of the studied additives in real construction.

8.1 Summary of the research findings

The literature survey has shown that several additives were used traditionally for the reinforcement of earthen materials (Paul & Changali, 2020; Vissac et al., 2013) but that their impacts on the properties of earthen mortars have either not been studied or only partially studied. Therefore, after that a selection of promising additives had been done with regard to their availability from local resources, the work focused on determining an optimum mix of earth, sand and fibres and the type of impacts that the replacement of original sand and fibre by alternative ones would make as well as the impacts the addition of biopolymers would have.

8.1.1 Impact of the amount of sand and fibres

The properties of earthen materials vary depending on the amount of clay and the amount of reinforcing materials. The amount of sand and fibres used to reinforce the mortar have been varied and the properties of the mortar have been determined (see CHAPTER 5). The impacts of the addition of sand or fibres are found very different and are sometimes beneficial and sometimes detrimental but the addition of reinforcing material is necessary for the usage of the earth mortar as a plaster as plain earth mortars have a shrinkage too large to be of any use. Therefore it has been found that despite the reduction of density and strength due to the addition of fibres and/or sand, decreasing the amount of clay to 10% by weight for sand-reinforced mortars and 23% by weight for fibres-reinforced mortars is necessary to decrease the shrinkage below 2%. However, the addition of sand and the addition of fibres lead to different impacts in terms of durability, water resistance and hygric behaviour.

8.1.2 Impact of the usage of alternative sands and fibres

The impact of substituting "plaster" sand with alternative sands of different types and particle sizes and of replacing plain chaff with sieved chaff or fibres from diverse origins have been studied and the findings are included in CHAPTER 6.

The usage of different types of sand has a limited impact on most of the properties of earth mortars probably because of its limited impact on the density of the mortars. However, the sand type and especially the particle size distribution of the sand has an impact on the shrinkage and more interestingly on the strength, the usage of fine angular sand leading to a large increase in flexural and compressive strength whereas the usage of sands without fine or coarser sand decreases the strength. From the different types of sand used (as summarized in Table 8-1), it appears that the usage of fine yellow sand has the highest beneficial impact on most of the properties tested, except shrinkage which is increased. Moreover, using well-graded and angular sand (e.g. yellow sand) leads to higher mechanical properties and better resistance to erosion and abrasion while on the contrary using sand without fines or having only one size of particle as well as rounded sand decreases the strength and the resistance to abrasion while increasing the resistance to immersion. Therefore the usage of fine well-graded and angular sand is recommended for plasters.

On the other hand, the usage of different fibres, despite their low amount, has a large impact on several properties of earth mortars, especially when the source of fibres is changed.

Overall, despite leading to a higher shrinkage, the usage of thin and flexible fibres increases most of the properties of earth plasters, especially in terms of strength and cohesion. Therefore, the usage of fibres such as flax or wool – for those tested in this work – should be encouraged. However, this type of fibre is more difficult to use as the homogeneity of the mix is more difficult to achieve and the prevention of clusters of fibres is difficult. The second property of the fibres that seems to impact the properties of the mortar is the water absorption and swelling of the fibres as already pointed out by several authors and using already saturated fibres has only little impact on the reduction of the mortars' properties. Therefore, it is not recommended to use fibres such as pine needles or even wool. Finally, the roughness of the fibre's surface which can be evaluated by the touch of the researcher is also an important indicator of the possibility of increasing the cohesion of the mix.

An interesting feature in terms of vapour behaviour is the possibility that the chemical composition of the fibres will impact the amount of vapour absorbed as the mortars made with plant-based fibres seem to have a higher sorption rate than the one made with animal-based fibres. However, as the differences are very low, focusing on the type of clay to be used might be more effective.

8.1.3 Impacts of the usage of biopolymers

The impacts of adding biopolymers into reference mortars whose properties were adequate enough to comply with the relevant standards or protocols have been studied and are presented in CHAPTER 7. These impacts are summarized in Table 8-2.

From the results obtained, it seems that some of the additives have clearly a beneficial impact on the properties of earth mortars whereas some might be beneficial for some specific properties. However, the main outcome of the study are as follow:

- The usage of used frying oil and molasses should be avoided despite some interesting impacts on strength and water resistance. Used frying oil stabilized mortars have a crumbly surface which is not represented by the results of the erosion test but makes it unsuitable for usage as plaster whereas mortars stabilized with molasses have a very brittle behaviour once fully dried – since no fibres could be used – but they will directly lose their properties in presence of vapour or water and the drying will be very long. Moreover, both samples have additional drawbacks such as a persistent smell for used frying oil-stabilized mortars and a very dark colour for molasses-stabilized mortars.
- Linseed oil and mayonnaise have very similar impacts on mechanical strength, cohesion and water resistance with even slightly better resistance to water of mayonnaise stabilized mortars for the same amount of biopolymer, and despite a decrease of the vapour permeability and a lower amount of water vapour absorbed after 12 hours in the humid room, the results show that these mortars still retain their good vapour sorption properties due to the low amount of additives used. A possible way would be to test the addition of lower amounts of additives in order to determine if the impacts are still beneficial.
- Despite good impacts on the strength of mortar and the increase of cohesion, and especially the increase in vapour absorption, the usage of juice of fermented fibres is not sufficient to provide enough water resistance and therefore mortars stabilized with cellulose-based materials as tested should only be used in protected conditions. One exception is the usage of mucilage of hollyhock flowers which provides an increase in water resistance despite a non-optimized mortar. Using a more systematic approach as shown by

Herredia-Zavoni (1988) for other mucilages might help to gain even better resistance and higher strength for the stabilized mortars.

- The most promising results were obtained for flour paste-stabilized, egg white-stabilized and casein-stabilized mortars which all increase the strength, cohesion and water resistance while decreasing the shrinkage and increasing the vapour absorption. Flour paste stabilized mortars especially obtained good results for erosion and abrasion test compared to the reference mortar, however, it should be noted that despite their positive impacts in comparison of the reference mortar, the increase in strength, water resistance or cohesion is limited compared to the mortars stabilized with linseed oil or mayonnaise for higher amounts of additives.

The biopolymers used have been carefully chosen to be natural and easy to obtain as well as already been studied previously in terms of improvement of mortar properties. However, some of these biopolymers have other usages – especially egg white and flour – which might be more important than mortar enhancement and therefore the benefit of using them for construction purposes should be carefully evaluated in regard to other usa

Table 8-1: Summary of the impact of alternative sands on the properties of earth mortars

Properties tested		Shrinkage	Cracks development	Density	Dry Flexural Strength	Dry Compressive Strength	Humid Flexural Strength	Humid Compressive Strength	Surface cohesion	Resistance to abrasion	Surface water absorption	Capillarity absorption rate	Total absorption	Drying Behaviour	Resistance to erosion	Resistance to immersion	Water Vapour Permeabilty	Water Vapour Absorption rate	Amount of vapour adsorbed	Water vapour desorption
Properties of sands	Well graded	NC	NC	NC	NC	NC	=	=	NC	↑	↓	=	NC	=	NC	NC	NC	↑	↑	NC
	Finer particles	↓	NC	NC	↑	↑	=	=	NC	NC	NC	=	↑	=	↑	↑	NC	NC	NC	NC
	Coarser particles	↓	NC	↑	↓	↓	=	=	NC	NC	NC	=	↓	=	NC	↓	NC	NC	NC	NC
	High amount of fines	↑	↑	=	↑	↓	=	=	NC	NC	NC	=	↑	=	NC	NC	NC	NC	NC	NC
	No fines	NC	NC	NC	NC	NC	=	=	NC	NC	↑	=	↓	=	NC	↓	NC	NC	NC	NC
	Lower angularity	NC	NC	NC	↓	↓	=	=	NC	↓	NC	=	NC	=	↓	NC	NC	NC	NC	NC
	Higher angularity	NC	NC	NC	↑	↑	=	=	NC	↑	NC	=	NC	=	↑	NC	NC	NC	NC	NC
Properties of fibres	Fineness	↑	NC	↑	↑	↑	=	=	↑	↑	↑	NC	=	NC	NC	NC	NC	NC	NC	NC
	Stiffness	↓	↑	↑	NC	↑	=	=	NC	NC	NC	NC	=	NC	↓	↓	NC	NC	NC	NC
	Water absorption and swelling	↑	↓	↓	↓	↓	=	=	NC	↑	↑	↑	=	NC	NC	↓	NC	NC	NC	NC
	Roughness	↓	NC	NC	NC	↑	=	=	↑	↑	NC	NC	=	NC	NC	NC	NC	NC	NC	NC
	Brittleness	NC	NC	NC	↓	↓	=	=	NC	NC	NC	NC	=	NC	NC	NC	NC	NC	NC	NC
	Tensile strength	NC	NC	NC	↑	NC	=	=	NC	NC	NC	NC	=	NC	NC	NC	NC	NC	NC	NC
	Crushability / Tubular	↓	NC	↑	↓	↓	=	=	NC	NC	NC	↑	=	NC	NC	NC	NC	NC	NC	NC
	Low amount of dust/fine elements	↓	NC	NC	NC	↓	=	=	NC	NC	NC	NC	=	NC	NC	NC	NC	NC	NC	NC

All properties were tested and the results were compared with the reference mortars. From the comparison, conclusions were drawn and are summarized in the table. NC stands for Non-Conclusive, the green arrow stands for increase, the blue arrow stands for decrease and the equal sign stands for no changes.

Table 8-2: Summary of the impact of the addition of biopolymers on the properties of earth mortars

Properties tested	Shrinkage	Cracks development	Density	Dry Flexural Strength	Dry Compressive Strength	Humid Flexural Strength	Humid Compressive Strength	Surface cohesion	Resistance to abrasion	Surface water absorption	Capillarity absorption rate	Total absorption	Drying Behaviour	Resistance to erosion	Resistance to immersion	Water Vapour Permeability	Water Vapour Absorption rate	Amount of vapour adsorbed (12h)	Water vapour desorption
Polysaccharides																			
Fermented fibres	↑	=	=	↑	↑	=	=	↑	↑	↓	NC	=	=	=	↓	NC	↑	↑	↘
Hollyhock stem mucilage	=	=	=	↓	↓	=	=	=	↑	=	=	=	=	=	=	↓	=	=	=
Hollyhock flowers mucilage	↓	=	=	↓	=	=	=	=	=	↓	↓	↓	=	=	↑	↓	↑	↑	↑
Flour paste	↓	=	↘	↗	NC	=	=	↗	↗	↘	NC	=	=	↗	↗	↘	↑	↑	↓
Molasses	↑	=	=	↗	↗	=	=	↗	↗	↓	↘	↘	↘	NC	↗	↘	↑	↑	NC
Lipids																			
Linseed oil	↓	=	=	↗	↗	↗	↗	↓	↗	↘	↓	↓	↘	↑	NC	↘	↓	↓	↘
Used frying oil	↓	=	=	↘	↘	=	=	↑	↗	↘	↓	↓	↓	↑	↗	↘	↓	↓	↘
Proteins																			
Egg white	NC	=	=	↗	↗	=	=	↑	↓	↘	=	=	=	↗	↗	↘	↑	NC	↗
Casein	↘	=	=	NC	↘	=	↗	↗	↗	↓	=	=	↘	=	↑	↘	↗	↗	=
Complex mix																			
Mayonnaise	↘	=	=	=	↗	=	=	↗	↗	↓	↓	↓	↘	↑	↑	↘	↘	↘	↘
Fresh cow dung	↗	↑	↘	↘	↘	↘	↘	NC	↑	↘	NC	=	=	↗	↗	NC	↓	↓	↓
Dried cow dung	↓	=	↓	=	=	=	=	↑	=	↓	=	=	=	=	=	↓	↓	↓	↑

All properties were tested and the results were compared with the reference mortars. From the comparison, conclusions were drawn and are summarized in the table. NC stands for Non-Conclusive, the green vertical arrow stands for increase independently of the amount of biopolymer tested, the green diagonal arrow stands for increase while increasing the amount of stabilizer, the blue vertical arrow stands for decrease independently of the amount of biopolymer tested, the blue diagonal arrow stands for decrease for decreasing amount of material and the equal sign stands for no changes.

8.2 Improvements achieved in earth mortars

Several ways of improving an earth mortar have been tested, either through the transformation of the matrix by the addition of different amounts of sand and different type of sand, either by the creation of a 3D mesh containing the bulky materials through the addition of fibres or by the addition of a material interacting with the clay to enhance its binding properties or by the addition of a material preventing the passage of water. However, depending on the type of action needed to improve the mortar, different materials can be chosen.

8.2.1 Improvement of the shrinkage

As pure earth materials containing a large amount of clay often come with good properties in terms of strength and water resistance, they also have a high shrinkage that prevents their use as construction materials because of the development of micro and macro cracks if large elements are produced. Therefore the reduction of shrinkage is necessary and can be achieved by

- the addition of a large amount of sand to reduce the clay proportion to about 10% to 15%;
- the addition of fibres whose amount will depend on the amount of clay but 4% to 5% by weight was found necessary in the case of the studied earth that contained 24.5% of clay in order to reduce the shrinkage to below 3%,
- the replacement of the sand by fine well-graded sand or conversely by coarse well-graded sand
- the replacement of the fibres by stiff and thick fibres but in this specific case it leads to the appearance of cracks
- the addition of flour paste or linseed oil as an additive allows up to a 50% reduction of the shrinkage compared to the reference mortar

On the other hand, some fibre substitutions or usage of stabilizers will have a strong adverse impact on shrinkage with an increase of more than 20% with the replacement of chaff by flax fibres or an increase of 50% with the addition of a low amount of casein or molasses.

8.2.2 Improvement of mechanical strength

The highest strength of earth mortars is achieved by using plain earth without any additional material as the addition of sand or fibres has an adverse impact even in low quantities. However, as there is a need for preventing shrinkage and cracks, the best solution possible can be found by adding or using the following:

- Fine well-graded sand instead of coarse or normal sand
- Angular sand instead of round shape sand
- Fine and strong fibres such as flax fibres as they increase the strength of mortar – especially the flexural strength – by more than 40% or wool fibres which have a lower impact although the impact is higher on flexural strength than on compressive strength
- The addition of stabilizers such as egg whites, decomposition juice, and especially flour paste or linseed oil at a high amount or molasses even at only 2 % by weight also increases the mechanical strength compared to the reference mortar. Most of the stabilizers – except linseed oil – have a higher impact on flexural strength than compressive strength.

Among all materials tested, it is important to point out that choosing coarse sand even well-graded or rounded sand will have a strong adverse impact on the strength similar to the usage of used frying oil.

8.2.3 Improvement of the cohesion

The improvement of the cohesion is important as this property is related to the resistance to abrasion but also to the mechanical strength and in a certain manner to the resistance to erosion and immersion in water. Among all tested materials, the ones that led to the highest cohesion – except the usage of plain earth – are as follow:

- Coarse sands were able to provide a higher resistance to abrasion than reference sands but not as high as the usage of fine sands,
- Flax fibres
- Mayonnaise, linseed oil and molasses from 2% by weight
- and a high concentration of flour paste or casein (the highest concentration tested)

8.2.4 Improvement of water resistance

The lack of resistance to water of earth materials and their high absorption rate is one of the major drawbacks to the more widespread usage of these materials. Despite plain earth having a certain resistance to water and the addition of fibres preventing both disaggregation of the material immersed in water and erosion, reinforced earth mortar especially the ones with added sand have very low water resistance. Therefore in order to counterbalance the negative impact of the addition of sand, stabilizers are necessary such as

- oils and mayonnaise that wrap the clay particles, thus preventing their separation by water,
- molasses and in a more limited way cow dung that chemically interact with the clay to create more water-resistant particles
- flour paste and cellulose-based stabilizer which create a microscopic net preventing the separation of molecules

However, the water resistance should also be accompanied by lesser water absorption and especially by a fast drying process therefore the usage of mayonnaise is somewhat questionable as it prevents a fast drying of the mortar.

8.3 Perspectives and recommendations for future work

This dissertation intended to determine in which way an earth mortar could be improved using materials which do not necessitate sensitive storage and difficult preparation. Therefore mostly locally available fibres, sands and biopolymers (egg white, flour paste or decomposition juice) have been used together with widely and commercially available additives (molasses, linseed oil, flax fibres, washed sand…). All these materials have been tested for several different properties with the same earth and in the same conditions to overcome the disparity of results found in the literature due to partial research on specific properties. However, despite very interesting and promising findings, especially on the impact of biopolymers like egg, whites flour paste of casein, some of the results need to be expanded to determine the best solution to create resistant plasters. Recommendations and perspectives for future works designed to determine the proper additives to use could be summarised in three parts:

- Better understanding of the mechanism of interaction between clays and additives at a microscopic level,
- Determining the optimum amount of additives to account for all properties and especially the ones that were not tested in this study.
- Testing more additives based on traditional knowledge to account for local resources

8.3.1 Interaction between clays and additives

The study dealt here with determining the impacts of additives on one type of earth at a macroscopic level. Large-size samples were used and only visible transformations were accounted for. However, despite the findings of this study giving clear indications of which additive could be used and how for this type of earth, it is not enough to generalize for the usage with other types of earth or additives with slightly different sources. Therefore more research is needed to understand the impacts of additives:

- by comparing the action of the same additives in similar quantities on other types of earth
- by examining the reinforced mortars and stabilized earth more deeply to understand either the changes that occurred in the disposition of particles

while adding sands and fibres or the chemical transformations and the modification in the organization of molecules that happened while adding a biopolymer.

- Determining the exact molecules that are interacting with the clays in order to get more precise dosages and better results.

Understanding the mechanisms that lead to improvements in properties more than the results would lead to more efficient stabilization and a better understanding of which other additives could be used.

8.3.2 Usage of local resources and traditional knowledge

Despite this study initiated in a country with a long tradition of using earth for construction and hosting very different cultures in climatic and geographical conditions, finding which additives and which earths were used traditionally for these purposes were challenging and energy-consuming. Only one traditional additive could be found from oral reports – usage of hollyhock flower which gave interesting results – and its proper usage was not clearly determined. Moreover, speaking with locals and which earth and which materials were used would bring some very different results that would need proper testing. Therefore a widely accessible inventory of traditional knowledge on earth construction is necessary so the local practices could be questioned and possibly used to their best advantage.

8.3.3 Reliable testing campaign

In this work because of space and resources limitations, plasters could only be tested as mortars as their most important feature – i.e. their ease of implementation on a vertical surface and their adhesive strength – has not been tested and according to the personal trial of the author in other conditions, the addition of molasses or linseed oil can lead to a material with reduced adhesion on the support during implementation and that would result in detachment from the wall while drying.

Therefore all mortars studied in this work would need to be examined from this perspective to be used as plaster.

Moreover, due to the same limitations, the testing of the hygric properties could not be precise enough and led to results which are not comparable with the literature and should only be used as a trend. A better determination of the vapour permeability and vapour sorption of stabilized mortars could bring more knowledge on how to use the additives and which quantities should be used. For similar reasons, the thermal testing of the materials – especially thermal conductivity and diffusivity – could not be done too in the scope of the thesis, but these values could also inform the interest in using a stabilizer in specific conditions.

Another limitation of this research is the testing of materials in laboratory conditions in a short time span. However, it is known that climatic conditions and especially UV wind or frost have an impact on materials and their behaviour. Testing the materials under real conditions and determining their evolutions through time is a necessary step to determine the long-lasting impact of the additives used.

Finally, to determine the appropriateness of using these stabilizers for creating an ecological material, the life cycle assessment of the stabilized material should be done with a particular emphasis on its end-of-life and the continuity of endless reuse as some additives are used in large quantity and prevent its degradation by water and therefore might prevent its reuse.

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APPENDICES

A. Classification of the corpus on earth mortars

Table A 1 to Table A 3 present the integrity of the corpus of studies on earth mortars and present a summary of their content classified according to the type of material produced, i.e., Adobe (Mud Brick - MB), Pressed Adobe Brick (PAB), Mortar (MO) and Plaster (PL). Articles are classified by research and the number is the number of the research, therefore the number of articles reviewed is higher.

Table A 4 introduces the properties and the amounts of the different types of earth used in the literature on earth mortars. Mortars are classified according to the type of material produced, i.e., Adobe (Mud Brick - MB), Pressed Adobe Brick (PAB), Mortar (MO) and Plaster (PL).

Table A 5 summarizes the properties and quantities of the different types of aggregate used in the literature on earth mortars. Mortars are classified according to the type of material produced, i.e., Adobe (Mud Brick - MB), Pressed Adobe Brick (PAB), Mortar (MO) and Plaster (PL).

Table A 6 presents the properties and quantities of the different types of pellets used in the literature on earth mortars. Mortars are classified according to the type of material produced, i.e., Adobe (Mud Brick - MB), Pressed Adobe Brick (PAB), Mortar (MO) and Plaster (PL).

Table A 7 shows the properties and quantities of the different types of fibres used in the literature on earth mortars. Mortars are classified according to the type of material produced, i.e., Adobe (Mud Brick - MB), Pressed Adobe Brick (PAB), Mortar (MO) and Plaster (PL)

Table A 8 presents the different types of hydraulic binders used for stabilizing earth mortars. Mortars are classified according to the type of material produced, i.e., Adobe (Mud Brick - MB), Pressed Adobe Brick (PAB), Mortar (MO) and Plaster (PL).

Table A 9 shows the different types of mineral binders other than hydraulic binders used for stabilizing earth mortars. Mortars are classified according to the type of material produced, i.e., Adobe (Mud Brick - MB), Pressed Adobe Brick (PAB), Mortar (MO) and Plaster (PL).

Table A 10 summarizes the properties and quantities of the different types of biopolymers used in the literature on earth mortars. Mortars are classified according to the type of material produced, i.e., Adobe (Mud Brick - MB), Pressed Adobe Brick (PAB), Mortar (MO) and Plaster (PL).

Table A 11 present the type of mineral and synthetic stabilizers used for earth mortars. Mortars are classified according to the type of material produced, i.e., Adobe (Mud Brick - MB), Pressed Adobe Brick (PAB), Mortar (MO) and Plaster (PL).

Table A 12: summarizes the dimensions of the samples used for determining the physical properties of the mortars.

Table A 13: summarizes the dimensions of the samples and the speed of the device used for determining the mechanical properties of the mortars.

Table A 14: summarizes the dimensions of the samples used and the experimental set-up used for determining the durability properties of the mortars.

Table A 1: Studies on earth mortars made on mud bricks and pressed adobe blocks

No	Type	Mortar production	Mortar Composition					Water amount (%)	Reference
			Earth type / Clay amount (%)	Aggregates amount (%)	Pellets amount (%)	Fibres amount (%)	Additives amount (%)		
1	MB	cast	Natural / 0.5	-	-	10	0 ; 10	n.a.	(Achenza & Fenu, 2007)
2	MB	cast	Natural / 36	-	-	-	0 - 3	15 ; 20	(Aguilar et al., 2016)
3	MB	n.a.	Natural / n.a.	4.7 - 13	-	0 – 1.2	0 - 12	48	(Al-Ajmi et al., 2016)
4	MB	cast	Natural / n.a.	-	-	0 – 2	0 – 10	n.a.	(Alam et al., 2015)
5	MB	Cast + Tamped	Natural / 11	-	-	0 ; 0.5 , 2	-	30.7 – 32.6	(Araya-Letelier et al., 2017, 2018)
6	MB	Cast + Tamped	Natural / 11	-	-	0 – 1	-	30.7	(Araya-Letelier et al., 2019)
7	MB	Cast + Tamped	Natural / 12	-	-	0 – 1	-	25	(Araya-Letelier et al., 2020; Gonzalez-Calderon et al., 2020)
8	MB	Cast + Tamped	Natural / 12	-	-	0 ; 0.5 , 2	-	25	(Araya-Letelier et al., 2021)
9	MB	Cast + Tamped	Natural / 25				0 – 4	22	(Babé et al., 2020)
10	MB	Cast + Tamped	n.a. / 40				0 – 15	n.a.	(Bahobail, 2012)
11	MB	Cast + Vibrated	Natural / 44	0 ; 50		0 – 4		22	(Bertelsen et al., 2021, 2019)
12	MB	Cast + Vibrated	Natural / 32	23		0.15 – 3	15+3+4.6	31	(Binici et al., 2005)

Table A 1 continued

No	Type	Mortar production	Mortar Composition					Water amount (%)	Reference
			Earth type / Clay amount (%)	Aggregates amount (%)	Pellets amount (%)	Fibres amount (%)	Additives amount (%)		
13	MB	Cast + Vibrated	Natural (4 types)	-	-	0;0.01;0.05	2.5	25	(Binici et al., 2007)
14		Cast + Vibrated	Natural / n.a.	-	-	0 – 3	-	n.a.	(Binici, 2017)
15		Cast	Quarry fine/ n.a.	-	-	3	n.a.	n.a.	(Bock-Hyeng et al., 2016)
16	Adobe	Cast	Natural / 18	-	-	0 – 1	-	15.7	(Brás et al., 2019)
17	Adobe	Cast + pressed	Natural / 38	0 - 80	-	*3 - 60*	0 – 3	33	(Caballero-Caballero et al., 2017)
18	Adobe	n.a.	Recycled earth	-	-	*0 ; 9 ; 30*	3	33	(Călătan et al., 2015, 2016; Călătan, Hegyi, & Mircea, 2014; Călătan, Hegyi, Dico, et al., 2014)
19	Adobe	n.a.	Natural / 11	-	-	0 ; 0.5 ; 2	-	30.7	(Călătan et al., 2017)
20	Adobe	Cast + Tamped							(Concha-Riedel et al., 2019)
21		Cast	Corrected / 23			0 – 6	0 ; 0.06 ; 0.2		(Corrêa, Mendes, et al., 2015; Corrêa, Protásio, et al., 2015)
22		Cast by force	Natural / n.a.		*30 - 70*	*30 - 70*	*42 ; 45*		(Costi de Castrillo et al., 2021)
23		n.a.	Natural / n.a.				0 - 25	n.a.	(Degirmenci, 2008)
24		n.a.	Natural / n.a.			0 - 4		n.a.	(Elhamdouni et al., 2015)

Table A 1 continued

No	Type	Mortar production	Mortar Composition					Water amount (%)	Reference
			Earth type / Clay amount (%)	Aggregates amount (%)	Pellets amount (%)	Fibres amount (%)	Additives amount (%)		
25		Cast Cast + tamped	Natural / 37.9 Natural / 31.4 Natural / 34.7 Natural / 29					28	(Dormohamadi & Rahimnia, 2020)
26		Cast + tamped	Natural / 31 Natural / 27				0 ; 0.1 0 – 0.5 0 ; 0.1	15 16 16	(Dove, 2014; Dove et al., 2016)
27		Cast	Corrected / 41	-	-	0 - 10	-	22.3 – 25.2	(Gandia et al., 2019)
28		Cast	Natural / 15	-	-	-	0 ; 2; 4	n.a.	(Gomes Battistelle et al., 2020)
29		Cast	Engineered / 13			0 – 5		20 - 31	(Rogiros Illampas et al., 2017)
30		Cast + pressed	Natural / N.a			*33*		*+/-30*	(Jové-Sandoval et al., 2018)
31	MB PAB	Cast	Natural / 25.5					17.5 – 24 14.7 – 20.7	(Kouakou and Morel 2009
32		Proctor comp	Quarry fine / n.a		0 ; 3 , 6	0 ; 3 , 6		14 - 21	(Laborel-préneron et al., 2016; Laborel-Préneron et al., 2015, 2018, 2021, 2019; Laborel-Préneron, Aubert, et al., 2017)

Table A 1 continued

No	Type	Mortar production	Mortar Composition					Water amount (%)	Reference
			Earth type / Clay amount (%)	Aggregates amount (%)	Pellets amount (%)	Fibres amount (%)	Additives amount (%)		
33	MB	Cast + pressed	Commercial / na			0 - 5	0 - 19	> 13	(Muhammad et al., 2018)
34	PAB	Extruded	Commercial / na			0 : 20		23.7 – 32.2	(Muñoz et al., 2020)
35	PAB	Extruded	Commercial / na			0 – 1			(Murillo et al., 2006)
36	MB	Cast + pressed	Natural / 30			0 - 1		24	(M. Ouedraogo et al., 2017)
37	MB	Cast + pressed	Natural / 30			0 - 1		24	(M. Ouedraogo et al., 2019)
38	MB	Cast + pressed	Natural / 22.4	*0 – 86*	-	*0 - 49*	-	n.a.	(Piattoni et al., 2011; Quagliarini & Lenci, 2010)
39	MB	Cast	Natural / 49.3	-	-	*33*	-	n.a.	(Picuno, 2016)
40	MB	n.a.	Commercial	70	-	-	0.33 ; 0.25	n.a	(Pineda-Piñón et al., 2007)
41	MB	Cast	Natural / n.a.	-	0 – 2	-	-	n.a.	(Sasui et al., 2018)
42	MB	Cast + tamped	Natural / n.a.			0 – 2	0 – 2.5		(Sharma et al., 2015, 2016)
	PAB								(Schicker & Gier, 2009)
43	MB	n.a.	Natural / n.a.	0 ; 71 ; 82	0 - 1	0 - 1			(Vatani Oskouei et al., 2017)
44	MB	Cast + pressed	Natural / 10	0 – 20			0 – 20		(Vilane, 2010)
45	MB	Cast + pressed	Natural / n.a.	37.5 – 55	-	0.5	-	19.5	(F. Wu et al., 2013)

Table A 1 continued

No	Type	Mortar production	Mortar Composition					Water amount (%)	Reference
			Earth type / Clay amount (%)	Aggregates amount (%)	Pellets amount (%)	Fibres amount (%)	Additives amount (%)		
46	MB	Cast + tamped	Natural / 14 Natural / 19 Natural / 26 Natural / 12 Natural / 33	-	-	0 – 3.84 0 – 3.23 0 – 2.27 0 – 3.34 0 – 3.24	-	19.5 – 40.5 20 – 34.2 21.3 – 41 24.4 – 28.1 27 – 51.5	(Yetgin et al., 2008)
47	MB	Cast	Natural / 26	-	-	0 ; 1 ; 3	0 ; 5 ; 10	n.a.	(Zak et al., 2016)

Table A 2: Studies on earth mortars developed for mortars

No	Type	Mortar production	Mortar Composition					Water amount (%)	Reference
			Earth type / Clay amount (%)	Aggregates amount (%)	Pellets amount (%)	Fibres amount (%)	Additives amount (%)		
48	Mo	Cast + Vibratiom	Kaolinite / 100	-	-	-	1	44 – 119	(Alhaik et al., 2017, 2015)
49	Mo	Cast + Tamped	Quarry fine / 17	-	-	3.5 ; 5.5	0 – 32.2	60 – 100	(Alhaik et al., 2018)
50	Mo	Cast + Tamped	Natural / 7			0 ; 2 ; 3		18 ; 29	(Aymerich et al., 2012)
51	Mo	Cast	Natural / 17.5				0 ; 8 ; 12		(Azeredo et al., 2007)
52	Mo	Cast + Shocks	Natural / n.a.		0 – 55	0 – 55		33	(Ba et al., 2021)
53	Mo	Cast	Natural / 40 Natural / 28 Natural / 21	-	-	0 ; 1 ; 1.5 ; 2 ; 2.5 ; 3 ; 3.5	-	28 19 19	(Bouhicha et al., 2005)
54	Mo	n.a.	Commercial clay	50	-	-	0 – 1.5	31	(Brzyski & Suchorab, 2018)
55	Mo	Cast	Natural / 31	80	-	-	0 – 0.75	16	(Brzyski & Grudzińska, 2020)
56	Mo	Cast + tamped	Illite clay Kaolinite clay	70	-	-	0 ; 0.015 ; 0.045 ; 0.09	11 11	(Clausell et al., 2020)
57	Mo	Cast + tamped	Natural / 31 Natural / 27				0 ; 0.1 0 – 0.5	15 16	(Dove, 2014; Dove et al., 2016)
58	Mo	Proctor comp.	Quarry fine / n.a.	-	-	0 ; 3 ; 6	-	14 - 21	(Giroudon et al., 2019)
59	Mo	n.a.	Commercial / 75	80	-	0 ; 5	0 - 15	n.a.	(Gomes et al., 2012)

Table A 2 continued

No	Type	Mortar production	Mortar Composition					Water amount (%)	Reference
			Earth type / Clay amount (%)	Aggregates amount (%)	Pellets amount (%)	Fibres amount (%)	Additives amount (%)		
60	Mo	Cast + compacted	Natural / 33 Natural / 25 Natural / 25	-	-	0 - 0.3	0 – 25	0 - 25	(Galán-Marín, Rivera-Gómez, and Petric-Gray 2010b; 2010a; Rivera-Gómez and Galán-Marín 2017; Petric-Gray et al. 2009; Rivera-Gómez, Galán-Marín, and Bradley 2014)
61	Mo	n.a.	Existing / 9.5 Existing / 27	0 49	-	-	-	n.a.	(Gomes et al., 2018)
62	Mo	cast	Engineered / 17 Natural / n.a.	-	-		0.8 - 5	n.a.	(Guihéneuf et al., 2019a, 2020)
63	Mo	Cast + vivrated	Natural / 90	90			0 - 2	17	(Lanzón et al., 2017)
64	Mo	Cast	Natural / 60	9		0 – 6		36	(Lertwattanaruk & Choksiriwanna, 2011)
65	Mo	Cast	Quarry fines	58	-	-	0 – 12	8 - 12	(Liuzzi et al., 2013)
66	Mo	Cast	Natural / 4.3-0.8	-	-	-	-	35; 15-61	(Meimaroglou & Mouzakis, 2019)
67	Mo	Cast + pressed	Natural / 17	-	-	0 ; 3 ; 6	-	35	(Mellaikhafi et al., 2021)
68	Mo	Cast + vibrated	Engineered / 17	-	-	4	0 - 5	n.a.	(Menasria et al., 2017)
69	Mo	n.a.	Natural / 46				0; sol. 0.5% - sol 2%	no	(Nakamatsu et al., 2017)
70	Mo	cast	Commercial	40		0 – 3		n.a.	(Olacia et al., 2019, 2020)

Table A 2 continued

No	Type	Mortar production	Mortar Composition					Water amount (%)	Reference
			Earth type / Clay amount (%)	Aggregates amount (%)	Pellets amount (%)	Fibres amount (%)	Additives amount (%)		
72	Mo	Cast	Quarry fine / 28 Natural / 22.5				0 ; 1 ; 4	n.a.	(K. A. J. Ouedraogo, 2019; K. A. J. Ouedraogo et al., 2019)
73	Mo	Cast	Commercial / na	75		n.a.		20	(Peetsalu et al., 2010)
74	Mo	Cast	Commercial	n.a.		0 ; 2; 4	0 ; 1 ; 3 ; 5	10 - 16	(Perrot et al., 2018)
75	Mo	Cast	Commercial	-	-	-	0 ; 5; 10	n.a.	(Pinto et al., 2014)
76	Mo	n.a.	Commercial	50	-	-	0 - 30		(Rasa et al., 2008, 2009)
77	Mo	Cast	Natural / 32	10	-	-	0 – 70	n.a.	(Reman, 2004)
78	Mo	Cast	Natural / 58	-	-	-	0 -15	17.1	(Rodriguez Cuervo, 2020)
79	Mo	Cast + tamped	Natural / n.a.	-	*	0 – 12	-	18.6	(Salih et al., 2020a)
80	Mo	Cast	Natural / 19	-	-	-	0 – 10	n.a.	(Sanou et al., 2019)
81	Mo	Cast	Natural / n.a.	25 ; 30	-	-	0 ; 5	38.46	(Scalisi, 2014)
82	Mo	Cast	Commercial / na	15 - 40	1 - 3	1 - 3		n.a.	(Serrano et al., 2016)
83	Mo	Cast	Commercial / 22	80			0 ;25 ;33	19.5 – 27.9	(Stathopoulos et al., 2021)
84	Mo	Cast + pressed	Natural / 9 Engineered / 20			- 0 ; 0.5		- 16.5	(Tavares et al., 2019)

Table A 2 continued

No	Type	Mortar production	Mortar Composition					Water amount (%)	Reference
			Earth type / Clay amount (%)	Aggregates amount (%)	Pellets amount (%)	Fibres amount (%)	Additives amount (%)		
85	Mo	n.a.	Natural / 27 Commercial / 80	71 -83 75				12.6 – 14.6	(Taylor et al., 2006)
86	Mo	Cast + shocked	Natural / 9	25			0; 1; 5; 10	20.5	(Tourtelot et al., 2021)

Table A 3: Studies on earth mortars developped for plasters

No	Type	Mortar production	Mortar Composition					Water amount (%)	Reference
			Earth type / Clay amount (%)	Aggregates amount (%)	Pellets amount (%)	Fibres amount (%)	Additives amount (%)		
87	Pl	Cast	Natural / n.a.	0 ; 70 ; 75	-	0 ; 3.5 ; 7	-	29 - 38	(Andres et al., 2016b, 2016a)
88	Pl	Cast + pressed (50kg)	Natural / 31	*0 – 75*	*0 – 75*	*0 – 75*		n.a.	(Ashour et al., 2011; Ashour, Bahnasawey, et al., 2010; Ashour, Bahnasawy, et al., 2010; Ashour, Wieland, et al., 2010; Ashour & Derbala, 2010; Ashour & Wu, 2010)
89	Pl	Cast	Natural / n.a.	45 - 49			0 ; 1; 4	11 – 21	(Atzeni et al., 2007)
90	Pl	Cast + Shocked	Natural / 40				0 – 6	31 – 35	(Bamogo et al., 2020)
91	Pl	Applied	Natural / 14	10 - 60				35 - 70	(Emiroğlu et al., 2015)
92	Pl	Cast / Applied	Clay / n.a.	90	-	-	-	16	(García-Vera & Lanzón, 2018)
93	Pl	Cast / applied	Natural / 18	0 – 88.2	-	0.5	-	2 - 27	(Hamard et al., 2013)
94	Pl	Cast / applied	Natural / n.a.	20 - 200	-	0 ; 2	0- 4	n.a.	(Heredia Zavoni et al., 1988)
95	Pl	Applied	Commercial / 33 Commercial / 10 Quarry fine / 28	50 – 80 50 – 85 50 – 80		0 ; 0.5	0 , 1	16.7 – 24.5 17.9 – 28.1 14.7 – 21.4	(Lagouin et al., 2019; Lagouin, Aubert, et al., 2021; Lagouin, Laborel-Préneron, et al., 2021)
96	Pl	Cast	Natural / 51.8	*0 - 75*		*0 - 75*		n.a.	(Lerner & Donahue, 2003)

Table A 3 continued

No	Type	Mortar production	Mortar Composition					Water amount (%)	Reference
			Earth type / Clay amount (%)	Aggregates amount (%)	Pellets amount (%)	Fibres amount (%)	Additives amount (%)		
97	Pl	Cast / Applied	Natural / n.a.	70.7 – 82.9	-	0 - 1	0 – 7.9	11.6 – 16.7	(Lima, Correia, et al., 2016; Lima, Faria, et al., 2016; Lima, Silva, et al., 2016; Lima & Faria, 2016, 2017)
98	Pl	Cast / Applied	Natural / n.a Natural / n.a	78.4 81.7	-	-	-	12.8 21.3	(Lima et al., 2020, 2019)
99	Pl	Cast + vibrated	Ready-made	-	-	-	0 – 0.6	n.a.	(Lišková et al., 2016)
100	Pl	Cast	Natural / n.a.	58	-	0 – 4	0 – 6	16 - 30	(Liuzzi & Stefanizzi, 2015)
101	Pl	n.a.	Quarry fines / 71	58	0 - 12	-	-	n.a.	(Liuzzi et al., 2018)
102	Pl	Applied	Natural / n.a.	-	-	0 – 2	-	n.a.	(Maddison et al., 2009)
103	Pl	Applied	Natural / 50	0 – 25	-	2 ; 3	0 - 15	n.a.	(Maheri et al., 2011)
104	Pl	Cast / applied	Natural / n.a.			2.18 – 5.13	0 - 5	n.a.	(García et al., 2013; Navarro et al., 2015)
105	Pl	Applied	Ready-made / 25		0 ; 1; 2	0 ; 1; 2		n.a.	(Palumbo et al., 2016)
106	Pl	Cast + applied	Ready-made				n.a.	n.a.	(Parracha et al., 2021)
107	Pl	Applied	Natural / n.a.	-	-	-	0 - 8	15 - 20	(Pinto et al., 2017)

Table A 3 continued

No	Type	Mortar production	Mortar Composition					Water amount (%)	Reference
			Earth type / Clay amount (%)	Aggregates amount (%)	Pellets amount (%)	Fibres amount (%)	Additives amount (%)		
108	Pl	Applied	Natural / 35 Modified / 12	n.a.	-	-	0 – 20 0 - 40	28 – 36 none	(Rescic et al., 2021)
109	Pl	n.a.	Ready-made	0 - 15				n.a.	(Sevilla Avila et al., 2015)
110	PL	Cast + pressed / Applied	Natural / 39	50 -83		0 – 7	0 – 7	17 – 21	(Stazi et al., 2015)

Table A 4: Type and properties of the earths used to develop earth mortars

No	Type	Clay type: Kaolinite (%) (presence or %)	Clay type: Illite (%) (presence or %)	Clay type: Smectite (presence or %)	Particle amount: Clay (%)	Particle amount: Silt (%)	Particle amount: Fines (%)	Particle amount: Sand (%)	Particle amount: Gravel (%)	Atterberg limits: Liquid Limit	Atterberg limits: Plastic Limit	Atterberg limits: Plasticity Index	Proctor test: OMC (%)	Proctor test: Maximum dry density (kg/m³)	Proctor test: Specific gravity (-)	Bulk density (kg/m³)	Methylene Blue Index	USCS classification	Reference
1	MB				0.5	51.5	52			24	21	3			2.64			ML	(Achenza & Fenu, 2007)
3	MB						91	8.9		81.5	41								(Al-Ajmi et al., 2016)
4	MB									39	19	15	16					CL	(Alam et al., 2015)
5 6 20	MB				11	69	80	20		29	17	12				2507		CL	(Araya-Letelier et al., 2017, 2018, 2019; Concha-Riedel et al.,
7	MB				12	54	76	34		26	16	10				2469		CL	(Araya-Letelier et al., 2020; Gonzalez-Calderon et al., 2020)
8	MB				12	54	76	34		29	17	12				2487		CL	(Araya-Letelier et al., 2021)
9	MB				25	13	38	62		36	22	14					3.5		(Babé et al., 2020)
10	MB						60	40											(Bahobail, 2012)
11	MB				44	53	96	4		31	17	14						CL	(Bertelsen et al., 2021, 2019)
					21	42	63	37		25	13	12						CL	
12 13	MB						55	43	2									SC	(Binici et al., 2005, 2007)
15	MB																		(Bock-Hyeng et al., 2016)

Table A 4 continued

No	Type	Clay type: Kaolinite (%) (presence or %)	Clay type: Illite (%) (presence or %)	Clay type: Smectite (presence or %)	Particle amount: Clay (%)	Particle amount: Silt (%)	Particle amount: Fines (%)	Particle amount: Sand (%)	Particle amount: Gravel (%)	Atterberg limits: Liquid Limit	Atterberg limits: Plastic Limit	Atterberg limits: Plasticity Index	Proctor test: OMC (%)	Proctor test: Maximum dry density (kg/m³)	Proctor test: Specific gravity (-)	Bulk density (kg/m³)	Methylene Blue Index	USCS classification	Reference
17	MB				18	9		38	35	40	22	19	16	1793		1287			(Caballero-Caballero et al., 2017)
18	MB				7	18	25	75											(Călătan et al., 2015, 2016; Călătan, Hegyi, & Mircea, 2014; Călătan, Hegyi, Dico, et al., 2014)
21	MB				40 23	45 27		15 50		59 55	14 21	43 35				1240			(Corrêa, Mendes, et al., 2015; Corrêa, Protásio, et al., 2015)
22	MB						92	8		44	26	18				1250			(Costi de Castrillo et al., 2021)
23	MB						81	18	1	56	36	21	38	1290	2.44			MH	(Degirmenci, 2008)
25	MB	+	+	+	37.9 31.4 34.7 29 10 [illegible]	51.9 55.8 60.7 57.4 79.7 [illegible]		9.9 12.8 4.6 9.3 10.1 [illegible]											(Dormohamadi & Rahimnia, 2020)
28	MB				15 65	8 19	23 84	77 16		22 46	14 25	7 21				1190 1020			(Gomes Battistelle et al., 2020)
29	MB				13	44	57	43		28	22	6							(Rogiros Illampas et al., 2017)

Table A 4 continued

No	Type	Clay type			Particle amount					Atterberg limits			Proctor test			Bulk density (kg/m³)	Methylene Blue Index	USCS classification	Reference
		Kaolinite (%) (presence or %)	Illite (%) (presence or %)	Smectite (presence or %)	Clay (%)	Silt (%)	Fines (%)	Sand (%)	Gravel (%)	Liquid Limit	Plastic Limit	Plasticity Index	OMC (%)	Maximum dry density (kg/m³)	Specific gravity (-)				
30	MB				26.2	9.3	34.5	65.5		27	13	14							(Jové-Sandoval et al., 2018)
33	MB						25	75		21	33	12			2.7				(Muhammad et al., 2018)
35	PAB									30	56	26							(Murillo et al., 2006)
36 37	MB	28			30	60	90	10		31	17	14					13		(M. Ouedraogo et al., 2017, 2019)
38	MB				22.4	49.9		24.5	3.2	26	18	8						CL	(Piattoni et al., 2011; Quagliarini & Lenci, 2010)
39	MB				49.3	36.8		13.8		39	21	18							(Picuno, 2016)
	PAB	+	+		26	67		7											(Schicker & Gier, 2009)
42	MB						18	72	10	23	18	7	13	1835	2.67			SC	(Sharma et al., 2015, 2016)
43	MB									19	17	14			2.7			CL	(Vatani Oskouei et al., 2017)
44	MB				10	5	15	85											(Vilane, 2010)
45	MB						88.6	11.4		36	19	17	20	1765					(F. Wu et al., 2013)

Table A 4 continued

No	Type	Clay type: Kaolinite (%) (presence or %)	Clay type: Illite (%) (presence or %)	Clay type: Smectite (presence or %)	Particle amount: Clay (%)	Particle amount: Silt (%)	Particle amount: Fines (%)	Particle amount: Sand (%)	Particle amount: Gravel (%)	Atterberg limits: Liquid Limit	Atterberg limits: Plastic Limit	Atterberg limits: Plasticity Index	Proctor test: OMC (%)	Proctor test: Maximum dry density (kg/m³)	Proctor test: Specific gravity (-)	Bulk density (kg/m³)	Methylene Blue Index	USCS classification	Reference
46	MB				14 19 26 12 33	20 28 23 16 20	34 47 49 28 53	66 53 51 72 47					8.7 9.2 8.9 8.5 12	2140 2120 2090 2020 2090	2.7 2.7 2.7 2.7 2.7				(Yetgin et al., 2008)
47	MB	50	30	10	26	66	92	5	3	32	17	15							(Zak et al., 2016)
48	Mo	12	7		17.2	81.3	98.5	1.5		33	21	12	14	1860				OL	Alhaik et al. 2015; 2017; 2018)
49	Mo	++			100					53	26	27							
50	Mo				5	60	65	35		28	17	11		2630					(Aymerich et al., 2012)
51	Mo		++		17.5	63.5	80	20											(Azeredo et al., 2007)
52	Mo									43	24	21	23	1620					(Ba et al., 2021)
55	Mo				31	3	34	60								1980			(Brzyski & Grudzińska, 2020)
56	Mo	95 33 7	5 60 24	0 0 35	100 100 100														(Clausell et al., 2020)

Table A 4 continued

No	Type	Clay type: Kaolinite (%) (presence or %)	Clay type: Illite (%) (presence or %)	Clay type: Smectite (presence or %)	Particle amount: Clay (%)	Particle amount: Silt (%)	Particle amount: Fines (%)	Particle amount: Sand (%)	Particle amount: Gravel (%)	Atterberg limits: Liquid Limit	Atterberg limits: Plastic Limit	Atterberg limits: Plasticity Index	Proctor test: OMC (%)	Proctor test: Maximum dry density (kg/m³)	Proctor test: Specific gravity (-)	Bulk density (kg/m³)	Methylene Blue Index	USCS classification	Reference
57	Mo	++ - ++	- ++ -		31 27 16	45 44 61	76 71 77	24 29 23		16 15 15	27 28 25	11 13 10	16 18 14	1820 1980 1920				CL	(Dove, 2014; Dove et al., 2016)
60	Mo				32	45	78	22		35	19	16							(Galán-Marín et al., 2010a, 2010b; Petric-Gray et al., 2009; Rivera-Gómez & Galán-Marín, 2017)
61 59	Mo	++ - + +			75 9 28 18	20 13 20 31	95 22 48 49	5 78 52 51		13	32	19							(Gomes et al., 2018, 2012)
16 58 32	Mo	11	11		28	66	94	6		30	21	9					5.9		(Brás et al., 2019; Giroudon et al., 2019; Laborel-préneron et al., 2016; Laborel-Préneron et al., 2015, 2018, 2021, 2019; Laborel-Préneron, Aubert, et al., 2017)
63	Mo				35.1	54.8	90.9	9.1		37	20	17		2680					(Lanzón et al., 2017)
64	Mo				60	20	80	20											(Lertwattanaruk & Choksiriwanna, 2011)

Table A 4 continued

No	Type	Clay type: Kaolinite (%) (presence or %)	Clay type: Illite (%) (presence or %)	Clay type: Smectite (presence or %)	Particle amount: Clay (%)	Particle amount: Silt (%)	Particle amount: Fines (%)	Particle amount: Sand (%)	Particle amount: Gravel (%)	Atterberg limits: Liquid Limit	Atterberg limits: Plastic Limit	Atterberg limits: Plasticity Index	Proctor test: OMC (%)	Proctor test: Maximum dry density (kg/m³)	Proctor test: Specific gravity (-)	Bulk density (kg/m³)	Methylene Blue Index	USCS classification	Reference
67	Mo				17	25	42	55		16	23	39	15	1800	2.6				(Mellaikhafi et al., 2021)
69 2	Mo		32		36	43	79	20	1	33	17							CL	(Nakamatsu et al., 2017) (Aguilar et al., 2016)
72	Mo	+ -	+ -		28 22.5	67 38.5		5 37		30 46		30 15	14 14	1988 1880					(K. A. J. Ouedraogo, 2019; K. A. J. Ouedraogo et al., 2019)
105	Mo				25	20	45	55		56	35	21						CL	(Palumbo et al., 2016)
108	Mo	+	+	+	35 12	47 16		18 72											(Rescic et al., 2021)
78	Mo				52	17	69	31		46	21	25	17	1720	2.7				(Rodriguez Cuervo, 2020)
80	Mo				19	36		46		42	22	20					7.5		(Sanou et al., 2019)
83	Mo				22	22	44	56		21	17	3				1200		SM	(Stathopoulos et al., 2021)
84	Mo				20 30	16.5 12.5		66.5 57.7		36 42	21 23	15 19				2680 2690			(Tavares et al., 2019)
85	Mo				27 80	69 20	96 100	4											(Taylor et al., 2006)
86	Mo	-	+		9					35	22	17							(Tourtelot et al., 2021)

Table A 4 continued

No	Type	Reference	USCS classification	Methylene Blue Index	Bulk density (kg/m³)	Proctor test: Specific gravity (-)	Proctor test: Maximum dry density (kg/m³)	Proctor test: OMC (%)	Atterberg limits: Plasticity Index	Atterberg limits: Plastic Limit	Atterberg limits: Liquid Limit	Particle amount: Gravel (%)	Particle amount: Sand (%)	Particle amount: Fines (%)	Particle amount: Silt (%)	Particle amount: Clay (%)	Clay type: Smectite (presence or %)	Clay type: Illite (%) (presence or %)	Clay type: Kaolinite (%) (presence or %)
88	Pl	(Ashour et al., 2011; Ashour, Bahnasawey, et al., 2010; Ashour, Bahnasawy, et al., 2010; Ashour, Wieland, et al., 2010; Ashour & Derbala, 2010; Ashour & Wu, 2010)											47	53	22	31			
89	Pl	(Atzeni et al., 2007)																5	80
90	Pl	(Bamogo et al., 2020)		1.4					23	21	44	16	34	50	10	40			62
91	Pl	(Emiroğlu et al., 2015)				2.7 2.6							28.2 21.5		57.6 51.7	14.7 26.7		71 72	28 29
97	Pl	(Faria & Santos, 2014; Santos et al., 2015, 2017; Santos, Gomes, et al., 2020; Santos & Faria, 2020, 2018) (Lima, Correia, et al., 2016; Lima, Faria, et al., 2016; Lima, Silva, et al., 2016; Lima & Faria, 2016, 2017)			1317								82	18				+	++

Table A 4 continued

No	Type	Clay type: Kaolinite (%) (presence or %)	Clay type: Illite (%) (presence or %)	Clay type: Smectite (presence or %)	Particle amount: Clay (%)	Particle amount: Silt (%)	Particle amount: Fines (%)	Particle amount: Sand (%)	Particle amount: Gravel (%)	Atterberg limits: Liquid Limit	Atterberg limits: Plastic Limit	Atterberg limits: Plasticity Index	Proctor test: OMC (%)	Proctor test: Maximum dry density (kg/m³)	Proctor test: Specific gravity (-)	Bulk density (kg/m³)	Methylene Blue Index	USCS classification	Reference
92	Pl									30 34	19 19	11 14							(García-Vera & Lanzón, 2018)
62 68	Pl	++ + +	 + +		17 - - -			83 - - -	- 5 - -	13 37 46 36	32 22 30 20	19 15 17 16							(Guihéneuf et al., 2019a, 2020) (Menasria et al., 2017)
93 31	Pl	- 90	- 10		18 25.5	12 30	30 55.5	70 44.5		38	20	18							(Hamard et al., 2013) (Kouakou & Morel, 2009)
94	Pl						62	38		27	15	12							(Heredia Zavoni et al., 1988)
95	Pl	23 16 11 -	11 10 11 21		33 10 28 23	40 88 66 37	73 98 94 62	27 2 6 38		40 43 33 34	18 30 21 22	22 12 12 23					8.0 7.8 5.9 17.8		(Lagouin et al., 2019; Lagouin, Aubert, et al., 2021; Lagouin, Laborel-Préneron, et al., 2021)
96	Pl				51.8	30.9	82.7	17.1	0.8	48	18	28							(Lerner & Donahue, 2003)
103	Pl				50	19	69	23	5	62	28	34			2.7				(Maheri et al., 2011)
104	Pl						64.5									1300		SC	(García et al., 2013; Navarro et al., 2015)
110	Pl				39	47	87	13		44	25	18						CL	(Stazi et al., 2015)

Table A 5: Type and properties of aggregates sued for earth mortars

No	Type	Clay (fines) amount (%)	Sand type	Added aggregates amount (% of the dry mix)	Minimum size / Maximum size (mm)	Aggregates distribution	Specific gravity (-) / Bulk density (kg/m³)	Water absorption	Filler amount (% passing 63µm sieve)	Specific property	Reference
3	MB	- (91)	Sand	4.7 - 13.1							(Al-Ajmi et al., 2016)
12 13	MB		Pumice	23						High porosity	(Binici et al., 2005, 2007)
18	MB	38 (58)	Natural sand	0 - 80	0 / 4						(Călătan et al., 2015, 2016; Călătan, Hegyi, & Mircea, 2014; Călătan, Hegyi, Dico, et al., 2014)
38	MB	22 (72)	Coarse sand	0 - 55	0 / 5	Well graded			1.5		(Piattoni et al., 2011; Quagliarini & Lenci, 2010)
40	MB	n.a.	Siliceous sand	70							(Pineda-Piñón et al., 2007)
	PAB	26 (93)	Tuff Diatomite Brick dust	10 10 10	well sorted					porous strength	(Schicker & Gier, 2009)
43	MB	n.a.	Sand Gravel				1.83 2.47				(Vatani Oskouei et al., 2017)
45	MB	n.a. (89)	Sand		0 /5						(F. Wu et al., 2013)
11	Mo	44 (96)	Silty gravels	0 ; 50	0 / 8						(Bertelsen et al., 2021, 2019)
54	Mo	n.a.	Granulated foam glass	33	0 / 2 2 / 4		na / 200			High thermal resistance	(Brzyski & Suchorab, 2018)
55	Mo	31 (34)	Quartz sand	80	0 / 2						(Brzyski & Grudzińska, 2020)

Table A 5 continued

No	Type	Clay (fines) amount (%)	Sand type	Added aggregates amount (% of the dry mix)	Minimum size / Maximum size (mm)	Aggregates distribution	Specific gravity (-) / Bulk density (kg/m³)	Water absorption	Filler amount (% passing 63µm sieve)	Specific property	Reference
	Mo	100 (0)	Quartz sand	70	0 / 2	normalized				Washed	(Clausell et al., 2020)
61	Mo	n.a.	Siliceous (quartz) sand	65 ; 70 : 80	0.6 / 2					Washed	(Faria, Silva, et al., 2014; Gomes et al., 2018)
63	Mo	39 (n.a.)			0 – 1 0 - 4				19.5 19.3		(Lanzón et al., 2017)
64	Mo	20 (80)	Sand	0 - 9							(Lertwattanaruk & Choksiriwanna, 2011)
100	Mo	n.a.	Quarry sand	60							(Liuzzi & Stefanizzi, 2015)
70	Mo	n.a.	Commercial	40							(Olacia et al., 2019, 2020)
73	Mo	20 (80)	Quarry sand	75	0.63 / 2						(Peetsalu et al., 2010)
74	Mo	n.a.	Fine sand Coarse sand	optimised	0.063 / 0.2 0 - 4						(Perrot et al., 2018)
76	Mo	29 (71)	River sand	50	< 0.6		2550			Washed	(Rasa et al., 2008, 2009)
77	Mo	10 (68)	Siliceous sand	2.5 - 20	< 2						(Reman, 2004)
81	Mo	n.a.	Basaltic sand		1.5 – 0.3	Uniformly distributed	44 ; 44			Washed	(Scalisi, 2014)
82	Mo	n.a	Commercial	15 - 40	1 / 4						(Serrano et al., 2016)

Table A 5 continued

No	Type	Clay (fines) amount (%)	Sand type	Added aggregates amount (% of the dry mix)	Minimum size / Maximum size (mm)	Aggregates distribution	Specific gravity (-) / Bulk density (kg/m³)	Water absorption	Filler amount (% passing 63µm sieve)	Specific property	Reference
83	Mo	22 (44)	Siliceous sand	15 - 20	0 / 4				0.28	Washed	(Stathopoulos et al., 2021)
86	Mo	n.a.	Rounded sand	25	0.315 / 1	uniformly distributed					(Tourtelot et al., 2021)
87	Pl	n.a.	Sand	70 - 75							(Andres et al., 2016a, 2016b)
88	Pl	31 (53)	Sand	0 - 75							(Ashour et al., 2011; Ashour, Bahnasawey, et al., 2010; Ashour, Bahnasawy, et al., 2010; Ashour, Wieland, et al., 2010; Ashour & Derbala, 2010; Ashour & Wu, 2010)
89	Pl	n.a.	Quartz sand	0 ; 55 - 59	1 / 2						(Atzeni et al., 2007)
91	Pl	14 (72) 27 (79)		10 - 60	<2		2.57	3.55			(Emiroğlu et al., 2015)
97	Pl	n.a. (18)	Silicate sand	70.7 – 82.9	0 – 2	Graded				-	(Faria & Santos, 2014; Santos et al., 2015, 2017; Santos, Gomes, et al., 2020; Santos & Faria, 2020, 2018) (Lima, Correia, et al., 2016; Lima, Faria, et al., 2016; Lima, Silva, et al., 2016; Lima & Faria, 2016, 2017)
			Fine silicate	72.4	0 - 0.75					Washed	
			Coarse silicate	72.2	0 - 4					Washed	
			PCM	20 ; 30							
92	Pl	n.a.	Calcite sand	90	0 / 0.5	Graded			0.18	Washed	(García-Vera & Lanzón, 2018)
					0.125 / 4				0.04	Washed	

Table A 5 continued

No	Type	Clay (fines) amount (%)	Sand type	Added aggregates amount (% of the dry mix)	Minimum size / Maximum size (mm)	Aggregates distribution	Specific gravity (-) / Bulk density (kg/m³)	Water absorption	Filler amount (% passing 63µm sieve)	Specific property	Reference
93	Pl	18 (30) 26 (58)	Hostun sand	0 – 65.8 0 – 88.2		Uniformly graded	2.65			Washed	(Hamard et al., 2013)
94	Pl	n.a. (62)	Coarse sand	0 - 67	0.43 – 4.75						(Heredia Zavoni et al., 1988)
95	Pl	33 (73) 10 (98) 28 (94)	Siliceous river sand	50 – 80 50 – 85 50 – 80	0 – 2		2.66	1.86	1.8		(Lagouin et al., 2019; Lagouin, Aubert, et al., 2021)
96	Pl	52 (83)	Plaster sand	*0 - 75*						Washed	(Lerner & Donahue, 2003)
101	Pl	71 (99)	Quartzite grit sand	58 2	0 / 2 2 / 4						(Liuzzi et al., 2013, 2018)
103	Pl	50 (69)	Crusher dust	0-27	<2.5	Well graded			70		(Maheri et al., 2011)
108	Pl	18 (65)	Siliceous sand	n.a.	0.6 / 2 0.6 / 1						(Rescic et al., 2021)
109	Pl	n.a.	PCM	0 – 15							(Sevilla Avila et al., 2015)
110	Pl	89 (86)	River sand	50 – 83 80	< 2 < 1						(Stazi et al., 2015)
85	Pl	27 (96) 80 (100)	Masonry sand	71 – 83							(Taylor et al., 2006)

Table A 6: Type and properties of pellets used for earth mortars

No	Type	Clay (fines) amount (%)	Pellet type	Source	Added pellets amount (% added to the dry mix)	Dimensions (mm)	Bulk density (kg/m³) *True density* (kg/m³)	Water absorption (%)	Thermal conductivity kW/mK	Porosity (%)	Reference
22	MB	n.a. (92)	Saw dust	White pine	*30 - 70*	L<30	120				(Costi de Castrillo et al., 2021)
	PAB	26 (93)	Sawdust	Timber	10						(Schicker & Gier, 2009)
43	MB	n.a.	Wood chips Rice husk	Timber Plant	4 ; 8; 12	L=10 -		286 410			(Vatani Oskouei et al., 2017)
44	MB	10 (15)	Sawdust	Pine tree	0 -20						(Vilane, 2010)
52	Mo	n.a. (77)	*Typha Australis* shavings	Plant	0 - 55	L<10 Φ=0.8	60	167	0.061	87	(Ba et al., 2021)
32	Mo	20 (60)	Corn cob Hemp shives	Plant	0 ; 3 ; 6	3.6x2.6 L=5.6 Φ=0.01	153 497	38 0 123	0.0 51 0.096		(Laborel-préneron et al., 2016; Laborel-Préneron et al., 2015, 2018, 2021, 2019; Laborel-Préneron, Aubert, et al., 2017)
41	Mo	n.a (52)	Rice husk	Plant	0 ; 2						(Sasui et al., 2018)
82	Mo	n.a.	Gr. olive stones Rubber crumbs	Plant Synthetic	1 ; 2 ; 3						(Serrano et al., 2016)

Table A 6 continued

No	Type	Clay (fines) amount (%)	Pellet type	Source	Added pellets amount (% added to the dry mix)	Dimensions (mm)	Bulk density (kg/m³) *True density* (kg/m³)	Water absorption (%)	Thermal conductivity kW/mK	Porosity (%)	Reference
88	Pl	31 (53)	Wood shavings	timber		L<20	111.4				(Ashour et al., 2011; Ashour, Bahnasawey, et al., 2010; Ashour, Bahnasawy, et al., 2010; Ashour, Wieland, et al., 2010; Ashour & Derbala, 2010; Ashour & Wu, 2010)
93	Pl	18 (30)	Hemp shives	Plant	0 ; 0.5	L=20 – S=2x5					(Hamard et al., 2013)
101	Pl	71 (28)	Olive tree pruning	Timber	4 - 12	L=20 Φ=5	*1251*			0.23	(Liuzzi et al., 2018)
105	Pl	25 (45)	Ground corn pith	Plant	0 ; 1 ; 2	Φ=1					(Palumbo et al., 2016)

Table A 7: Type and properties of fibres used for earth mortars

	Type of material produced	Number of types of fibres used	% of fibre added (by weight of dry mix)	Length (mm)	Diameter (mm)	A/R ratio (length / diamter)	Reference
Straw, grasses and stems (unprocessed and/or by-products							
Straws							
Undefined straw	MB, Mo, Pl	14		2-50	1-4.5	2.5 – 0.5	(Alam et al., 2015; Andres et al., 2016a, 2016b; Binici, 2017; Binici et al., 2007; Călătan, Hegyi, & Mircea, 2014; Rogiros Illampas et al., 2014; Maheri et al., 2011; Olacia et al., 2020; Piattoni et al., 2011; Picuno, 2016; Serrano et al., 2016; Vatani Oskouei et al., 2017)
Barley	MB, Pl	13		10-50	0.25-0.5		(Ashour et al., 2011; Ashour, Bahnasawey, et al., 2010; Ashour, Bahnasawy, et al., 2010; Ashour & Derbala, 2010; Ashour & Wu, 2010; Bouhicha et al., 2005; Brás et al., 2019; García et al., 2013; Giroudon et al., 2019; Laborel-Préneron et al., 2015, 2021; Laborel-Préneron, Aubert, et al., 2017; Laborel-préneron et al., 2016; Liuzzi & Stefanizzi, 2015; Navarro et al., 2015; Palumbo et al., 2016; Stazi et al., 2015)
Oat	Pl	1	0 ; 0.5 ; 1	10 - 20			(Faria & Santos, 2014; Lima & Faria, 2016, 2017; Santos et al., 2015, 2017; Santos & Faria, 2020)
Rice	Pl	1	0.88 – 4.42		1		(García et al., 2013)
Fonio	MB	1					(M. Ouedraogo et al., 2019)
Alpha	MB	1	0 - 80			0.01	(Elhamdouni et al., 2015)
Ichu	Pl	1	2	100			(Heredia Zavoni et al., 1988)

Table A 7 continued

	Type of material produced	Number of types of fibres used	% of fibre added (by weight of dry mix)	Length (mm)	Diameter (mm)	A/R ratio (length / diamter)	Reference
Straw, grasses and stems (unprocessed and/or by-products							
Straws							
Wheat	MB, Pl			5	50-80	3	(Ashour et al., 2011; Ashour, Bahnasawey, et al., 2010; Ashour, Bahnasawy, et al., 2010; Ashour & Derbala, 2010; Ashour & Wu, 2010; Costi de Castrillo et al., 2021; Jové-Sandoval et al., 2018; Meena et al., 2019; Muhammad et al., 2018; Yetgin et al., 2008)
Other Grasses							
Hay	MB	1					(Al-Ajmi et al., 2016)
Fescue	MB	1					(Serrano et al., 2016)
Spanish broom	MB	1	*33*		3.5 – 5.3		(Picuno, 2016)
Lavender	PAB	1	0 : 3 : 6	7.7	2.5	9.9	(Giroudon et al., 2019)
Bagasse	MB, Mo	4	0.3 - 7	0.9 - 50	0.2 - 1	10 - 187	(Bock-Hyeng et al., 2016; Corrêa, Protásio, et al., 2015; Lertwattanaruk & Choksiriwanna, 2011; Salih et al., 2020a, 2018)
Bast fibres							
Hemp	MB	3	3 - 15	25	0.2	0.008	(Călătan et al., 2016, 2017; Călătan, Hegyi, Dico, et al., 2014; Gomes et al., 2018, 2012; Zak et al., 2016)
Flax	Mo, Pl	3	<40 - 60			<30	(Lagouin, Laborel-Préneron, et al., 2021; Zak et al., 2016)

Table A 7 continued

	Type of material produced	Number of types of fibres used	% of fibre added (by weight of dry mix)	Length (mm)	Diameter (mm)	1/AR ratio (length / diameter)	Reference
Bast fibres							
Henequen	Mo	1	0 – 1	10 -25	0.2	0.02 – 0.008	(Murillo et al., 2006)
Jute	MB	1		7 - 30	<0.4		(Araya-Letelier et al., 2021; Concha-Riedel et al., 2019)
Kenaf	MB	1	0 – 1	15 – 30	0.14	0.04 – 0.09	(M. Ouedraogo et al., 2017)
Grewia Optiva	MB	1	0 – 2	30	0.03	0.001	(Sharma et al., 2015, 2016)
Palm trunk	MB	1	0 ; 3 ; 6	5 - 10	0.54 – 0.91	0.05 – 0.18	(Mellaikhafi et al., 2021)
Palm mesh	MB	1	0 - 6	5 - 40	0.2 – 0.8 1 – 2	0.02 – 0.16 0.03 – 0.4	(Mellaikhafi et al., 2021; Vatani Oskouei et al., 2017)
Leaves							
Corn leaves	MB	1	15 - 40				(Serrano et al., 2016)
Pine needles	MB	4	0 – 2 ; *25*	30 - 99	0.48 – 1.01	0.006 – 0.016	(Jové-Sandoval et al., 2018; Sharma et al., 2015, 2016)
Sisal	MB, Pl	2	0 - 1	25 - 40	0.15 ; 0.33	0.004 – 0.033	(Caballero-Caballero et al., 2017; Hamard et al., 2013)
Palm pinnate	MB	1	0 ; 3 ; 6	5 - 10	0.78 – 1.21	0.08 – 0.24	(Mellaikhafi et al., 2021)
Palm petiole	MB	1	0 ; 3 ; 6	5 - 10	0.09 – 0.21	0.01 – 0.04	(Mellaikhafi et al., 2021)

Table A 7 continued

	Type of material produced	Number of types of fibres used	% of fibre added (by weight of dry mix)	Length (mm)	Diameter (mm)	1/AR ratio (length / diameter)	Reference
Fruit envelope							
Palm cluster	MB	1	0 ; 3 ; 6	5 - 10	0.29 – 0.54	0.03 – 0.11	(Mellaikhafi et al., 2021)
Typha wool	PL	2					(Lima & Faria, 2016; Maddison et al., 2009)
Seaweed							
Seagrass	MB, Mo	2	0 – 3 ; 10	10 - 30			(Achenza & Fenu, 2007; Olacia et al., 2019, 2020)
Animal fibres							
Sheep wool	Mo, MB	2	0 ; 0.25 ; 0.5	10 - 30	0.035	0.001-0.003	(Aymerich et al., 2012; Galán-Marín et al., 2010a, 2010b; Petric-Gray et al., 2009; Rivera-Gómez & Galán-Marín, 2017)
Pig Bristles	MB	1		7 - 30	0.14	0.005 – 0.02	(Araya-Letelier et al., 2018)
Chicken feathers	MB	2		0.3 - 15	0.012 – 0.11; 0.15		(Araya-Letelier et al., 2020; Gonzalez-Calderon et al., 2020; Salih et al., 2018)

Table A 8: Hydraulic binders used for the stabilization of earth mortars

Type of additive	Mortar type	Amount used	Reference
Portland Cement			
Cement	MB, Mo, Pl	2.5 30	(Al-Ajmi et al., 2016; Alam et al., 2015; Azeredo et al., 2007; Binici et al., 2005, 2007; Pinto et al., 2017; Rasa et al., 2008, 2009; Sharma et al., 2015, 2016; Zak et al., 2016)
CEM I	MB	2-20	(Atzeni et al., 2006; Sanou et al., 2019; Vilane, 2010)
CEM II	Pl	5-15	(Gomes et al., 2018, 2012)
CEM IV	MB	5	(Atzeni et al., 2007)
Hydraulic Lime			
Lime	MB, Mo, Pl	1-12	(Al-Ajmi et al., 2016; Alam et al., 2015; Alhaik et al., 2018; Binici et al., 2005; Degirmenci, 2005; Lagouin et al., 2019; Lanzón et al., 2017; Muhammad et al., 2018; Pinto et al., 2017)
Hydraulic lime	Pl	5-15	(Gomes et al., 2018, 2012; Stathopoulos et al., 2021)
Pozzolanic Additives			
Ashes	Mo	5-15	(Bahobail 2012
Fly ashes	MB	10	(Degirmenci, 2005)
Rice husk ashes	MB	2-10	(Sanou et al., 2019; Sasui et al., 2018)
Blast furnace slag	MB	11	(Schicker & Gier, 2009)
Cement kiln dust	PL	5	(Rescic et al., 2021)
Ladle Furnace Slag			(Stathopoulos et al., 2021)
Trass	MB	11	(Schicker & Gier, 2009)

Table A 9: Other binders used for the stabilization of earth mortars

Type of additive	Mortar type	Amount used	Reference
Non Hydraulic binders			
Air-lime			
Lime putty	MB	2	(Călătan et al., 2015, 2017; Călătan, Hegyi, Dico, et al., 2014)
Hydrated lime	MP, MO, PL	2-6	(Atzeni et al., 2007; Brás et al., 2019; Braun, 2017b; Gomes et al., 2018, 2012; Guihéneuf et al., 2020; Liuzzi et al., 2013; Liuzzi & Stefanizzi, 2015; Maheri et al., 2011; Mattone et al., 2016; Santos et al., 2017)
Gypsum			
Gypsum	MB, Mo	3.5-12.5	(Alam et al., 2015; Binici et al., 2005, 2007; Brás et al., 2019; Mattone et al., 2016; Rasa et al., 2009; Rodriguez Cuervo, 2020; Zak et al., 2016)
Natural gypsum	MB, PL	2-25	(Degirmenci, 2008; Lima, Correia, et al., 2016; Lima & Faria, 2017; Rescic et al., 2021)
Phospho gypsum	MB	5-50	(Degirmenci, 2005, 2008)
Bitumen			
Bitumen		3-12	(Al-Ajmi et al., 2016; Braun, 2017b; Heredia Zavoni et al., 1988)
Geoplymers			
K2SiO3/KOH	Mo	5	(Rescic et al., 2021)
Others			
Waterglass	MB		(Braun, 2017a)
Soda	MB		(Braun, 2017a)
Salt	MB	1	(Călătan et al., 2015)
Laponite	Mo	9	(Scalisi, 2014)
Diatomite	MB	10	(Schicker & Gier, 2009)

Table A 10: Type and properties of biopolymers used as a stabilizer in earth mortars

Name		Preparation and dosage	Amount (% of mix)	Possible acting way	References
Polysaccharides					
Cellulose based					
Straw/hay washing water	M	500 grams of fibres have fermented in 10 litres of water during 1 month			(Guihéneuf et al., 2019a)
Cellulose	C	Used as received		Acting both as a fibre by linking different elements, as an aggregate by filling gaps in the soil matrix and a binder by connecting chemically clay particles.	(Tourtelot et al., 2021)
Cellulosic glue	C	6.25 g per litre of mixing water			(Guihéneuf et al., 2020)
Starches					
Flour paste	M	140 g rye flour with 14 g zinc sulphate boiled to a paste in 0.5 l water			(Braun, 2017a, 2017b)
Brown rice starch (Kanjivellam)	M	Water residue of boiling brown rice		Starch gel is shear- thinning. As it dries, the starch gel sticks more to the clays	(Paul & Changali, 2020)
Starch	C	Heated or not according to the type and mixed with mixing water	1		(Alhaik et al., 2017, 2018, 2015)
Starch			1		(Alhaik et al., 2017, 2018, 2015; Lagouin et al., 2019; Lagouin, Laborel-Préneron, et al., 2021; Tourtelot et al., 2021)

Table A 10 continued

Name		Preparation and dosage	Amount (% of mix)	Possible acting way	References
Polysaccharides					
Sugar					
Saccharose	C		5 – 10	Agglutination of clays through the action of sugar creating nanoclays particles	(Pinto et al., 2014)
Molasses	C		5 – 10 15 – 20	Calcium content of the ash fraction of molasses must be responsible for enhancing its adhesive properties	(Rodriguez Cuervo, 2020; Vilane, 2010)
Xanthan	C		0.5 - 1	Xanthan gum is forming microscopic bonds between the clay layers and on the surface of the clay	(Guihéneuf et al., 2020)
Mucilage and plant gels					
Locus bean pod	M				(Heredia Zavoni et al., 1988)
Banana stalk juice	M				
Cactus Juice	M				
Cissus glauca Roxb	M	Stem is crushed and placed in water	5	Creates microscopic reinforcement between clay particles	(Paul & Changali, 2020)
Cochlospermum religiosum	M	Skin of the fruit placed in water until water gets sticky	5	Creates microscopic reinforcement between clay particles	Paul and Changali 2020)
Pectin	C	Extracted from apple. Mixed with water to form a gel.	1		(Tourtelot et al., 2021)
Carrageenan	C	Extracted from red algae Chondracanthus and mix with water		Creatse a protection film around the particles and bind the particles.	(Nakamatsu et al., 2017)

Table A 10 continued

Name		Preparation and dosage	Amount (% of mix)	Possible acting way	References
Polysaccharides					
Mucilage and plant gels					
Chitosan	C	Solutions of chitosan mixed with mixing water	0.13 to 1		(Aguilar et al., 2016)
Alginate	C	Diluted in water	0.1 to 19.75	Dependant on the soil properties and type of alginate. Nanoscale interactions between alginate chains and clay praticles through clay and polymer cross-linking	(Dove, 2014; Dove et al., 2016; Galán-Marín et al., 2010b; Guihéneuf et al., 2019a, 2020; Lagouin et al., 2019; Navarro et al., 2015; Tourtelot et al., 2021)
Lipid					
Drying oils and Varnish					
Linseed oil	C		1 to 3 (20)	Linseed oil covers the surface of the materials and prevent intereaction between water and clay	(Braun, 2017a, 2017b; Brzyski & Grudzińska, 2020; Brzyski & Suchorab, 2018; Guihéneuf et al., 2019a, 2020; Lima, Silva, et al., 2016; Navarro et al., 2015; Tourtelot et al., 2021)
Boiled linseed oil	C		(20)		(Braun, 2017a, 2017b)
Vegetal based varnish	C	Coated with a brush on surface			(Guihéneuf et al., 2020)
Used frying oil	C		2; 4		(Gomes Battistelle et al., 2020)

Table A 10: continued

Name		Preparation and dosage	Amount (% of mix)	Possible acting way	References
Non-drying oils					
Palm oil	C		5, 10, 15		(Bahobail, 2012)
Castor oil	C		2, 4		(Gomes Battistelle et al., 2020)
Proteins					
Globular Proetins					
Albumin	C/M		1	Albumin creates strong hydrogen bonds with clay praticles and link the clay particles together	(Colas & Bourgès, 2013; Lagouin et al., 2019; Lagouin, Laborel-Préneron, et al., 2021)
Whey	C				(Braun, 2017a, 2017b)
Casein	C	Diluted with an alkali product such as lime or ammonium – some authors used without alkali products	0.5 to 5	Creating a waterproof barrier around clay particles due to their amphilic properties.	(Brzyski & Suchorab, 2018; Guihéneuf et al., 2019a, 2020; Lagouin et al., 2019; Navarro et al., 2015; Tourtelot et al., 2021)
Casein based products	M	Butter milk, goat milk, skimmed milk, curd use as such			(Braun, 2017a, 2017b)
Gluten	C		1		(Lagouin et al., 2019; Lagouin, Laborel-Préneron, et al., 2021)
Enzyme	C	Commercial enzymatic soltution diluted in water	5	Enzymes bind with large organic molecules and then srround the clay preventing the water to access	(Rescic et al., 2021)

Table A 10: continued

Name		Preparation and dosage	Amount (% of mix)	Possible acting way	References
Fibrous proteins					
Bone glue	C	Activated with lime	1		(Călătan et al., 2015, 2017; Călătan, Hegyi, Dico, et al., 2014)
Complex biopolimers					
Tannin	C	Tannins from different provenances (oak seed extract, chestnut, carob) and under different form (powder/solution) and activated with acid or not	0.4 to 1 and 0.015 to 0.09		(Clausell et al., 2020; Guihéneuf et al., 2019a, 2020; Lagouin et al., 2019; Lagouin, Laborel-Préneron, et al., 2021; Tourtelot et al., 2021)
Lignin	C		10		(Tourtelot et al., 2021)
Citric acid			1		(Guihéneuf et al., 2019a, 2020)
Biopolymer mix					
Animal dung	M		2 to 15	The presence of cow dung in an earth render influences its mineralogy through the formation of insoluble amine silicate (Si(OH)4.	(Bahobail, 2012; Bamogo et al., 2020; Braun, 2017a, 2017b)
Soap	C		5 to 15		(Bahobail, 2012)
Wall paper glue	C	Commercial mix of starch and methylcellulose (6.25g of powder or 22g of paste per litre of water)	0.5 to 1		(Braun, 2017a, 2017b; Guihéneuf et al., 2019a, 2020)
Tomatoes and beetroots	M			Combined action of sugar and gum	(Achenza & Fenu, 2007)

Table A 11: Synthetic additives used for the stabilization of earth mortars

Type of additive	Mortar type	Amount of additives (%)	Reference
Acrylic based			
Pure acrylic	MB	n.a.	(Braun, 2017a, 2017b)
Acronal S	MB, Mo	n.a.	(Braun, 2017a, 2017b; Pineda-Piñón et al., 2007)
Acrylic polymer	MB	5	(Atzeni et al., 2007)
Butyl acrylate	MB	n.a.	(Braun, 2017a, 2017b)
Synthetic latex	MB	n.a.	(Braun, 2017a, 2017b)
Silicon based			
Silicon	MB	0.3	(Lišková et al., 2016)
Funcosil	PL	n.a.	(Braun, 2017a, 2017b)
Silres drysoil	MB	n.a.	(Braun, 2017a, 2017b)
Organic derivates of silicon	PL	7	(Stazi et al., 2015)
Silicon nano-particles	PL	2	(Stazi et al., 2015)
Silane based			
Tetraethylorthosilicate	MB	n.a.	(Braun, 2017a, 2017b)
Alkyloxysilane	PL	0.3	(Lišková et al., 2016)
Silane coated amorphous silica	PL	0.3	(Lišková et al., 2016)
Soap			
Sodium oleate	PL	0.2	(Lišková et al., 2016)
Zinc stearate	Mo	1	(Lanzón et al., 2017)
Calcium soap	PL	0.2	(Lišková, Jelínek, and Ostrý 2016
Combination of zinc-soap sodium oleate	PL	0.2	(Lišková, Jelínek, and Ostrý 2016
Compound of oleo chemical substances	PL	0.6	(Lišková et al., 2016)

Table A 11 Continued

Type of additive	Mortar type	Amount of additives (%)	Reference
Other Additives			
Cationic dodecylamine	Mo	n.a.	(Pineda-Piñón et al., 2007)
Anionic fatty acid	Mo	n.a.	(Pineda-Piñón et al., 2007)
Superplasticizers	PL	1	(Alhaik et al., 2018; Atzeni et al., 2007; Lagouin, Laborel-Préneron, et al., 2021)
Sodium hexamatophosphate	MB, PL	1	(Guihéneuf et al., 2019a, 2020; Lagouin, Laborel-Préneron, et al., 2021)
Naphtalene Sulphonate	MB	1	(Atzeni et al., 2007)
Emulsified asphalt	Mo	n.a.	(Pineda-Piñón et al., 2007)
Limestone aggregates admixed with fatty acids and synthetic polymers	PL	1	(Stazi et al. 2015)
Synthetic termite saliva	MB	0.06-0.2	(Corrêa, Mendes, et al., 2015; Corrêa, Protásio, et al., 2015)

Table A 12: Samples sizes for determination of physical properties

Shrinkage				Density	References
Restrained shrinkage	Linear shrimkage	Volumetric shrinkage	On-site shrinkage		
Dia. 18 x 0.5 cm³					(Araya-Letelier et al., 2018, 2019)
30x30x6 cm³					(Araya-Letelier et al., 2020, 2021; Concha-Riedel et al., 2019)
	20x20x5 cm³			20x20x5 cm³	(Ashour & Derbala, 2010)
	15x10x10 cm³				(Atzeni et al., 2006)
	16x4x4 cm³			16x4x4 cm³	(Bamogo et al., 2020; Bertelsen et al., 2019; Călătan et al., 2015; Călătan, Hegyi, Dico, et al., 2014; Degirmenci, 2008; Dove et al., 2016; García-Vera & Lanzón, 2018; Lagouin, Laborel-Préneron, et al., 2021; Lanzón et al., 2017; Lima et al., 2020; Lima, Correia, et al., 2016; Lima, Faria, et al., 2016; Lima, Silva, et al., 2016; Lima & Faria, 2016; Santos, Gomes, et al., 2020)
Dia. 18 x 1 cm					(Bertelsen et al., 2021)
	12x6x6 cm³				(Bock-Hyeng et al., 2016)
	22x10.7x6 cm³				(Bouhicha et al., 2005)
	10x2x2 cm³				(Corrêa, Mendes, et al., 2015)
		5x5x5 cm³	18x10 cm²	5x5x5 cm³	(Bouhicha et al., 2005)
	60x8.5x3.5 cm³				(Gandia et al., 2019)
	28.7x2.5x2.5 cm³				(García et al., 2013; Navarro et al., 2015)
	30x3x3 cm³				(Gomes et al., 2018, 2012)
	16x4x4 cm³		25x25 cm²	16x4x4 cm³	(Hamard et al., 2013; Lagouin et al., 2019; Lagouin, Aubert, et al., 2021; Stazi et al., 2015)
			60x60 cm		(Heredia Zavoni et al., 1988)
			unknown		(Pinto et al., 2017)
	20x10x6 cm³				(Rasa et al., 2008, 2009)
	23.8x20x1.5 cm³	23.8x20x1.5 cm³		16x4x4 cm³	(Santos et al., 2018)
	23.8x20x1.5 cm³		29.5x19.5 cm ²	16x4x4 cm³	(Santos, Faria, et al., 2020)
	30x5x5 cm³				(Tavares et al., 2019)
		10x10x10 cm³			(Yetgin et al., 2008)

Table A 13: Size of samples and test speed organized according to compressive strength test

Flexural strength	Testing speed	Compressive strength	Testing speed	Reference
Prismatic samples				
30.5x15.25x7.62 cm ³		5x5x5 cm³		(Alam et al., 2015)
		5x5x5 cm³		(Ashour, Bahnasawey, et al., 2010; Emiroğlu et al., 2015; Rogiros Illampas et al., 2014, 2017)
45x15x5 cm³		Cut 5x5x5 cm³		(Costi de Castrillo et al., 2021)
16x4x4 cm³		5x5x5 cm³		(Degirmenci, 2005, 2008)
16x4x4 cm³		5x5x5 cm³		(Scalisi, 2014)
		5x5x5 cm³	0.485 mm/min	(Taylor et al., 2006)
		5x5x5 cm³	1 mm/min	(Tourtelot et al., 2021)
		10x10x10 cm³		(Achenza & Fenu, 2007; Lertwattanaruk & Choksiriwanna, 2011; Tavares et al., 2019; Yetgin et al., 2008)
31x10.5x7 cm³		10x10x10 cm³		(Araya-Letelier et al., 2020, 2021)
30x30x5 cm³		10x10x10 cm³		(Maheri et al., 2011)
16x4x4 cm³		Broken parts of 16x4x4 cm³		(Andres et al., 2016b, 2016a; Ba et al., 2021; Călătan et al., 2015, 2016; Călătan, Hegyi, Dico, et al., 2014; Clausell et al., 2020; Dove et al., 2016; García-Vera & Lanzón, 2018; García et al., 2013; Gomes et al., 2014, 2018; Gonzalez-Calderon et al., 2020; Guihéneuf et al., 2019a; Hamard et al., 2013; Lima et al., 2020, 2019; Lima, Correia, et al., 2016; Lima, Faria, et al., 2016; Lima, Silva, et al., 2016; Lima & Faria, 2016; Lišková et al., 2016; Muñoz et al., 2020; Navarro et al., 2015; Pinto et al., 2017; Serrano et al., 2016; Sevilla Avila et al., 2015)
16x4x4 cm³	4N/s	Broken parts of 16x4x4 cm³	48KN/s	(Alhaik et al., 2017, 2015)
16x4x4 cm³	0.5 mm/min	Broken parts of 16x4x4 cm³	0.5 mm/min	(Babé et al., 2020; M. Ouedraogo et al., 2017, 2019; Salih et al., 2018)
16x4x4 cm³	0.5 mm/min and 50 N/s	Broken parts of 16x4x4 cm³	2400 N/s	(Bamogo et al., 2020)
16x4x4 cm³	0.5 mm/min	Broken parts of 16x4x4 cm³	64 N/s	(Bertelsen et al., 2021, 2019)
16x4x4 cm³	8 mm/min	Broken parts of 16x4x4 cm³	0.2 mm/min	(Brzyski & Grudzińska, 2020)
16x4x4 cm³	0.5 MPa/s	Broken parts of 16x4x4 cm³		(Faria & Santos, 2014)
16x4x4 cm³	10 N/s	Broken parts of 16x4x4 cm³	50 N/s	(Lagouin, Aubert, et al., 2021; Lagouin, Laborel-Préneron, et al., 2021)
16x4x4 cm³	5 kg/s	Broken parts of 16x4x4 cm³	2.4 mm/min	(Olacia et al., 2019)
16x4x4 cm³	0.2 mm/min	Broken parts of 16x4x4 cm³	0.7 mm/min	(Santos et al., 2017; Santos & Faria, 2020)
16x4x4 cm³	50 N/s	Broken parts of 16x4x4 cm³	50 N/s	(Zak et al., 2016)

Table A13: Continued

Flexural strength	Testing speed	Compressive strength	Testing speed	References
Prismatic samples				
31x10.5x7 cm³		Broken parts of 31x10.5x7 cm³		(Araya-Letelier et al., 2018, 2019)
31x10.5x7 cm³				(Concha-Riedel et al., 2019)
28x7x7 cm³	4N/s	Broken parts of 28x7x7 cm³	48KN/s	(Alhaik et al., 2018)
50x65x7cm³	20KN/s	Broken parts of 50x65x7cm³	1mm/min	(Alhaik et al., 2018)
		10x2.5x2.5 cm³		(Atzeni et al., 2007)
		8x4x4 cm³	0.01 mm/s	(Azeredo et al., 2007)
		15x15x15 cm³		(Binici et al., 2005, 2007)
		12x6x6 cm³	0.5 mm/s	(Bock-Hyeng et al., 2016)
28x7x7 cm³		22x10.7x6 cm³		(Bouhicha et al., 2005)
29.2×15.4×8.4 cm³		Broken parts of 29.2×15.4×8.4 cm³		(Caballero-Caballero et al., 2017)
29x14x10 cm³	0.01 N/m²s	Broken parts of 29x14x10 cm³	0.01 N/m²s	(Jové-Sandoval et al., 2018)
45x13x5 cm³	0.012 mm/s	Broken parts of 45x13x5 cm³	0.02 mm/s	(Rogiros Illampas et al., 2017)
		31x43x13 cm³		(Piattoni et al., 2011)
		15x23x13 cm³		(Piattoni et al., 2011)
18x6x4 cm³		6x6x6 cm³		(Pinto et al., 2014)
		20x10x6 cm³		(Rasa et al., 2008, 2009)
12x3x1.4 cm³		5.2x2.5x2.2 cm³		(Schicker & Gier, 2009)
		22x22x7 cm³	35 N/mm²min	(Vatani Oskouei et al., 2017)
		20x9x5 cm³		(F. Wu et al., 2013)
Cylindrical specimens				
12.5x4.2x4.4 cm³		dia. 3.4 h.7.1 cm		(Aguilar et al., 2016)
18x7x3.5 cm³	1 mm/min	Dia 5x10 cm³	3 mm/min	(Laborel-Préneron et al., 2015; Laborel-Préneron, Aubert, et al., 2017)
		Dia. 5x10 cm³		(Murillo et al., 2006)
4.2x4.5x12.5 cm³	1.27 mm/min	Dia. 3.4x7.5 cm³	1.27 mm/min	(Nakamatsu et al., 2017)
		Dia. 3.8x7.6 cm³	0.04 mm/min	(Sharma et al., 2015, 2016)
		Dia 4x8 cm³	0.9144 mm/min	(Stazi et al., 2015)
Superposed samples				
Full adobe		Half adobe on top of each other		(Corrêa, Mendes, et al., 2015; Corrêa, Protásio, et al., 2015; Gandia et al., 2019)
		3 stacked samples of 15x10x5 cm³	0.5-1.0 MPa/min	(Sasui et al., 2018)

Table A 14: Durability experiments and specimens sizes

Water resistance	References
Wettability	
Drop contact angle (10 µL)	(Aguilar et al., 2016; Colas & Bourgès, 2013)
Drop contact angle after 5 s, 15 s 2 min, 10 min	(Stazi et al., 2015)
Erosion	
Drip test (SAET)	
Specimen inclined at 30° - 200 mL of water dripping from 40 cm during 1h	(Achenza & Fenu, 2007)
Specimen inclined at 27° - 500 mL of water flowing from 1 m during 10 min (SAET test)	(Aguilar et al., 2016; Clausell et al., 2020; Muñoz et al., 2020; Nakamatsu et al., 2017)
Specimen inclined at 27° - 500 mL of water dripping from 1 m during 10 min with drop every second	(Navarro et al., 2015)
Drip test (Geelong)	
Specimen inclined at 30° - 100 mL of water dripping from 40 cm during 30 min (Geelong NZS)	(Araya-Letelier et al., 2021; Giroudon et al., 2019; Laborel-Préneron et al., 2021; Mattone et al., 2016; Pinto et al., 2014; Rescic et al., 2021)
Specimens inclined at 30° - water dripping at 1 US gallon (3.8 L) per hour from 4.5 feet (137.2 cm) until collapse of the specimen	(Lerner & Donahue, 2003)
Specimen inclined at 45° - water dripping from 1 m and number of drop measured	(Pinto et al., 2017)
Specimen inclined at 45° - 100 mL of water dripping from 40 cm during 30 min	(Stazi et al., 2015)
Specimen inclined at 30C- dripping 65 cm³/min of water from 1.35 m until failure	(Ashour & Wu, 2010)
Water dripped for 10 min (unknown height and unknown amount)	(García-Vera & Lanzón, 2018)
Spray test	
Specimen inclined at 30° - water showered from 50 cm during 10 min at 2 bar pressure	(M. Ouedraogo et al., 2017, 2019)
Specimen inclined at 60° - water showered for 10 min at 2 bar pressure	(Sanou et al., 2019)
Constant pressure water jet during 60s	(Alam et al., 2015)
Specimen inclined at 30° - 50 L of water dripping from 120 cm during 10 min	(Babé et al., 2020; Bamogo et al., 2020)
Specimen inclined at 45° - 15 L of water dripping from 40 cm during 2 min	(Braun, 2017a)
20 cycles of 3h of water sprayed by garden sprinkler	(Heredia Zavoni et al., 1988)
Vertical specimens sprayed from 47 cm at 0.5 bar pressure for 1h (Spray test NZS)	(Mattone et al., 2016; Rasa et al., 2008, 2009; Rescic et al., 2021; Stazi et al., 2015)
IS:1725 (1982)	(Sharma et al., 2016)

Table A14: continued

Water resistance	
Stability in water	
Submersion	
30.5x15.25x7.62 cm³ specimens fully submersed during 24h and visual assessment of the impacts	(Alam et al., 2015)
10x2x2 cm³ specimens fully submersed during 6h and mass loss measured	(Corrêa, Mendes, et al., 2015)
10x10x5 cm³ specimens fully submersed during 1h and mass loss measured	(Costi de Castrillo et al., 2021)
12x6x6 cm³ specimens submersed until deterioration	(Bock-Hyeng et al., 2016)
25x15x10 cm³ specimens submersed until deterioration	(Sasui et al., 2018)
Partial immersion	
10x10x3 cm³ specimens immersed in 1.5 cm of water until water reaches the top	(Babé et al., 2020)
10x10x10 cm³ specimens immersed in 5 cm of water until water reaches the top	(Degirmenci, 2008)
4x4x8 cm³ specimens immersed in water for 7 min	(Brzyski & Grudzińska, 2020)
4x4 cm² section specimens suspended in 5 cm of water for 30 min.	(Brzyski & Suchorab, 2018)
22x11x7 cm³ samples placed in chanel with water flowing at 8.6 cm/s	(Vatani Oskouei et al., 2017)
Abrasion	
DIN 18947	
20 rotations of a 65 mm hard plastic brush loaded with 2 kg	(Laborel-Préneron et al., 2021)
20 rotations of a 65 mm medium hard plastic brush loaded with 2 kg	(Lima et al., 2020; Lima, Correia, et al., 2016; Lima, Silva, et al., 2016; Santos et al., 2018)
Regles Pro	
30 cycles of a wire brush loaded with 3kg	(Babé et al., 2020; Bamogo et al., 2020; García et al., 2013)
60 cycles of a wire brush loaded with 3kg – 1 cycle per second during 60 s	(Giroudon et al., 2019; Gonzalez-Calderon et al., 2020)
Others	
Wide wear disc	(Clausell et al., 2020)
Sand blasting at 10 m/s from 52 cm during 1 min	(Atzeni et al., 2007)
Sclerometer with 1.5 kg load	(Colas & Bourgès, 2013)
Cohesion	
Adhesive of 2x5 cm² manually pressed	(Colas & Bourgès, 2013; García-Vera & Lanzón, 2018)
Adhesive of 5x5 cm² with a constant weight and constant time	(Lima, Silva, et al., 2016)
Adhesive of 7x5 cm² with a 4kg weight and 1 min pressure	(Santos et al., 2018)
Field tests	
Specimens exposed for 2 years and then property measured	(Achenza & Fenu, 2007)
Specimens exposed for 1 month with 45° angle and then property measured	(Colas & Bourgès, 2013)
Plaster on wall exposed for 6 months and then visually assesed	(Faria, dos Santos, et al., 2014)
Plaster exposed for 6 year and visually assessed every year	(Morton & Little, 2015)

B. Summary of the properties of Reference Earth mortar

Table B 1 to Table B 5 summarize the properties of earth mortars. From these values, the properties of the Reference Earth are determined either as the average of the values found during the tests or as the most appropriate value after discarding outlying values and comparing the results with the literature. These values will be used as a reference to compare the impact of different additives on the properties of the mortars. The value here is given for physical properties (Table B 1) mechanical properties (Table B 2) surface properties (Table B 3) durability properties (Table B 4) and finally hydric properties (Table B 5). For the hygric properties, the values of Ka000000-10 have been used as a reference as they are much more representative than the average values.

Table B 1 Average physical and mechanical properties of non-reinforced and non-stabilized earth mortars measured on 16x4x4 cm³ samples

	Amount of water (% weight of dry earth)	slump test (cm)	settling time	shrinkage (%)	*standard dev.*	average dry density (kg/m³)	*standard dev.*	Average Flexural strength (MPa)	*Standard dev.*	Average compressive strength (MPa)	*Standard dev.*
Ka000000-01						1695	*4*	1.12	*0.20*	5.80	*0.35*
Ka000000-04				7.8	*0.3*	1670	*13*	1.13	*0.24*	5.34	*0.21*
Ka000000-06				8.5	*0.1*	1683	*12*	1.46	*0.06*	5.32	*0.34*
Ka000000-07				6.2	*0.2*	1685	*14*	1.42	*0.09*	5.34	*0.34*
Reference Earth	**35**	**15.1-17.1**	**0 - 2**	**7.7**	***0.9***	**1682**	***12***	**1.35**	***0.22***	**5.31**	***0.46***

Table B 2: Average physical and mechanical properties of non-reinforced and non-stabilized earth mortars measured on 24x20x4 cm³ samples

	Amount of water (% weight of dry earth)	Slump test (cm)	Settling time	Shrinkage (%)	*Standard dev.*	Average dry density of uncut samples (kg/m³)	*Standard dev.*	Average dry density of cut samples (kg/m³)	*Standard dev.*
Ka000000-10				6.5	1.1	1741	*8*	1750	0
Ka000000-11						1648		1738	
Ka000000-12				7.4		1677	*24*	1716	8
Reference Earth	**35**	**15.1-17.1**	**0 - 2**	**7.1**	***0.8***	**1691**	***22***	**1745**	***37***

Table B 3: Average mechanical properties (dry and humid strength) of non-reinforced and non-stabilized earth mortars

	Average Flexural strength (MPa)	*Standard dev.*	Average compressive strength (MPa)	*Standard dev.*	Humidity level (weight increase in %)	Humid flexural strength (MPa)	Loss in strength (weight increase in %)	Humid compressive strength (MPa)	Loss in strength (%)
Ka000000-01					2.5	0.60	-46	3.35	-42
Ka000000-10	1.54	*0.02*	4.15	*0.12*	2.5	0.62	-60	2.71	-35
Ka000000-11	1.81	*0.36*	4.82	*0.58*					
Ka000000-12	1.31	*0.04*	4.57	*0.23*					
Reference Earth	**1.55**	***0.29***	**4.51**	***0.46***	***2.5***	***0.61***		***3.03***	

Table B 4: Average surface and durability properties of non-reinforced and non-stabilized earth mortars

	Surface water absorption ($g/m^2 \cdot s$) for 90 s.	Peeling test – virgin samples (g)	Visual scale (1-10)	Peeling coefficient (g/cm^2)	Peeling test – tested samples (g)	Visual scale (1-10)	Water resistance (min)	Abrasion resistance (DIN18947) Material loss (g)	Abrasion resistance (French rules) Abrasion Coefficient (cm^2/g)	Abrasion resistance (French rules) Ditch depth (cm)
Ka000000-01	13.2	0.02	2	0.5			35	0.8		
Ka000000-10	14.7	0.00	1	0	0.39	4	20	2.9	6.4	1.25
Ka000000-11		0.04	1	1.1						
Ka000000-12		0.04	1	1.2						
Reference Earth (Ka000000-10)	**14.7**	**0.00**	**1**	**0**	**0.39**	**4**	**20**	**2.9**	**6.4**	**1.25**

Table B 5: Average hygric and hydric properties of non-reinforced and non-stabilized earth mortars

	Capillarity coefficient ($kg/m^2/min^{0.5}$)	Drying rate (1st phase) ($kg/m^2/h$)	Drying rate (2nd phase) ($kg/m^2/h^{0.5}$)	Drying index	Water vapour diffusion resistance factor (-)	Water vapour adsorption (12h - g/m^2)	primary adsorption rate - first 6h (g/m^2h)	secondary adsorption rate – 6h – 24h (g/m^2h)	water vapour desorption (12h - g/m^2)	primary desorption rate - first 3h (g/m^2h)	secondary desorption rate - 12h-48h (g/m^2h)
Ka000000-10	1.0	0.15	1.35	0.29	4.1	158	*18.7*	*9.7*	167	*20.4*	*5.2*
Ka000000-11	1.0	0.14	1.28	0.32	4.0	148	*15.6*	*9.5*	127	*14.7*	*3.9*
Ka000000-12					3.8						
Reference Earth	**1.0**	**0.15**	**1.31**	**0.30**	**4.1**	**158**	***18.7***	***9.7***	**167**	***20.4***	***5.2***

C. Comparison of properties of the reference mortars

Table C 1: Composition and physical properties of Reference Mortars

Mortar Name	Type of aggregate	Amount of aggregate (%vol)	Amount of fiber (%vol)	Smount of water (%wt)	Slump test (cm)	Settling time	shrinkage (%)	*standard dev.*	average dry density (kg/m³)	*standard dev.*
Ref. Mortar 1	sand 1	54	1.2	29	16.2-16.8	1-2	1.8	*0.4*	1571	*24*
Ref. Mortar 2	sand 2	55	1.0	27	16.0-17.0	1-2	2.0	*0.5*	1638	*13*
Ref. Mortar 3	sand 1	71		18	16.3-17	0-2	0.8	*0.2*	1712	*17*

Table C 2: Dry and humid Mechanical properties

Mortar Name	Average dry flexural strength (MPa)	*Standard dev.*	Average dry compressive strength (MPa)	*Standard dev.*	Humidity level (% in mass increase)	Average humid flexural strength (MPa)	Standard dev.	Loss of flexural strength (%)	Average humid compressive strength (MPa)	Standard dev.	Loss of compressive strength (%)
Ref. Mortar 1	0.77	*0.12*	1.34	*0.12*	0.6-1.5	0.36	0.10	-54	0.76	0.22	-44
Ref. Mortar 2	0.88	*0.14*	1.95	*0.15*	0.9	0.74	0.07	-25	1.38	0.09	-30
Ref. Mortar 3	0.60	*0.08*	1.39	*0.25*	0.01	0.22	0.07	-61	0.45	0.11	-67

Table C 3: Surface, durability and hydric properties of Reference Mortars

	Surface properties				Durability properties										Hygric properties							
Mortar Name	Surface water absorption (g/m²·s) for 90 s.	*Standard dev.*	Peeling test (Material loss in µg/m2)	*Standard dev.*	Water resistance (min)	*Standard dev.*	DIN 18947 Abrasion resistance test (Material loss (g)	*Standard dev.*	Regles Pro Abrasion resistance test Abrasion coefficient (cm2/g)	*Standard dev.*	Erosion test Ditch depth (mm)	Ersoison test Hole depth (mm)	*Standard dev.*	Hole diameter (mm)	capillarity coefficient	*Standard dev.*	drying rate (1st phase)	*Standard dev.*	Drying rate (2nd phase)	*Standard dev.*	drying index	*Standard dev.*
Ref. Mortar 1	26.2	*3.5*	2214	*1260*	13	*8*	9	*3*	0.6	*0.3*	10	8	*1*	22	1.06	*0.11*	0.13	*0.02*	1.12	*0.11*	0.26	*0.04*
Ref. Mortar 2	17.3	*2.4*	1192	*404*	24	*6*	3	*0*	1.2	*0.2*	5	6		25	0.94	*0.07*	0.11	*0.02*	1.20	*0.08*	0.24	*0.03*
Ref. Mortar 3	29.3	*3.3*	639	*135*	4	*2*	10	*0*	0.3	*0.0*	15	8	*2*	25	1.07	*0.01*	0.13	*0.01*	1.05	*0.00*	0.99	*0.00*

Table C 4: Hygric properties of Reference Mortars

Mortar Name	water vapour permability	diffusion resistance (-)	Sd coefficient (m)	Water vapour adsorption (12h) (g/m²)	primary adsorption rate - first 6h (g/m²h)	secondary adsorption rate - 12h-48h (g/m²h)	water vapour desorption (12h) (g/m²)	primary desorption rate - first 3h (g/m²h)	secondary desorption rate - 12h-48h (g/m²h)
Ref. Mortar 1 A	13	8	9	149	14.5	5.7	101	13.8	3.4
Ref. Mortar 1 B				162	16.1	5.1	129	15.6	4.3
Ref. Mortar 1 C				123	12.6	6.3	132	20.0	4.6
Ref. Mortar 1 D				174	17.3	4.7	105	16.6	3.1
Ref. Mortar 2A	24	6	3	85	8.5	3.2	94	15.3	11.8
Ref. Mortar 2B				186	14.0	6.3	114	33.1	3.4
Ref. Mortar 3	3.94E-11	5.0	0.2	124.8	12.1	4.4	121.6	15.7	3.4

D. Water vapour permeability of chaff reinforced mortars

Table D 1: water vapour permeability of chaff reinforced mortars classified by testing batches

Mortar name	Amount of clay (% by weight)	Density (kg/m³)	Water vapour permeability	Water vapour diffusion resistance factor μ (-)	Sd (m)
Set 1					
Ka000001-2001c	24.1%	1496.0	3.75E-11	5.23	0.195
Ka000001-3001b	23.9%	1476.6	4.05E-11	4.73	0.175
Ka000001-4001d	23.6%	1247.6	4.94E-11	4.84	0.182
Ka000001-4002a	23.6%	1333.2	4.14E-11	3.97	0.147
Ka000001-4003b	23.6%	1333.0	3.94E-11	4.98	0.175
Ka000001-5001b	23.1%	1149.2	4.24E-11	4.62	0.172
Set 2					
Ka000001-2001b	24.1%	1512.8	3.81E-11	5.14	0.190
Ka000001-2002a	24.1%	1516.8	3.89E-11	5.04	0.176
Ka000001-2003b	24.1%	1509.7	3.87E-11	5.07	0.173
Ka000001-3001a	23.9%	1449.1	3.67E-11	5.35	0.189
Ka000001-4001a	23.6%	1238.5	4.00E-11	4.90	0.177
Ka000001-4001c	23.6%	1262.7	4.06E-11	4.83	0.179
Ka000001-5001c	23.1%	1170.2	3.85E-11	5.09	0.186
Ka000001-5001a	23.1%	1174.8	3.55E-11	5.52	0.184
Set 2b					
Ka000001-0501a	24.4%	1666.7	4.47E-11	4.39	0.163
Ka000001-0501b	24.4%	1667.1	4.49E-11	4.37	0.164
Ka000001-0501c	24.4%	1662.9	4.52E-11	4.34	0.160
Ka000001-1001a	24.2%	1595.0	4.51E-11	4.34	0.160
Ka000001-1001b	24.2%	1606.2	4.48E-11	4.37	0.164
Ka000001-1001c	24.2%	1610.8	4.48E-11	4.38	0.163
Ka000001-3001c	23.9%	1457.9	4.22E-11	4.64	0.164
Ka000001-4002a	23.6%	1333.2	4.73E-11	4.14	0.150
Set 4					
Ka000001-2010a	24.2%	1504.4	5.08E-11	3.86	0.143
Ka000001-2013a	24.1%	1531.6	5.37E-11	3.65	0.150
Ka000001-4006a	23.2%	1334.8	4.63E-11	4.24	0.159

E. Water vapour properties of earth mortars reinforced with sand and chaff

Table E 1: Water vapour sorption properties of mortars reinforced with Grey Sand and Chaff

Mortar Name	Amount of clay (% weight of dry mix)	Water vapour adsorption (12h - g/m²)	Primary adsorption rate - first 3h (g/m²h)	Secondary adsorption rate - 12h-48h (g/m²h)	Water vapour desorption (12h - g/m²)	Primary desorption rate - first 3h (g/m²h)	Secondary desorption rate - 12h-48h (g/m²h)
Ka000101-2210004 A	11.6	146	14.4	5.6	100	13.0	3.5
Ka000101-2210006 A	11.0	143	14.0	5.7	92	12.4	3.3
Ka000101-221 A	11.3	144	14.2	5.7	96	9.4	3.4
Ka000101-2210004 B	11.6	167	16.6	5.6	128	35.8	4.6
Ka000101-2210006 B	11.0	158	15.6	4.6	130	35.0	4.0
Ka000101-221 B	11.3	162	16.1	5.1	129	15.6	4.3
Ka000101-2210004 C	11.6	132	12.9	7.0	135	19.9	4.9
Ka000101-2210006 C	11.0	114	12.3	5.7	129	20.1	4.3
Ka000101-221 C		123	12.6	6.3	132	20.0	4.6
Ka000101-221001 A	11.0	160	13.9	5.0	94	13.4	3.3
Ka000101-221008 A	10.1	154	15.6	5.8	116	15.9	3.7
	10.6	157	14.7	5.4	105	14.7	3.5
Ka000101-221001 D	11.0	171	16.9	4.4	101	16.6	3.2
Ka000101-221008 D	10.1	178	17.7	5.1	109	16.7	3.0
	10.6	174	17.3	4.7	105	16.6	3.1

The letter behind the name of the sample refer to the batch in which the specimen has been tested. The testing period is important as the testing conditions might have changed between tests as the humid chamber was shared between different researchers.

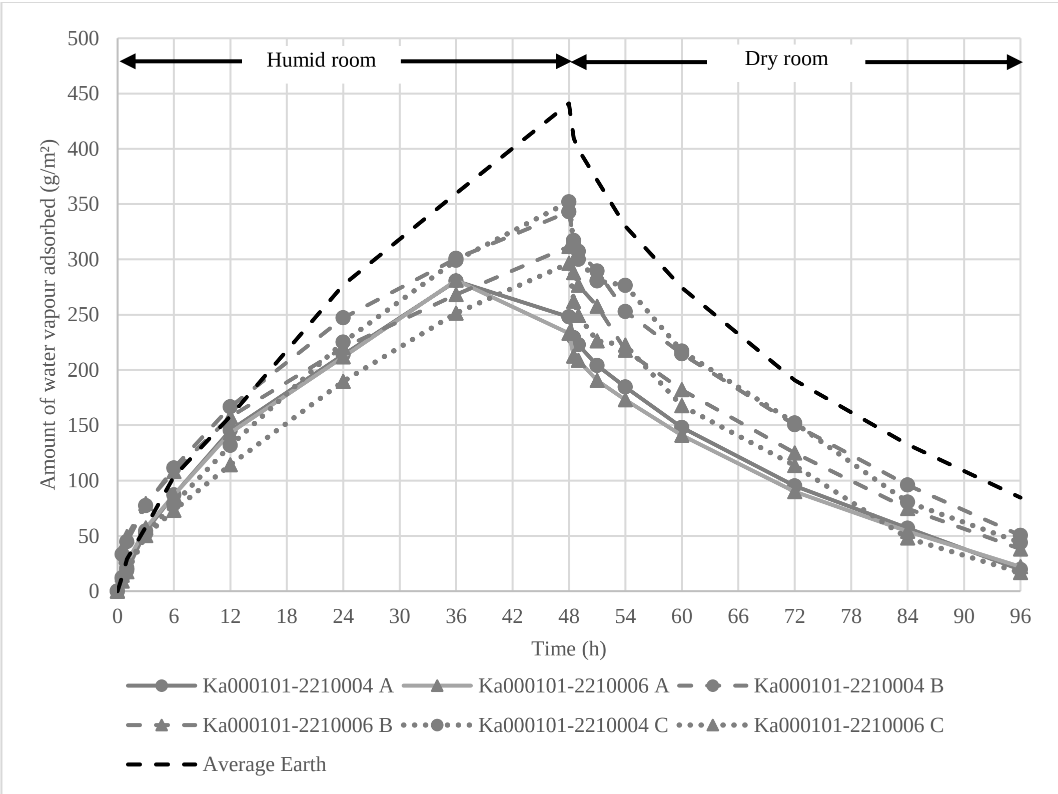

Figure E 1: Absorption and desorption behaviour of similar mortars in different batches and therefore different test conditions. The decrease of humidity absorption after 36 h is clearly seen on samples from the batch A. The absorption behaviour are very similar for this 2 type of mortars (same specimens tested in different batches), but slight difference may occurs due to the lack of precision of the test condition and the error margin of the weigths used.

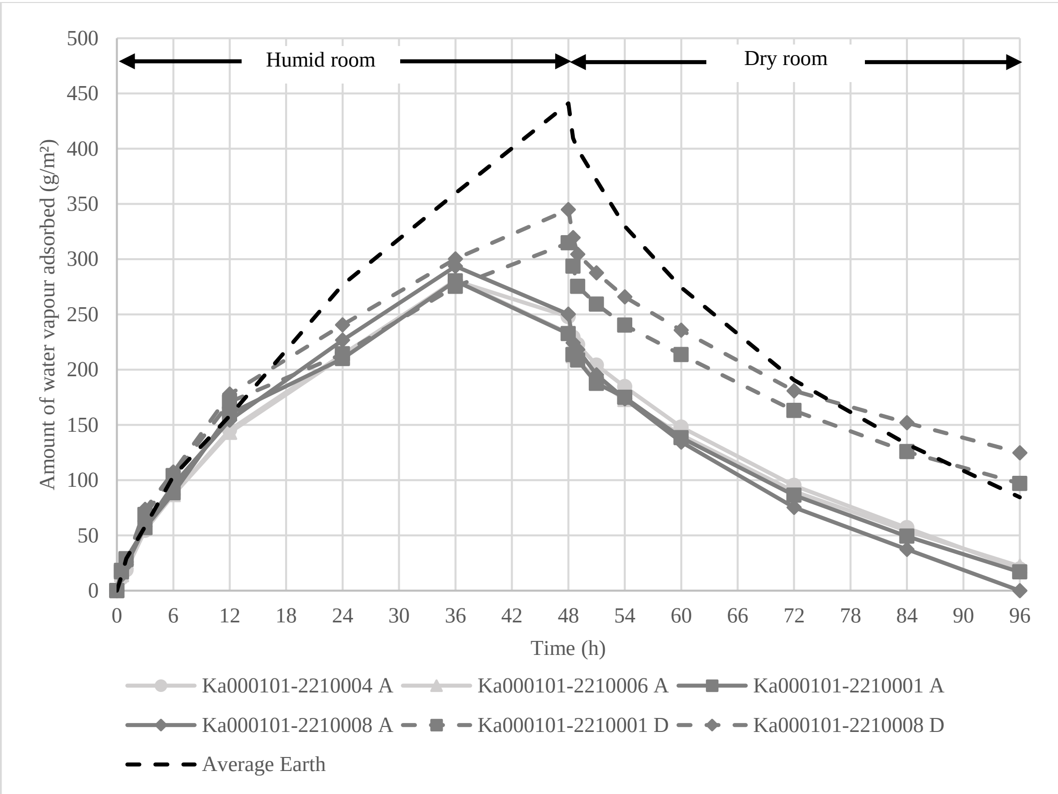

Figure E 2: Absorption and desorption behaviour of similar mortars in different batches and therefore different test conditions. The decrease of humidity absorption after 36 h is clearly seen on samples from the batch A. From this figüre, it can be understood that the absorption of mortars until 12h is very similar independantly of the mortar type and of the batch.

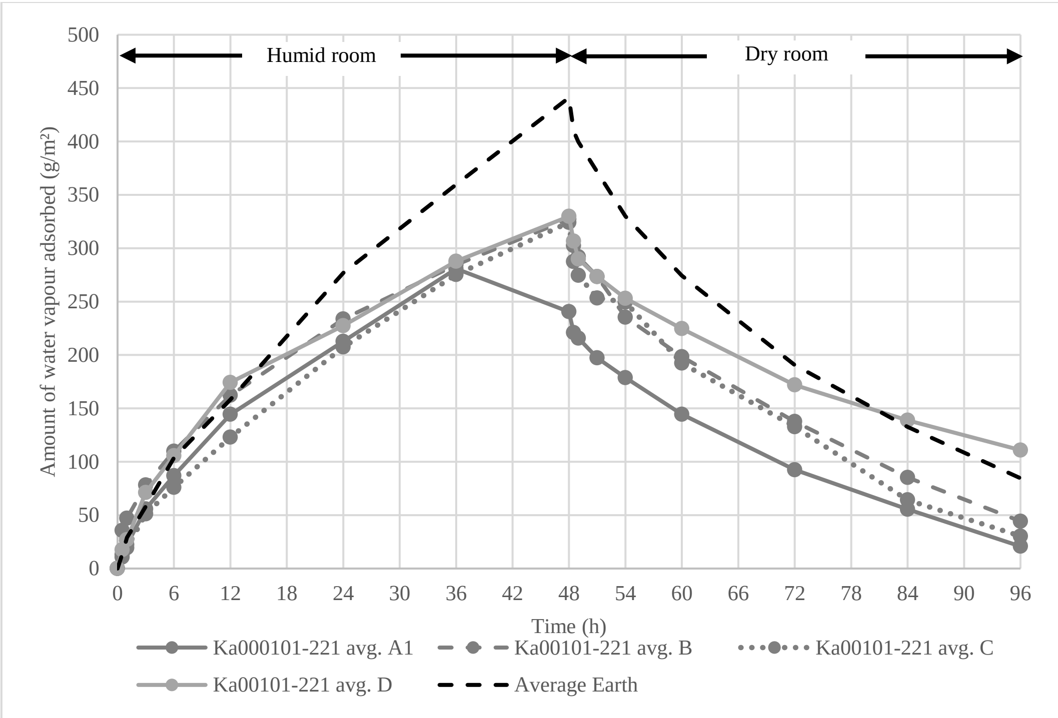

Figure E 3: Average of curves of similar mortars in the same batch. These mortars will be further used for comparison instead of a general Reference Mortar 1.

F. Water vapour properties of earth mortars reinforced with alternative fibres

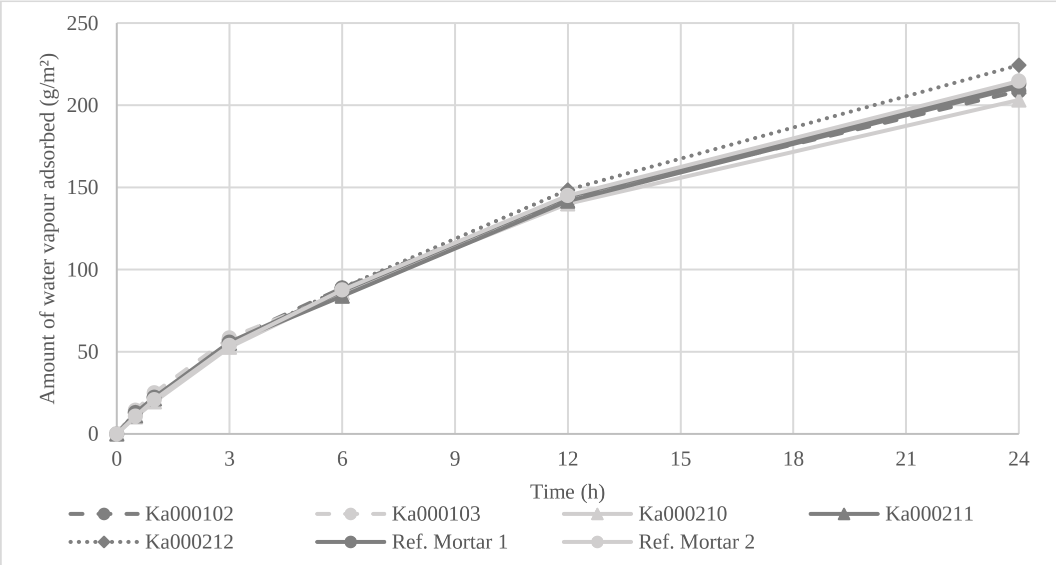

Figure F 4: Water vapour absorption of chaffs and straw reinforced earth mortars

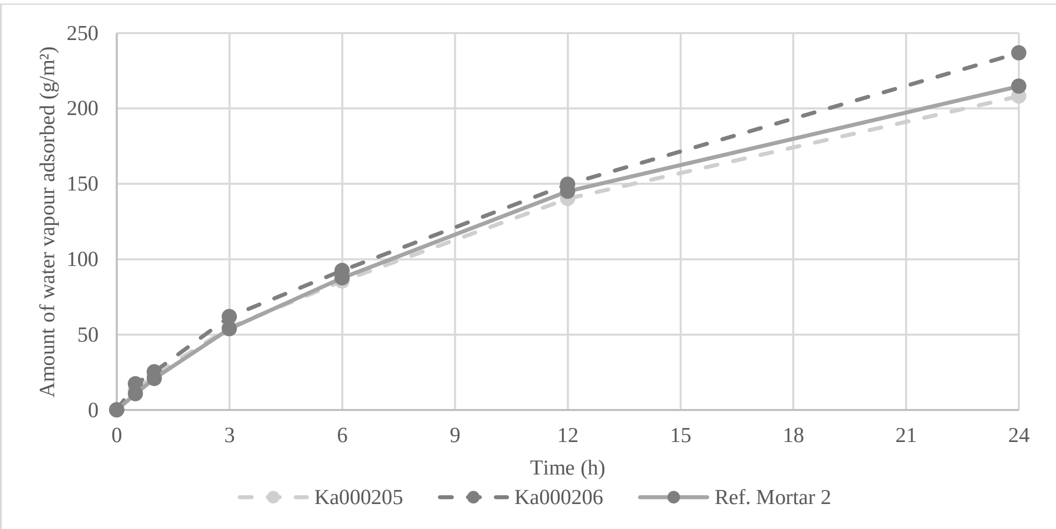

Figure F 5: Water vapour absorption of othe plant fibres reinforced earth mortars

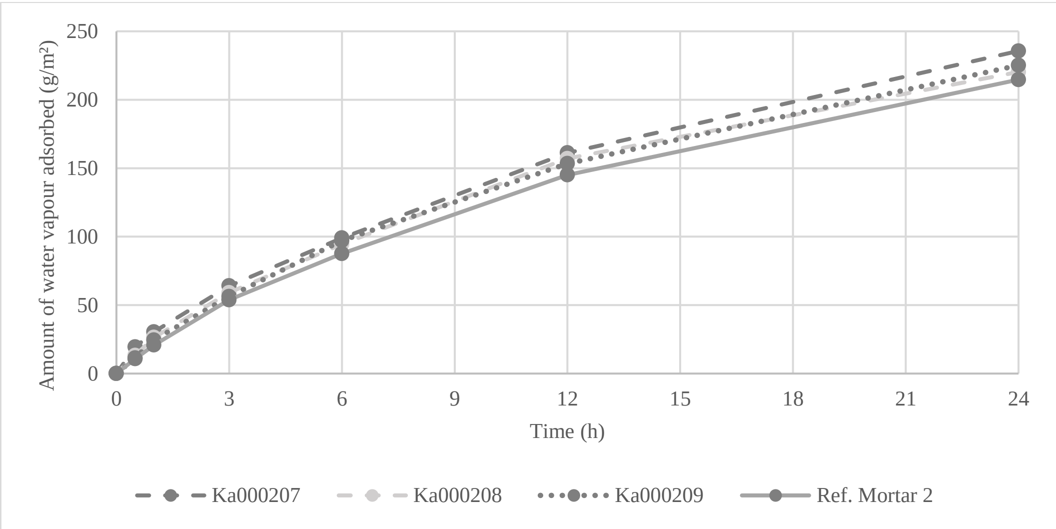

Figure F 6: Water vapour absorption of animal fibres reinforced earth mortars

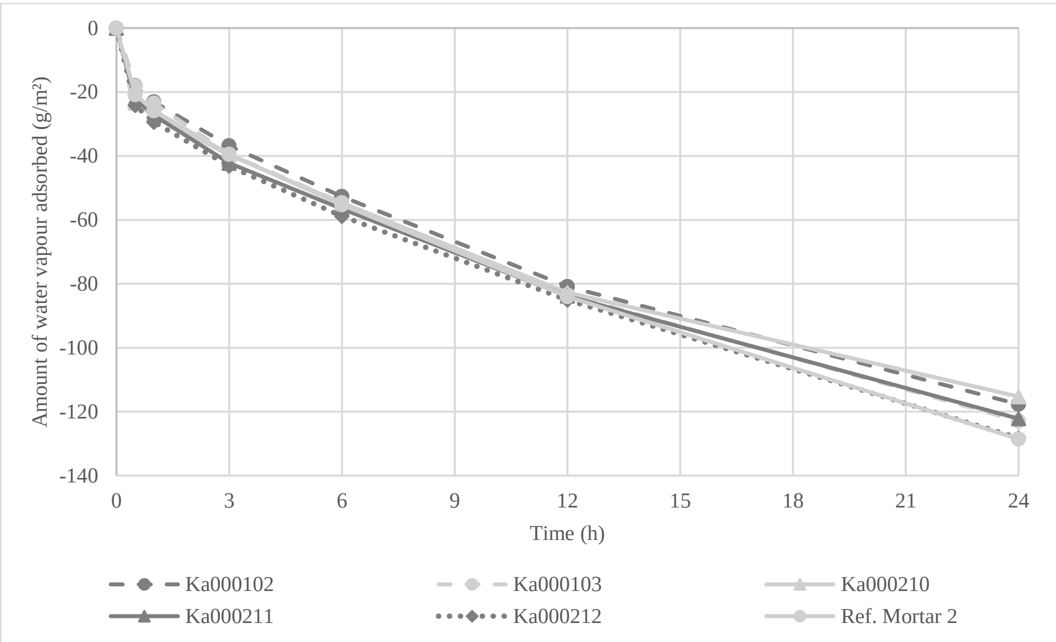

Figure F 7: Water vapour desorption of chaffs and straw reinforced earth mortars

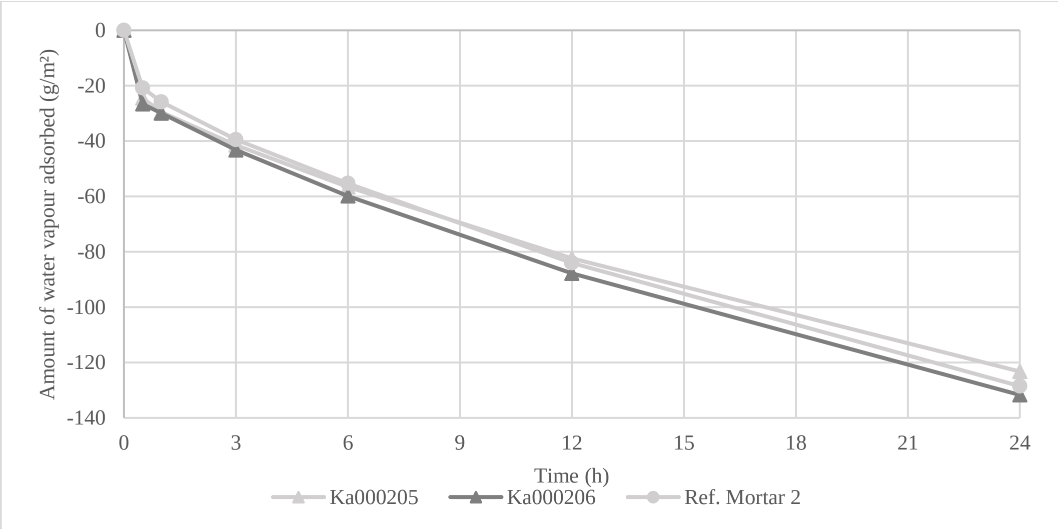

Figure F 8: Water vapour desorption of other plant-fibres based earth reinforced mortars

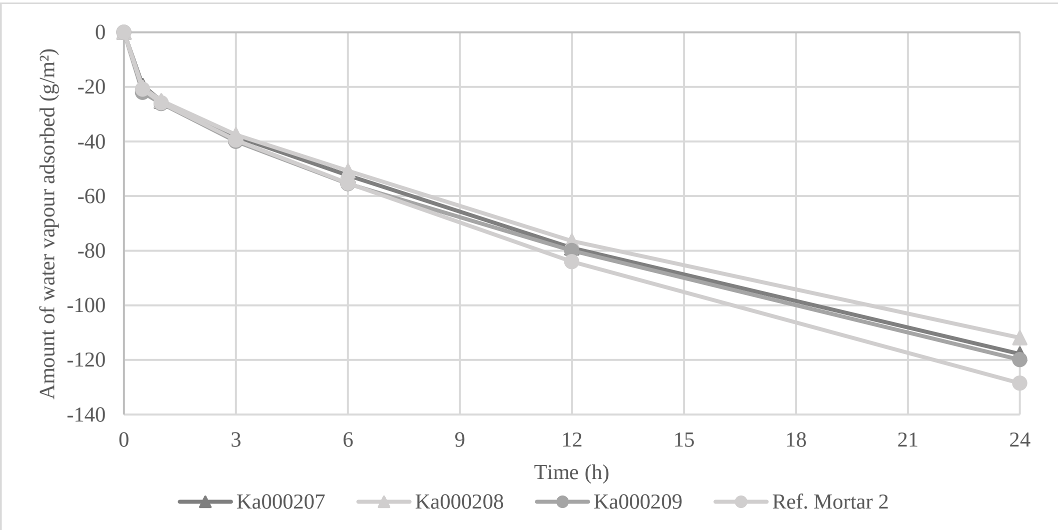

Figure F 9: Water vapour desorption of animal-based fibres earth reinforced mortars

CURRICULUM VITAE

Pedergnana, Matthieu Joseph

EDUCATION

Degree	Institution	Year of Graduation
MS	ENS Architecture Lyon	2010
BS	ENS Architecture Nantes	2008
High School	Lycée Jacques Amyot, Auxerre (France)	2000

WORK EXPERIENCE

Year	Place	Enrollment
Since 2019	Yasar University (Izmir) Dept. of Architecture	Lecturer
2013 - 2019	All over Turkey	Natural Building Workshop Instructor
2015 - 2016	Çankaya University (Ankara) Dept. of Architecture	Scholarship on TÜBİTAK project n°: 113K799
2013 - 2016	METU (Ankara) Dept. of Architecture	Volunteer teaching assistant on specific classes
2013 - 2016	METU (Ankara) Dept. of Architecture	Assistant on BAP projects
2011 - 2013	All over Europe	Volunteer on natural construction projects
2010 - 2011	TTAA Carpentry and Woodenhouses	Carpenter
Before 2010	All over France + Indonesia	Volunteer as site construction worker and site manager

FOREIGN LANGUAGES

Native French, Advanced English, Fluent Turkish, Intermediate German, Beginner Spanish

PUBLICATIONS

1. Pedergnana M. and Elias-Ozkan S. T. (2021) “Impact of various sands and fibres on the physical and mechanical properties of earth mortars for plasters and renders” in Construction and Building Materials, vol. 308.

2. Pedergnana M. and Elias-Ozkan S. T. (2021) "Hygro-Thermal, Hydric And Mechanical Properties Of Fibre And Aggregate Reinforced Earth Plasters," in International Journal of Digital Innovation in the Built Environment, vol. 10

3. Harputlugil G. U., Harputlugil T., Pedergnana M., Sarıoğlu E. (2019, May) “A novel approach for renovation of current social housing stock based on energy consumption in Turkey: significance of occupant behaviour” in Architectural Science Review

CONFERENCE

1. Pedergnana M. and Elias-Ozkan S. T. (2016, July) Impact of local additives on properties of earthen plasters, Terra 2016, Lyon, France

2. Pedergnana M. and Elias-Ozkan S. T. (2016, February) Post-occupancy evaluation of straw-bale buildings in Turkey, International Straw-bale Conference, Methven, New-Zealand

3. Summers F., Elias-Ozkan S. T. and Pedergnana M. (2015, September) The Kerkenes Eco-Center: A Show-Case for Appropriate Housing and Sustainable Development in Rural Turkey, PLEA, Bologna, Italy

4. Pedergnana M. and Elias-Ozkan S. T. (2015, July) Earth plaster for durable straw-bale walls, European Straw-bale Gathering, Montargis, France

5. Pedergnana M. (2015, July) Straw-bale Buildings in Turkey, European Straw-bale Gathering, Montargis, France

6. Pedergnana M. and Aslan E., (2013, September) Preliminary Study on Lightweight Pine Needles Loam, Kerpic’13 – New Generation Earthern Architecture: Learning from Heritage, Istanbul, Turkey

HOBBIES

Carpentry and woodwork, Earth construction, Bicycle travelling