THE LONG-TERM ENGINEERING PROPERTIES AND SUSTAINABILITY INDICES OF DEWATERING HYDRATED LIME MORTARS THROUGH JACARANDA SEED PODS

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Approval of the Board of Graduate Programs

Prof.Dr. Cumali Sabah
Chairperson

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science

Assoc. Prof. Dr.
Ceren İnce Derogar
Program Coordinator

This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

Assist. Prof. Dr. Shahram Derogar
Co-Supervisor

Assoc. Prof. Dr.
Ceren İnce Derogar
Supervisor

Examining Committee Members

Assoc. Prof. Dr. Tülin Akçaoğlu	Civil Engineering Program, Eastern Mediterranean University	
Assoc. Prof. Dr. Ceren İnce Derogar	Civil Engineering Program, METU NCC	
Prof. Dr. Murat Fahrioğlu	Electrical and ElectronicsDepartment, METU NCC	

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ABSTRACT

THE LONG-TERM ENGINEERING PROPERTIES AND SUSTAINABILITY INDICES OF DEWATERING HYDRATED LIME MORTARS THROUGH JACARANDA SEED PODS

Ayasgil, Dilara
Master of Science, Sustainable Environment and Energy Systems Program
Supervisor: Assoc. Prof. Dr. Ceren İnce Derogar
Co-Supervisor: Assist. Prof. Dr. Shahram Derogar

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Concrete, after water, is the most widely used material on the world, according to the World Business Council for Sustainable Development. Cement production cause high level CO_2 emission. Although the compatibility of hydrated lime in masonry is well comprehended in the literature, the unsuccessful replacement of lime with cement is a common challenge that introduces various problems, particularly in the conservation and restoration of historic masonry. The thesis begins with investigating the properties of hydrated lime mortars comprising Jacaranda waste collected from the METU Northern Cyprus Campus (NCC). METU NCC, used as the base location in this thesis. There are nearly 190 Jacaranda trees that produce this waste in enormous amounts every fall on Campus. In practice, the addition of powdered Jacaranda seed pods and silica fume to establish mortar-masonry optimization modified the low water retaining qualities of hydrated lime mortars, leading to insufficient bond development with the succeeding substrate. Although there have been numerous studies on incorporating agricultural waste in cement-based products, no studies on the incorporation of Jacaranda seed pods on construction materials have been published. The study presents verified experimental research findings on the use of Jacaranda seed pods as a binder alternative in hydrated lime mortars, emphasizing the influence of dewatering on long-term engineering characteristics and sustainability indices. According to the thesis, the degree of dewatering experienced at the freshly mixed stage defines the authentic performance of hydrated lime mortars in masonry construction and dictates the verifiable sustainability analysis to be performed.

Keywords: Cement, Lime Compatibility, Jacaranda Seed Pods, Dewatering, Sustainability Indices

ÖZ

SÖNMÜŞ SUSUZLAŞTIRILMIŞ KİREÇ HARÇLARININ JACARANDA TOHUM PODLARININ TOZU İLE SU İZİNLENMESİNİN UZUN VADELİ MÜHENDİSLİK ÖZELLİKLERİ VE SÜRDÜRÜLEBİLİRLİK ENDEKSLERİ

Ayasgil, Dilara
Yüksek Lisans, Sürdürülebilir Çevre ve Enerji Sistemleri
Tez Yöneticisi: Doç.Dr. Ceren İnce Derogar
Ortak Tez Yöneticisi: Dr. Öğretim Üyesi Shahram Derogar

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Dünya Sürdürülebilir Kalkınma İş Konseyi'ne göre beton, sudan sonra Dünya'da en yaygın kullanılan malzemedir. Çimento üretmi yüksek CO_2 emisyonuna neden olur. Sönmüş kirecin eski yığma yapılarda kullanımının uygunluğu literatürde iyi anlaşılmış olsa da, pratikte sönmüş kireç yerine çimento kullanımının yaygınlaşması bu eski yapıların korunumu ve restorasyonuyla ilgili çeşitli problemlere neden oluyor. Bu Tezde, ODTÜ Kuzey Kıbrıs Kampusun'dan toplanan Jakaranda tohum kabuğu atığı içeren sömüş kireç harçlarının özelliklerinin araştırılmasıyla başlamaktadır. Bu tezde temel lokasyon olarak ODTÜ KKK kullanılmıştır. Her sonbaharda bu atığı yüksek miktarlarda tohum kabuğu atığı üreten Jakaranda ağacından kampüste yaklaşık 190 adet bulunmaktadır. Uygulamada, harç-substrat optimizasyonu sağlamak için toz haline getirilmiş Jakaranda tohum kabukları ve silis külü ilavesi, sönmüş kireç harçlarının düşük su tutma niteliklerini değiştirdi ve bu da tipik olarak sonraki alt tabaka ile yetersiz bağ gelişimine yol açtı. Tarımsal atıkların çimento bazlı ürünlere dahil edilmesi konusunda çok sayıda çalışma olmasına rağmen, Jacaranda tohum kabuklarının inşaat malzemelerine dahil edilmesiyle ilgili herhangi bir çalışma yayınlanmamıştır. Çalışma, susuzlaştırmanın uzun vadeli mühendislik özellikleri ve sürdürülebilirlik endeksleri üzerindeki etkisini vurgulayarak, sönmüş kireç harçlarında bağlayıcı bir alternatif olarak Jakaranda tohum kabuklarının kullanımına ilişkin doğrulanmış deneysel araştırma sonuçlarını sunar. Teze göre, taze karıştırılmış aşamada deneyimlenen susuzlaştırma derecesi, tarihi yığma yapılarda sönmüş kireç harçlarının özgün performansını tanımlar ve gerçekleştirilecek doğrulanabilir sürdürülebilirlik analizini belirler.

Anahtar Kelimeler: Çimento, Kireç Uyumluluğu, Jakaranda Tohum Kapsülleri, Susuzlaştırma, Sürdürülebilirlik Endeksleri

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Lime is a natural, historic binder usually used for historic masonry buildings. Lime is the healthiest and eco-friendly material among construction materials. Lime used to be the most popular construction material because it is a functional material for jointing stones and bricks. It is also suitable for protecting historic masonry structures against water in renders and plasters (Deng et al., 2020). Although the usage of lime has decreased as the use of cement has increased, lime's moderate mechanical qualities, good water vapor permeability, and great durability make it a good building material. These properties are used in mortar-based works such as restoring old walls and buildings, and their area of use is expandable. Traditional lime mortar has advantages as a building material, including minimal drying shrinkage, good water vapor permeability, low early strength, and slow condensation hardening (24 -48 hours) (Zhang et al., 2018). While doing restoration and conservation work, the most critical factor is the choice of binder because it plays a vital role in these works.

The most crucial factor that affects the ability of water retaining is the desorptivity character of lime and cement is dewatering. It is a critical property of lime mortars that affects both substrate and fresh and hardened properties of lime mortar as absorbent surface and the substantial effect water transport kinetics. Furthermore, it affects the relationship between mortar and substrate in a reasonable manner. This influence on the kinetics of water also affects the microstructure of lime mortars (Ince et al., 2021). Lime mortar and plasters are applied in a thin layer, freshly mixed and wet, between absorbent layers in masonry structures. Lime mortar starts when it encounters substrates such as brick and stone. The dewatering process affects the mortar's fresh and hardened properties and genetically changes the structure's performance (Ince, et al., 2015). It also shows disadvantages such as poor water resistance and ready decomposition in wet or aqueous environments (Zhang et al., 2018).These disadvantages can be overcome by using pozzolanic materials (Aalil et al., 2019; Aggelakopoulou et al., 2011; Aškrabić et al., 2021; Vejmelková et al., 2012).

Civilization, technological and industrial innovations, and exponential growth in the world's population yielded an enormous rise in waste generation, particularly in industrial and agricultural terrains (Mannan & Ganapathy, 2004). The existing waste management alternatives such as recycling, incineration, and landfilling are either not sufficiently recognized or are not yet established in developing countries (Ganiron, 2013). In agricultural waste management, controlled and uncontrolled burning inappropriately is the standard method in practice. Although existing waste management alternatives have their drawbacks (Adams, 1979; Dhir et al., 2001; Ganiron, 2013; Hu & Srinivasan, 1999), burning the agricultural waste through a disposal process cause substantial air pollution and soil contamination (Ganiron, 2013) and yields the biodiversity loss of the terrain (Ganiron, 2013; Nagendran, 2011; Ongley & FAO, 1996; H. yuan Wang et al., 2015). Jacaranda seed pods are an agricultural waste produced by the Jacaranda tree every autumn. There are about 190 trees on the Middle East Technical University Campus, and there is a considerable waste generated each year. These wastes are disposed of using the landfilling method, which is not considered environmentally friendly.

There are diverse applications of agricultural waste utilization in construction materials (Aciu & Cobîrzan, 2013; Bakatovich et al., 2018; He et al., 2020; Ma et al., 2012; Mannan & Ganapathy, 2004; Middendorf et al., 2002a; Nguyen et al., 2019; Pavía et al., 2014a; Sathiparan & de Zoysa, 2018). For instance, wheat straw, sugar cane straw, rice husks, and oil palm shell are used as a substitute material in cement mortars and concrete and demonstrated substantial improvements in physical properties, strength, and durability, along with workability and air content (Bakatovich et al., 2018; He et al., 2020; Ma et al., 2012; Mannan & Ganapathy, 2004; Sathiparan & de Zoysa, 2018). Agricultural waste such as bagasse ash, wheat straw, sugarcane bagasse ash, sugarcane straw in lime mortars as building materials, and thermal isolation material are often reported in the literature. (Hasan et al., 2016; Kumar & Preethi, 2014; Middendorf et al., 2002b) However, there are not many studies in literature examining replacing agricultural waste with lime. Although there are studies reporting utilization of agricultural waste such as rice husk ash and wood ash in lime mortars, there are no studies that were adressing incorporation of any kinds of seed pods in hydrated lime mortars. (Kang, Kwon, Hong, et al., 2019; Méndez et al., 2012; Nikolaenko et al., 2020; Pavía et al., 2014b; Tampus et al., 2020), There is no study in the literature in which the jacaranda seed pod is incorporated in any building material. In addition to the issues mentioned above, dewatering is usually neglected, particularly waste material utilized in lime mortars.

1.2 Scope of Thesis

This thesis investigates the long-term engineering properties and sustainability indices of dewatering hydrated lime mortars through Jacaranda seed pods. Powdered Jacaranda seed pods and silica fume are used to hydrate lime as partial replacement material. The lime mortar mix design approach is adopted to produce mortars with various replacement levels of powdered jacaranda seed pods and silica fume. Characterization studies for the raw materials and jacaranda seed pods have been done using X-ray florescence and Malvern Mastersizer 2000 particle size analyzer. Mechanical properties, including compressive, flexural, and split tensile strength of mortars comprising powdered Jacaranda seed pods are investigated. The experimental investigations on the water transport kinetics of hydrated lime mortars comprising Jacaranda seed pods enabled the degree of dewatering to be monitored. Physical properties of lime mortar with jacaranda seed pods, including absorption, sorptivity, porosity, were also investigated in the thesis. The incorporation of the powdered pods along with silica fume on the sustainability indices such as the CO_2 emissions, cost efficiency, and eco-strength efficiency of hydrated lime mortar is reported in this thesis.

1.3 Structure of Thesis

This thesis is composed of five chapters. Chapter 1 contains summarized introductory information addressing lime and waste management compatibility issues. In Chapter 2, theoretical background, and a literature review on the effects of cement and lime production on the environment, waste management, agricultural wastes, substitution of agricultural wastes for cement, and its consequences. Chapter 3 contains the details of the materials used in this thesis. The lime mortar mix design approach was introduced and formulated to produce various lime combinations containing silica fume and powder of jacaranda seed pods. Chapter 4 addresses the experimental procedures for determining mechanical properties, durability characteristics, and microstructural analyses adopted for this thesis. Chapter 4 addresses the practical techniques of determining characterization study, mechanical properties, water transport kinetics, physical properties, and sustainability indices adopted for this thesis. Chapter 5 has investigated experimental results, interpretations, and discussions on the influence of using jacaranda seed pods and silica fume on the mechanical and physical properties, water transport kinetics, and sustainability indices for lime mortar.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter reports a literature review and theoretical background of supplementary cementitious materials and agricultural wastes on general durability, mechanical properties, and fresh state properties of mortars. Firstly, environmental effects and sustainability characteristics of lime and cement were reported. After that, waste types and disposal methods are investigated using the theoretical background. Afterwards, agricultural waste characteristics are investigated. Lastly, utilization of agricultural waste in construction material and the effect on durability characteristics, physical, mechanical, and fresh state properties of sustainable binding materials are summarized.

2.2 Sustainable Aspects of Construction Binders

Cement constitutes approximately 12% of concrete and is seen as the main ingredient of concrete (Van Oss & Padovani, 2002). Cement has been transformed into a widely used material thanks to its strength and good setting time in the building industry. The need for cement increases steadily due to the growing population and developing urbanization. According to Lippiatt & Ahmad, 2004, cement per person is 1 ton. It is estimated that cement needs can reach up to 1361 million (World Business Council for Sustainable Development and International Energy Agency, 2013).

The three fundamental phases of cement production are preparing and grinding raw materials, heating freshly created clinker in a kiln, and final cement manufacturing through grinding. In the first instance, raw materials (mined limestone and other materials) are converted into pieces 1 cm by drilling, blasting, and crushing machines. The cause of Green House Gases (GHG) release is the electrical energy consumed. Separating raw materials into small pieces is a very energy-consuming task, and this step causes GHG release. In the second stage, the raw materials obtained with fossil fuels are dried at a temperature of approximately 1500 degrees and turn into small, rounded nodules between 1 mm and 25 mm. This material in the furnace is called the clinker. A considerable amount of CO_2 is released at this stage, and a large amount of energy obtained from fossil fuels is consumed. In the last step, a combination is obtained by mixing gypsum and clinker in rotary clay. Cement production involves complex materials and complex energy flows (Y. Wang et al., 2013).

Lime mortars are essential in the construction industry as they are used in works such as laying ceramics and covering walls. Mortars should have some desirable properties in their use. These properties help us understand mortar materials such as good mechanical strength, water absorption capacity, adhesion and hardening to the applied surface, tolerance to deformations (García-Cuadrado et al., 2017; Palomar et al., 2015). According to the desired properties, cement or hydrated lime is used in the mortar (Marvila et al., 2019). Lime is the most used material with sand for brick external render and brick or stone masonry. More water is needed to make lime mortar workability higher than Portland cement. A higher water/binder ratio causes an increase in setting time and decreases the strength and durability of hardened lime mortar. It is one of the main barriers to using lime mortar in construction. While doing restoration and conservation work, the most critical factor is the choice of binder because it plays a vital role in these works. Inappropriate selection can cause an enhanced degeneration of the restored structure. Lime mortar and plasters are applied in a thin layer, freshly mixed and wet, between absorbent layers in masonry structures. Lime mortar starts when it encounters substrates such as brick and stone (Ince et al., 2015).

The lime cycle consists of three stages. The first stage is the production of hydrated lime from limestone, called calcination. For lime production, limestones are calcined with the help of heat. This reaction, which can also be explained as the decomposition of the carbonates in the limestone with the heat received in a kiln, response moving from the limestone surface towards the center, forms the quicklime shell in the center of the limestone. Limestone, a temperature of about 900 degrees Celsius, is required for this process, and at this stage, CO_2 is released. (Chen et al., 2007; Oates, 1998; Senegačnik et al., 2007, 2008; Specht et al., 2006). In the second stage, hydration is carried out by combining lime with water. In the last stage, it gives the water in the lime and hardens with CO_2 in the air, called carbonation (Sagastume Gutiérrez et al., 2012). Lime production is typical in both developing and industrialized countries. Harmful gases (such as sulfur dioxide, nitrogen oxides, and carbon dioxide) released during lime production can cause regional acid rain and increase greenhouse gas emissions that cause global warming (Sagastume Gutiérrez et al., 2012).

With the increase of environmental awareness, the value given to lime cured with carbon dioxide has increased. The CO_2 density of 0.04%, in natural conditions, consumes half of the CO_2 released during the production of lime within three months(Kang, Kwon, & Moon, 2019). At the same time, Cement consumes about one percent of the carbon dioxide released during its production(Possan et al., 2017). In addition, the min. 1400 °C required while producing cement is much less than the temperature necessary while producing lime(Cheng et al., 2017; Rahman et al., 2017). In this respect, lime is a much more sustainable material than cement.

2.3 Waste Generation

Approximately 2 billion tons of waste are produced globally, and the average daily waste production per person is around 0.74 kg. At least 33% of these wastes are not applied correctly (*Trends in Solid Waste Management*, 2018). With the increasing population, developing industry, and technology, waste management is on the way to becoming one of the biggest problems of the 21st century (D’Amato et al., 2016; de Feo et al., 2019; Stoeva & Alriksson, 2017). With the improvement of the quality of human life, waste production is expected to triple in 2100 in the future (Hoornweg et al., 2013).

The most significant sources of waste generation are concrete manufacturing and building and demolition waste. Constructions often cause waste production due to inappropriate materials and over-ordered materials. At the same time, wastes arising from earthquakes and similar disasters or from the destruction of buildings that have completed their lives also cause problems such as transportation and storage (Akhtar & Sarmah, 2018). These construction and demolishing wastes come in many varieties and large quantities. For example, it is estimated that there are around 4 million tons of C&D waste in New Zealand (Inglis, 2007).

It combines the separation of advanced technological devices into smart devices, the increasing population, and the management of rapid mass production e-waste. It has become why it is preferred in developing technology and widely used places (Kiddee et al., 2013). For example, while an average life span of a computer was 4.5 years in 1992, it was 2 in 2005 (Widmer et al., 2005). Approximately 1.11 million tons of e-waste in China each year, 10 million new televisions have been sold since 2003 alone (Hicks et al., 2005).

Domestic wastes include paper, packaging, vegetable and meat residues, polyethylene, coal, wood, and ash generated in homes. In addition, commercial wastes such as printing press, jewelry, and restaurant wastes are also included in these wastes (Demirbas, 2011). It is estimated that average EU citizens produce 435 kilograms of waste per day, while US citizens produce 735 kilograms of garbage. The systems established for the gathering and disposal of waste are outdated. Gathering costs are high (Pichtel, 2005). The storage and transportation of these wastes also harm the environment (Jouhara et al., 2017).

2.3.1 Agricultural Waste

Agricultural wastes are manure or harvest wastes from farms, poultry, slaughterhouses various agricultural activities(United Nations, 1997). Agricultural waste generation is more than about 5%-%10 each year from the following year (Ibrahim, 2015). Agricultural production has increased due to rapid population growth, expanded available areas of farming activities, and technological developments(FAO, 2017; OECD & FAO, 2019). They were leaving waste to the fields, or inadequate recycling techniques cause air, soil, water pollution, harmful gas emissions, soot, and ash formation. The burning of wastes pollutes the environment with the toxic gases it emits and causes water and soil pollution due to parasites and pathogens it contains (Wang et al., 2016a). Traditionally, farmers burn agricultural waste or leave it to rot in the field. However, these methods are harmful to the environment (Dhir et al., 2001; Sujatha et al., 2020). Incineration of debris can cause air pollution and soil erosion. Some studies have also observed that the biodiversity in the land where the waste is burned has decreased (Adams, 1979; Hu & Srinivasan, 1999). Another traditional method, leaving the waste to rot in the field, is not sustainable enough. These wastes can increase soil fertility, but the decay is prolonged, and the manure can accumulate in the soil and attract some pest species or cause the accumulation of some harmful oils that can harm the health of the plants (Adams, 1979; Hu & Srinivasan, 1999).

Agricultural wastes affect the size of countries, agricultural activities, geographical and cultural differences, and the number of agricultural wastes. For example, China produces approximately 56.2 million tons of waste per year (Agamuthu, 2009). Indonesia has about 9 million tons of garbage(GTZ International Services, 2006). Agricultural wastes play a vital role in polluting both land and water resources. 70% of the clean water in the world is used in the agricultural sector, and agriculture is one of the leading causes of water pollution. However, underdeveloped and developing countries prefer to burn agricultural wastes in open areas, causing air pollution (Ongley & FAO, 1996). On the other hand, agricultural waste management is made in many ways and the products released are used in various sectors (EA-UK R&D, 2001).

The jacaranda tree is a tropical tree grown in the tropics and subtropic areas. This tree can reach up to 13 meters. May begins to bloom, and the seed pods turn to brown colors at the end of the autumn (El Harim, 1998). There are approximately 190 trees on the METU Campus, and a significant amount of waste is generated every year. The landfill method is not considered environmentally friendly, and these wastes are disposed of by the landfill method.

2.4 Utilization of Agricultural Waste in Construction Material

Non-recyclable wastes caused by cement production (Jensen & Hansen, 2001; Thorpe & Zhuge, 2010; Woodward & Duffy, 2011), and high greenhouse gas emissions (Frías et al., 2017), sustainable, recyclable, and low-cost materials have gained importance (Asdrubali et al., 2015).

The most suitable agricultural wastes for these construction materials have inspired these studies. These materials can not only be used as support materials for cement but also as aggregates (Liew et al., 2017). A large amount of solid waste is generated each year, consisting of palm fibers, skins, and fruit waste. These wastes have adverse effects on health and the environment. It has been revealed that the ash released as a result of the combustion of wastes can be used as a pozzolanic material due to the high amount of silica it contains (Mehta, 1977; Payá et al., 1996; Udoeyo & Dashibil, 2002). Sugarcane bagasse ash, sawdust, groundnut shell, oyster shell, tobacco waste, palm oil fuel ash, coconut shell, rice husk, wild giant reed are the most used agricultural wastes (Gunasekaran et al., 2013). Agricultural wastes contain silica after combustion and improved durability and reduced permeability of cement mortars after acid exposure (Chatveera & Lertwattanaruk, 2011). Studies have shown that the high silica and amorphous structure of sugarcane bagasse ash and rice husk ash show pozzolanic properties. It provides an advantage against sulfate and chlorine attacks by improving the pore structure of mortar and concrete

(Chopperla et al., 2019; Singh et al., 2007; Villar-Cociña et al., 2011). RHA can be used as a filling material for hot mix asphalt concrete (Al-Hdabi, 2016). In addition, the researchers concluded that 100% replacement of RHA and date seed ash (DSA) mixture is suitable, and a 75% replacement is required for the optimum result. This mixture also causes an increase in the fatigue resistance of concrete (Tahami et al., 2018).

According to Ataie & Riding (2016), agricultural wastes are materials that can be found, inexpensive, and adapt well to concrete. In addition, the use of these wastes in concrete offers an alternative recycling method for such wastes. Some agricultural wastes used for a concrete replacement that Rice husk(Raheem & Kareem, 2017; Sargin et al., 2013); corn cob ash(Adesanya & Raheem, 2009a, 2009b; Ganesan et al., 2008); wood ash (Abdullahi & Abdullahi, 2006; Raheem & Adenuga, 2013; Raheem & Orogbade, 2018); sawdust ash (Raheem et al., 2012; Raheem & Ige, 2019); sugarcane bagasse; (Danso, 2017; Imran & Anwar Khan, 2018) is in the literature.

Agricultural wastes contribute to improving cement mortar and concrete's mechanical characteristics. Thanks to the free $CaOH_2$ found in farm wastes, it helps form a gel, also known as CSH gel, which plays a role in increasing the long-term strength of concrete(Bheel, Sohu, et al., 2021). In addition, agricultural wastes show pozzolanic properties with high silica content (Bheel, Ibrahim, et al., 2021). Thanks to these features help increase concrete's long-term compressive and flexural strength. Palm Oil Fuel Ash (POFA) produces high compressive strength concrete. POFA reduces the water requirement of concrete, increasing the strength of concrete (Aldahdooh et al., 2013; Awal & Shehu, 2013; Bamaga et al., 2013; Sata et al., 2007; Tangchirapat et al., 2009; Tangchirapat & Jaturapitakkul, 2010). It is also known that sugarcane bagasse ash is ideal for high-strength concrete(Rukzon & Chindaprasirt, 2012). In addition to compressive and flexural strength, agricultural wastes also contribute to split tensile strength (Bheel, Ibrahim, et al., 2021; Bheel, Sohu, et al., 2021).

Porosity is another property for the durability of the specimen (Moretti et al., 2018). According to the experimental studies, although the porosity structure increases in the samples containing POFA, these internal pore networks are closed with the crest of CSH gels. This feature also causes the sample to have higher durability when exposed to acid and sulfate attacks (Aprianti et al., 2015; Ranjbar et al., 2016). According to Salam et al., (2013), while POFA increases, the concrete's strength increases. An increasing rate of POFA also reduces the permeable porosity and increases the durability of the concrete (Chindaprasirt et al., 2008; Ganesan et al., 2008; Hesami et al., 2014; Mahmud et al., 2010; Nagaratnam et al., 2016; Ranjbar et al., 2016).

At the same time, concrete achieved less surface water absorption in the samples containing agricultural residues. Water penetration is associated with capillary action, and wastes contribute to concrete healing. In addition, sorptivty should be present for minor corrosion, which indicates that the sample is of higher quality (Mo et al., 2020; Ranjbar et al., 2016).

Changing agricultural wastes makes the fresh properties of concrete adversely. Higher replacement reduces workability, and the sample can exhibit lower consistency and lower segregation resistance. Plasticizers can be used to prevent this situation (Nagaratnam et al., 2016; Ranjbar et al., 2016; Saleh et al., 2019).

2.5 General Discussion

Today, the most commonly used material in the building sector, greenhouse gas emissions from concrete manufacturing are high, resulting in global warming, ecological degradation, and climate change. In this thesis, hydrated lime was used because it is less harmful to the environment and has a high carbonation reaction rate. In addition, this thesis has tried an alternative and clean recycling method for waste management. Another environmental problem is substituting the jacaranda seed coat, one of the agricultural wastes on the campus, with hydrated lime. Characterization study comprising the X-ray fluorescence of the raw materials and the elemental composition and physical properties of Jacaranda seed pods were essential in assessing the compatibility of pods utilization in hydrated lime mortars. The inclusion of powder capsules with silica fume in sustainability indices includes CO_2 emissions, cost-effectiveness, and eco-resilience efficiency of slaked lime mortar. In this thesis, experiments investigated the dewatering degree of powdered jacaranda with hydrated lime substitution and the water transport kinetic dewatering degree of hydrated lime mortar with jacaranda seed pod substituted. With these experiments and reviews, the performance and sustainability of the lime mortar were examined

CHAPTER 3

MATERIALS AND MIX DESIGN

3.1 Introduction

In this section, the materials used in the experimental study are introduced. The materials used are Lime, Silica Fume, Standard Sand, Jacaranda seed coat powder, and water. The standards on which the use of these materials is based are also described. In addition, this section mentions the casting processes of the samples used in the study and the standards used in this process.

3.2 Materials

3.2.1 Lime

The European standard EN 459-1, 2015, defines hydrated lime and quicklime for construction and civil engineering applications, including domes. CL80, produced by Nur Kireç, can be seen from Figure 3-1, is used for this experimental research. It is high purity micronized (200 microns) hydrated calcium lime. It is used in the construction industry, construction materials, treatment plants, chemical and pharmaceutical industries, and agriculture.

Figure 3-1: CL 80S Lime

3.2.2 Silica Fume

Silica fume is a pozzolanic additional cementitious substance that enhances binding material properties. Silica Fume can be seen from Figure 3-2, used in this experimental procedure accord with ASTM C1240-15 and produced as a by-product during the smelting process in silicon metal production ferrosilicon in Cyprus Environmental Enterprises Ltd. (CEE).

Figure 3-2: Silica Fume

3.2.3 Standard Sand

The fine aggregates utilized in the mortar making comply with the standard following EN 196-1; the fine aggregate was used to prepare mortar mixes. Standard sand can be seen from Figure 3-1 is produced by Limak Cement Factory. The particle size distribution of the fine aggregates is in accord with ASTM C128-15.

Figure 3-3: Standard Sand

3.2.4 Jacaranda Seed Pod Powder

Jacaranda seed pods are agricultural waste produced by jacaranda trees every fall. About 190 trees on the Middle East Technical University campus generate large garbage every year. After harvesting the pods can be seen from Figure 3-4, immediately remove the seeds from the pods to avoid further fertilization of the mixture in later stages can be seen from Figure 3-5. Then crush the pods until they become powder can be seen from Figure 3-6.

Figure 3-4: Collected Jacaranda Seed Pods

Figure 3-5: Jacaranda Seed Pod after Removing Seeds

Figure 3-6:Jacaranda Seed Pod Powder

3.2.5 Water

Water quality is vital because the mixed design directly affects the mortar's mechanical and physical properties. In this thesis, the mixing water used to produce lime mortar follow ASTM C1489-15.

3.3 Mix Design

The seed pods that are fallen from the jacaranda trees can be seen in Figure 3-7 and Figure 3-8, of which there are approximately 190 on the campus. Jacaranda seed pods are fallen, can be seen from Figure 3-9, collected, and the seeds inside are removed to avoid further fertilization of the mixture at later stages. The pods were then pulverized until they became powder. (Particle size distribution is discussed later in Section 4.1). They are used as a binder substitute in mortar production.

Figure 3-7: Jacaranda Tree

Figure 3-8:Jacaranda Tree

Figure 3-9:Fallen Jacaranda Seed Pods

The collected and pulverized jacaranda seed pods are shown in Figure 3-10 and Figure 3-11 and

Figure 3-12, respectively. For the experimental study, a volume ratio of 0.538:1:2 as water: binder: sand was used to prepare slaked lime mortars. Also, 0.538:1:2 as water: binder: sand volume ratios are used to prepare hydrated lime mortars for the experimental work. The 1:2 binder: sand ratio initially proposed by the manufacturer Nur Kireç has also been suitable in the previous studies on hydrated lime mortars

ASTM C348-21, ASTM C496/C496M-17, and ASTM C807-21. The mix design utilized in this research is predicated on the bulk densities of the raw ingredients and the volume fractions of the mixtures. These substitute quantities and types of both powdered jacaranda seed pods and silica fume have explicitly been established to keep the consistency of hydrated lime mortars within a closed range as much as possible without the need for additional water. In this principle, the water-binder ratio is kept constant, considering that the volume fraction of the binder is obtained by the sum of the fractions of hydrated lime, powdered jacaranda seed pods, and silica fume for all combinations. Keeping the water-to-border ratio constant was essential to study the sole influences of the properties of hydrated lime mortars with powdered jacaranda seed pods and silica fume. The additional consequences of changing the water-binder ratio at dewatering and engineering properties were circumvented by keeping the water content constant.

Figure 3-10:Jacaranda Seed Pod

Figure 3-11:Jacaranda Seep Pod Pulverized

Figure 3-12: Jacaranda Seed Pod Pulverized

For this thesis, seven different proportion samples were designed. First, the sample containing only CL80 as a control sample containing 582.32 grams of lime is intended to be a control specimen. This sample includes neither jacaranda seed coat powder nor silica fume to compare the properties of lime mortar. In the second sample, 10% jacaranda was substituted. This sample contains 524.09 grams of lime. The third sample was obtained by covering 20% jacaranda. The second and third samples were designed to examine the effect on the long-term properties of lime mortar when only jacaranda was replaced. In addition, it was aimed to determine the impact of increasing jacaranda substitution on lime mortar by increasing the jacaranda substitution rate. The fourth and fifth samples contain 10% and 20% silica fume substitution. These samples aim to examine the effect of the pozzolanic substitution made to the lime mortar on the long-term properties of the lime mortar and the impact of the change in the amount of silica fume contained on the properties of the lime mortar. The sixth and seventh samples include both jacaranda and silica fume. While 20% silica fume and 10% Jacaranda seed pod powder replacement were applied in the sixth sample, a 20% substitution rate for 20% jacaranda shell powder was determined for silica fume in the seventh sample. With these samples, it is aimed to examine how jacaranda bark powder and silica fume affect the lime mortar together. In addition, it is desired to explore the long-term properties of the pozzolan added lime mortar with the increase of the jacaranda ratio by keeping the silica fume ratio constant.

First, the necessary materials for the casting process of the samples were weighed and placed on the tray can be seen in Figure 3-13. Then, the required amount of water was added while mixing with the mixer. After all the ingredients are added slowly within 1.5 minutes, Figure 3-14, and combined with the help of a mixer, the mortar is mixed by hand, Figure 3-15, and then blended for another 1.5 minutes using a mixer.

Figure 3-13: Raw materials in the tray

Figure 3-14: Mixing raw materials with mixer

Figure 3-15: Mixing raw materials by hand

The prepared mortar is started to be filled into the molds prepared by lubrication beforehand (Figure 3-16). Secondly, half of the mold is filled, and the air spaces inside are taken with the help of a vibration table. After the remaining half of the molds are filled with lime mortar, the air spaces are removed again by a vibration machine can be seen from Figure 3-17. The prepared samples in Figure 3-18 and Figure 3-19 are removed from the molds after 3-4 days and cured with air. Experimental mix designs combinations shown in Table 3-1.

Figure 3-16:Mold

Figure 3-17: Vibration Table

Figure 3-18: Prepared Samples

Figure 3-19: Prepared Samples

Table 3-1: Mix Design

No	Specimen	Materials	Volume Proportions	Mass (g)
1	Hydrated lime mortar Control (**CL80**)	Water	0.538	474.68
		Lime	1	582.32
		Jacaranda Waste	0	0
		Silica Fume	0	0
		Sand	2	2699.84
2	Hydrated lime with 10% Jacaranda Waste (**CL80+10J**)	Water	0.538	474.68
		Lime	0.9	524.09
		Jacaranda Waste	0.1	38.82
		Silica Fume	0	0
		Sand	2	2699.84
3	Hydrated lime with 10% Jacaranda Waste (**CL80+20J**)	Water	0.538	474.68
		Lime	0.8	465.85
		Jacaranda Waste	0.2	77.64
		Silica Fume	0	0
		Sand	2	2699.84
4	Hydrated lime with 10% Silica Fume (**CL80+10SF**)	Water	0.538	474.68
		Lime	0.9	524.09
		Jacaranda Waste	0	0
		Silica Fume	0.1	21.62
		Sand	2	2699.84
5	Hydrated lime with 20% Silica Fume (**CL80+20SF**)	Water	0.538	474.68
		Lime	0.8	465.85
		Jacaranda Waste	0.2	0
		Silica Fume	0	43.23
		Sand	2	2699.84
6	Hydrated lime with 20% Silica Fume and 10% Jacaranda Waste (**CL80+20SF+10J**)	Water	0.538	474.68
		Lime	0.7	407.62
		Jacaranda Waste	0.1	38.82
		Silica Fume	0.2	43.23
		Sand	2	2699.84
7	Hydrated lime with 10% Silica Fume (**CL80+20SF+20J**)	Water	0.538	474.68
		Lime	0.6	349.39
		Jacaranda Waste	0.2	77.64
		Silica Fume	0.2	43.23
		Sand	2	2699.84

CHAPTER 4

EXPERIMENTAL PROCEDURE

4.1 Introduction

This chapter describes the experimental procedures followed for this exploratory study. First, the physical and chemical properties of the raw materials used in the Characterization Study are explained. Then, Fresh State Properties are defined, and experimental studies to determine these properties are presented. Then, the experimental process for water transport kinetics is explained. Then, the physical and mechanical properties of the lime mortar were defined, and the experiments carried out to determine these properties were examined. Finally, the process of reviewing the material in terms of sustainability and environmental impact is discussed.

4.2 Characterization Study

Characterization is an essential step before using the material for any purpose. This step investigates the chemical, physical, and other properties depending on the material's intended use. In this experimental study, materials were examined both chemically and physically before starting the experiments. Identification for all material used in this practical work, along with its chemical composition and particle size distribution, was performed at the research and development education and measurement center of the main campus of METU. The chemical composition of materials is determined by X-ray florescence. ZSX Primus II, as shown in Figure 4-1 from central laboratory of METU, is utilized to determine the chemical composition of powdered Jacaranda seed pods. The bulk materials' grain size distribution was investigated according to Mie scattering and quantifying principles through the Malvern Mastersizer 2000, Figure 4-2 from central laboratory of METU. To compute the particle size distribution, laser diffraction methods may use a variety of light scattering models. Mie and Fraunhofer optical models are commonly utilized in laser diffraction devices (Etzler & Deanne, 1997).

Figure 4-1: ZSX Primus II

Figure 4-2: Malvern Mastersizer 2000

Particle Size Distribution is assessed using the Malvern Panalytical Mastersizer 2000 laser diffraction testing device. This approach has been widely employed in various industries, including pharmaceuticals, the environment, food, health, and beauty. When a laser beam passes a sample material, the laser light is scattered at various angles. The intensity of the light is measured via detectors. The chemical characters of the materials are examined and the chemical components they contain. By determining the chemical compositions in the materials and the amounts of these components, it is tried to predict the mortar's properties.

4.3 Fresh State Properties

Although the fresh state constitutes a brief period of the life of lime-based mortars, it significantly influences the long-term properties of the material. Fresh state properties also considerably impact the material's adhesion to the substrate, or leveling and finishing of mortars, determining the material's workability. Workability is one of the essential fresh state properties of mortars. Workability is the ability of the mortar to be molded to obtain it (Bauerová et al., 2019). In this experiment, the consistency and setting times of the samples were examined to determine the workability of the lime mortar. Consistency is an indicator of the hardness and fluidity of the mortar. To have good workability, all samples should have a similar consistency (Vyšvařil & Krebs, 2020). To determine the consistency of the mortar, an experiment was carried out according to ASTM C230/C230M standards. According to this standard, a flow table is used for consistency. As shown in Figure 4-3, the table used for consistency testing is a flow table. Flow table and mold are cleaned before each test. The conical mold is filled with mortar precisely.

Figure 4-3: Flow Table

Make sure that there are no gaps in the mold. Then, the excess mortar is removed from the top of the vocal mold with the help of a spatula, ensuring that the upper part of the lime is entirely smooth and the mold is removed. Then, the mortar flow is monitored by slowly turning the handle of the flow table 15 times. The mortar diameter is checked after turning the handle 15 times, as seen in Figure 4-4.

Figure 4-4: Consistency Test

Setting time is defined as the time when the mortar completely loses its plasticity and reaches a certain hardness from the moment water is added to the binder material. Experiments to determine the setting time of the mortar were carried out according to ASTM C807-21. The Vicat apparatus seen in Figure 4-5 was used for this experiment. First, the lime mortar is filled into the Vicat mold.

Figure 4-5: Vicat Apparatus

This mold is placed on a non-porous glass plate and filled with lime mortar to avoid gaps. Then the mold is placed in the center of the Vicat apparatus and mold with the sample, as seen in Figure 4-6. The needle at the tip of the Vicat apparatus is released, and penetration is measured. The experiment is repeated at regular intervals until the penetration is 4 mm. The elapsed time gives us the setting time of the mortar.

Figure 4-6: Vicat Apparatus and mold with sample

4.4 Water Transport Kinetics

Mortars renders and plasters are applied to surfaces such as stone and brick in their fresh state and a thin layer. The mixture used as a thin layer dehydrates over time, and in this way, the rock gradually transforms from a soft state. The ability of the mortar to hold water while in a fresh form is defined as desorptivity. Control dewatering helps eliminate and match the compatibility problems between mortar/substrate caused by too low or too high sorptivity. The desorptivity ability of lime helps reduce the amount of water required by the cement mortar and increases the mortars' workability by using lime in cement mortars (Ince, Carter, et al., 2015). Desorptivity of fresh mix and sorptivity of the substrate directly affect the absorption of water from fresh mortar (Ince et al., 2011). In addition, studies show that the water-retention of lime-based mortars can be reduced by simple ionic solutions that can be used with water and by the capillary pressure applied by substrates such as bricks (Ince, Carter, et al., 2015). The speed of the dewatering reaction affects the durability and strength of the mortar, so it is a critical action. Although it is not known in practice how dewatering involves the strength of the mortar, a laboratory-based study by Robinson has listed several essential factors that affect the bond strength of the mortar. These can be listed as mortar fluidity, physical bonding, chemical bonding, and brick properties (Robinson, 1996). Desorptivity is a general parameter that symbolizes the desorptivity ability of mixtures such as fresh state mortar render and plasticity. The absorbency of freshly prepared mixtures can be easily examined using an American Petroleum Institue, pressure cell (API, 1998; Carter et al., 2003; Green et al., 1999; Ince et al., 2011). The theory of water loss in wet mixtures had first been developed by API based on slurry filtration and dewatering analyses used in oil field engineering. (Bolton & Ckinley, n.d.; Meeten & Sherwood, 1994; Sherwood & Meeten, 1997; Smiles, 1970). Then, based on these studies, the application of this theory to construction materials was carried out (Hall & Hoff, 2021). This theory predicts that forcing water in the slurry by an inert gas, such as nitrogen, and dewatering a slurry at constant applied filtration pressure P progresses half of the time (Hall & Hoff, 2021; McKinley & Bolton, 2015).

Since the aim was to evaluate the effect of dehydrated hydrated lime mortars using Jacaranda seed pods in this study, regular absorbency (~2mm/min1/2) firebricks were deliberately used in transfer absorbency experiments. Sorptivity is measured by drying firebricks in an oven at 105˚C for 24 hours and placing them in a shallow layer of water. The bricks were separated from the water and weighed from time to time. After absorbency measurements, the firebricks are dried again in the oven at 105˚C and then contacted with a shallow layer of fresh mix. Transfer absorbency is defined as the slope of a graph of the volume of bulk absorbed water per unit area of firebricks adjacent to the wet mix versus the square root of time. They are removing the brick mass before and after dewatering allowed the determination of the total water absorbed by each brick during this process. This amount of water absorbed is then proportional to the total mass of the mixture used in the dewatering experiment to obtain the total water loss of the mixture (Ince et al., 2010).

4.5 Mechanical Properties

Flexural and compressive strength of hydrated lime mortars comprising powdered Jacaranda seed pods is performed following ASTM C348-21, respectively. The ability of the specimen to withstand the bending force applied perpendicular to its axis determines the flexural strength of the material. In this experimental study, Flexural strength was investigated with the UTEST Electromechanical Universal Testing Machines can be seen from Figure 4-7. After ensuring that the samples are dry to find the flexural strength, the samples are placed on the device. After making sure that the flexural strength apparatus of the device is attached, it is ensured that the sample is placed at the same distance from both supports. The specimen shall be set directly above the midpoint of both supports. Care is taken to put the center point loading device so that its abutment edge is precisely at right angles to the length of the prism and parallel to its upper face as placed. The maximum flexural strength of the sample is noted.

Figure 4-7: Compressive&Flexural Strength Machine

Compressive strength is the ability of a material or structure to withstand compressive loads. Specimens subjected to the flexural strength test are divided into two separate parts. These parts are subjected to a compressive strength test. First of all, ensure that the apparatus used for the compressive strength test is attached and that the device is installed. The specimens are then placed so that they are centered on the base bearing block of the machine, and the bearing plate assembly is in the middle of this base. The samples should be placed in the device sideways according to the molded position. The split tensile strength of mortars is inspected according to the ASTM C496/C496M.

4.6 Physical Properties

The relationship between the porosity structure and strength of mortars was known intuitively or empirically even in ancient times. Porosity is defined as the total volume of open spaces in the mortar structure and may include pores and cracks that occur even in the later stages of the mortar's life. The area of the voids is also affected by the water/binder ratio and the volume, size, gradation, and origin of the aggregates. Also, the structure of the porosity system interferes with the strength-porosity relationship(Papayianni & Stefanidou, 2006).

Open porosity, vacuum saturation obtained after the samples were exposed to a pressure of 25 mbar on earth, was determined according to the following equation 4.1.

$$\rho = \frac{M_3 - M_1}{M_3 - M_2} \times 100 \tag{4.1}$$

M_1 indicates the mass of the mortar sample after carbonation. M_2 represents the mass of the carbonated sample in water following saturation. The group of the M_3 carbonated piece is the value weighed in air (El-Turki et al., 2010). Porosity measurements were determined from the mean value of three mortar samples attained from the same batch. The depth of water penetration was measured in line with BS EN 12390-8, 2000.

The sorptivity of mortar specimens was determined using the slope of a chart of the cumulative volume of absorbed water per unit area of bed surface of mortars vs. the square root of time, as previously indicated.

All material thicknesses with relatively high absorption content and specific samples that can show a significant variation within 2 hours are kept underwater for 24 hours, and their weight is weighed. As aforementioned, the sorptivity of mortar specimens was measured from the slope of a chart of the cumulative volume of absorbed water per unit area of bed surface of mortars versus the square root of time. The water absorption on hydrated lime mortars comprising powdered Jacaranda seed pods are determined in compliance with ASTM D570 .

4.7 Sustainability Indices

Sustainability metrics examined in this thesis included cost efficiency, CO_2 emissions, and environmental strength of slaked lime mortar. The analysis of CO_2 emissions considers the entire manufacturing process of mortar raw materials such as lime and fine aggregate.   summarizes the CO_2 emission aspects of raw materials and the costs of these ingredients (Arel, 2016; Kim et al., 2013). Emissions from burning fuel, process-related emissions, and the fuel used to disassemble and transport segments contribute to CO_2 emissions. The CO_2 emission factor of sand considers extraction, cutting, crushing, sieving and transportation. Silica fume's CO_2 emission factor only finds the processes of grinding, processing, and sieving. This is a necessary process used before replacing such materials in concrete. The cost-efficiency factor (CEF) is determined by the ratio of the compressive strength of concrete in mortar to the total material cost per m^3(Ince, 2019; Ince, Derogar, et al., 2021; Ince et al., 2020; Ince, Tayançlı, et al., 2021). The prices of the local mix ingredients summarized in Table 4-1. The cost of mortar that makes up the powdered jacaranda seed pod, so the cost is based on the ratio of the compressive strength of the mortar to the total material cost. The effect of the coefficient can be calculated. The Environmental Strength Efficiency Factor (ESEF) is then determined by the ratio of the compressive strength of the mortar to the CO_2 emissions of the material per kg. The environmental strength effect factor is determined using the specified compression strength value and the corresponding CO_2 emissions of each sample.

Total CO_2 emissions are also calculated based on the cumulative CO_2 emissions of each raw material used to make the mortar sample.

Table 4-1: The cost and CO2 emissions of the raw materials

Raw Materials	**Cost**	**CO_2 emissions**
Hyrdated lime	\$0.14/kg	1.2 ton-CO_2/ton(Arel, 2016)
Silica fume	\$0.03/kg	0.014 ton-CO_2/t (EPA)
Fine aggregate	\$0.01/kg	0.053 kg-CO_2/m^3 (Kim et al., 2013)

CHAPTER 5

EXPERIMENTAL RESULTS

5.1 Introduction

In this section, the experimental results are analyzed, and the consequences of this analysis are examined. First, the physical and chemical properties of the raw materials used in the experimental results of the Characterization Study are explained. Then, the effects of the Consistency and setting time experimental results were examined. Moreover, the experimental results for water transport kinetics are presented. Then, physical experimental results such as absorption, absorbency, and water depth are explained. The mechanical properties of the lime mortar, compressive, flexural, and were split tensile strength results of experiments were examined. Finally, the process of reviewing the material in terms of cost efficiency, CO_2 emissions, and eco-strength efficiency is discussed.

5.2 Characterization Study

X-ray florescence is utilized to determine the chemical composition of the raw materials used in making hydrated lime mortars in this study. The chemical composition of hydrated lime and fine aggregates, summarised in Table 5-1, exhibited regular distribution in amount and type for such materials. The hydrated lime binder used in this study, CL80, demonstrated a high content of CaO (84%) and therefore complied with EN 459-1. The pozzolanic replacement material, silica fume, conventionally indicated a high range of SiO_2 (higher than 94%), affirmed its high pozzolanic activity and complied with ASTM C1240-15. The particle size distribution of fine aggregates complied with ASTM C128. The elemental distribution of powdered Jacaranda seed pods, utilized as a binder substitute in making hydrated lime mortars, is summarised in Table 5-2. It is revealed from the elemental analysis that powdered Jacaranda seed pods are rich in carbon. The elemental composition of powdered Jacaranda seed pods, summarised in Table 5-2, correlates well with the previously reported studies (Bonelli et al., 2001; Durán-Valle et al., 2005; Hernández-Montoya et al., 2011; Treviño-Cordero et al., 2013).

Table 5-1: Chemical composition of hydrated lime and fine aggregates

Chemical composition	**Lime (%)**	**Fine aggregate (%)**	**Silica fume (%)**
CaO	84.52	0.51	1.19
CO_2	-	-	-
MgO	0.86	0.13	0.57
SO_3	0.20	0.03	0.25
SiO_2	0.89	92.23	94.8
Al_2O_3	0.22	4.03	0.88
Fe_2O_3	0.26	0.64	1.74
Cl	0.07	0.02	0.01
V_2O_5	-	-	-
K_2O	0.01	1.24	1.06
Na_2O	-	0.51	0.32
TiO_2	-	0.81	-
MnO	-	0.03	0.08

Table 5-2: Elemental composition of the Jacaranda seed pods used as a substitute material in hydrated lime mortars (wt. %)

Characteristics	**Jacaranda seed pod**
Shape	Elliptical
Length, mm	~ 60
Width, mm	~ 55
Inner thickness, μm	~ 250
Middle thickness, μm	~ 1200
Outer thickness, μm	~ 350
Cellulose content (% wt.)	~ 41

Table 5-3: Physical characteristics of Jacaranda seed pods

Elemental composition	**Jacaranda seed pod (%)**
C	81.41
H	2.36
N	0.49
S	0.02
O	15.71

Physical characteristics such as shape, length, and width of Jacaranda seed pods, summarised in Table 5-3, are typical and are in line with Bar-On et al. (2014). It is also demonstrated in Table 5-3 that cellulose is the principal component of Jacaranda seed pods.

The cellulosic and lignocellulosic character of such agricultural roots and pods, previously reported by (Elizalde-González & Hernández-Montoya, 2007) and Elizalde-González et al., (2007) also show similar compositions.

Particle size distributions of raw materials used in making hydrated lime mortars, on the other hand, are exhibited in

Figure 5-1. Silica fume, used as a binder substitute, demonstrated high fineness compared to that of the binder materials. Powdered Jacaranda seed pods, on the other hand, showed more excellent particle size distribution compared to the hydrated lime binder. Fine aggregates used in mortar making provided the coarsest distributions of all.

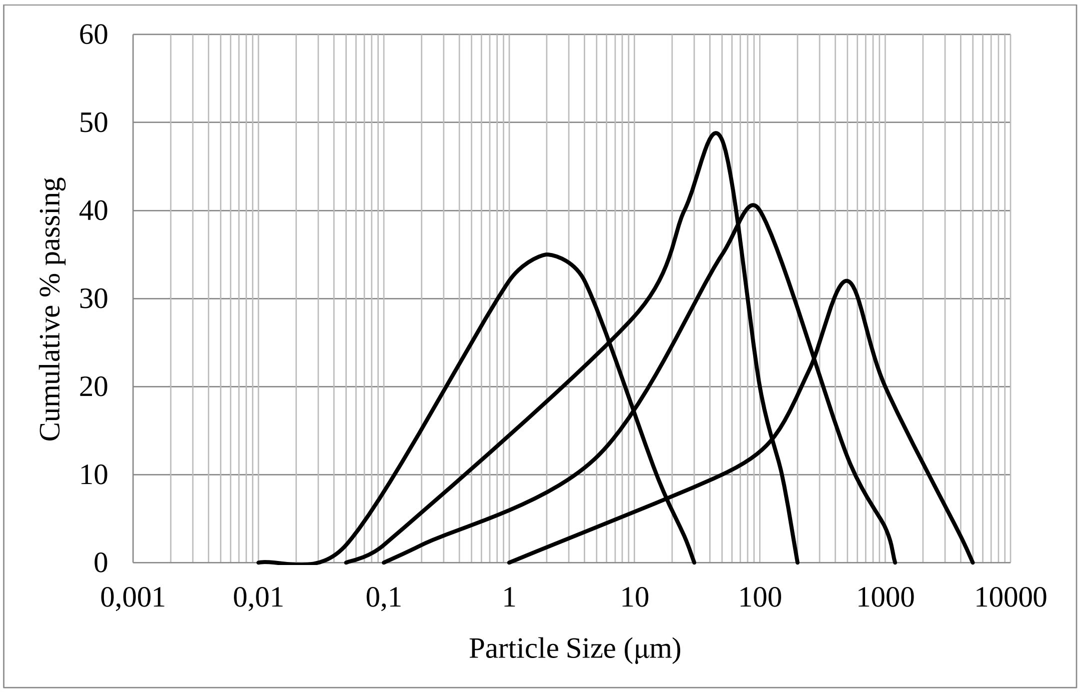

Figure 5-1: Particle size distributions of raw materials

5.3 Fresh State Properties

5.3.1 Consistency

The consistency of hydrated lime mortars comprising Jacaranda seed pods and silica fume used as binder substitutes is shown in Figure 5-2. Control specimen, CL80 mortar, deliberately is prepared to provide consistence of 135mm. Volume proportions of solid constitutes plotted on the secondary axis in Figure 5-2 provided more insights into the fresh properties of hydrated lime mortars. It is demonstrated in Figure 5-2 that the increase in Jacaranda seed pods, used as binder replacement, resulted in a slight rise in the consistency of lime mortars.

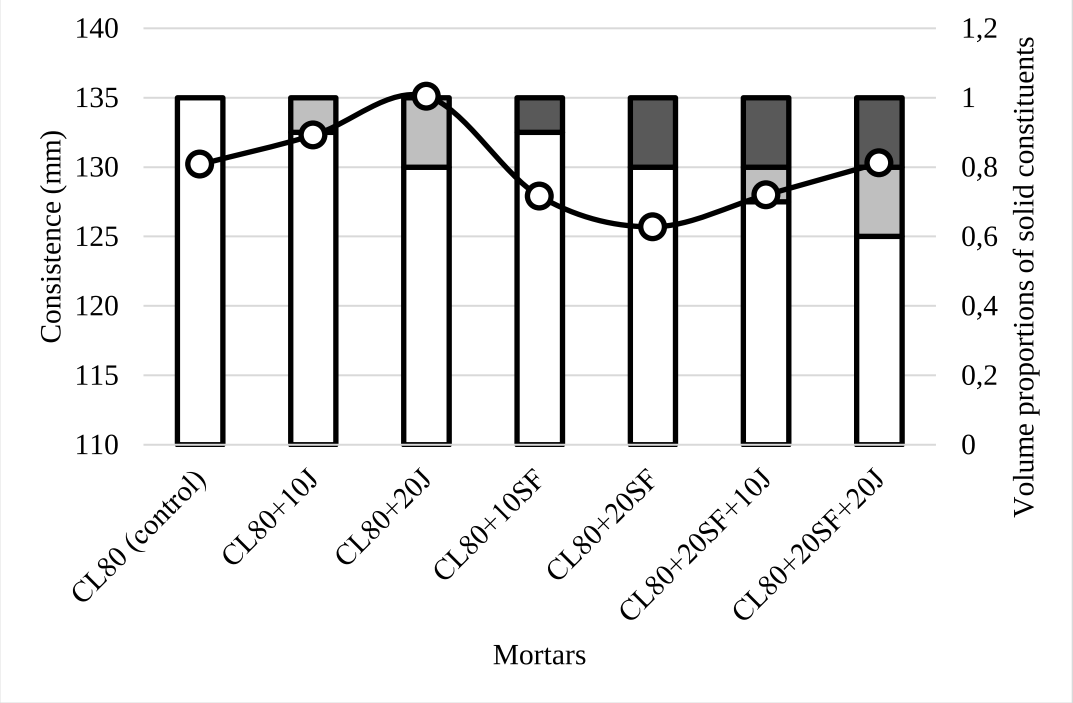

Figure 5-2: Consistence of hydrated lime mortars comprising Jacaranda seed pods and silica fume

The coarser particle size of powdered Jacaranda seed pods compared to the binder resulted in a decrease in the overall surface area of the raw materials, which reduced the water demands of the mixture, enhancing the consistency of lime mortars. This feature is mainly responsible for increasing the consistency of hydrated lime mortars as the water: binder ratios were kept constant throughout the combinations examined in the thesis. The use of silica fume, a finer substitute material used to replace hydrated lime binder, resulted in a reduced consistency of mortars. An increase in the surface area and the increase in the demand for water to saturate the raw material resulted in a slight decrease in the consistency. When Jacaranda seed pods are systematically added to the mixture of CL80 mortars with 20% silica fume, a systematic increase in the surface of hydrated lime mortars is observed. It must be reported that the consistency of hydrated lime mortars comprising 20% Jacaranda seed pods and 20% silica fume is almost identical to the consistency of the control mortar. It should be highlighted that the variations detected in consistence are inconsiderable (~5mm) as the hydrated lime mortars containing both Jacaranda seed pods and silica fume were within the ‘workable’ range and that the fluctuations observed in consistence were only negligible.

5.3.2 Setting Time

Setting times of hydrated lime mortars comprising Jacaranda seed pods and silica fume are shown in Figure 5-3. Volume proportions of water and CL80 binder are plotted in the secondary axis for comparison purposes. The results shown in Figure 5-3 indicated that the increase in the Jacaranda seed pods increased the setting time of hydrated lime mortars. The increase in the setting time attained in Figure 5-3 is in a good correlation with the previously reported results in Choi & Choi (2021); Omikrine Metalssi et al. (2014); Ornaghi et al. (2014); Poletto et al. (2012); Si-Yang et al., (2010); Su et al., (1991) The presence of high content of cellulose and hemicellulose was reported to be responsible from the delayed setting time (Choi & Choi, 2021; Doudart de la Grée et al., 2017; Hachmi et al., 1990; Miller & Moslemi, 1991b, 1991a; Su et al., 1991). Glucose, formed through the polysaccharides in cellulose, produces various acids due to chemical reactions. Salt, produced in the matrix to neutralize these acids with hydroxide ions, conglomerates on the reaction products, causes a delay in setting time. (Choi & Choi, 2021; Doudart de la Grée et al., 2017; Hachmi et al., 1990; Miller & Moslemi, 1991b, 1991a; Su et al., 1991). Apart from the cellulosic composition of Jacaranda seed pods, the courser particle size distribution of these wastes generates more significant and more accessible pathways for the water removal at the fresh stage that contributed to increasing the setting time of such mortars.

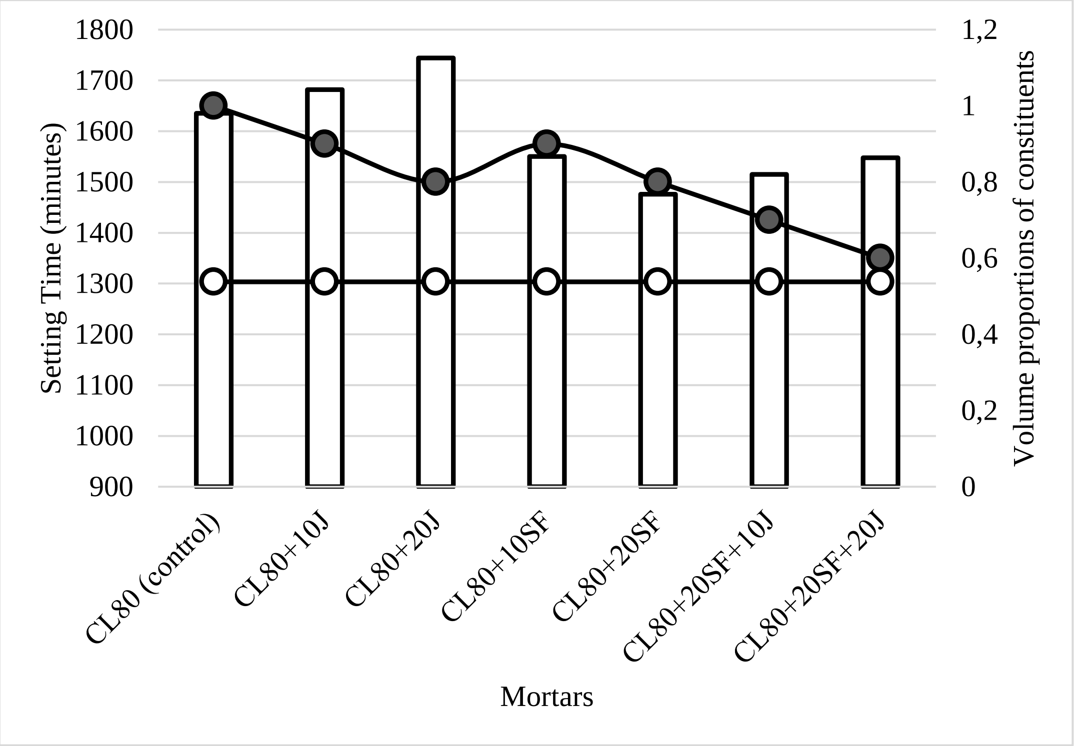

Figure 5-3: Setting times of hydrated lime mortars comprising Jacaranda seed pods and silica fume

It is also shown in Figure 5-3 that the increase in the substitution level of silica fume resulted in a systematic decrease in the setting time of hydrated lime mortars. The high fineness of the pozzolanic replacement material resulted in a denser microstructure of the mixtures due to the increased amount of water demand at the freshly mixed stage, which possibly caused a decrease in the setting time of such mortars. When hydrated lime mortars with 20% silica fume are incorporated with 10 and 20% Jacaranda seed pods, a similar increase in these mortars' setting time was attained. Although the setting time of hydrated lime mortars comprising silica fume and Jacaranda seed pods are much lower than that of the hydrated lime mortars alone, the delayed setting time attained with the increase in Jacaranda seed pods is attributed to the high content of cellulose and hemicellulose of the agricultural wastes. It is also shown in the secondary axis in Figure 5-3 that the volume proportion of water of the mixtures examined in the thesis is kept constant. Besides, Jacaranda seed pods and silica fume as binder replacement resulted in a substantial decrease in hydrated lime consumption. It is previously reported in Kulesza et al. (2018) and Ball et al. (2011). that the amounts of these additives and, therefore, the volume proportions of cellulose and hemicellulose embedded in the matrix play a significant role in extending the delayed setting time. The substitution levels of Jacaranda seed pods used as a binder replacement in this investigation were therefore limited to 20% in purpose. The rise attained in the setting times was within the tolerable limits.

5.4 Water Transport Kinetics

Transfer sorptivity of hydrated lime mortars comprising Jacaranda seed pods and silica fume are exhibited in Figure 5-4. Water loss experienced by the freshly mixed mortars when they are in contact with the dry substrates are plotted in the secondary axis for comparison. The results displayed in Figure 5-4 exhibited that the rise in the Jacaranda seed pods increased the transfer sorptivity of hydrated lime mortars.

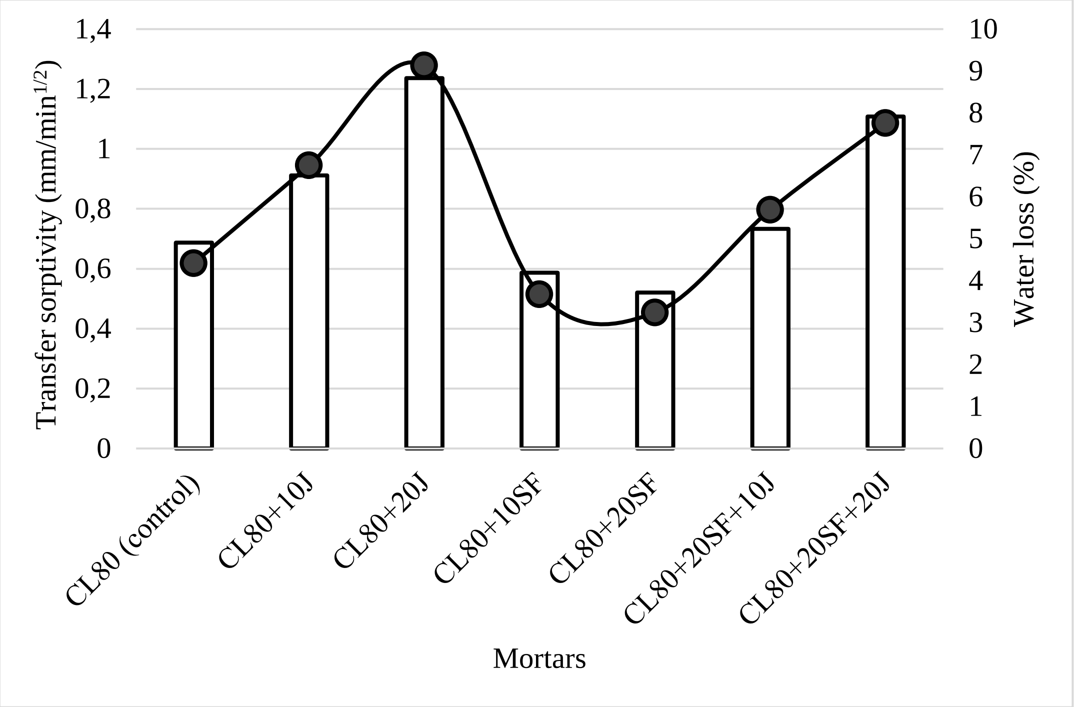

Figure 5-4: Transfer sorptivity of hydrated lime mortars comprising Jacaranda seed pods and silica fume

Increasing the transfer sorptivity indicate that the high water retentivity of hydrated lime mortars could be transformed to more water releasing to achieve improved optimization in mortar-masonry systems. The results are shown in Figure 5-4 also indicate that using silica fume further enhances the high water retentivity of hydrated lime mortars. These results might have some practical consequences in practice, particularly for the conservation and restoration of historic masonry. As the substrate material used in such applications could not easily be replaced, further decreasing the degree of transfer sorptivity could be helpful in correlation with high sorptivity substrates. Incorporating Jacaranda seed pods in hydrated lime mortars comprising 20% silica fume further yielded a systematic rise in the transfer sorptivity of such mortars for the same reasons as mentioned above. The results in Figure 5-4 exhibited a direct correlation between the transfer sorptivity and water loss experienced by the freshly mixed hydrated lime mortars. The capability to control transfer sorptivity and the degree of water loss contributes to optimizing mortar-masonry systems. For instance, the use of very high water releasing mortar with the high sorptivity substrate leads to a significant amount of water loss that adversely affect the fresh and hardened properties of such mortars (Ball et al., 2011; Derogar, 2017; Ince, 2014; Ince, Carter, et al., 2015; Ince, Derogar, et al., 2021; Ince et al., 2014; Ince & Derogar, 2018; Kulesza et al., 2018). Insufficient water transfer at the fresh stage is also caused by high water retention mortars with low sorptivity substrates, leading to inadequate bond development.

Table 5-4: Transfer sorptivity and time to dewater of CL80 mortars comprising jacaranda seed pods and silica fume.

Specimen	**Transfer Sorptivity ($mm/min^{1/2}$)**	**Time to dewater (min)**	**Change in time to dewater (%)**
CL80-Control	0.687	36.5	-
CL80+10J	0.912	31.3	%14.2 decrease
CL80+20J	1.236	26.8	%26.6 decrease
CL80+10SF	0.587	39.1	%6.6 increase
CL80+20SF	0.521	41.4	%11.8 increase
CL80+20SF+10J	0.733	39.4	%7.4 decrease
CL80+20SF+20J	1.108	42.3	%13.7 decrease

The sorptivity rate transfer and the time required to dewater hydrated lime mortars incorporating Jacaranda seed pods and silica fume are reported in Table 5-4. A column demonstrates the change in time to dewater attained in percent. It is noticeably summarised in Table 5-4 that the increase in transfer sorptivity due to the use of Jacaranda seed pods caused a methodical reduction in the time to dewater. On the other hand, the utilization of silica fume yielded a gradual reduction in the transfer sorptivity responsible for the systematic increase in the time taken to dewater such mortars. It can be seen in Table 5-4 that the hydrated lime mortars comprising 20% silica fume with 10 and 20% Jacaranda seed pods exhibited a considerable rise in the transfer sorptivity and a related reduction in the dewatering time. It should be mentioned that the Jacaranda seed pods had a significant role in the analysis in increasing the transfer sorptivity of lime mortars compared to that of silica fume, which had a reduced effect in decreasing the water transfer.

5.5 Mechanical Properties

5.5.1 Effect of Jacaranda Seed Pods on the Compressive Strength Development of Hydrated Lime mortars Comprising Silica Fume

The compressive strength of hydrated lime mortars comprising silica fume and Jacaranda seed pods is shown in Figure 5-5. Compressive strength of hydrate lime mortars, also shown in Figure 5-5 for comparison purposes, exhibited a progressive increase up to 91 days then demonstrated a decelerating growth afterward. The carbonation reaction had a higher rate until 91 days due to the matrix's substantial $Ca(OH)_2$ availability. The rate shows a descending growth after the first three months as the vast majority of the portlandite already transformed to $CaCO_3$. The results are shown in Figure 5-5 exhibited that the addition of pozzolanic material, such as silica fume, caused a significant increase in the strength development of hydrated lime mortars. The early growth attained in the compressive strength of hydrated lime mortars comprising silica fume could be attributed to the filler effect of the pozzolanic replacement material that densifies the matrix and improves the load-bearing characteristics such materials under compression. The continued increase in strength in long-term is mainly due to the pozzolanic reaction that transforms the portlandite to calcium-silicate-hydrate gels and improves the hydraulic binding capacity of the mortars examined in the thesis.

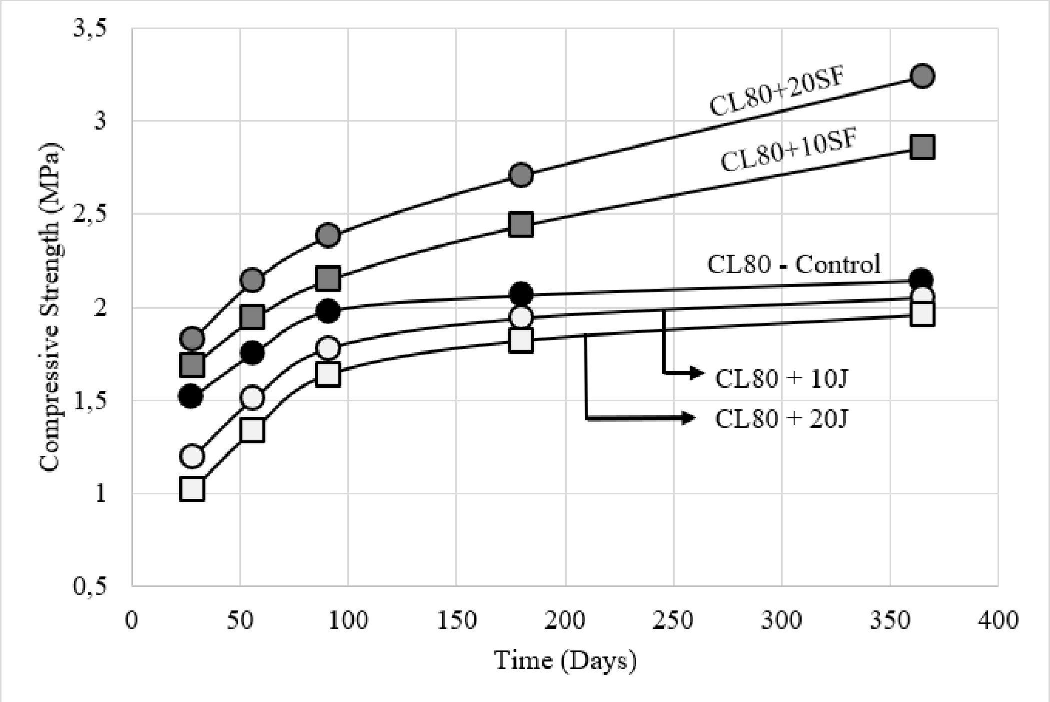

Figure 5-5: Compressive strength of hydrated lime mortars comprising silica fume and Jacaranda seed pods

Although much less, it must also be noted that the carbonation reaction between the portlandite and CO_2 also contributed to the strength development of hydrate lime mortars examined in this study. The increase in Jacaranda seed pods used as a binder replacement also yielded a slight decrease in the compressive strength of hydrated lime mortars at all ages. Therefore, the delayed setting time and the associated delay of the carbonation reaction are already addressed in the thesis's former sections (4.2.Fresh State Properties). These pods' cellulose and hemicellulose content were essentially responsible for the slight decrease observed in the strength of hydrated lime mortars. Hydrated lime mortars comprising 20% silica fume were then incorporated with 10 and 20% Jacaranda seed pods.

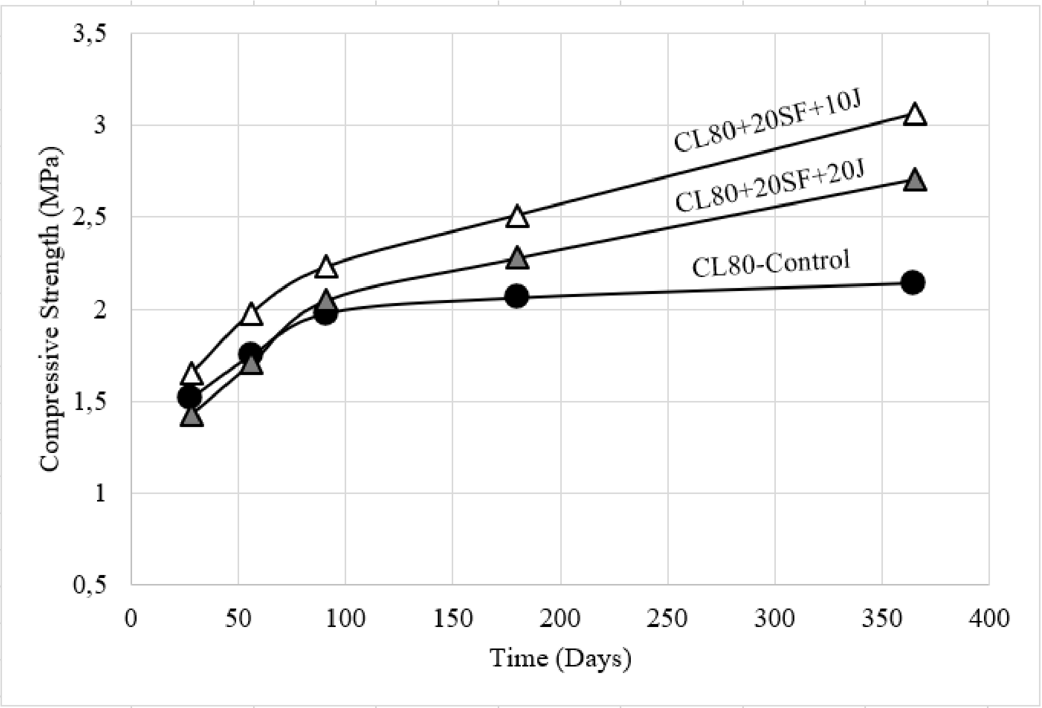

Figure 5-6: The strength development of the specimens

The strength development of these mortars is demonstrated in Figure 5-6. The results shown in Figure 5-6 indicate a substantial increase in the strength of hydrated lime mortars comprising both silica fume and pods at all times examined compared to the compressive strength of the control specimen. As envisaged, the hydrated lime mortars incorporating 20% Jacaranda seed pods yielded a superior reduction in strength than that of the 10%. The results in Figure 5-6 exhibited that incorporation of Jacaranda seed pods caused a minor reduction in the strength development of hydrated lime mortars comprising silica fume alone. Suppose the results are studied from a different perspective. In that case, it can be detected that the utilization of silica fume enabled developed properties of such mortars comprising pods to be attained, particularly at long-term.

5.5.2 Influence of Dewatering on the Strength Development of Hydrated Lime Mortars Comprising Jacaranda Seed Pod and Silica Fume

The effects of dewatering on the compressive strength development of hydrated lime mortars comprising Jacaranda seed pods and silica fume are investigated in this section. The impact of dewatering on the short-term and long-term compressive strength of hydrated lime mortars is exhibited in Figure 5-7 and Figure 5-8, respectively. The results in Figure 5-7 demonstrated that the effect of dewatering on the compressive strength of hydrated lime mortars is negligible due to the high water retentivity of these binders at the fresh stage. The control specimen performed the minimum water loss during dewatering. This feature resulted in an insignificant reduction in the water: binder ratios and, therefore, an inconsiderable rise in the compressive strength of these mortar at 91 days. The addition of silica fume as a partial substitution to the lime binder increased the water-retaining capacity of these mortars further and therefore even reduced differences in the compressive strength among the dewatered and non-dewatered hydrated lime mortars are observed.

On the other hand, dewatering hydrated lime mortars comprising Jacaranda seed pods yielded a substantial rise in the compressive strength of hydrated lime mortars due to the increased ability to transfer sorptivity and therefore the increased water loss attained during dewatering. The influence of Jacaranda seed pods on achieving higher transfer sorptivity characteristics is also reflected in the mortars comprising both silica fume and Jacaranda seed pods. Dewatering hydrated lime mortars incorporating both Jacaranda seed pods and silica fume, shown in Figure 5-7, also demonstrated a significant increase in compressive strength compared to non-dewatered mortars.

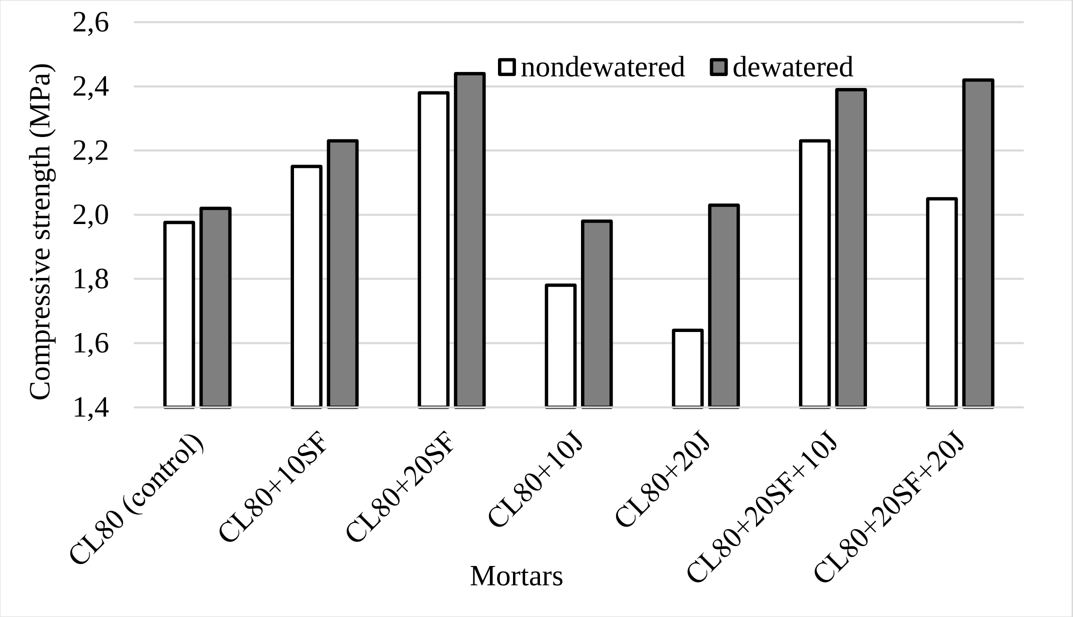

Figure 5-7: The effect of dewatering on the short-term compressive strength of hydrated lime mortars

The effect of dewatering on the compressive strength of hydrated lime mortars comprising both Jacaranda seed pods and silica fume at one year is shown in Figure 5-8. It can be seen at first sight that the results shown in Figure 5-8 follow a similar pattern with the results demonstrated in Figure 5-7. Consequently, the results in Figure 5-7 and Figure 5-8 established that the degree of dewatering could be manipulated using silica fume and Jacaranda seed pods and that transfer sorptivity and the associated water loss are governed for the mortar-substrate optimization. It should also be noted that, although similar in trend, the compressive strength results shown in Figure 5-8 are higher than the results exhibited in Figure 5-7.

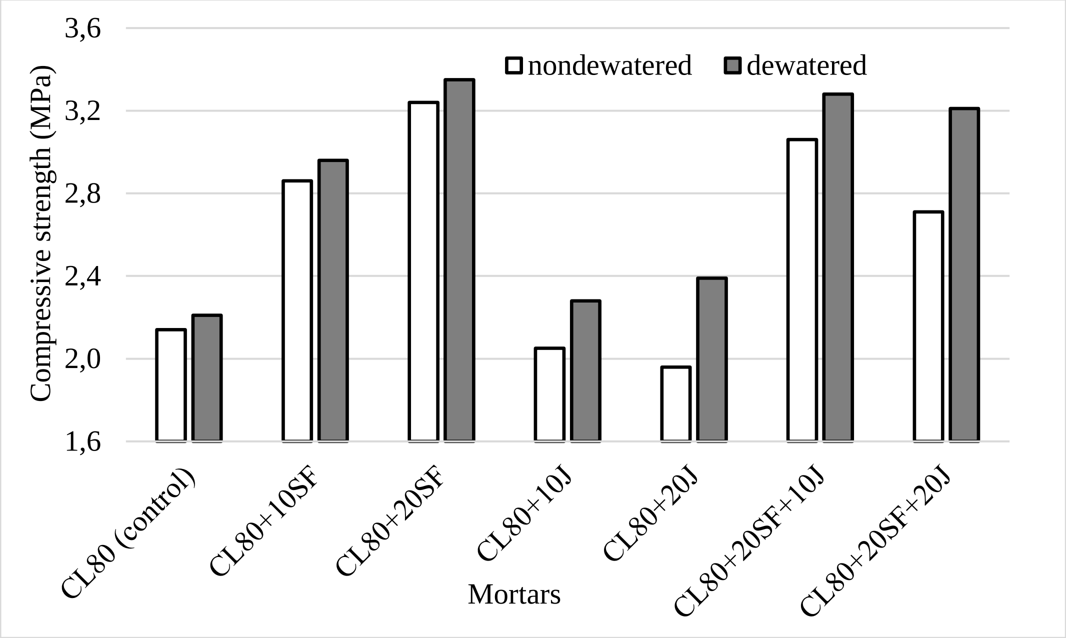

Figure 5-8: The effect of dewatering on the long-term compressive strength of hydrated lime mortars

The carbonation reaction is predominantly responsible for the strength development of hydrated lime mortars and mortars comprising Jacaranda seed pods. The accelerated increase attained in the strength development of mortars comprising silica fume at one year is associated with the high pozzolanic activity of silica fume. Portlandite is consumed through the pozzolanic reaction, and calcium-silicate-hydrate gels are produced by the hydraulic binding property. Although much slower, the carbonation reaction accompanies the pozzolanic reaction and further contributes to the development of these mortars.

5.5.3 Influence of jacaranda seed pod and silica fume on flexural and split tensile strength of hydrated lime mortars

Split tensile and flexural strength of hydrated lime mortars comprising Jacaranda seed pods at 91 days and one year are shown in Figure 5-9 and Figure 5-10, respectively. The compressive strength of these mortars is also provided in the secondary axis in both figures for comparison. The results shown in Figure 5-9 exhibited that the use of silica fume has an increasing effect on the split tensile and flexural strength of hydrated lime mortars. This improvement in strength is accredited to the refined microstructure attained due to the filler effect of silica fume in the short term. The use of Jacaranda seed pods, on the other hand, resulted in a systematic reduction in the split tensile and flexural strength of hydrated lime mortars as a consequence of the delayed reactions due to the presence of cellulose in the composition of pods. However, it must be noted that the effect of silica fume in increasing the strength of these mortars is more influential than that of the impact of Jacaranda seed pods in decreasing the split tensile and flexural strength. The specimens comprising both Jacaranda seed pods and silica fume had higher strength than mortars incorporating Jacaranda seed pods alone.

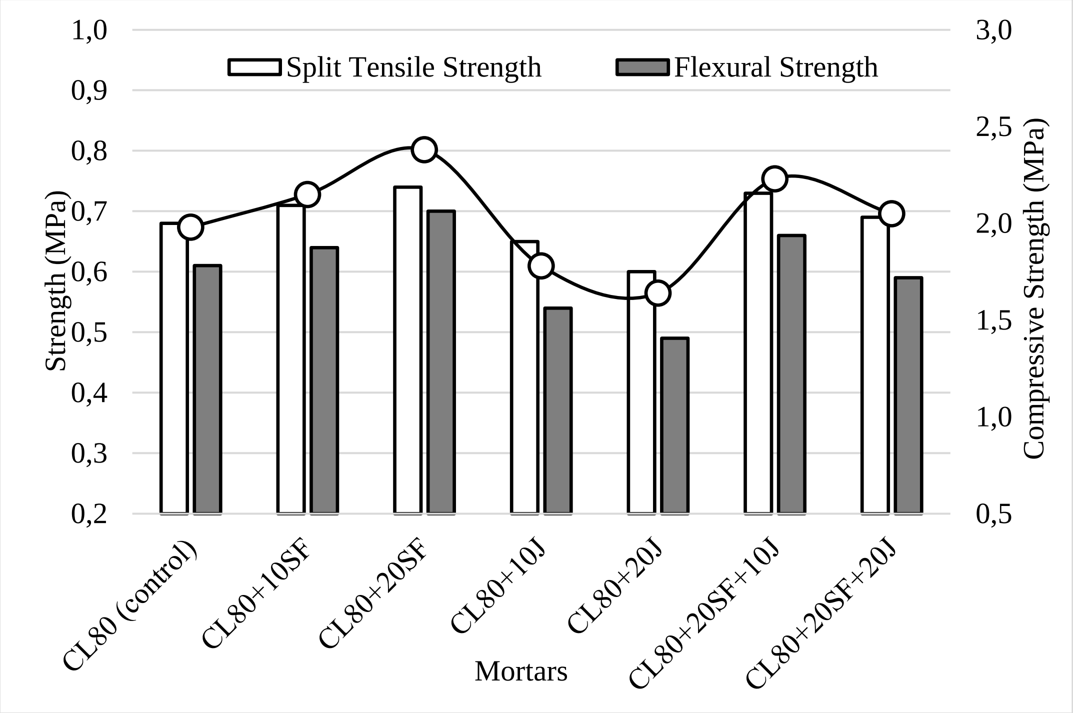

Figure 5-9: Split tensile and flexural strength of hydrated lime mortars comprising Jacaranda seed pods at 91 days

Compressive strength results, plotted on the secondary axis in Figure 5-9, are in good agreement with the variations attained in split tensile and flexural strength results. The compliance of these results also provided reliability control for the strength parameters examined in the thesis. The split tensile and flexural strength of hydrated lime mortars exhibited in Figure 5-10 also demonstrates a good agreement with the results previously shown in Figure 5-9. As explained earlier, the higher strength values of mortars attained at one year are mainly attributed to the carbonation reaction for lime comprising Jacaranda seed pods and the pozzolanic reaction accompanied by the carbonation for mortars comprising silica fume.

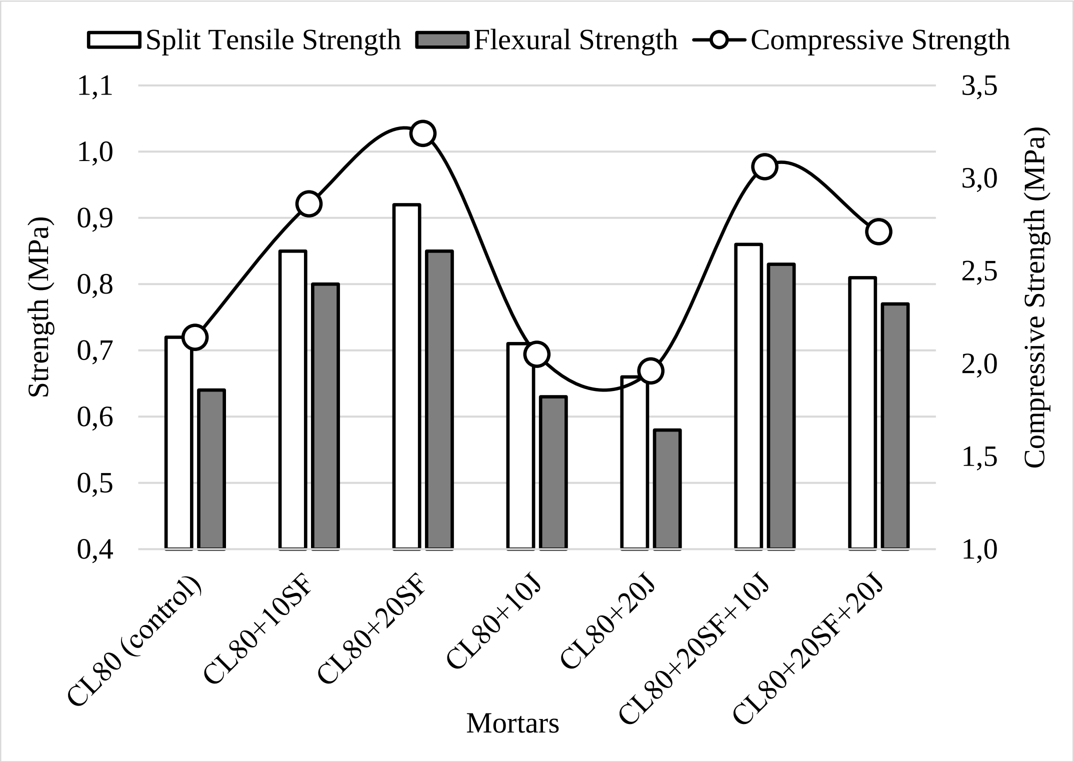

Figure 5-10: Split tensile and flexural strength of hydrated lime mortars comprising Jacaranda seed pods at one year

Flexural and split tensile strength of dewatered and non-dewatered hydrated lime mortars at one year are shown in Figure 5-11. The results have shown that, although, at different degrees, dewatering and the associated water loss of mortars led to a greater flexural and split tensile strength of mortars. When the results are studied, it can be seen that mortars comprising Jacaranda seed pods resulted in a more significant increase in strength than mortars comprising silica fume. This is previously explained in the thesis that the higher degree of dewatering and therefore the higher transfer sorptivity of mortars comprising Jacaranda seed pods are essentially accountable for the reduced water: binder ratios and the associated rise flexural and split tensile strength of such mortars.

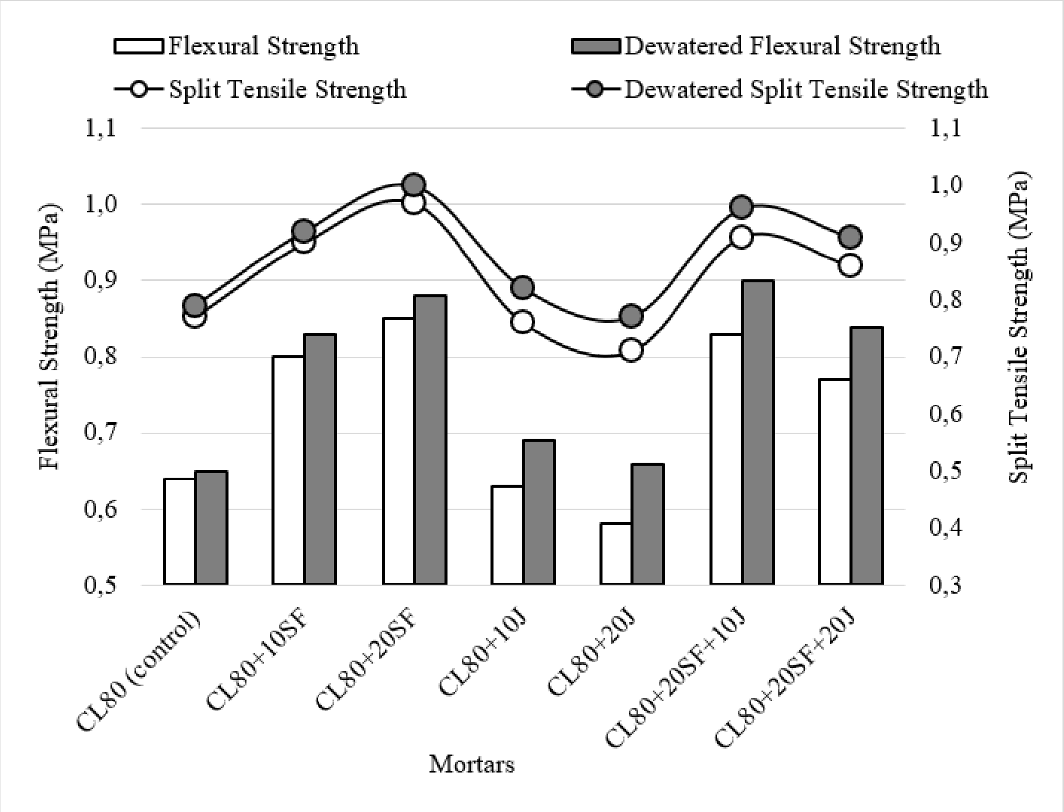

Figure 5-11: Flexural and split tensile strength of dewatered and non-dewatered hydrated lime mortars at 1 year

5.6 Physical Properties

5.6.1 Effect of Jacaranda Seed Pods on the Absorption and Sorptivity of Hydrated Lime mortars Comprising Silica Fume

It is demonstrated in Figure 5-12 that the rise in the substitution level of Jacaranda seed pods yielded an increase in the absorption of hydrated lime mortars at all times examined in the study. The increase in the absorption of hydrated lime mortars comprising Jacaranda seed pods is supported by the rise in the sorptivity conquered at simultaneous times. The courser particle size of Jacaranda seed pods compared to that of the binder and the inert character of the powdered pods reduced the adherence within the mixture and created a more porous matrix development. This feature is mainly responsible for the substantial absorption and sorptivity of the hydrated lime mortars comprising Jacaranda seed pods. On the contrary, silica fume reduced hydrated lime mortar's absorption and sorptivity characteristics. The considerable decrease attained in the physical measures at 28 days is mainly due to the fine particle size. Therefore, the filler effect of silica fume enriched and densified the matrix and resulted in more consolidated mortars. The progressive decrease attained in absorption and sorptivity of hydrated lime mortars comprising silica fume is attributed to the high activity index of the pozzolanic replacement material.

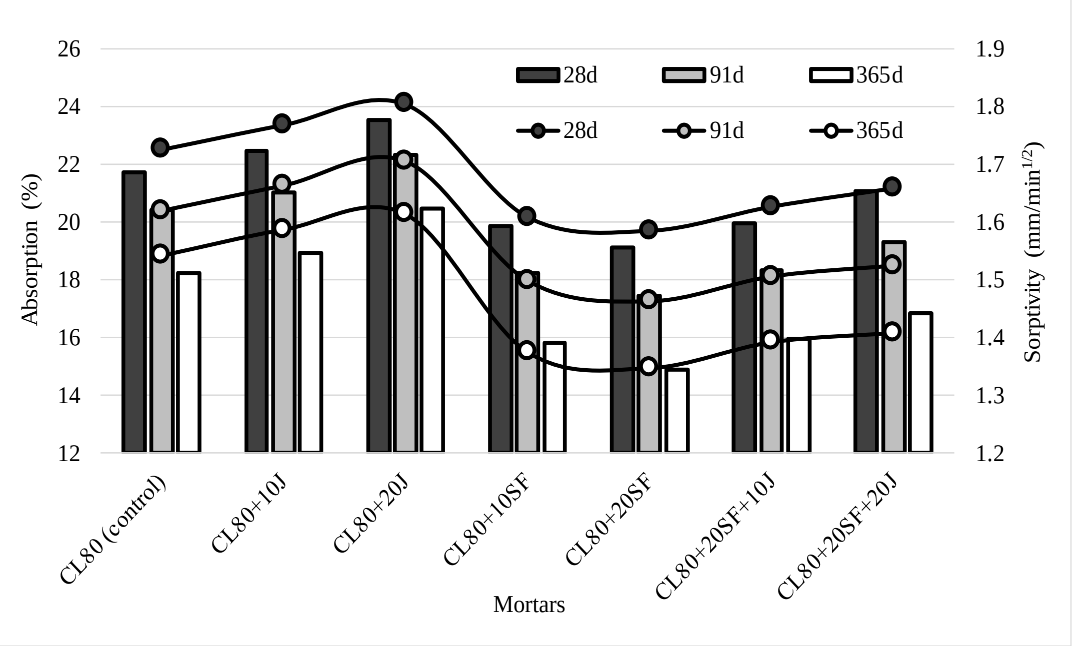

Figure 5-12: The effect of Jacaranda seed pods and silica fume replacement level and curing age on absorption and sorptivity

The increased replacement level of Jacaranda seed pods on the absorption and sorptivity of hydrated lime mortars comprising silica fume resulted in a slight increase in these physical measures. However, it must be noted that the effect of silica fume in decreasing the aforementioned physical measures had an increased influence than that of the impact of Jacaranda seed pods in increasing the absorption and sorptivity of hydrated lime mortars. It is also evidently demonstrated in Figure 5-12 that a rise in the curing time, in other words, an increase in the specimen's age, yielded a considerable reduction in the physical measures due to the more consolidated matrix attained in hydrated lime mortars at older ages. When the results are studied carefully, it can be seen that the decrease obtained in the physical measures for mortars comprising Jacaranda seed pods is much less than that of the silica fume. The more significant decline brought in absorption and sorptivity of mortars incorporating silica fume, particularly at older ages, is attributed to the pozzolanic reaction that consumes the portlandite to enrich the matrix.

5.6.2 Effect of Jacaranda Seed Pods on the Water Penetration Depth and Porosity of Hydrated Lime Mortars Comprising Silica Fume

Water penetration depth and porosity of hydrated lime mortars comprising powdered pods and silica fume are shown in Figure 5-13. It should be noted that these physical measures are conducted following the specimens being cured for one year. The results exhibited in Figure 5-13 demonstrated that the utilization of powered pods yielded a substantial rise in the water penetration depth and porosity of hydrated lime mortars. These experimental observations are in good agreement with the results shown in Figure 5-12.

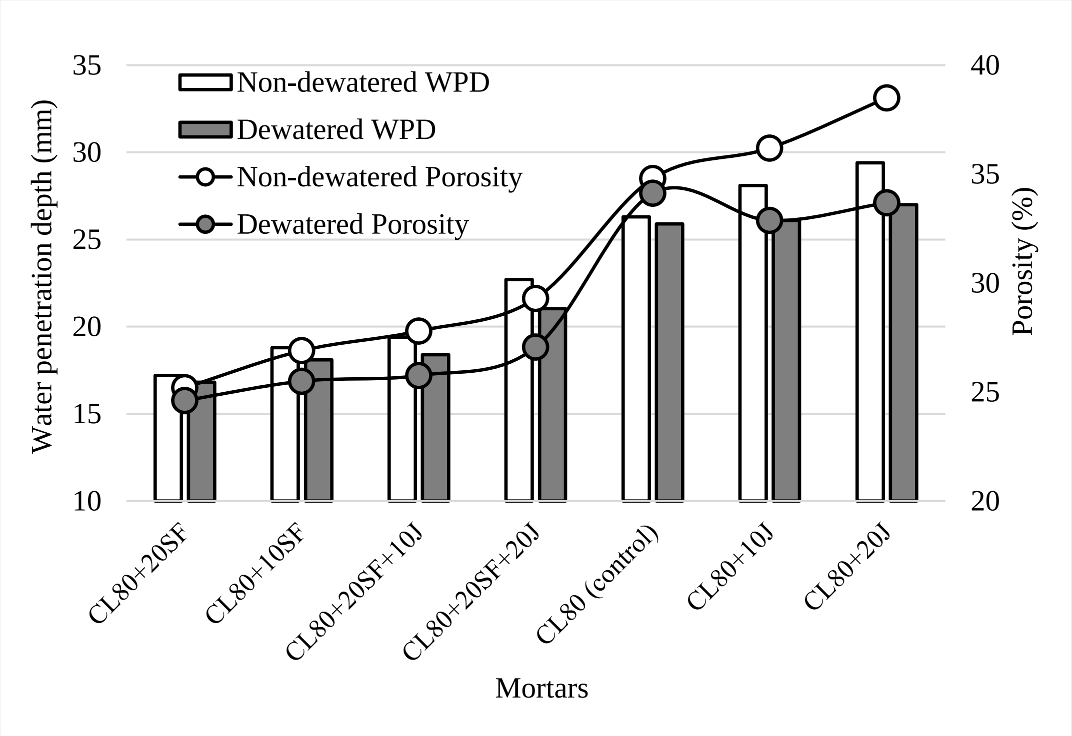

Figure 5-13: Water penetration depth and porosity of hydrated lime mortars comprising powdered pods and silica fume

The use of powdered pods increased the porosity of the matrix due to the considerable increase in the particle size distribution and hence enabled easier water ingress into these specimens. The specimens comprising silica fume, as anticipated, resulted in the most significant decrease in porosity and consequently the greatest reduction in the water penetration depth of mortars. The long-term influence of dewatering on the water penetration depth and porosity of hydrated lime mortars comprising powdered pods and silica fume is also exhibited in Figure 10. Increased pathways for the water removal attained in mortars due to the utilization of Jacaranda seed pods yielded a greater dewatering to be performed at the fresh stage. The increased water releasing ability of mortars attained using the powdered pods led to a considerable water loss during dewatering and yielded reduced water: binder mixture to harden. This feature caused a more significant reduction in porosity of hydrated lime mortar comprising powdered pods at one year. The effect of silica fume on the water transport kinetics is precisely the opposite. The utilization of silica fume enriches the matrix and therefore reduces the transfer sorptivity of hydrated lime mortars. In other words, the filler effect of silica fume plays a crucial role in decreasing the dewatering characteristics of such mortars at the fresh stage. It is exhibited in Figure 5-13 that the dewatering hydrated lime mortar comprising silica fume had a negligible decrease in the porosity and water penetration depth. The dewatering and, therefore, the water loss during this process at the fresh stage was insignificant. The dewatering performed by the control specimen was the least as this was mostly water retaining mortar examined throughout the thesis. The increase in the powdered pods also increased the water releasing ability of mortars comprising 20% silica fume. Since powdered pods also play a considerable role in increasing the dewatering characteristics of mortars, the decrease attained in porosity, and therefore the decline attained in water penetration depth were more prominent compared to the control specimen as a consequence of the reduced water: binder ratio and hence increase enrichment of the matrix experience following dewatering.

5.7 Sustainability Implications of Hydrated Lime Mortars Comprising Jacaranda Seed Pods

5.7.1 Cost Efficiency

The cost efficiencies of dewatered and non-dewatered hydrated lime mortars at short- and long-term are exhibited in Figure 5-14. The mix constituents and the associated cost of each mixture used in the calculation of cost efficiency are also summarised in Table 5-5,5-6 and 5-7.

It is evident in Figure 5-14 that the utilization of Jacaranda seed pods in hydrated lime mortars reduced the cost efficiency of hydrated lime mortars at 91 days mainly due to the slight reductions attained in compressive strength. The utilization of silica fume, on the other hand, enriched the cost efficiency as a result of the minor cuts in the total cost of materials along with the substantial increase in the compressive strength of hydrated lime mortars.

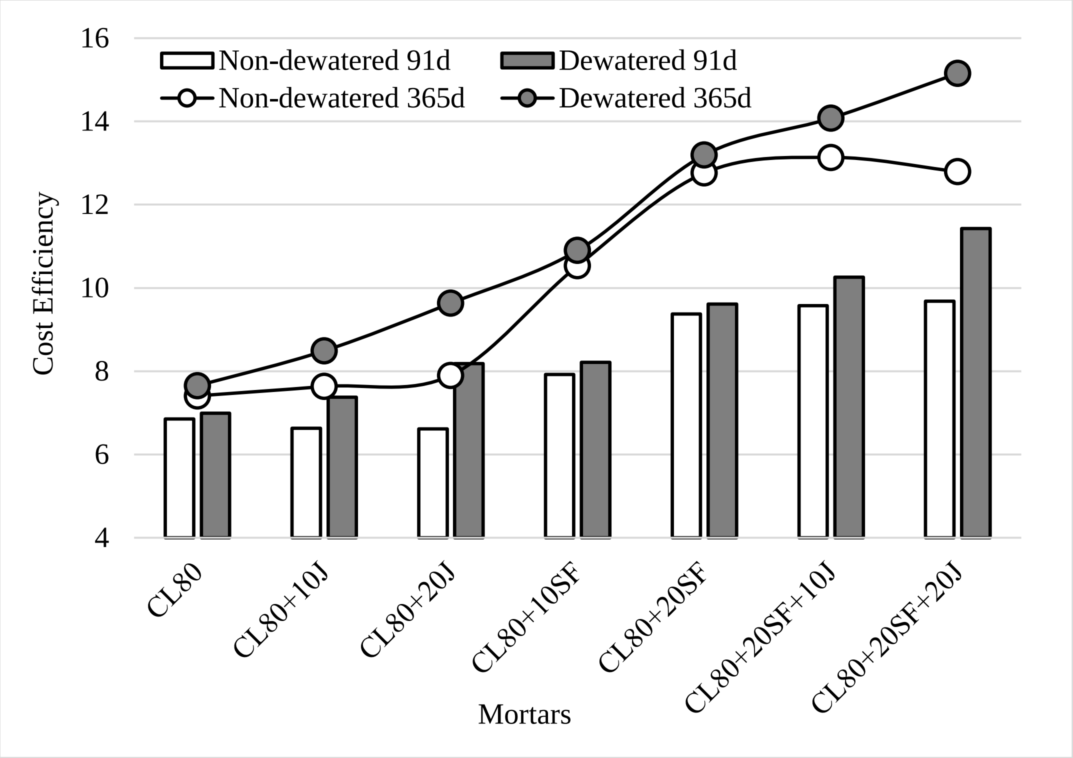

Figure 5-14: The cost efficiencies of dewatered and non-dewatered hydrated lime mortars short&long term

It is also evident in Figure 5-14 that the cost-effective use of powdered pods could only be possible when silica fume is used as a binder replacement in hydrated lime mortars. On the other hand, Dewatering was more influential on mortars comprising powdered pods as this replacement material increased the water releasing ability of such mortars at the fresh stage. As previously demonstrated in 5.4 Water Transport Kinetics, Figure 5-4, mortars comprising powdered pods yielded a more significant water loss and consequently led to greater strength development. Therefore, dewatering is more influential in increasing the cost efficiency of mortars comprising powdered pods at 91 days.

Table 5-5:Mix Constituents of Samples

			Cost efficiency of lime mortars containing jacaranda seed pods and silica fume				
Specimen	Repl. level of jacaranda seed pods (%)	Repl. level of silica fume	Mix Constituents				
			Lime (kg)	Fine agg. (kg)	Water (kg)	Jacaranda seed pods (kg)	Silica fume (kg)
CL80	-	-	155.01	718.7	126.36	0	0
CL80+10J	10	-	140.23	722.4	127.01	10.39	0
CL80+20J	20	-	125.31	726.2	127.68	20.88	0
CL80+10SF	-	10	140.88	725.77	127.6	0	5.81
CL80+20SF	-	20	126.48	733.01	128.87	0	11.74
CL80+20SF +10J	10	20	111.25	736.84	129.55	10.39	11.74
CL80+20SF +20J	20	20	95.87	740.78	130.24	20.88	11.74

Table 5-6: Mix Cost of Samples

			Cost efficiency of lime mortars containing jacaranda seed pods and silica fume		
Specimen	Repl. level of jacaranda seed pods (%)	Repl. level of silica fume	Mix Cost		
			Lime ($)	Fine agg. ($)	Silica fume ($)
CL80	-	-	21.7014	7.187	0
CL80+10J	10	-	19.6322	7.224	0
CL80+20J	20	-	17.5434	7.262	0
CL80+10SF	-	10	19.7232	7.2577	0.1743
CL80+20SF	-	20	17.7072	7.3301	0.3522
CL80+20SF +10J	10	20	15.575	7.3684	0.3522
CL80+20SF +20J	20	20	13.4218	7.4078	0.3522

Table 5-7: CEF of Samples

			Cost efficiency of lime mortars containing jacaranda seed pods and silica fume				
Specimen	Repl. level of jacaranda seed pods (%)	Repl. level of silica fume	CEF				
			fc_{91d} (nondew)	fc_{91d} (dew)	Cost/m3 ($)	CEF$_{91d}$ (nondew)	CEF$_{91d}$ (dew)
CL80	-	-	1.98	2.02	28.89	6.85	6.99
CL80+10J	10	-	1.78	1.98	26.86	6.63	7.37
CL80+20J	20	-	1.64	2.03	24.81	6.61	8.18
CL80+10SF	-	10	2.15	2.23	27.16	7.92	8.21
CL80+20SF	-	20	2.38	2.44	25.39	9.37	9.61
CL80+20SF +10J	10	20	2.23	2.39	23.30	9.57	10.26
CL80+20SF +20J	20	20	2.05	2.42	21.18	9.68	11.42

The results exhibited in Figure 5-14 also demonstrated that the cost efficiency of hydrated lime mortars has increased at one year in general. It can be seen that the mortars comprising silica fume had the most significant increase in the cost efficiency as a result of the pozzolanic reaction that substantially improved the strength at one year. Similar to the case in the short term, the dewatering was also more influential on mortars comprising powdered pods as they performed higher water loss at the fresh stage and higher strength attainment at one year. It should be noted that mortars that completed a certain degree of dewatering, in other words, mortars that comprise powdered pods, demonstrated the most significant increase in the cost efficiency both at short- and long-terms. Therefore, the effect of dewatering, particularly in masonry construction, should not be underestimated as this effect reflects the authentic performance of hydrated lime mortars in practice.

5.7.2 CO_2 Emissions

CO_2 emissions of hydrated lime mortars comprising Jacaranda seed pods and silica fume are shown in Figure 5-15. The mix constituents were given before in

Table 5-5.

The associated CO_2 emissions of each mixture used in the calculation of CO_2 emissions are also summarised in Table 5-8 and Table 5-9.

This section does not aim to precisely calculate the CO_2 emissions of hydrated lime mortars after carbonation. This approximation of 50% re-absorption of CO_2 emissions is only demonstrated to create awareness that hydrated lime binders are the sole binders that absorb a significant amount of CO_2 during the hardening process. As carbonation is the sole means of strength development for such binders, this feature of hydrated lime binders brings crucial sustainability credentials for environmental concerns.

CO_2 emissions of hydrated lime mortars comprising Jacaranda seed pods and silica fume demonstrated in Figure 5-15 that the utilization of both the powdered pods and silica fume as a replacement to the binder yielded a considerable, and almost identical, decrease in the CO_2 emissions of hydrated lime mortars. The utilization of both materials simultaneously obviously caused a more significant reduction of CO_2 emissions to be attained.

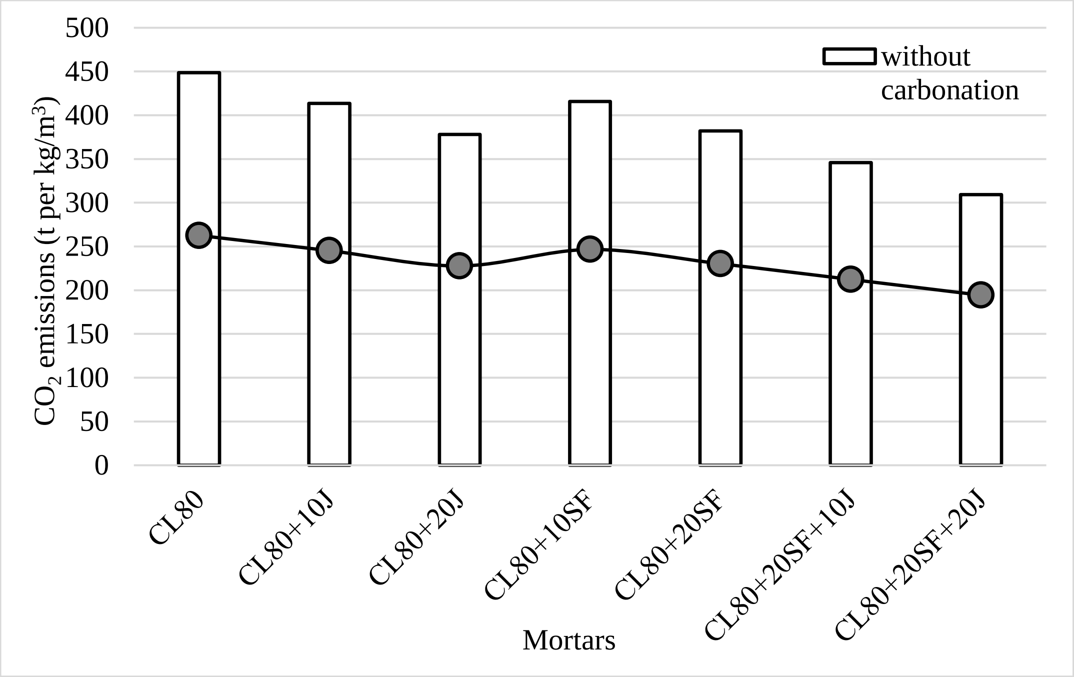

Figure 5-15: CO_2 emissions of hydrated lime mortars comprising Jacaranda seed pods and silica fume

It must be documented that the utilization of 20% of powdered pods and 20% of silica fume yielded an approximately 31% decrease in the CO_2 emissions of hydrated lime mortars. When the lime carbonation is taken into consideration, in which the sole means of hardening is due to the reaction of CO_2 with calcium hydroxide, it can be seen that there is a substantial reduction in the carbon footprint. Although much higher CO_2 could be re-absorbed during hardening, 50% of the CO_2 generated during the production of hydrated lime binder is assumed to be re-absorbed for simplicity(Kang et al., 2020).

Table 5-8: CO_2 Emissions for each mixture

			CO_2 emission of hydrated lime mortars comprising Jacaranda seed pods and silica fume		
Specimen	Repl. level of jacaranda seed pods (%)	Repl. level of silica fume	CO_2 emission		
			Lime (m^3)	Fine agg. (m^3)	Silica fume (m^3)
CL80	-	-	372.0240	76.6134	0
CL80+10J	10	-	336.5520	77.0078	0
CL80+20J	20	-	300.7440	77.4129	0
CL80+10SF	-	10	338.1120	77.3671	0.16268
CL80+20SF	-	20	303.5520	78.1389	0.32872
CL80+20SF +10J	10	20	267.0000	78.5471	0.32872
CL80+20SF +20J	20	20	230.0880	78.9671	0.32872

This section does not aim to precisely calculate the CO_2 emissions of hydrated lime mortars after carbonation. This approximation of 50% re-absorption of CO_2 emissions is only demonstrated to create awareness that hydrated lime binders are the sole binders that absorb a significant amount of CO_2 during the hardening process. As carbonation is the sole means of strength development for such binders, this feature of hydrated lime binders brings crucial sustainability credentials for environmental concerns.

Table 5-9: Total CO_2 emissions

			CO_2 emission of hydrated lime mortars comprising Jacaranda seed pods and silica fume	
Specimen	Repl. level of jacaranda seed pods (%)	Repl. level of silica fume	Total CO_2 emission	
			Total CO_2 emission	Total CO_2 emission considering the reabsorption of carbon dioxide
CL80	-	-	448.6	262.6
CL80+10J	10	-	413.5	245.2
CL80+20J	20	-	378.1	227.7
CL80+10SF	-	10	415.6	246.5
CL80+20SF	-	20	382.0	230.2
CL80+20SF +10J	10	20	345.8	212.3
CL80+20SF +20J	20	20	309.3	194.3

5.7.3 Eco-Strength Efficiency

The eco-strength efficiency of hydrated lime mortars comprising Jacaranda seed pods and silica fume is shown in Figure 5-16. It is demonstrated in Figure 5-16 that the use of powdered pods is negatively influencing the eco-strength efficiency of mortars in the short term. Although there is a slight reduction of CO_2 emissions attained when powdered pods are incorporated, the decrease observed in the strength of such mortars governs the reductions of eco-strength efficiency. Silica fume, which considerably increases eco-strength efficiency, enables powdered pods to be utilized in hydrated lime mortars with improved eco-strength efficiency.

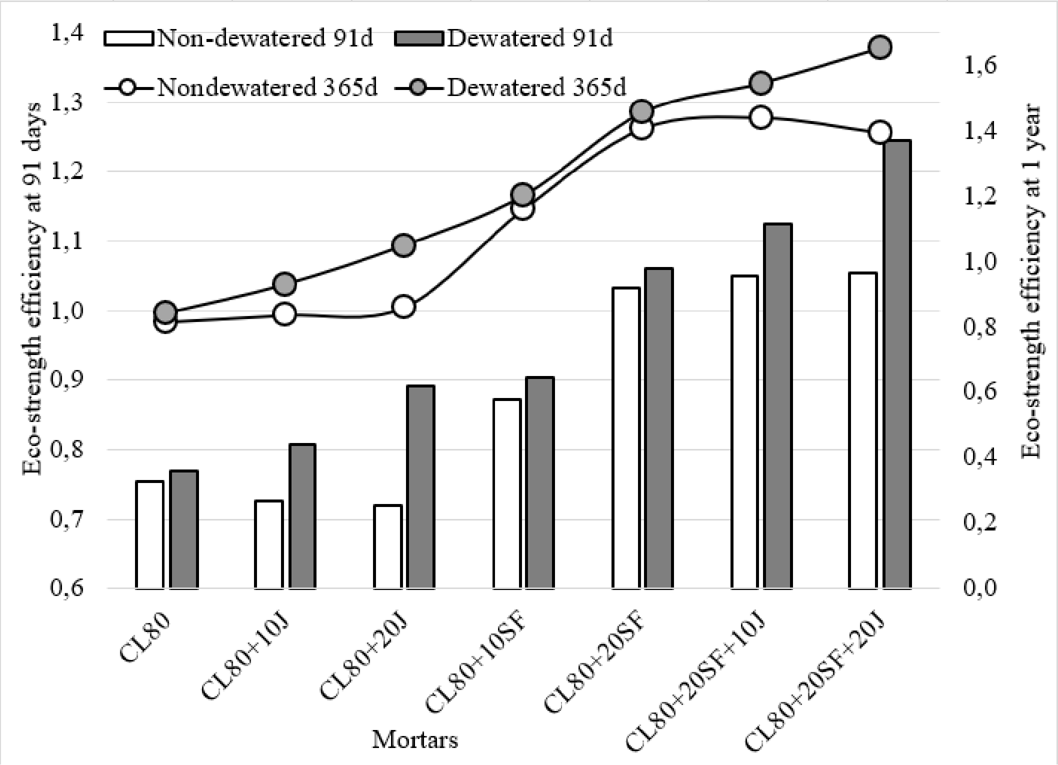

Figure 5-16: Eco-strength efficiency of hydrated lime mortars comprising Jacaranda seed pods and silica fume

The improvement attained in the eco-strength efficiency of mortars comprising both the powdered pods and silica fume is mainly due to the substantial reductions in CO_2 emissions and the considerable rise in strength. As anticipated, this feature of lime mortars is also demonstrated in the long term. When the powdered pods are utilized in conjunction with silica fume enrichments, in eco-strength efficiency of such mortars was identified. On the other hand, Dewatering is again more influential in increasing the eco-strength efficiency of mortars comprising powdered pods. As higher water removal is being performed during dewatering mortars incorporating powdered pods, the higher strength of such mortars attained through this incident

enriched the eco-strength efficiency. The effect of dewatering, once again, is demonstrated to play a crucial role in the attainment of the authentic performance of hydrated lime mortars comprising powdered pods and silica fume.

CHAPTER 6

RESULTS AND CONCLUSIONS

6.1 Results and Discussion

This thesis investigates long-term engineering properties and sustainability indices of dewatering hydrated lime mortars through Jacaranda seed pods.The following conclusions can be driven from the thesis research work.

- The characterization study chemical composition of the raw materials and particle size disstribution of raw materials used in making hydrated lime mortars is enabled to compatibility of the utilization of powdered seed pod in the hydrated lime mortars to be investigatedResults have confirmed the compatibility of the utilization of powdered pods in hydrated lime mortars with and without silica fume and suggested potential substitution levels be estimated.
- Fresh state properties as setting time and consistency of jacaranda incorporated lime mortars are investigated. The incorporation of powdered Jacaranda seed pods yielded a slight increase in the consistency of hydrated lime mortars. However, it is emphasized that the slight variations detected in consistency are negligible as the hydrated lime mortars containing both Jacaranda seed pods and silica fume were within a workable range. Although not dramatic, the incorporation of powdered pods yielded a rise in the setting time of hydrated lime mortars.Conversely, when silica fume is substituted in hydrated lime mortars along with the powdered pods, compensated the increase in setting time.
- The water transport kinetics of jacaranda incorporated lime mortars and lime mortars with pozzolanic replacement were investigated throughout the study. The results are shown that the incorparation seed pods along with silica fume enabled manipulation of water transport kinetics properties this resulted in an

establisment of optimize mortar masonry systems in constructinal practices. The utilization of Jacaranda seed pods increased the transfer sorptivity of hydrated lime mortars.The rise in Jacaranda seed pods yielded a slight decrease in the compressive strength of hydrated lime mortars at all ages.

- The incorporation of silica fume and the powdered pods enabled higher compressive, flexural and tensile strength of such mortars to be attained throughout the study. The flexural and split tensile strength of hydrated lime mortars followed a similar tendency with the compressive strength; however, the effect of silica fume in increasing the strength was more influential than that of the impact of Jacaranda seed pods in decreasing the split tensile and flexural strength of hydrated lime mortars. Also, the effect of dewatering on the mechanical properties is reported. The degree of dewatering, on the contrary, is raised through the use of powdered pods enabled a higher strength development of such mortars compared to that of non-dewatered at all ages examined in the study. Effect of dewatering was also found to have more pronounced impacts on mortars comprising Jacaranda seed pods.
- The study reported absorbtion, sorptivity characteristics, water penetration depth, and porosity. The enhancement in the physical properties of mortars comprising silica fume was more remarkable in the long term. The effect of dewatering by means of Jacaranda seed pods has also been shown to enhance the physical properties of hydrated lime mortars, particularly in the long term.
- Sustainability indices of jacaranda incorpareted lime mortars and lime mortars with pozzolanic replacement are investigated. The substitution of powdered pods and silica fume resulted in an increased cost-efficiency of artillery due to the increased strength and reduced total cost of such mortars. The dewatering effects on sustainability characteristics of the jacaranda seed pod and pozzolanic material incorporated lime mortar have also been investigated. Mortars comprising powdered pods exhibited a remarkable degree of dewatering and hence demonstrated a tremendous increase in the cost efficiency both in the short- and long terms. Correspondingly, mortars

comprising 20% powdered pods and 20% silica fume yielded an approximately 31% decrease in the CO_2 emissions of hydrated lime mortars.

- The results shown that thesis also provide a cleaner wate management method for the jacaranda seed pod which is an agricultural waste. Compared to the existing methods such as, landfilling and incineration this approach proposed in the thesis could be advanced approach for agricultural waste method.

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