FACTORS AFFECTING SUSTAINABILITY INDICES AND LIFE CYCLE ASSESSMENT OF CONCRETE CONTAINING RICE HUSK ASH: A DATABASE STUDY

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Approval of the Board of Graduate Programs

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ABSTRACT

FACTORS AFFECTING SUSTAINABILITY INDICES AND LIFE CYCLE ASSESSMENT OF CONCRETE CONTAINING RICE HUSK ASH: A DATABASE STUDY

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The rice husk ash (RHA), attained by burning the husk that is removed in the process of the production of rice, possesses high pozzolanic activity and therefore is a promising, supplementary cementitious material. The thesis comprises a large database comprising over 1000 data on the RHA incorporation in concrete to examine the principal sustainability components such as CO_2 emissions, cost efficiency, and eco-strength efficiency, as well as to perform a comprehensive life cycle assessment attained during this practice. Independent determination of the boundary conditions played a vital role in both the sustainability and life cycle assessment. The results showed that the use of RHA along with the pozzolanic materials could lead to a 25% reduction in the CO_2 emissions generated during the concrete production in conjunction with a 65% rise in the cost efficiency of such practices. Life cycle assessment has already shown that 30% RHA as cement replacement along with the 30% fly ash already resulted in a 59% reduction in a global warming potential along with the 46% reduction in ozone depletion. It was vital to perform the life cycle assessment to validate the preciseness of the sustainability analysis as well as to demonstrate that the results in both analyses are in a great correlation. The findings reported in this study do not only suggest significant sustainable consequences for the construction practice but also encourage greener waste management routes to be established for RHA.

Keywords: Rice husk ash, waste utilisation, database, sustainability & life cycle assessment, concrete.

ÖZ

SÜRDÜRÜLEBİLİRLİK ENDEKSLERİNİ ETKİLEYEN FAKTÖRLER VE PİRİNÇ KABUĞU KÜLÜ İÇEREN BETONUN YAŞAM DÖNGÜSÜ DEĞERLENDİRMESİ: BİR VERİTABANI ÇALIŞMASI

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Pirinç üretimi sürecinde çıkarılan kabuğun yakılmasıyla elde edilen pirinç kabuğu külü (RHA), yüksek puzolanik aktiviteye sahiptir ve bu nedenle umut verici, destekleyici bir çimentolu malzemedir. Tez, CO_2 emisyonları, maliyet verimliliği ve eko-güç verimliliği gibi temel sürdürülebilirlik bileşenlerini incelemek ve bu uygulama sırasında elde edilen kapsamlı bir yaşam döngüsü değerlendirmesini gerçekleştirmek için betonda RHA birleşimi hakkında 1000'den fazla veri içeren büyük bir veri tabanından oluşmaktadır. Sınır koşullarının bağımsız olarak belirlenmesi, hem sürdürülebilirlik hem de yaşam döngüsü değerlendirmesinde hayati bir rol oynadı. Sonuçlar, RHA'nın puzolanik malzemelerle birlikte kullanılmasının, beton üretimi sırasında ortaya çıkan CO_2 emisyonlarında %25'lik bir azalmaya ve bu tür uygulamaların maliyet verimliliğinde %65'lik bir artışa yol açabileceğini göstermiştir. Yaşam döngüsü değerlendirmesi, %30 uçucu kül ile birlikte çimento ikamesi olarak %30 RHA'nın halihazırda küresel ısınma potansiyelinde %59'luk bir azalma ile birlikte ozon incelmesinde %46'lık bir azalma ile sonuçlandığını göstermiştir. Sürdürülebilirlik analizinin kesinliğini doğrulamak ve her iki analizdeki sonuçların büyük bir korelasyon içinde olduğunu göstermek için yaşam döngüsü değerlendirmesinin yapılması hayati önem taşıyordu. Bu çalışmada rapor edilen bulgular yalnızca inşaat uygulaması için önemli sürdürülebilir sonuçlar önermekle kalmaz, aynı zamanda RHA için daha yeşil atık yönetimi yollarının oluşturulmasını teşvik eder.

Anahtar Kelimeler: Pirinç kabuğu külü, atık kullanımı, veri tabanı, sürdürülebilirlik değerlendirmesi ve yaşam döngüsü değerlendirmesi, daha temiz atık yönetim yolları, çimento.

To my beloved family

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LIST OF ABBREVIATIONS

CEF	Cost efficiency
CO2	Carbon dioxide
CSH	calcium-silicate-hydrate
ESEF	Eco strength efficiency
FETP	Fresh water ecotoxicity
GHG	Greenhouse gasses
GPD	Gross domestic product
GWP-(100)	Global warming potential over a time period of 100 years
HTP	Human toxicity
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle inventory assessment
METP	Marine ecotoxicity
ODP	Ozone deplation
RHA	Rice husk ash
SCM	Supplementary cementitious material
WDP	Water deplation

CHAPTER 1

INTRODUCTION

1.1 Introduction

Construction sector has a considerable share in the economic development and growth of the nations. According to (Lopes, 2012), it is the only sector that is represented in national accounts twice due to the fixed capital formation as well as gross domestic product (GPD) development that is the function for the economic wealth of a country in terms of a value of a product in a defined time. However, this large sector, which provides job opportunities to many people, is responsible for 8% of global CO_2 emissions. According to United Nations Environmental Programme (UNEP) (2007), building and construction activities are responsible for 45-55% of the energy production in Europe. Most of the energy consumption and greenhouse gas emissions (GHG) are the consequence of cement manufacturing. In addition, the share of other emission factors of concrete-making materials on environmental degradation cannot be disregarded due to the degradation of natural resources.

Inevitable increase in world population resulted in an enormous rise in waste generation in general. Therefore, the importance of resource conservation and resource efficiency are of top priority, and waste materials have to be evaluated as important sources for raw materials (Turk et al., 2015).

Waste is the unwanted part of the main material after the primary use. The amount of solid waste has almost tripled since 1960s (EPA, n.d.). Since then, landfilling, recycling, combustion, composting, etc., are the popular waste management techniques. For instance, when the total capacity for landfilling is reached, the effects on the environment, such as groundwater pollution, increase in fire risks due to the accumulated gasses, and increase in GHG emissions, will be experienced more dramatically (Purmessur & Surroop, 2019). Also, landfilling is an expensive waste management technique; therefore, a greener method should be developed to address accordance between technical challenges and environmental consequences for waste disposal.

Construction industry generates almost 8% of the total waste generation. Nearly 70-80% of the CO_2 emission caused by concrete production is the result of cement production (WWF, 2019). The incorporation of supplementary cementitious materials plays the key role in decreasing this high rate of emission. Over the last decades, replacing the raw materials in making concrete with waste materials has also gained significant importance. One of the main challenges in incorporating waste materials in concrete is the compatibility of the used waste in cement matrix. Determination of the optimum replacement level for the waste materials also requires expertise. It is largely discussed in the literature that the incorporation of waste materials in concrete becomes a more common practice with the use of pozzolans which could compensate for the adverse effects of waste utilisation in concrete at the long term. Therefore, it is a vital practice to use pozzolans along with the utilisation of waste materials in concrete making that can have a dramatical influence in decreasing the emission as well as decreasing the associated rate of global warming.

Rice is the second most consumed product on the earth and is expected to increase by 14% by 2050 (Agricultural Development Economics Division Economic and Social Development Department, 2009; Patil & Khan, 2011). The structure of the rice is comprised of the following parts (bran, rice, etc.). Since around 20% of the total rice volume/mass is husk, there are approximately 140 million tons of husk produced every year (FAO, 2015). The most common waste management technique for the rice husk is incineration. However, this practice can cause significant health problems such as lung-related diseases. The second most commonly used method is landfilling. However, the generation of methane and other toxic gasses causes soil and underground water pollution. The rice husk is reported to be used also as animal nutrition; however, this method might require expensive treatment and increases the carbon footprint substantially.

It is substantially reported in the literature that when rice husk is burned, the product, which is called rice husk ash (RHA), possesses high pozzolanic activity. This property of waste material makes the incorporation of RHA more compatible within the cement matrix. The high pozzolanic character of RHA enables higher generation of calcium-silicate-hydrate gels, a hydration product responsible for the strength increase, which enhances the durability of concrete particularly at long term. When the studies addressing the RHA incorporation of concrete are examined, it was noticed that different replacement levels and types of RHA are used in concrete. Researchers often reported individual optimum replacement level for the RHA used in concrete. Along with that, authors also reported different replacement levels and types of pozzolanic materials to support the incorporation of RHA in concrete. It was also observed that different performance of concrete incorporating RHA are reported by individual authors. For instance, Tahwia et al. (2022) stated 10% of increase in compressive strength of concrete with 12% of RHA utilasition whereas Madandoust et al., (2011a) et al stated a substantial decrease in the mechanical properties around 12% of RHA. When the studies are investigated in detail, the contradicting experimental research results become intelligible. Several factors such as physical-chemical properties of RHA, replacement level and type of RHA, and pozzolanic activity of RHA contribute to attaining the contradicting experimental results of concrete comprising RHA.

The other major concern of concrete comprising RHA is the comprehensive examination of such an utilasition in terms of sustainable and environmental perspectives. There are only few studies in the literature addressing cost efficiency, CO_2 emission, and eco strength of concrete comprising RHA. It is therefore essential to conduct a study that determines the optimum replacement level of RHA along with the optimum replacement level of the pozzolans used in concrete making in a more comprehensive manner. It is also essential to perform a study addressing the sustainability indices as well as the life cycle assessment (LCA) of concrete incorporating RHA.

1.2 Objective of the thesis

Despite the fact that there are number of studies in the literature on the successful incorporation of RHA in concrete, a comprehensive assessment on the sustainable aspects of these practices is not entirely addressed. The thesis, therefore, is aiming to assess and re-evaluate the RHA incorporation on concrete to examine the common sustainable indices such as CO_2 emissions, cost efficiency and eco-strength efficiency attained during this practice. The thesis begins with a construction of a database containing over 1000 data attained from the literature on the RHA incorporation on concrete. The key factors that have an eminent influence on the mechanical properties of concrete comprising RHA are investigated in the thesis. Water: binder ratio, replacement type and level of RHA, the replacement type and level of pozzolans, constitute the key factors affecting the mechanical properties of concrete comprising RHA, are investigated independently and comprehensively in this thesis. The database approach adopted in the thesis also enabled the reassessment of incorporation of RHA in concrete and significantly contribute to addressing the contradictory research finding among the published studies in the literature undividedly and effectively. The thesis eminently demonstrated that the determination of the boundary conditions was vital to comprehend at the first stage and hence enabled a successful reassessment on the sustainable indices and life cycle assessment to be conducted precisely. The thesis demonstrates, for the first time, the key factors that affect both the mechanical properties and sustainable indices of the incorporation of RHA in concrete and offers important practical consequences for the construction practice and for the waste management corporations.

1.3 Structure of the thesis

The thesis comprised of 9 Chapters. Chapter 1 includes the introduction of waste generation and waste usage in concrete as a replacement material. The background of RHA usage is explained in Chapter 2. The details of constructing the database is given in Chapter 3. In Chapter 4, data analysis and used techniques are presented. The optimum replacement level and type of RHA and pozzolan are determined based on the key parameters influencing the compressive strength of concrete in Chapter 5. Similar approach is adapted to determine the optimum replacement level and type of RHA and pozzolan based on the key parameters influencing the durability characteristics of concrete in Chapter 6. Sustainability assessment comprising CO2 emissions, cost efficiency, and eco strength efficiency of concrete comprising RHA based on the boundary conditions, determined previously in Chapters 5 and 6, is reported in Chapter 7. Life cycle assessment of concrete comprising RHA is performed using openLCA software in Chapter 8, which addressed global warming potential (GWP 100), freshwater ecotoxicity (FETPinf), human ecotoxicity (HTPinf), marine ecotoxicity (METPinf), ozone depletion (ODPinf), water depletion (WDPinf). Finally, the conclusion of the thesis is reported in Chapter 9.

CHAPTER 2

LITERATURE REVIEW

The dramatic increase in the environmental pollution and its associated adverse effects on health is threatening the entire planet unprecedentedly. One of the major contributors for this incident is the unlimited generation of raw materials as a result of the continual increase in demand for food production, particularly in developing countries (Bhuvaneshwari et al., 2019). The waste generation exponentially increases as a result of the dramatic increase in the consumption of raw materials, is expected to reach 3.4 billion tons by 2050 (Kaza et al., 2018). Most commonly utilised existing disposal methods also further contribute to facing this consequence. For instance, Sathiparan and de Zoysa (2018) stated that open dumping and burning, the two frequently utilised methods for waste disposal, have significant adverse effects on human health and the environment.

The agriculture industry, for instance, has dramatically grown by about three times over the last 50 years as a result of the growing population, improvements in green production technology, and agricultural land development (Bhuvaneshwari et al., 2019; FAO, 2017; FAO & OECD, 2019). As defined by Ramírez-García et al. (2019), agricultural waste, undesirably generated by agricultural activities, significantly contributed to the waste generation primarily as a result of the increase in agro-based products. Although environmental pollution and its associated health hazards caused by agricultural wastes remain to be the growing global challenges, the inadequacies in the waste disposal methods apparently is one of the most devastating factor influencing the environmental deprivation (Ramírez-García et al., 2019). Incineration, for instance, is not only leading to a substantial increase in the production of greenhouse gas emissions but also is a low-cost effective method of disposal (Bhuvaneshwari et al., 2019). It is also documented in Sabiiti (2011) that burning agricultural waste is a conventional method, particularly in under-developed nations. This approach eminently is one of the biggest contributors to the environmental contamination. Ezcurra et al. (2001) reported that, gaseous pollutants, in particular carbon monoxide, nitrous oxide, nitrogen dioxide and particles such as smoke carbon are liberated to the environment as a result of the agricultural waste burning. These pollutants significantly contribute to the acid deposition (Lacaux et al., 1992) as a result of the ozone and nitric acid formation (Hegg et al., 1987), and hence endangering human and ecological health (Alston & Pardey, 2014). Dumping, on the other hand, often adversely affects the soil properties mainly as a result of the ingress of the methane gas in the land. Treatment methods or alternatively utilising the wastes as fertilizer or animal food often not reported to be environmentally friendly due to heavy chemicals used for this process that both pollute the environment and negatively affect all living creatures (Vadiveloo et al., 2009). It must be emphasized that the potency of agricultural waste on the ecosystem predominantly relies on the quantity produced as well as the disposal methods utilised.

Rice, one of the most commonly produced agricultural products, is the second most-consumed food item globally (Fernandes et al., 2016). It is an important staple food that provides half of the nutrients with a yearly production of 742 million tons (FAO, 2015). On average, paddy comprises 72% rice, 5-8% of bran, and 20-22% of husk (Issa Khassaf et al., 2014; Muthadhi & Kothandaraman, 2010). The husk is removed in the process of the production of rice. Production of rice produces two types of husks. Bran surrounds the rice and has high nutritional properties. Glume (outer husk of rice) has a stiff structure and low nutritional properties. Glume comprises a high volume of amorphous silica and carbon content with low density and high volume (Yuzer et al., 2013). As Della et al. (2010) stated that cellulose, lignin, and inorganic compounds are the main constituents of glume. It is reported in the literature that the inorganic portion contains about 95% on average of amorphous hydrated silica by weight. Although this is a cost-effective material, high silica content discourages the rice husks recycle in the rice production industry. The use of rice husk is also not suggested for animal feeding due to the high silica content that results in the low nutritional properties and is also reported to be dangerous as it causes serious accumulation problems (Zerbino et al., 2011a).

Application of rice husk in diverse professions are well comprehended in the literature. These extend from utilising the rice husk in energy storage/capacitor, production of silica gels, silicon chips, production of lightweight construction materials and insulation, fertilizer, and to synthesis of activated carbon and silica. However, it must be emphasized that these methods require either burning or additional treatment techniques that are not only uneconomical but are also harmful to health and the environment (Pode, 2016). Rice husk is considered as a biomass energy source in the green technologies. Rice husk ash (RHA), produce as a result of burning rice husk, is approximately the 20% of the weight of the rice. However, the byproduct attained following the biomass operation is often disposed in rivers or landfills, which cause substantial soil contamination and water pollution. Considering the fact that this process has many environmental deficiencies and often the byproduct requires treatment before it can be re-used, this approach cannot entirely be considered an "eco-friendly" method (Liu et al., 2012).

It is well documented in the literature that rice husk ash, obtained through the appropriate methods, possess high pozzolanic activity and therefore is a promising supplementary cementitious material to be used in mortar and concrete making. It is reported in Xu et al. (2012) that RHA has a porous microstructure, high specific surface area as well as high amorphous nano-silica content. The chemical composition of RHA essentially depends on the combustion conditions (de Sensale et al., 2008; James & Subba Rao, 1986; Prasara-A & Gheewala, 2017). When calcined at temperatures greater than 700°C, crystalline silica alone is formed that can be utilised in the steel and ceramic industries only (Malhotra & Mehta, 1996). Conversely, when crystalline silica is subjected to air, it can be dangerous to human exposure as it often causes a disease called silicosis. Thus, the lower burning temperatures, particularly below 700°C, of RHA are recommended in order to produce amorphous silica that is utilised as supplementary cementitious material

(SCM) in construction materials as well as a filler material in rubber or paint industry (He et al., 2017; Prasara-A & Gheewala, 2017). The optimal combustion temperature is reported to be between 500–700°C for the attainment of the highest content of amorphous silica (Msinjili et al., 2017; Nair et al., 2008; Rêgo et al., 2015; Xu et al., 2012). Using temperature below 500°C led to an uncontrolled burning that does not properly convert the husk to ash due to the insufficient ignition, and consequently a substantial amount of unburnt carbon was left in the resulting ash. Carbon content above 30% is expected to have a negative impact upon RHA's pozzolanic activity (Cook, 1986). It is comprehensively documented in the literature that incorporation of RHA provides significant improvement on the mechanical properties and durability characteristics of concrete (Ezcurra et al., 2001; Madandoust et al., 2011b; Yuzer et al., 2013). The considerable enhancements on the compressive and flexural strength, reduction in permeability, enrichment in workability, and reduction in efflorescence due to reduced calcium hydroxide are commonly reported by the researchers as a result of the incorporation of RHA on cement-based materials (Mehta & Monterio, 2014).

It is reported in Feng et al. (2004) that the utilisation of RHA as a cement substitute led to a rise in the compressive strength of concrete. This feature further caused a great reduction in the average pore radius of the concrete, and decreased the amount of $Ca(OH)_2$ in concrete. Zhang et al. (1996) also reported that the RHA, a high pozzolanicity material, enhances the interfacial transition zone (ITZ) between the cement matrix and the aggregate in high-performance concrete. Yu et al. (1999) reported that, concrete properties such as strength and resistance to acid attack, carbonation, and penetration can be enhanced for the RHA blended concrete as a result of the formation of calcium-silicate-hydrate (CSH) gel and less portlandite, $Ca(OH)_2$. Saraswathy and Song (2007) further reported that incorporating RHA up to a 30% substitution level decreases the chloride penetration and permeability, and considerably enhances the strength and the corrosion resistance of concrete. Safiuddin et al. (2010a) also demonstrated that optimum strength of concrete is attained when 15% RHA is added to the existing mixture in concrete. 5% RHA with respect to the total volume of binder, reported to improve mechanical properties of concrete when used as cement replacement. Cordeiro et al. (2009) studied the utilisation of ultrafine RHA (particle size of 3 μm). The study showed that the use of 20% RHA as cement replacement resulted in an enhanced mechanical and durability properties. Rêgo et al. (2015) also showed that residual RHA demonstrated to be a suitable supplement for cement even with low amorphous silica content. Chatveera and Lertwattanaruk (2011) utilised RHA with the particle size of less than 12 μm and cement replacement up to 20%. Enhanced compressive strength and durability properties of concrete were attained in the study. Chopra et al. (2015) also reported that the use of RHA up to 20% as cement substitute improved the strength and durability properties in self-compacted concrete. Black RHA with a particle size of 12 μm was also reported to produce high-strength concrete, particularly at 5% substitution (H. Mahmud, 2010). Sulfate, progressively attacks concrete and changes its internal microstructure, has direct influence on the material's engineering properties, such as swelling, spalling, and cracking (Marchand et al., 2001). Bolla et al. (2015) reported that the RHA significantly improved the concrete durability in particular the resistance of concrete to sulphate attack. Bahri et al. (2018) also utilised black and grey RHA as a replacement of cement (20% by weight) and stated that the RHA enhanced the mechanical properties and permeability of the concrete considerably.

It is reported in Le et al. (2014) that the utilisation of RHA yielded a substantial decrease in the chloride penetration indicating an enhanced attainment of durability (Le et al., 2014). The fresh properties of concrete, on the other, such as the workability is considerably influenced by the use of RHA in concrete. Liu et al. (2012) and Van et al., (2013) reported a noticeably decrease in the workability of concrete comprising particularly higher replacement levels of RHA due to the densification of the matrix as a result of the high fineness of the ash (Foong et al., 2015; Kannan & Ganesan, 2014; Padhi et al., 2018). It was also noted in Sua-iam and Makul (2012) that lower ultrasonic pulse velocity values are attained in concrete comprising 20% RHA compared to that of the control, indicating the lower quality of concrete acquisition (Sua-iam & Makul, 2012). There are also contradicting findings in the literature indicating a substantial increase in the quality of concrete comprising RHA (Kannan & Ganesan, 2014; Kizhakkumodom Venkatanarayanan et al., 2013; Safiuddin et al., 2010b). It is also reported in the Sua-iam and Makul (2012) that at long-term, the utilisation of RHA up to 20% eventually reaches the same ultrasonic pulse velocity value as in the control concrete (Sua-iam & Makul, 2012). It must be emphasized that the authentic engineering performance of concrete comprising RHA, a high pozzolanicity material, could only be established at long-term due to the slow nature of the pozzolanic reaction and its dependency on the formation of calcium hydroxide through hydration (McCarter & Tran, 1996; Pomakhina et al., 2012). Tuck Lun (2015) also reported that the use of RHA yielded a more consolidated matrix as a result of the contraction of the pore structure which in turn resulted in a more homogenous and impermeable concrete at long-term. While H. B. Mahmud et al. (2016) reported 50% reduction in porosity of concrete by the inclusions of RHA, reduction in porosity of concrete was noted to be in the range of 5-35% for various RHA contents by Safiuddin et al. (2010b). The incorporation of RHA essentially enhances the electrical resistivity of concretes as a consequence of the reduced porosity and associated pore refinement attained by the inclusions of ash (Hossain, 2005; Tumidajski, 2005). Furthermore, the utilisation of RHA, also condenses the quantity of hydroxyl and alkali ions, the chief ions responsible from carry charge, and therefore improves the electrical resistivity of concrete further (Ampadu & Torii, 2002; Roper, 1994).

Although there are enormous amounts of studies on concrete incorporating RHA, the majority of these studies are addressing the engineering properties of the end product and not comprising the sustainability indices of such application in construction practice. For instance, Gursel et al. (2016) reported the implication of Life Cycle Assessment (LCA) on sustainable cementitious materials by considering the cradle-to-gate approach. Gastaldini et al. (2009), on the other hand, studied the unit cost of concrete incorporating RHA. It is reported in the study that increase in the unit cost of concrete when utilising RHA should not be considered alone as higher compressive strength of concrete is attained compared to the conventional supplementary cementitious materials. Gastaldini et al. (2014) further reported that the cost of 5% RHA is less than 5% silica fume specimen while taking several critical factors into account when computing the cost per cubic meter of concrete. Sua-Iam and Makul (2014) also exhibited that when used as a fine aggregate replacement, the cost of concrete could reduce substantially compared to the control mixture. Brown (2012) also reported that the unit cost of the RHA is less than cement and that the replacement of RHA reduces the unit cost by around 43-51%. Later in 2018, Gill & Siddique, also demonstrated that the unit price of concrete decreases with the replacement of RHA in concrete due to the lower unit prices of RHA compared to the cement binder. Despite the fact that these studies provide significant insights into the use of RHA with respect to sustainability, the studies in the literature often are limited with life cycle assessment and cost. Also, a few studies in the literature are conducting the life cycle assessment by using the openLCA software (Dollente et al., 2021; Font et al., 2020; Passuello et al., 2017; Varadharajan et al., 2020). There is a growing need to conduct a more comprehensive study reporting the consequences and the significances of the RHA use in concrete making.

The reduction in natural sources and mitigation of greenhouse gas (GHG) emissions associated with concrete manufacturing and construction activities are emerging challenges in the construction industry. The global concrete production reached up to 10 billion tonnes in 2019 and is expected to rise to 18 billion tonnes by 2050 (Lehne & Preston, 2018). The rapid growth in population and the accelerated demand for infrastructures are the main contributors for the dramatic increase in the global concrete production. Although cement comprises 20–40% of the total volume of concrete and/or cementitious mortar, cement processing and manufacturing are associated with significant CO_2 emissions (Büchs & Schnepf, 2013; Ince, 2019; Ince et al., 2020; Mi et al., 2017). Approximately 0.82 tonnes of CO_2 emissions are generated as a result of the 1 tonne of cement manufacture (Collins, 2010) and this contributes to approximately 5-6% of global CO_2 emission along. Cement production, known as the most energy-intensive production among all the manufacturing industries, necessitates high energy and high temperature for the calcination of limestone – a limited natural resource. Chatham House stresses the fact that we would require approximately 40% more clinker replacements by 2050 than that of today, particularly considering that the availability of the traditional substitutes may likely commence to fall at a time (Lehne & Preston, 2018).

Therefore, utilising RHA as a replacement to cement and/or to the raw materials strongly suggests a significant reduction on the consumption of cement as well as the raw materials used for making mortar and concrete. The reduction on the consumption of the raw materials as a result of the utilisation of RHA is significantly contributing in the reduction in the associated GHG emissions as well as in the energy required for the process (Sousa-Coutinho & Papadakis, 2011). Replacing raw materials with RHA also enables a tremendous decrease in the consumption of natural aggregates in construction. Insensate hazard mining and quarrying activities to attain the aforementioned raw materials, the ingredients, could have adverse environmental consequences such as intrusions in the eco-system, wrecked landscape and pollution of air, water, and soil (Sathiparan & de Zoysa, 2018). For instance, the over exploration of the sand used in concrete making in Sri Lanka, resulted in diverse problems such as an increase in the depth of the riverbed, low water table, and disappeared aquatic lives (Sathiparan & de Zoysa, 2018).

There was a growing need to conduct a comprehensive study to assess the RHA and pozzolan utilisation in concrete. It also has a crucial importance to conduct a sustainability analysis as well as the life cycle assessment to gain a deep insight into the ecological, environmental and sustainable perspectives of this practice.

CHAPTER 3

DEVELOPMENT OF RICE HUSK ASH (RHA) DATABASE

The database congregated in this thesis focuses on the RHA incorporation in concrete. Although there are many parameters that affect the performance of concrete in particular the type of cement, aggregate used, curing temperature and the compaction method, the key factors such as the water:binder ratio, replacement types and levels of RHA and pozzolanic materials are determined to be the most influential parameters and hence were used to establish the boundary conditions for the optimal RHA incorporation in concrete. These boundary conditions are then utilised in the assessment of CO_2 emissions, cost efficiency and the eco-strength efficiency. The database comprises of data for material mix constituents, water:binder ratio, replacement types and replacement levels of RHA and pozzolanic materials, the use of plasticisers, as well as the short- and long-term strength and some durability properties of concrete incorporated RHA. The database used in the analysis for the construction of boundary conditions and then in the analysis of sustainability indices is shown in Table 3.1. Table 3.1 comprises the authors of the papers, number of data points used in each paper, compressive strength at 28 days and greater than 28 days, sand and cement replacement, replacement level of RHA, type and amount of pozzolans and plasticisers used in making concrete. The references used to construct the database are summarised in Appendix A.

Table 3.1: Details of the database

#	Author	# of data	Sand/Cement Replacement	RHA Replacement Range (%)	Pozzolan Type	Pozzolan Amount (Range %)	Plasticizer type	Plasticizer Amount
1	Gursel et al.	9	Cement	10-20	Fly Ash and Limestone Flour	30-45	Superplasticizer	2.6-4.8
2	Le et al.	6	Cement	5-20	SF	0-10	Superplasticizer	0.5-0.6
3	Koushkbaghi et al.	12	Cement	0-20	-	-	High-range water-reducing	4
4	Muthukrishnan et al.	6	Cement	0-20	-	-	Superplasticizer	6.3-8
5	Givi et al.	9	Cement	5-20	-	-	-	-
6	Jindal and Ransinchung	11	Mineral Addition	5-15	Fly Ash and Bagasse Ash	5-15	Superplasticizer	2
7	Kannan and Ganesan	17	Cement	5-30	Metakaolin	5-30	Superplasticizer	8
8	Makul	28	Cement	10-20			Superplasticizer	6.5-33.6
9	Sathawane et al.	8	Cement	2.5-15	Fly Ash	15-30	Superplasticizer	5.7-7.7
10	Salas et al.	10	Cement	5-20	Silica Fume	0-10	Superplasticizer	1.8-17.6
11	Zerbino et al.	15	Cement	15-25			Superplasticizer	0.2-1.7
12	Chatveera and Lertwattanaruk	27	Cement	20-40				
13	Gill and Siddique	4	Fine Aggregate	0-10	Metakaolin	5-15	Superplasticizer	7.2-9.6
14	Makul and Sua-iam	24	Cement	0-20	Urea	5-20	High-range water-reducing	0.2-8.2
15	Venkatanarayanan and Rangaraju	7	Cement	7.5-15	Silica Fume	7.5-15	Superplasticizer	2.1-5.5
16	Sua-iam and Makul	6	Fine Aggregate	5-20			High-range water-reducing	11
17	Le and Ludwig	8	Cement	5-20	Silica Fume and Fly Ash	30-40	Superplasticizer	13.3-15.6
18	Talsania et al.	9	Cement	10-20				
19	Mahmud et al.	4	Cement	10-20			Superplasticizer	3.1-4
20	Chao-Lung et al.	6	Cement	10-30			Superplasticizer	0.3-3.7
21	Lertwattanaruk et al.	28	Cement	0-20	Calclium Carbonate	20-40	HRWR	11-13
22	Olutoge and Adesina	6	Cement	5-15				
23	Foong et al.	20	Cement	5-20			Superplasticizer	3.3-6.6
24	Patel and Shah	5	Cement	5-25			Superplasticizer, NaOH, Na-silicate	15,8
25	Chatveera and Lertwattanaruk	18	Cement	10-50			HNO3 and CH3COOH	10
26	Chatveera and Lertwattanaruk	16	Cement	10-50				
27	Cordeiro et al	8	Cement	0-20	Sugar cane Bagasse Ash	0-20	Superplasticizer	0.5-2.4
28	Zareei et al.	6	Cement	5-25	0	10	Superplasticizer	15

Table 3.2: Details of the database (continued)

#	Author	# of data	Sand/Cement Replacement	RHA Replacement Range (%)	Pozzolan Type	Pozzolan Amount (Range %)	Plasticizer type	Plasticizer Amount
29	Muthadhi and Kothandaraman	19	Cement	10-30			Superplasticizer	0.9-11
30	Safiuddin and Soudki	15	Cement	5-30			High-range water-reducing and AEA	1.7-10.6
31	Gastaldini et al.	19	Cement	10-35	Slag and Fly Ash	35-50	Superplasticizer	0.1-2.9
32	Padhi et al.	16	Cement	5-35			Superplasticizer	3,7
33	Kunchariyakun et al.	5	Sand	30-50	Lime	4	Superplasticizer	
34	Huang et al.	6	SF Replacement	17-83	Silica Fume	17-100	Superplasticizer	19,1
35	Raisi et al.	5	Cement	5-20			Superplasticizer	4.5-9.2
36	Tangchirapat et al.	13	Cement	20-50			Superplasticizer	1.7-3.3
37	Gastaldini et al.	18	Cement	10-30	Slag and Fly Ash	35-50	Superplasticizer	0.4-9.5
38	Horsakulthai et al.	7	Cement	10-40			Superplasticizer	1-6.4
39	Bahri et al.	5	Cement	10-20	Silica Fume	0-10	Superplasticizer	2.4-4.2
40	Raisi et al.	17	Cement	5-20			Superplasticizer	2.7-9.8
41	Madandoust et al.	7	Cement	5-30			Superplasticizer	3.8-4.6
42	Mahmud et al.	15	Cement	5-20			Superplasticizer	0.6-4.4
43	Madandoust and Ghavidel	13	Cement	5-20	Glass Powder	10-25	Superplasticizer	0.4-4.6
44	Modarres and Hosseini	12	Cement	3-5			Superplasticizer	
45	Mohseni et al.	13	Cement	5-15	0	1-5	Superplasticizer	4.2-8
46	Sua-iam et al.	4	Cement	10-20	Lime Stone	10-20	Superplasticizer	9
47	Ameri et al.	10	Cement	5-30	Bacteria content addition, Limestone and Micro silica	28	Superplasticizer	14
48	Bui et al.	24	Cement	10-20			Superplasticizer	5-7.5
49	Nehdi et al.	18	Cement	7.5-12.5	Silica Fume	7.5-12.5	High-range water-reducing	1.5-4
50	Mohseni et al.	26	Cement	7.5-12.5	Nano-alumina	1-3	SP	0.9-4.5
51	Siddique et al.	10	Cement	5-20	Bacillus aerius	10^5 cells/mL		
52	Zareei et al.	6	Cement	5-25	Micro-silica	8-10	Plasticizer: poly carboxylic	15
53	Ganesan et al.	8	Cement	5-35				
54	Zhang et al.	3	Cement	0-10	Silica Fume	0-10	Superplasticizer	6.9-9.6
55	Rahman et al.	4	Cement	20-40			Superplasticizer	3.7-8.8
56	Kannan	26	Cement	5-30	Metakaolin	5-30	Superplasticizer	7.6-9.5
57	Gill and Siddique	16	Fine Aggregate	10-30	Metakaolin	5-15	Superplasticizer	4,2
58	Abalaka	20	Cement	5-25				
59	Chindaprasirt et al.	9	Cement	20-55	Fly Ash	20-40		

Table 3.3: Details of the database (continued)

#	Author	# of data	Sand/Cement Replacement	RHA Replacement Range (%)	Pozzolan Type	Pozzolan Amount (Range %)	Plasticizer type	Plasticizer Amount
60	de Sensale	15	Cement	10-20			Superplasticizer	0.1-2.1
61	Chopra et al.	4	Cement	10-20			Superplasticizer	5,5
62	Praveenkumar et al.	7	Cement	0-10	0	1-5		
63	Mehta and Siddique	7	GGBS	5-30			Superplasticizer and Alkali solution	166
64	Gastaldini et al.	21	Cement	5-30	Silica Fume	5-10	Superplasticizer and Plasticizer chemical admixture	0.9-12.1
65	Cordeiro et al.	4	Cement	10-20			Superplasticizer	1.4-2.4
66	Sua-iam and Makul	7	Cement	10-40	Fuel Ash	10-20	Superplasticizer	11
67	Anwar et al.	3	Cement	10-20				
68	Sua-iam and Makul	20	Fine Aggregate	25-100	Fly Ash	20-60	High-range water-reducing	5.5-6.6
69	Sua-iam and Makul	25	Fine Aggregate	10-100			Superplasticizer	11
70	Chalee et al.	10	Cement	15-50			Superplasticizer	0.3-3.8
71	Sua-iam et al.	14	Cement	10-20			Superplasticizer	6.4-27.8
72	Rattanachu et al.	9	Cement	20-50			Superplasticizer	0.4-1.7
73	Kusbiantoro et al.	9	Fly Ash	3-7			NaOH and Na 2SiO3 Solution	144
74	Krishna et al.	5	Cement	5-20				
75	Naveen et al.	10	Cement	5-20				
76	Prayuda et al.	16	Fine Aggregate	20-60	Silica Fume	0-5	Superplasticizer	4,85
77	Zubairu et al.	9	Cement	2.5-20	0	2.5-10		
78	Nair et al.	15	Cement	10-25			Superplasticizer	1.7-9
79	Hussain et al.	8	Cement	10-20			0	4.5-8
80	Amin et al.	4	Cement	10-20			Superplasticizer	5.1-7.1
81	Vieira et al.	5	Cement	8-12			Superplasticizer	2.9-4.5
82	Das et al.	6	Fly Ash	1-10	0	63-70	Alkaline Liquid	147
83	Sakr	30	Cement	5-20	Silica Fume	5-20	Superplasticizer	22.5-30
84	Lun	10	Cement	2.5-10			Plasticizer	4,69
85	Brown	23	Cement	10-40				
		1018						

The test data found in the literature was critically examined for quality, test procedure and data accuracy. For instance, data with missing information with regards to the mix constituents, replacement levels and replacement types of RHA, strength of concrete were omitted in the database. Studies failed to cite the relevant standards for testing and inspecting are also not included in the database.

Establishing the allocated criteria was indispensably significant, predominantly for the attainment of a data set and the test results in the database. Set of criteria such as standard mix constituent materials, sufficient quality data, standard compressive strength data, RHA origin, replacement types and levels of RHA, type of pozzolans, replacement types and levels of pozzolans, the use of plasticisers were therefore assessed in detail before a data set or a test result is essentially included in the database. A total of 1018 number of data of concrete containing RHA were primarily collected. Of these, 64 experiments which did not fulfill the aforementioned criteria were disregarded for further evaluation in the database.

The database comprises 5 number of major sections. The first section comprises the author details as well as the coding determined for each publication considered in the database following it has passed set criteria. The second section of the database comprised the mix constituents such as cement, fine aggregate, coarse aggregate, water. The replacement level and type of RHA and pozzolanic material are also carefully noted. The third section of the database is comprised of compressive strength of concrete comprising RHA and pozzolanic materials both at short and long term. The fourth section of database provides physical properties of concrete such as porosity and water absorption. Fifth section of the database offers the comprehensive data on durability of concrete comprising RHA, such as chloride penetration and mass loss after sulfuric acid exposure.

CHAPTER 4

DATA ANALYSIS

4.1 Introduction

In this chapter, the data analysis using the constructed database is reported. This was an essential step to determine the sustainability indices of concrete comprising RHA using the database approach. Sustainability indices comprised CO2 emissions, cost efficiency, and eco-strength efficiency. The main principles of openLCA, a software used to investigate the life cycle assessment of concrete comprising RHA, are addressed in this chapter.

4.2 Sustainability Assessment with the Calculation of CO_2, Cost Efficiency and Eco-strength

4.2.1 CO_2 Emissions

One of the established ways for the sustainability assessment is to calculate the total CO2 emission, eco-strength, and cost efficiency. The analysis of the CO_2 emissions takes into account the whole manufacturing and preparation processes of the basic ingredients of concrete such as cement, fine aggregates and coarse aggregates. For instance, the CO_2 emission factor of cement used in this study includes the emissions generated by the fuel combustion, process-related emissions as well as the emission generated as a result of the fuel required to mine and transport the raw materials. Fuel combustion-related CO_2 emissions are derived from the clinker production and particularly the fuel used for pyro-processing. Process related emissions, on the other hand, are generated as a result of the chemical reactions that converts limestone to calcium oxide and CO_2. The CO_2 emission factors of fine and coarse aggregates also take into account the extraction, cutting, grinding, sieving and transportation. The CO_2 emission factors of RHA and the pozzolans simply consider the grinding, preparation and sieving operations, the essential processes employed prior to the replacement of such materials in concrete. The CO_2 emission factors, and the unit prices of the raw materials used in concrete making are summarised in Table 4.1.

Table 4.1. CO_2 emission factors of constituent materials

Constituent materials	CO_2 emission factor (kg CO_2/kg of the material)
Portland cement	0.82 (Collins, 2010)
Coarse Aggregates	0.0459 (Flower & Sanjayan, 2007)
Fine Aggregates	0.0139 (Flower & Sanjayan, 2007)
Rice Husk Ash (RHA)	0.1032 (Alnahhal et al., 2018)
Silica fume	0.028 (King, 2012)
Metakaolin	0.330-0.423 (Hammond & Jones, 2008)
Fly ash	0.004-0.027 (Flower & Sanjayan, 2007)
Slag	0.052-0.143 (Flower & Sanjayan, 2007)

4.2.2 Cost Efficiency

Cost efficiency factor (CEF) is determined using the ratio of concrete compressive strength to the total cost of material per m^3. This approach is adapted from Agarwal & Gulati, 2006; Ince et al., 2021. The local prices of mix constituents, summarised in Table 4.2, are used to estimate the total cost of concrete and concrete containing RHA and pozzolans in dollars. Therefore the total cost of concrete was calculated by multiplying the specified raw material in the database, summarised in Table 4.2 with its associated CO_2 emissions factor, summarised in Table 4.1. The CEF equation is shown in Equation 4.1.

Table 4.2: Costs of constituent materials

Constituent materials	Cost (Local price in $)
Portland cement	$0.11/kg
Coarse Aggregates	$0.008/kg
Fine Aggregates	$0.0075/kg
Rice Husk Ash (RHA)	$0.015/kg
Silica fume	$0.095/kg
Metakaolin	$0.093/kg
Fly ash	$0.080/kg
Slag	$0.072/kg

$$CEF = \frac{F_c}{C} \times 100 \qquad (4.1)$$

In Equation 4.1**Error! Reference source not found.**, F_c represents the compressive strength and C is the total cost of the concrete specimen. The database provides the associated strength values of the corresponding specimens and therefore the cost efficiency factor could be computed using the ratio of compessive strength of concrete to the total cost of material.

4.2.3 Eco-strength Efficiency

Eco-strength efficiency factor (ESEF) is then determined using the ratio of concrete compressive strength to CO_2 emissions of the materials per kg. The eco-strength efficiency factor also is determined based on the specified compressive strength values summarised in Table 4.1 and 4.2 along with the corresponding CO_2 emissions of each specimen. The total CO_2 emissions are also calculated based on the cumulative CO_2 emissions of each raw material used in the production of concrete specimens.

4.3 Life Cycle Assessment

Life cycle assessment of concrete comprising RHA is conducted using the openLCA software. Increasing awareness on environmental protection leads to a further investigation for the development of a new method of the potential adverse effects of the products and dependent processes (*ISO - ISO 14040:2006 - Environmental Management — Life Cycle Assessment — Principles and Framework*, 2006). Life cycle assessment (LCA) could offer a sound solution for this approach. LCA is defined as “a systematic, standardized approach to quantifying the potential environmental impacts of a product or process that occur from raw materials extraction to end of life” (Algren et al., 2021). It is an effective method that helps quantify the impacts on the environment and human health. LCA is analysed starting from mid-20th century; however, the concerns raised due to the lack of a procedure that makes the comparison challenging (de Fatima Dias, 2019). One of the most important steps in LCA is the determination of each step clearly for the assessment. In Chau et al. (2015), it is stated that 3 different LCA methods are commonly applied in the literature. These are Life Cycle Assessment (LCA), Life Cycle Energy Assessment and Life Cycle Carbon Emission Assessment (Chau et al., 2015). Comparison of these methods has revealed the differences in the evaluation methods and objectives caused by different methodology, focus, and functional units (Chau et al., 2015). Since there are many methods for environmental assessment, the framework is defined by International Organization for Standardization (ISO) 14040 and 14044 to "guarantee its reliability and transparency" (Huerta, 2020). The phases of LCA are divided into four categories and are listed below.

1. Goal and scope definition
2. Life cycle inventory
3. Life cycle inventory assessment
4. Interpretation of results

The differences in the assessment outcomes are due to the variations in functional units, definition of studied materials, inventory data that can differ region by region, system boundaries, etc. (Guinée et al., 2002). For instance, Passuello et al. (2017) reported that RHA usage in concrete might reduce the environmental impacts by about 60%. However, this study is done for the geopolymer concrete and has a different functional unit. For the production of 1 m^3 of concrete, the kg-CO_2 Eq. is reported as around 280 in van Gijlswijk et al. (2015), while it is found as more than 500 in (Gursel et al., 2016). On the other hand, Turner and Collins (2013) found that the kg-CO2 eq around 350. Apart from these data, during the development of the database, only a few studies are examined the usage of the RHA in concrete as a replacement material. Although there are many studies reported that the inclusion of the RHA in concrete as a sustainable concrete, only a few studies assessed the sustainability aspect of this practice. Gastaldini et al. (2009, 2010) and Muthadhi and Kothandaraman (2013) reported the cost analysis and mechanical property assessment, while Rodríguez de Sensale and Rodríguez Viacava (2018) measured CO2 reduction with calcination effect and pozzolanic inclusions. In (Gill & Siddique, 2018), cost analysis is done simply by providing the unit cost of the raw material for concrete comprising RHA.

In addition to this, there are differences in life cycle assessment outputs generated as a result of using different technologies, using different materials and methods, etc. In this thesis the life cycle assessment of concrete comprising RHA is performed using global warming potential (GWP 100), freshwater ecotoxicity (FETPinf), human ecotoxicity (HTPinf), marine ecotoxicity (METPinf), ozone depletion (ODPinf), water depletion (WDPinf).

In this study, the methodology defined for the LCA includes the stages until production stage of the concrete with the product stage of cradle-to-gate. It includes the raw materials and their processes to be used in the concrete. The processes accounted for the $1m^3$ of concrete production are given in Chapter 8 in detail.

4.4 Goal and Scope of LCA

First of all, the goals and scopes of the LCA are defined for the evaluation of concrete comprising RHA. The major goal of the study is assessing the sustainability and environmental benefits of using RHA as a replacement material in concrete. The scope of the assessment is to create models considering the optimum replacement types and levels of RHA and pozzolans previously determined in Chapters 5 and 6 for $1m^3$ of concrete as a functional unit. The details of the functional unit such as transportation and production data are both determined using the ELCD software and the literature.

The life cycle assessment transforms the inventory data into an indicator that finds the impact scores (de Fatima Dias, 2019). There are many evaluation models for the life cycle inventory analysis in the literature. One of the most commonly used impact assessment methods is ReCiPe. The ReCiPe offers two different approaches to assess life cycle assessment, namely: midpoint and endpoint approaches (de Fatima Dias, 2019). These characterisation models offer different indicator levels to calculate the environmental impacts (Dong & Ng, 2014). The major difference between endpoint and midpoint approach is that endpoint approach assesses the impacts in areas of protection (AoP), while midpoint approach does the evaluation in cause-effect chain (Dong & Ng, 2014). Although the differences in the interpretation of the results of these two approaches are discussed in the literature, the results are obtained due to the differences in characterization, normalization and weighting factors, and hence should be taken into account when interpreting (ILCD, 2011).

Although there exist a number of options in openLCA such as ILCD 2011, CML baseline and non-baseline, and hierarchist, individualist, and egalitarian ReCiPe methods, in this thesis ReCiPe method and midpoint approach involving hierarchist is adapted to conduct the analysis. Life cycle assessments of these models are assessed by evaluating their contribution to climate change (GWP100), human toxicity level (HTPinf), marine ecotoxicity (METPinf), ozone depletion (ODPinf), and water depletion (WDP).

4.5 LCI (Life Cycle Inventory) and Collection of Data

Life cycle inventory (LCI) is defined for most of the raw material in making concrete; however, missing inputs are determined from the literature to feed the LCI in this approach. The determination of these inputs includes comprehensive literature survey as well as assessing material data provided for 1 m3 of concrete. The 4 elements of the openLCA are used to create flows and processes. These elements are flows, processes, product systems, and projects.

4.5.1 Used Materials

Cement is the main raw material used in making concrete in this study. It is not surprising to observe various emission coefficients for this binder mainly due to the differences in production processes, technology used, production lines that can be vastly different with respect to the geographical limitations. In this study, "Portland cement type I", defined for Europe, was used in the ELCD database. Cement production details in the ELCD database are shown in Figure 4.1.

CEMBUREAU_Cement_8c2d452b-f17e-4523-b...

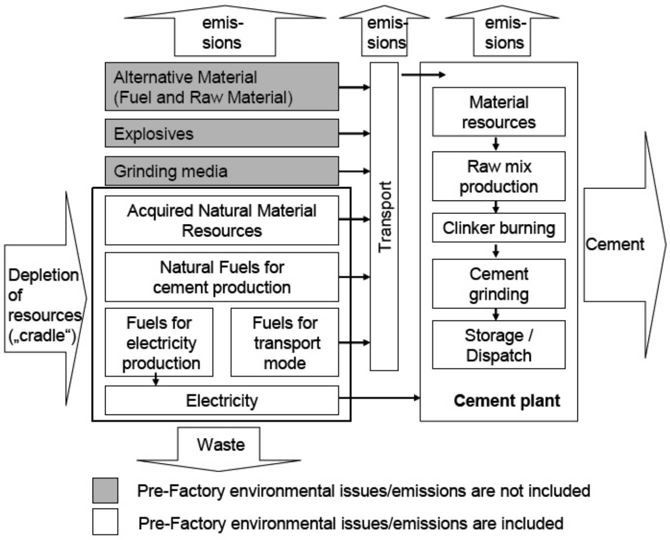

Figure 4.1: Cement production details defined in ELCD database

Coarse and fine aggregates, comprising nearly 70% of concrete, are also taken into account in estimating the emission coefficients in this study. For the same reason, sand and gravel, defined in the ELCD database, were used. Although the production stages of these materials are the same, they differ with the outputs originating from the classification part. Production steps for sand and gravel are shown in Figure 4.2.

PE_LBP-GaBi_Construction_Sand_Gravel_...

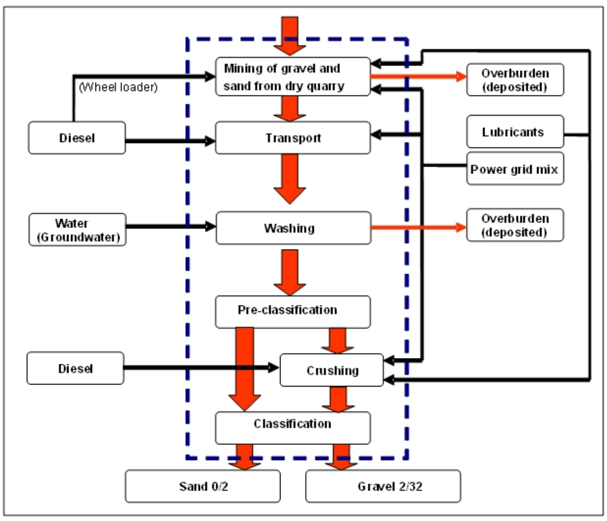

Figure: Production of sand and gravel from dry quarry - flowchart

Figure 4.2: Sand and Gravel production details defined in ELCD database

CHAPTER 5

MECHANICAL PROPERIES OF CONCRETE CONTAINING RICE HUSK ASH

The database approach adopted in the thesis is used to investigate the key factors such as the water:binder ratio, replacement types and levels of RHA and pozzolans, the short- and long-term measures on the performance of concrete containing RHA. The results attained in this section enabled the independent determination of the boundary conditions which was essential for the holistic reassessment of the sustainable analysis to be implemented precisely.

5.1 Water:binder Ratio

Water: binder ratio, significantly influences the compressive strength of concrete comprising RHA, is categorised under 3 distinct groups; water: binder ratio less than 0.3, water: binder ratio in the range of 0.3 to 0.6 and water: binder ratio greater than 0.6. 28-day compressive strength of concrete at all replacement levels are shown in Figure 5.1. Figure 5.1 shows the compressive strength of concrete comprising RHA with varying water:binder ratios. It should be noted that Figure 5.1 consists of 954 data points representing the compressive strength of concrete containing RHA. It is shown in Figure 5.1 that the majority of the data points (above 67%) represents concrete with water: binder ratio in the range of 0.3 – 0.6. Only 6% of the data points represent water: binder ratio less than 0.3. This is expected as the water: binder ratio less than 0.3 usually is not practical to achieve in concrete without the use of plasticisers. Water is essential for the consistence of the mixture at the plastic stage and for the hydration reaction to attain the ultimate properties of concrete at the hardened state. It is a known practice that usually, the water content required to proceed the chemical reactions could be much less than the amount of water required to attain the standard consistence for workability. It should be noted that the water:binder ratio less than 0.3 shown in Figure 5.1 are the concrete samples often prepared using plasticisers to attain the required workability. 26% of the data demonstrated in Figure 5.1 uses water:binder ratio greater than 0.6. It is clearly shown in the thesis that rise in the water:binder ratio, irrespective of the substitution levels of RHA, led to a reduction in the compressive strength of concrete. The results are shown in Figure 5.1 clearly demonstrated that the rise in the replacement levels of RHA led to an increase in the compressive strength of concrete at both water:binder ratios less than and equal to 0.3 as well as water:cement ratios in the range of 0.3 – 0.6. This trend is no longer valid when water:binder ratio is 0.6 and above. Increase in water content could be adopted to allow greater replacement levels of RHA to be incorporate in mixtures however, the excess water which is unnecessary for the chemical reactions often evaporates and form unwanted air pockets in the material's matrix. This feature is mainly attributed for the reduction in the compressive strength of concrete containing particularly high replacement levels of RHA.

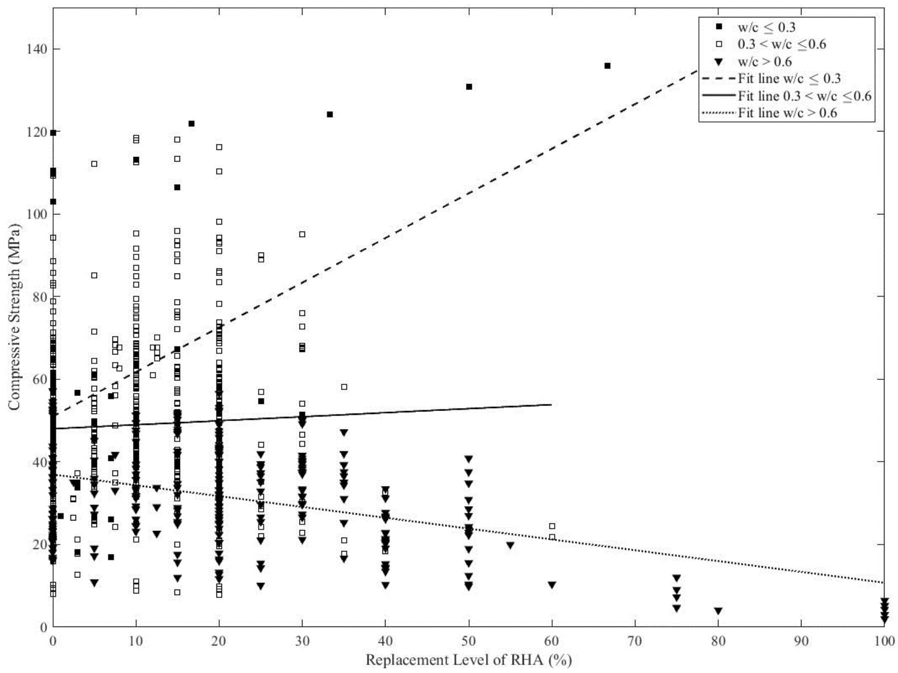

Figure 5.1: Compressive strength of concrete comprising RHA with varying water:binder ratios. ■, w/c≤0.3 (60 data points); □, 0.3<w/c≤0.6 (644 data points); ▼, w/c>0.6 (250 data points).

It was also notice that the incorporation of RHA in concrete with water:binder ratios less than 0.3 could often not be possible without the use of the plasticizers. High compressive strength of concrete particularly at high replacement levels are attained as a result of the use of plasticiser. It should also be noted that very high water:binder ratios also led to a dramatic reduction in the strength of concrete incorporated with RHA predominantly at higher replacement levels. It was eminently shown in Figure 5.1 that the use of more than 55% replacement levels of RHA in concrete resulted in a substantial reduction in the compressive strength which was often lower than the minimum structural grade of 20MPa. Also, attaining very high compressive strength values particularly 100MPa could be achieved in a laboratory condition but this range is rarely met in practice. Therefore, the replacement levels greater than 55% and compressive strength values greater than 100 MPa are disregarded in the second attempt and are re-plotted in Figure 5.2. The number of data points are reduced from 954, shown in Figure 5.1 to 920 in Figure 5.2.

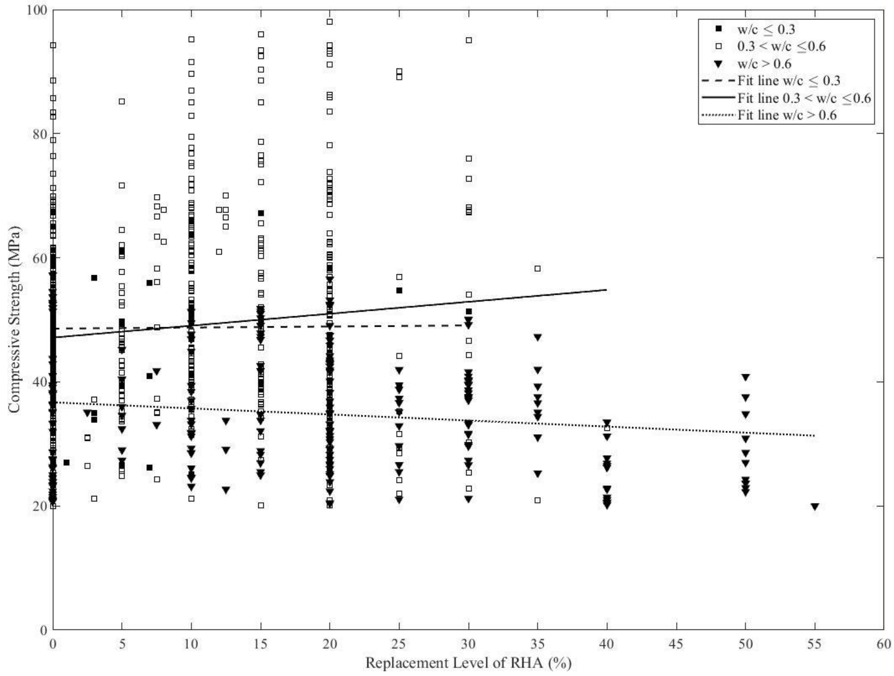

Figure 5.2: Compressive strength of concrete comprising RHA with varying water:binder ratios. ■, w/c≤0.3 (49 data points); □, 0.3<w/c≤0.6 (632 data points); ▼, w/c>0.6 (239 data points).

Confining the replacement levels with 55% and the compressive strength with 100MPa enabled more authentic behaviour of concrete containing RHA with all water:cement ratios to be examined in the thesis. It should be noted that Figure 5.2 consists of 920 data points representing the 28-day compressive strength of concrete containing RHA. Water: cement ratios in the range of 0.3-0.6 provided the greatest fit line indicating the attainment of the best performance of concrete incorporating RHA. Although the water:cement ratios of 0.3-0.6 and the water:cement ratios less than 0.3 provided an accelerating gradient of compressive strength of concrete incorporated RHA, the concrete with water:cement ratios above 0.6 remained to provide a decelerating gradient of compressive strength with the increase replacement levels of RHA. Due to the decelerating gradient attained at water:cement ratios greater than 0.6 shown in Figure 5.2, the replacement ratios of

RHA are re-examined in the thesis. It was observed that increasing gradient of compressive strength of concrete with water:cement ratios above 0.6 could only be commenced when the replacement level of RHA was confined to 35%. The compressive strength of concrete containing RHA at all water:binder ratios are replotted in Figure 5.3 and the replacement levels of RHA were limited to 35%.

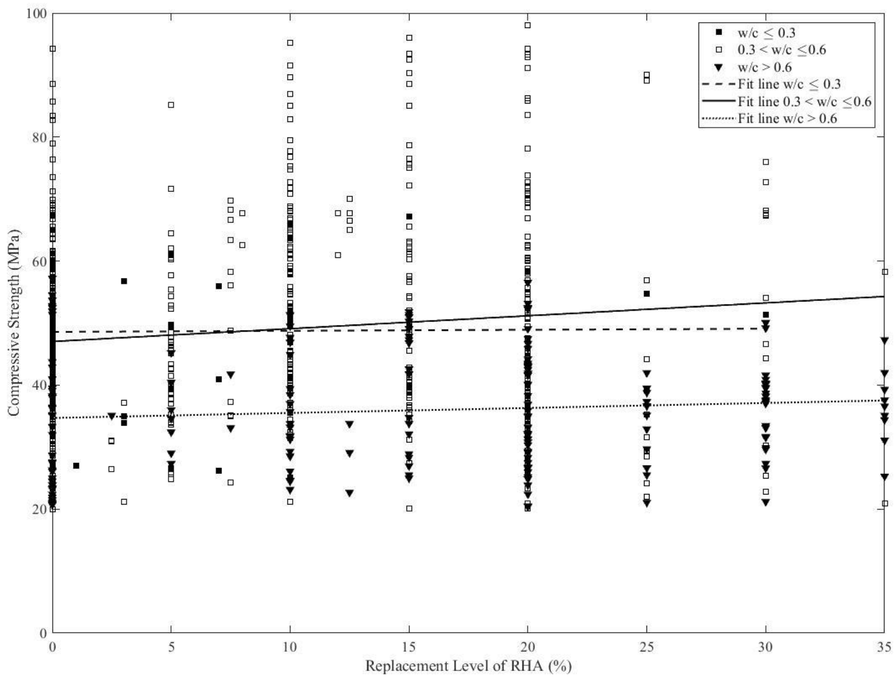

Figure 5.3: Compressive strength of concrete comprising RHA with varying water:binder ratios. ■, w/c≤0.3 (49 data points); □, 0.3<w/c≤0.6 (630 data points); ▼, w/c>0.6 (204 data points).

It must be reported that Figure 5.3 comprises 883 number of data points in total where 5.5% of the data represents of water:cement ratios less than 0.3 and that the 23.1% of the data represents of water:cement ratios greater than 0.6. Therefore, the majority of the data points, above 71%, represents the 28-day compressive strength of concrete with water:cement ratios in the range of 0.3-0.6. Compared to Figures

5.1 and 5.2, increasing gradients of compressive strength of concrete at all water:binder ratios are attained for the first time in Figure 5.3 when the replacement level of RHA were confined to 35%. The results shown in Figure 5.3 further demonstrated the incompatibility of the use of very high replacement levels of RHA in concrete which often is achieved either by increasing the water:binder ratio or the use of plasticiser that the extensive use which may generate diverse adverse effects to the resulting materials particularity at the hardened state. The results displayed in Figure 5.3 also correlate well with the studies in the literature that often report the optimum replacement levels of RHA to be in the range of 15% to 35% to attain the ultimate performance of concrete.

5.2 Replacement Type

Binder and sand replacements were the two types of replacement of RHA examined in this thesis. 28-day compressive strength of concrete containing RHA used both as cement and sand replacements were plotted versus the replacement levels of RHA in Figure 5.4. It must be reported that Figure 5.4 comprises 915 data points of which more than 90% represents the compressive strength of concrete containing RHA used as cement replacement.

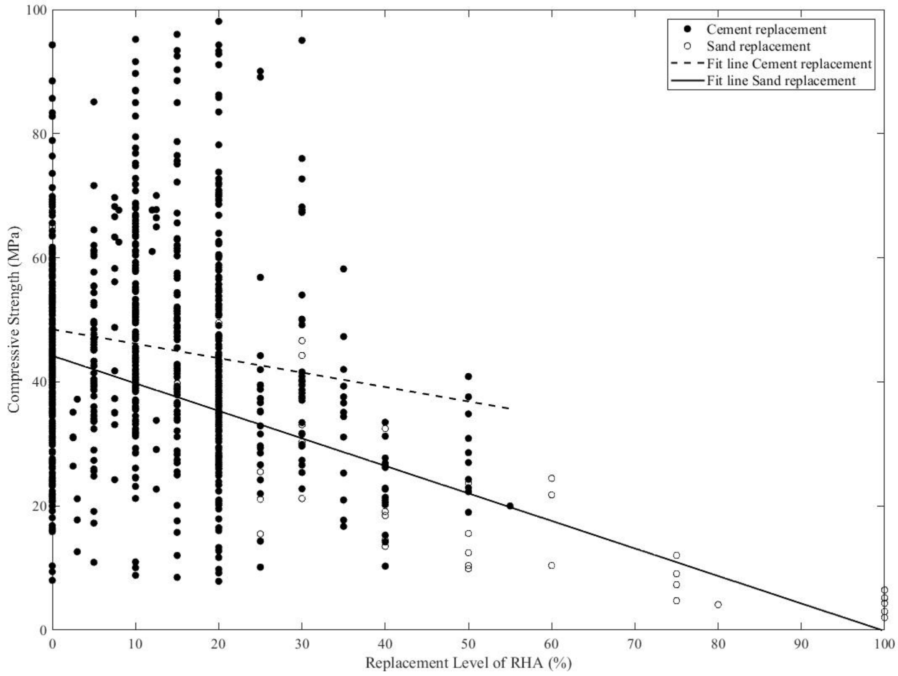

Figure 5.4: Compressive strength of concrete comprising RHA used as ●; cement replacement (828 data points) and ○; sand replacement (87 data points).

It should be noted that Figure 5.4 consists of 915 data points representing the 28-day compressive strength of concrete containing RHA. It is shown in Figure 5.4 that rise in the substitution levels of RHA has resulted in a decrease in the compressive strength of concrete. ‘It must also be reported that higher substitution levels of RHA ranging from 60 to 100%, used as sand replacement, are only reported at water:cement ratios greater than 0.6 as shown in Figure 5.4. As discussed previously, the increase in the water content, to attain the required consistence with high replacement levels of RHA, is causing a dramatic reduction in the compressive strength of concrete. It is also shown in Figure 5.4 that when the entire data is considered with all water:cement ratios, an authentic assessment of the effectiveness of the replacement types of RHA in concrete could not be performed. Therefore, the similar approach, previously pursued in the former section, also is adopted here. Hence, the water:binder ratios were limited to be in the range of 0.3-0.6, replacement levels were confined with 35% and compressive strength values were also confined to be in the range of 20-100 MPa in Figure 5.5.

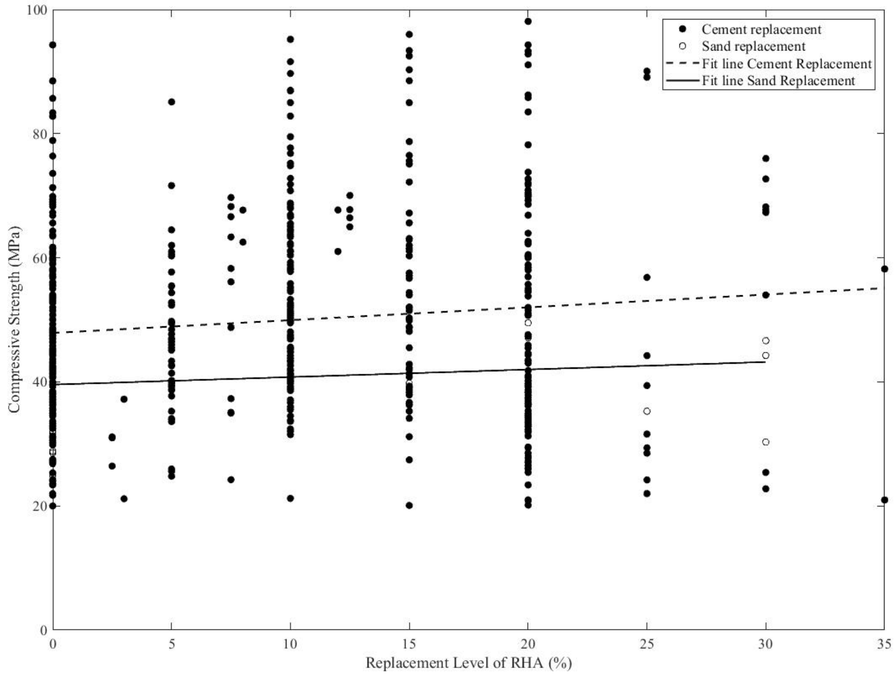

Figure 5.5: Compressive strength of concrete, at 0.3<w/c≤0.6, comprising RHA used as ●; cement replacement (559 data points) and ○; sand replacement (45 data points).

The influence of the substitution type of RHA on the compressive strength of concrete is investigated using a total number of 604 data points demonstrated in Figure 5.5. It is evidently shown in Figure 5.5 that both replacement types examined in the thesis had increasing effects on the compressive strength of concrete comprising RHA and that increase in the substitution levels of RHA up to 35% had a methodical increase in the compressive strength. It is also demonstrated in Figure 5.5 that the use of RHA as a cement replacement had a greater influence in increasing the compressive strength of concrete than that of sand replacement. The great majority of the data (97%) collected from the literature were on the short-term compressive strength of concrete. Although the RHA often possesses high pozzolanic activity and hence its contribution in the development of definitive mechanical properties could only be seen at the long-term, the physical effects of RHA and therefore the associated influence on the physical properties on strength is demonstrated in Figure 5.5 alone. Although 46% of the studies, used to construct the database in this thesis, reported the prevalence of the pozzolanic activity of the RHA, only ~3% of these actually reported the long-term properties of concrete containing RHA. It is a common knowledge that the pozzolanic reaction, depending on the hydration reaction and more specifically the formation of the calcium hydroxide, has a very slow nature and hence the actual influence of the pozzolans can only be seen at long-term.

5.3 The use of Pozzolans

The use of pozzolans on the compressive strength of concrete incorporating RHA with water:binder ratios in the range of 0.3-0.6 is shown in Figure 5.6. It should be noted that the compressive strength of concrete was confined with the range of 20 to 100MPa and that the replacement levels of RHA were limited to the 35%.

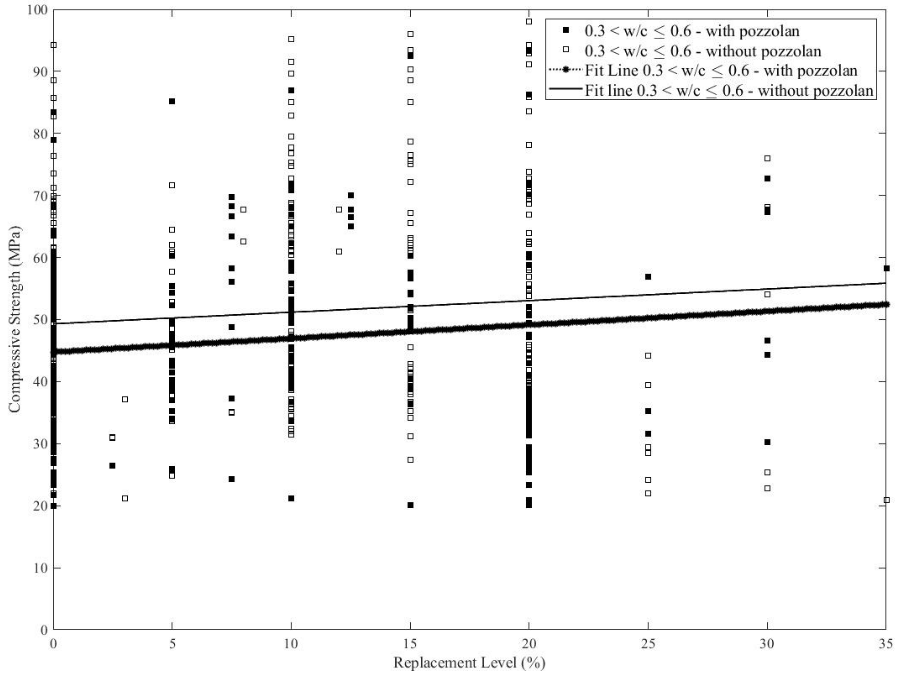

Figure 5.6: Compressive strength of concrete comprising RHA in conjunction ■, with pozzolanic materials (285 data points) and; □, without pozzolanic materials (330 data points) used as cement replacement.

It is shown in Figure 5.6 that the use of pozzolans resulted in a lower increase in the compressive strength of concrete compared to the concrete specimens with no pozzolans. It should be emphasized again that the majority of the data (~97%) used in the database reported the short-term properties of concrete and hence the actual influence of the RHA and the additional use of pozzolans may not essentially be reflected to the results shown in Figure 5.6. In order to gain an insight into the actual performance of RHA and the additional use of pozzolans, the short- and long-term compressive strength of concrete containing RHA along with the pozzolans are replotted in Figure 5.7.

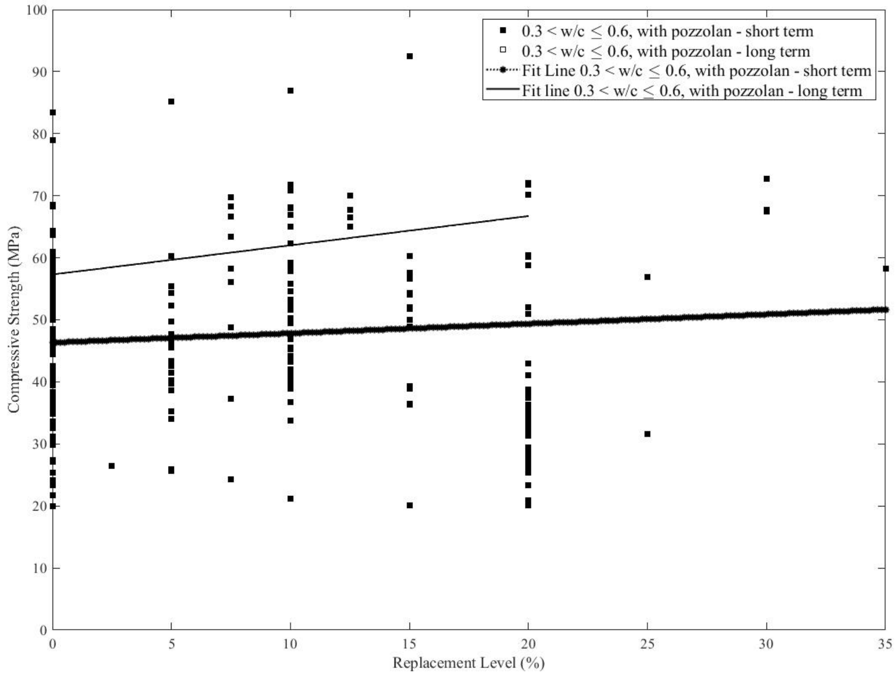

Figure 5.7: Compressive strength of concrete comprising RHA. ■; short-term data (239 data points) and; □, long-term data (8 data points) used as cement replacement.

Although the long-term results consist only about 3% of the data points shown in Figure 5.7, it is evidently demonstrated that the long-term results enabled the actual performance of the pozzolans to be detected. It must be noted that the data points stand for the long-term strength are overlapped under the data points represent the short-term strength of concrete. Calcium hydroxide, formed by means of the cement hydration, sufficiently reacted with the silica of the pozzolans and formed additional formations of the calcium-silica-hydrate gels that are entirely responsible from the development of strength. Long-term results, comprised using compressive strength of concrete aging 180 days and older, provided much higher performance compared to that of the data points representing the short-term performance. It should be noted, however that Figure 5.7 comprises compressive strength of concrete incorporated RHA with varying types of pozzolans. The independent influence of the pozzolans on the strength of concrete is then investigated in Figure 5.8.

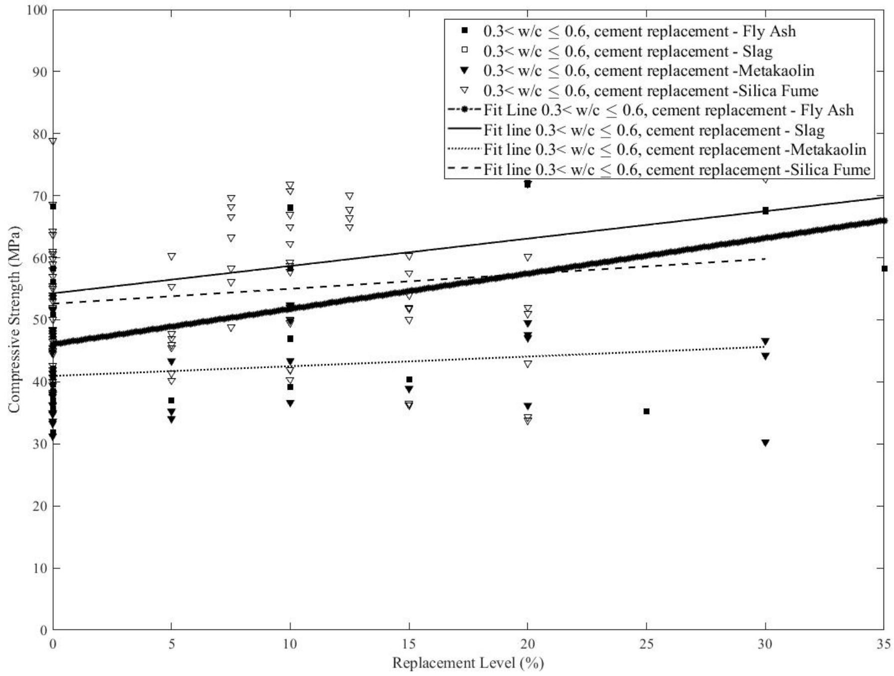

Figure 5.8: Compressive strength of concrete, at 0.3<w/c≤0.6, comprising RHA and pozzolanic materials used as cement replacement. ■, Fly ash (34 data points); □, Slag (15 data points); ▼, Metakaolin (39 data points); , Silica fume (87 data points).

It should be noted that out of 954 number of data points used to construct the database in this thesis, only 46% contained the incorporation of pozzolans in concrete following the set constraints. It must also be noted that Figure 5.8 omits data points that have less than 20MPa and higher than 100MPa of concrete compressive strength, RHA used as sand replacements and RHA replacement level higher than 35%. Nevertheless, out of 285 concrete specimens that contained pozzolans, the use of more than 10 different types of pozzolans were identified. In fact, the most commonly utilised pozzolans such as silica fume, fly ash, slag and metakaolin are taken into consideration to construct Figure 5.8 here. It can be seen in Figure 5.8 that the use of slag and fly ash significantly contributed the strength development of concrete, whereas silica fume and metakaolin had less influence in enhancing the compressive strength of concrete.

5.4 Boundary Conditions

The designated key factors that significantly affected the performance of concrete incorporating RHA enabled the following boundary conditions to be established which are then used in the evaluation of the sustainability indicators in the thesis.

The water:cement ratios in the range of 0.3 to 0.6 were found to provide the most accomplished strength values of concrete.

Compressive strength values lower than 20MPa and greater than 100MPa were disregarded as they were not often practically acceptable and applicable on site respectively.

It was recognized that up to 35% increase in the replacement level of RHA had an increasing effect on the strength of concrete and therefore the maximum allowable replacement level of RHA was detected to be 35% at all water:binder ratios examined.

The use of RHA as cement substitute was found to provide higher compressive strength of concrete than that of the sand replacement.

The use of pozzolans, particularly at the long-term, enabled greater strength of concrete to be attained.

The utilisation of fly ash and slag were more influential in increasing the compressive strength of concrete at long-term.

The aforementioned key findings formed the based constraints employed to assess the sustainability indicators in the latter section.

CHAPTER 6

DURABILITY PROPERTIES OF CONCRETE CONTAINING RICE HUSK ASH

This section encompasses the assessment of the database comprising concrete incorporating RHA. The following sub-sections in Chapter 6 are designed to determine the optimum replacement level and type of RHA and pozzolans to be used in concrete within the acceptable limits by the standards as well as at construction practice.

6.1 Replacement Level of RHA

The optimum replacement level of RHA, incorporated in concrete, is analysed in this section. The ultrasonic pulse velocity of concrete incorporating RHA is plotted versus the replacement level of RHA in Figure 6.1. The compressive strength of concrete comprising RHA is also plotted in the secondary axis in Figure 6.1. There are 308 number of data points standing for ultrasonic pulse velocity of concrete comprising varying content of RHA, whereas there is 954 number of data points for compressive strength of concrete incorporating RHA.

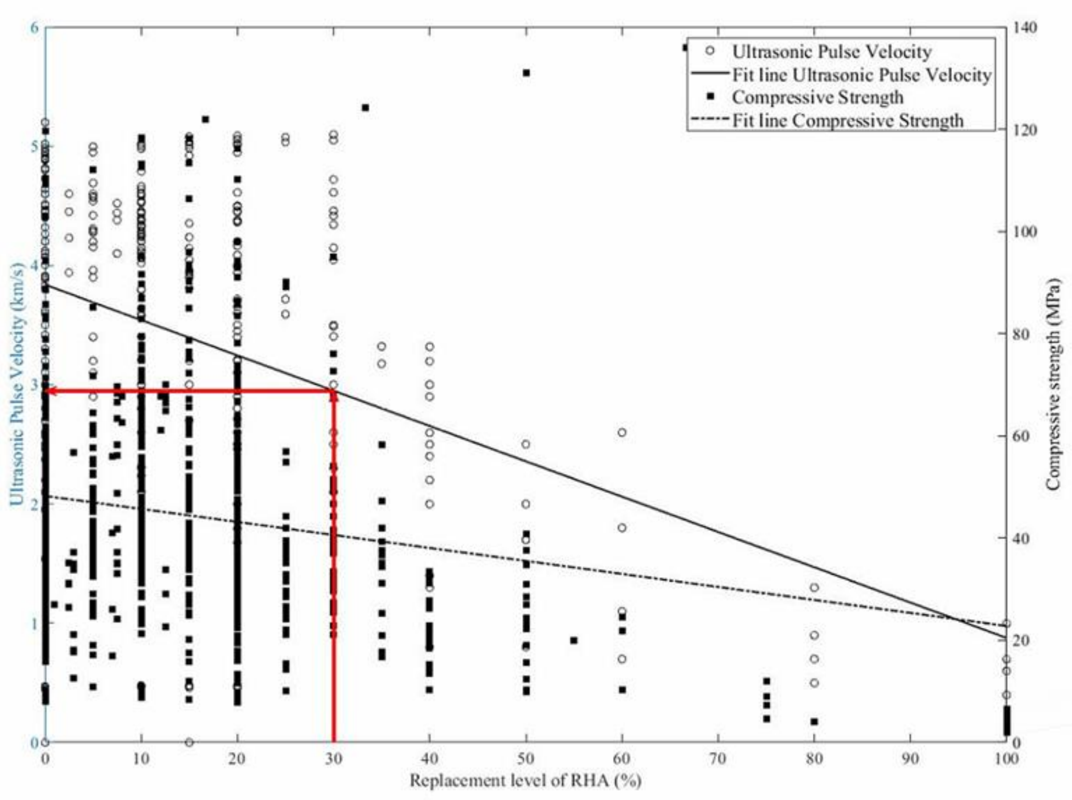

Figure 6.1: Ultrasonic pulse velocity and compressive strength of concrete incorporating RHA

The results exhibited in Figure 6.1 show that the increase in the replacement level of RHA, regardless of the type of substitute, decreases both the ultrasonic pulse velocity and the compressive strength of concrete. Increase in the ultrasonic pulse velocity is an indication of the increase in the concrete quality, and therefore, the decrease attained in the pulse velocity attributes to the low-graded concrete in general. The ultrasonic pulse velocity less than 3 km/s is accepted to provide doubtful concrete quality (Danjuma et al., 2021; Hasbullah et al., 2016), and this point corresponds approximately to the 30% RHA used in concrete. Although the higher replacement levels of RHA are exhibited in Figure 6.1, most of these attempts remained under 20MPa, which is accepted as low-grade concrete and is not suitable to be used in structural applications in practice. The results shown in Figure 6.1 suggest that the optimum replacement level of RHA could be determined to be 30%.

The chloride penetration (399 data points) of concrete incorporating RHA is plotted versus the replacement level of RHA in Figure 6.2. The porosity (181 data points) of concrete comprising RHA is also plotted in the secondary axis in Figure 6.2.

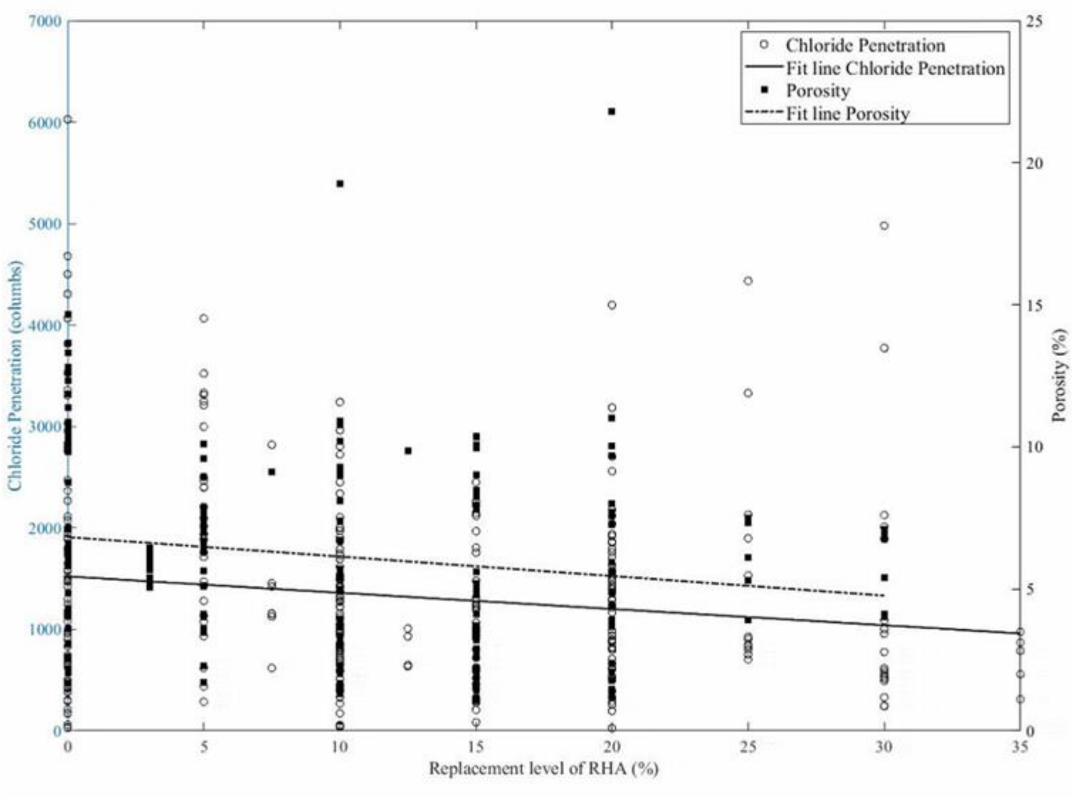

Figure 6.2: Chloride penetration and porosity of concrete incorporating RHA

The results demonstrated in Figure 6.2 indicate that the increase in the replacement level of RHA yielded a substantial decrease in both the chloride penetration and the porosity of concrete. The regression line of chloride penetration, ranging between 1000 to 2000 coulombs, is an indication of the low chloride permeability of concrete (Pathak & Siddique, 2012; *Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration, ASTMC 1202-97*, 2006). The decrease in the chloride penetration of concrete is accompanied by the associated reduction in porosity and is the measure of improved physical properties and durability of concrete. It must be noted, however, that the replacement level of RHA is deliberately limited to 35% here. The results are shown in Figure 6.1 comprised replacement level of RHA up to 100%, and therefore, the increase in the RHA level, influentially, yielded a continual reduction in the quality and the compressive strength of concrete. The results exhibited in Figure 6.2, on the contrary, demonstrated that the increase in the replacement RHA yielded less permeable and less porous concrete that attributed to the enhanced durability of concrete when RHA is confined to 35%. The results are shown in Figure 6.2 also re-validated the determination of the optimum replacement level of RHA preliminary assessed formerly.

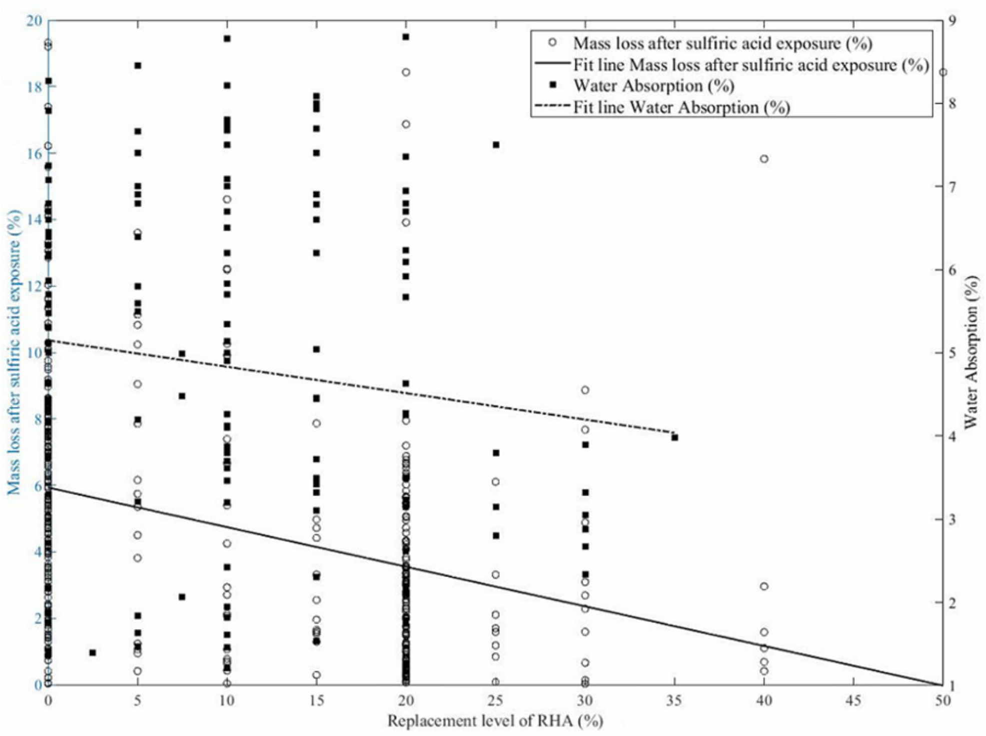

Figure 6.3: Mass loss after sulfuric acid exposure and water absorption of concrete incorporating RHA

Figure 6.3 comprises the mass loss after sulfuric acid exposure (380 data points) and water absorption (145 data points) of concrete versus the replacement level of RHA. The results shown in Figure 6.3 demonstrated that the increase in the RHA replacement level yielded a substantial decrease in the mass loss after sulfuric acid exposure of concrete. The significant reduction of the mass loss, exhibited in Figure 6.3, is an indication of the improved resistance and hence enhanced durability of concrete subjected to sulfuric acid exposure. The reduction in the mass loss of concrete subjected to acid exposure is associated with considerable reduction observed in water absorption. Decrease attained in the water absorption of concrete is attributed to the formation of the more consolidated and less porous matrix by means of the utilisation of RHA, and therefore this physical measure is chiefly responsible for the higher resistance attained in sulfuric acid exposure. The optimum replacement level of RHA is also observed to be in the range of 30-35%.

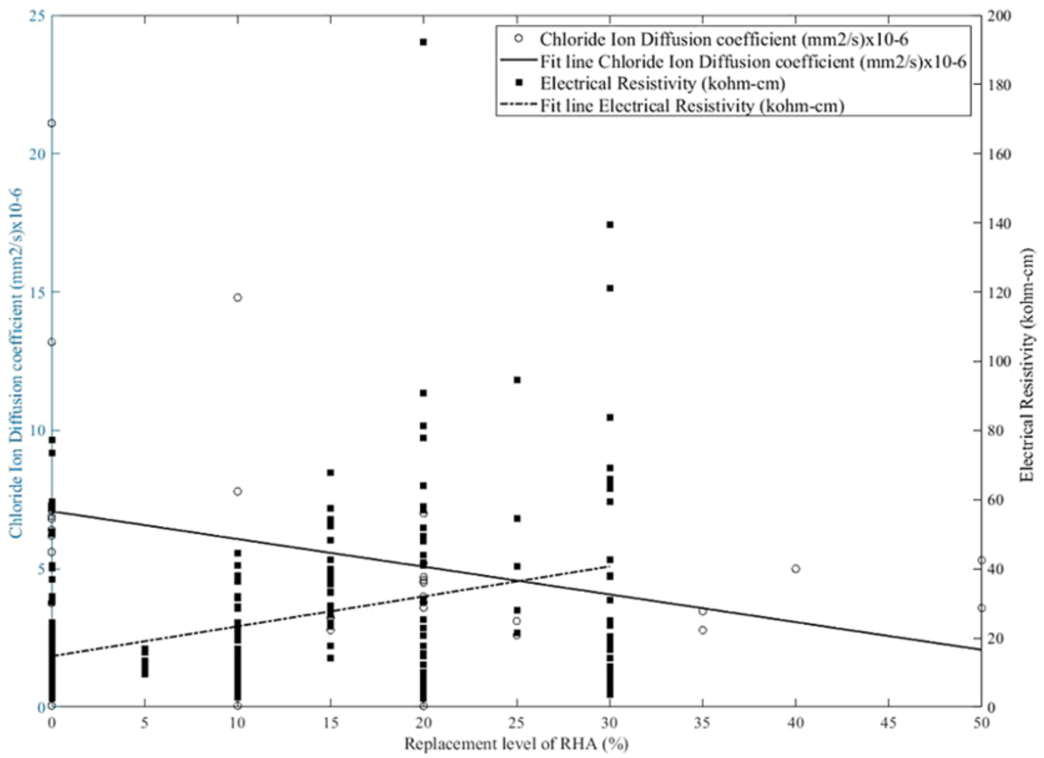

Figure 6.4: Chloride diffusion coefficient and electrical resistivity of concrete incorporating RHA

Figure 6.4 comprises the chloride ion diffusion coefficient (32 data points) and electrical resistivity (221 data points) of concrete versus the replacement level of RHA. The results exhibited in Figure 6.4 revealed that the increase in the RHA replacement level yielded a considerable decrease in the chloride ion diffusion coefficient. The presence of RHA densifies the matrix due to the high fineness and improves the diffusion resistance of concrete (Ambedkar et al., 2017; Koushkbaghi et al., 2019; Siddika et al., 2021). Electrical resistivity, which is also closely related to the corrosion resistance of concrete, is also shown to improve with the increased replacement level of RHA (Balapour et al., 2017; Chao-Lung et al., 2011). Electrical resistivity is known to improve with the densification of the cement matrix (Kaur et al., 2020). The high fineness of RHA, as well as the rich content of SiO_2, Al_2O_3, Fe_2O_3, enriches the matrix and enables higher densification of concrete which is essentially responsible for the improved electrical resistance shown in Figure 6.4. The parameters discussed herein for enhanced durability of concrete also highly attribute the optimum replacement levels of RHA to be between 30 to 35%.

6.2 Replacement Type of RHA

This section examines the optimum replacement type of RHA used in concrete making. Among the 85 number of papers, used for the construction of the database here, only two types of replacements; namely cement replacement and sand replacement were observed. The ultrasonic pulse velocity of concrete incorporating RHA used as cement and sand replacement is shown in Figure 6.5. There are 190 data points for RHA used as cement replacement and 118 data points for sand replacement in Figure 6.5.

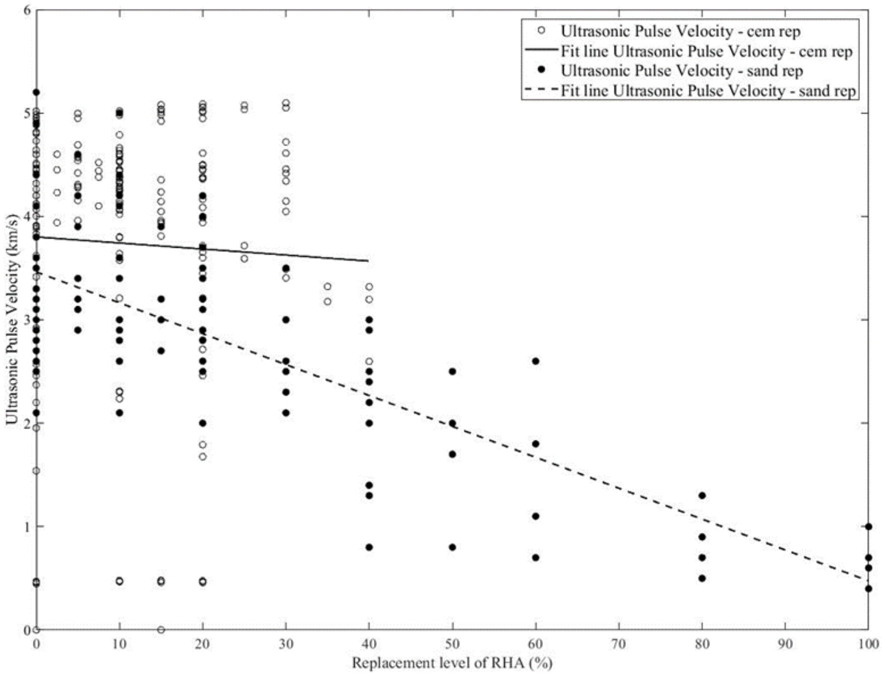

Figure 6.5: Ultrasonic pulse velocity of concrete incorporating RHA

It is shown in Figure 6.5 the use of RHA as cement replacement yielded a higher ultrasonic pulse velocity of concrete compared to that of the sand replacement alternative. The utilisation of RHA as cement replacement in concrete provided ultrasonic pulse velocity values higher than 3.5 km/s at all substitution levels, indicating an attainment of very good quality of concrete. The pulse velocity values of concrete comprising sand replacements ranged from 3.6 km/s to below 1 km/s. Considering that pulse velocity below 3 km/s attributes doubtful concrete quality in general, replacement levels higher than ~20% RHA should not be used as sand replacement in concrete making. The results are shown in Figure 6.5 clearly demonstrated that replacing cement with RHA provides much higher pulse velocity values at all replacement levels examined. This is eminently indicating that the use of RHA as a cement replacement is an optimal case. Although the replacement levels of RHA, when used as cement substitute, provide acceptable quality of concrete up to 40%, the replacement levels of RHA, when used as sand substitute, must be confined with ~20% to attain at least the ‘medium grade’ concrete quality.

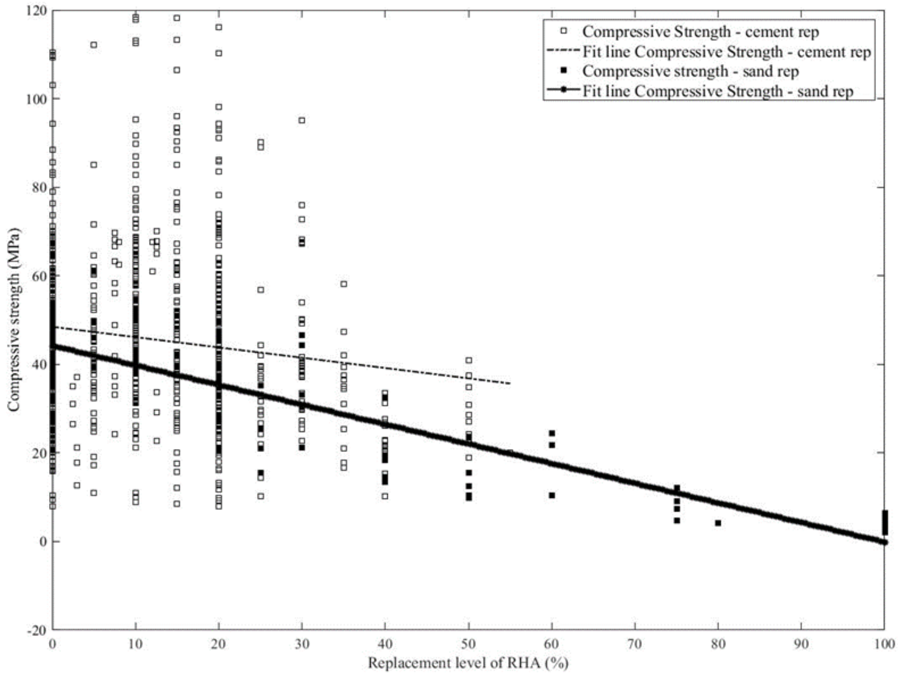

Figure 6.6: Compressive strength of concrete incorporating RHA

The compressive strength of concrete comprising RHA utilised both as cement and sand substitute is shown in Figure 6.6. There are 828 number of data points for compressive strength concrete comprising RHA as cement substitute and 87 number of data points for sand substitute. It can be seen in Figure 6.6 that the use of RHA as a cement substitute provides higher compressive strength of concrete at all replacement levels when compared to that of sand substitute alternative. These findings demonstrated in Figure 6.6 attribute that the utilisation of RHA as cement substitute is a superior instance. Much greater number of data points available for concrete comprising RHA as cement replacement also is an indication of this type of replacement to be more superior than that of sand substitute.

6.3 The use of RHA with Pozzolans

The use of pozzolans often is a common practice to compensate for the negatively influenced properties of concrete incorporating agricultural wastes (AlBiajawi et al., 2022; Mohamad et al., 2019). The effectiveness of the utilisation of pozzolans in concrete incorporating RHA is assessed in Figure 6.7. The results demonstrated in Figure 6.7 showed that RHA concrete comprising various types of pozzolans provided smaller porosity values compared to that of RHA concrete without pozzolans. Correspondingly, the RHA concrete comprising pozzolans also provided much lower chloride penetration than that of RHA concrete without pozzolans. The significant decrease observed in the chloride penetration, and the accompanying reduction in porosity of RHA concrete incorporating pozzolans are the indications of the attainment of improved physical properties as well as enhanced durability. The results demonstrated in Figure 6.7 revealed that the use of pozzolans in RHA concrete has affirmative consequences and should be taken into account for the development of enhanced durability.

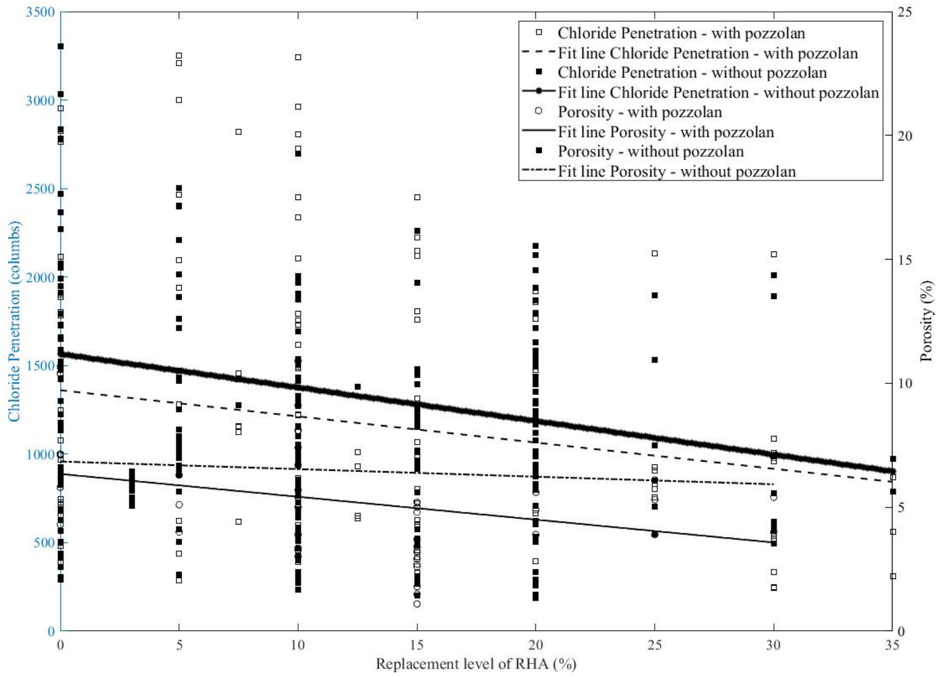

Figure 6.7: Porosity and chloride penetration of RHA concrete comprising varying degrees of pozzolans.

The replacement type of pozzolans utilised in RHA concrete is assessed in Figure 6.8, where chloride penetration and porosity of RHA concrete incorporating pozzolans used both as sand and cement replacements were displayed. The results shown in Figure 6.8 indicated that the use of pozzolans as cement replacement yielded a greater reduction in chloride penetration as well as a greater reduction in porosity of RHA concrete. The significant reduction attained in porosity and associated diminishing in chloride penetration of RHA concrete comprising pozzolans as cement replacement is an implication of the improved durability accomplishment. Although both replacement types, cement and sand replacements of pozzolans, yielded considerable decrease in these physical measures, the cement replacement of pozzolans resulted in a greater reduction in porosity and chloride penetration, and hence binder replacement became prominent in this study.

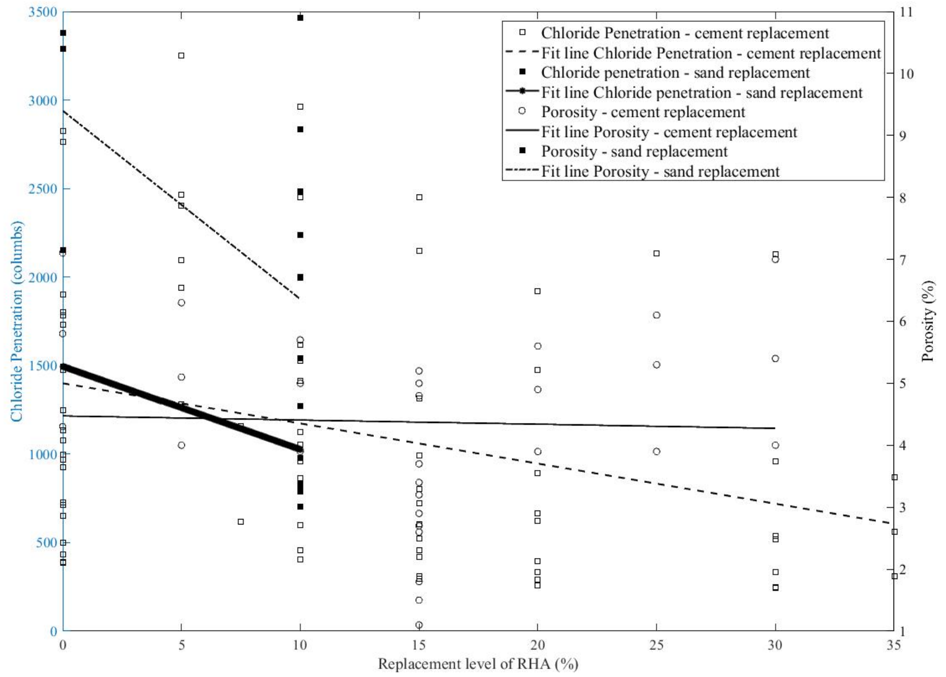

Figure 6.8: Chloride penetration of RHA concrete comprising varying degrees of pozzolans.

Majority of the studies (40 out of 85 number of studies) composed in the database utilised pozzolans in RHA concrete essentially to compensate the negative influences of RHA in the long-term. In the database, 19 number of different types of pozzolans used in RHA concrete are summarised. Out of these, metakaolin, slag, fly ash, and silica fume were the most commonly used in RHA concrete and, more importantly, provided superior properties compared to that of the other types of pozzolans such as glass powder, micro silica, and TiO_2. In this section, the enhanced effectiveness of the metakaolin, fly ash, and silica fume pozzolans against the others (micro silica, lime, and TiO_2), determined through the literature study and observed as a result of the preliminary analysis of the database, is assessed. Figure 6.9 shows the chloride penetration of RHA concrete comprising effective pozzolans (pozzolans such as fly ash, metakaolin, and silica fume) and other pozzolans (pozzolans such as micro silica, lime, and TiO_2). The results demonstrated in Figure 6.9 attribute that the use of effective pozzolans yielded a greater reduction in chloride penetration of RHA concrete compared to that of the other pozzolans. The greater decrease attained in chloride penetration of RHA concrete incorporating the effective pozzolans is an indication of the improved performance of such materials and hence is pioneering the use of metakaolin, silica fume, and fly ash in RHA concrete.

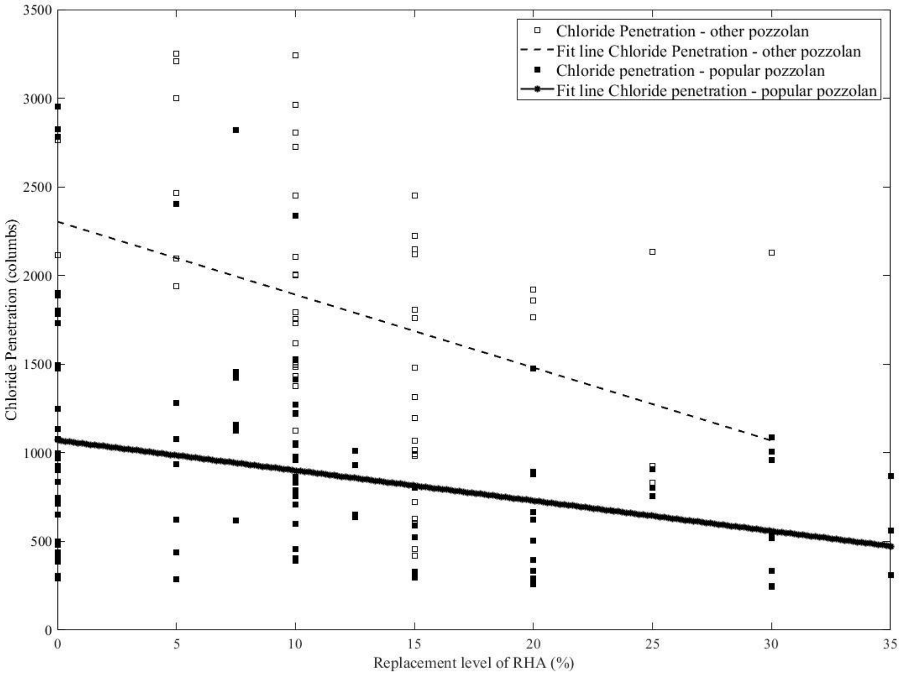

Figure 6.9: Chloride penetration of RHA concrete comprising varying degrees of pozzolans.

The optimum replacement level of the pre-determined effective pozzolans, silica fume, fly, and metakaolin, were investigated in Figure 6.10. The results are shown in Figure 6.10 re-validate the effectiveness of these pozzolans in enhancing the durability of RHA concrete as a consequence of reducing the chloride penetration. Considering the charged passed coulombs in the range of 1000-2000 indicates a low chloride permeability of concrete, the effectiveness of these determined pozzolans in improving the durability is substantiated. In accordance with this aforementioned comprehension, the replacement level of metakaolin, silica fume, and fly ash could be confined as 15%, 30%, and 40%, respectively.

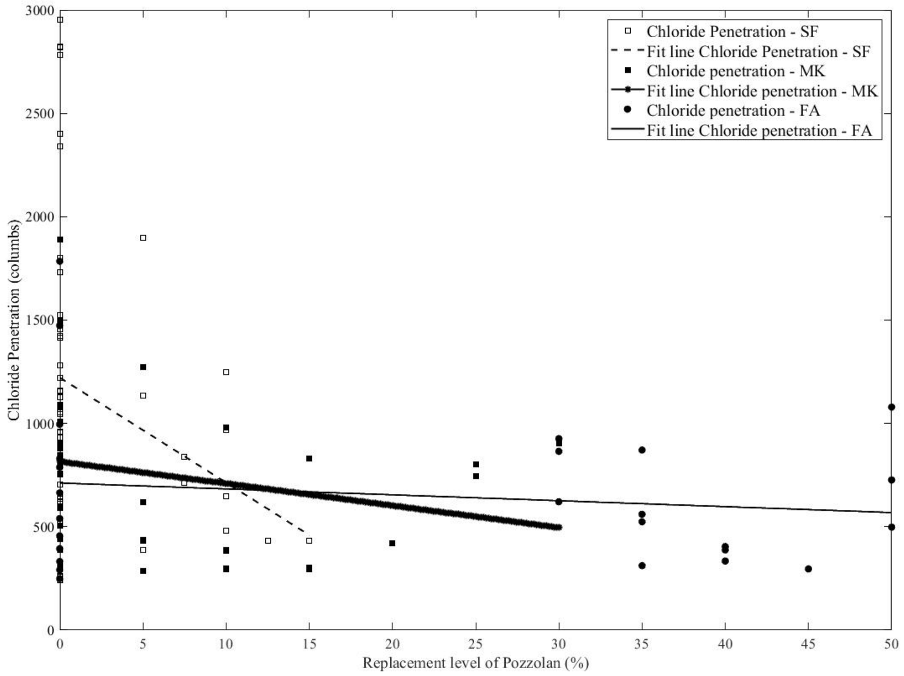

Figure 6.10: Chloride penetration of RHA concrete comprising varying degrees of pozzolans.

CHAPTER 7

SUSTAINABILITY ASSESSMENT OF CONCRETE CONTAINING RICE HUSK ASK

In this chapter, the durability characteristics of RHA concrete will be investigated by using the database approach. The factors will be investigated are water:cement ratios, replacement types, pozzolan usage and long-short term performance of RHA concrete. Global Warming Potential (GWP) will be calculated by using the determined boundary conditions.

The database approach adopted in the paper is also utilised to investigate the effect of CO_2 emissions, the cost efficiency, and the eco-strength efficiency of concrete incorporated RHA. The key factors that have eminent influence of the performance of concrete containing RHA, reported in the former section, enabled the independent determination of the boundary conditions. These boundary conditions are implemented in this section for the holistic reassessment of the sustainability analysis to be implemented precisely.

7.1 CO_2 Emissions

The CO2 emissions of concrete containing RHA as well as concrete containing both RHA and pozzolans are shown in Figure 7.1. The CO_2 emissions of concrete control is also added to this figure for comparison purpose. It must be emphases that data points shown in Figure 7.1 represents only cement replacement of RHA up to 35% where the water:cement ratios is designated to be in the range of 0.3-0.6, the pozzolanic replacements were confined with silica fume, fly ash, slag and metakaolin. It must also be reported that the specimens (the data points) that are provided lower than 20MPa and higher than 100MPa of concrete compressive strength were omitted from the sustainability analysis and hence were not taken into consideration in Figure 7.1.

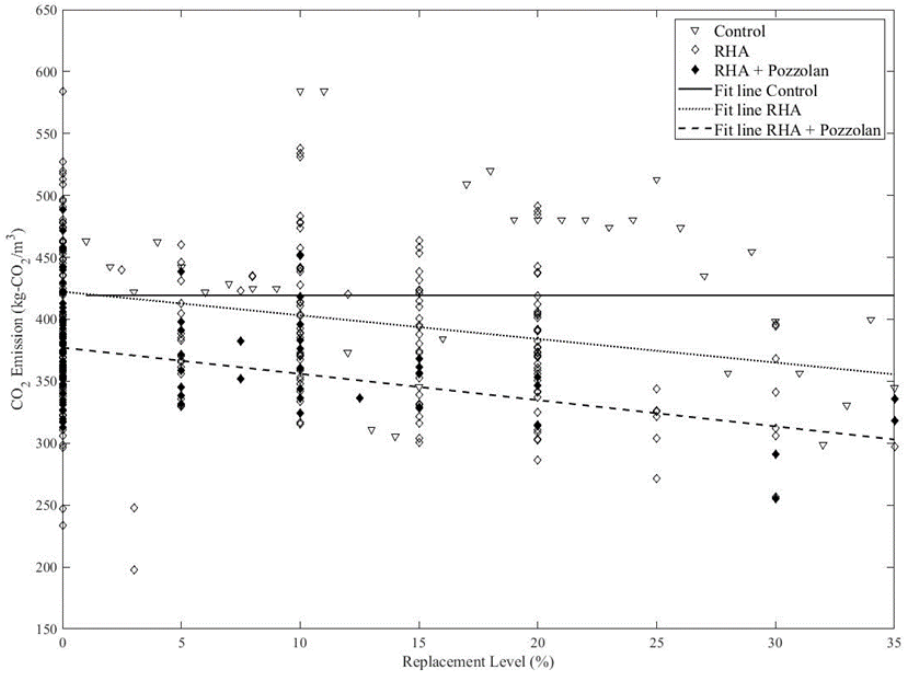

Figure 7.1: CO2 emissions of ; concrete control (87 data points), ◊; concrete containing RHA (314 data points), ♦; concrete containing RHA and pozzolans (141 data points).

It is evidently revealed in Figure 7.1 that the rise in the binder substitution of RHA resulted in a substantial reduction in the CO_2 emissions of concrete. The significant decrease (~25%) attained in the CO_2 emissions of concrete is attributed to the considerable decrease in the cement consumption necessary to make up the correspondent concrete. In this case, the high CO_2 emitting of cement is partially replaced with the low CO_2 emitting RHA resulting in a substantial decrease in the process-related emissions. It should also be emphasised that the utilisation of RHA as a cement substitution also reduces the demand for cement manufacture and hence this further results in the reduction of fuel combustion and therefore contributes to reducing the carbon footprints. The use of pozzolans in conjunction with the RHA used as a binder replacement further reduces the necessity of cement and therefore accelerates the reduction of CO_2 emissions and likewise independently contributes to carbon footprint recovery. It must also be noted that 587 number of data points, shown in Figure 7.1, are used in the CO_2 emission analysis of pozzolanic concrete containing RHA.

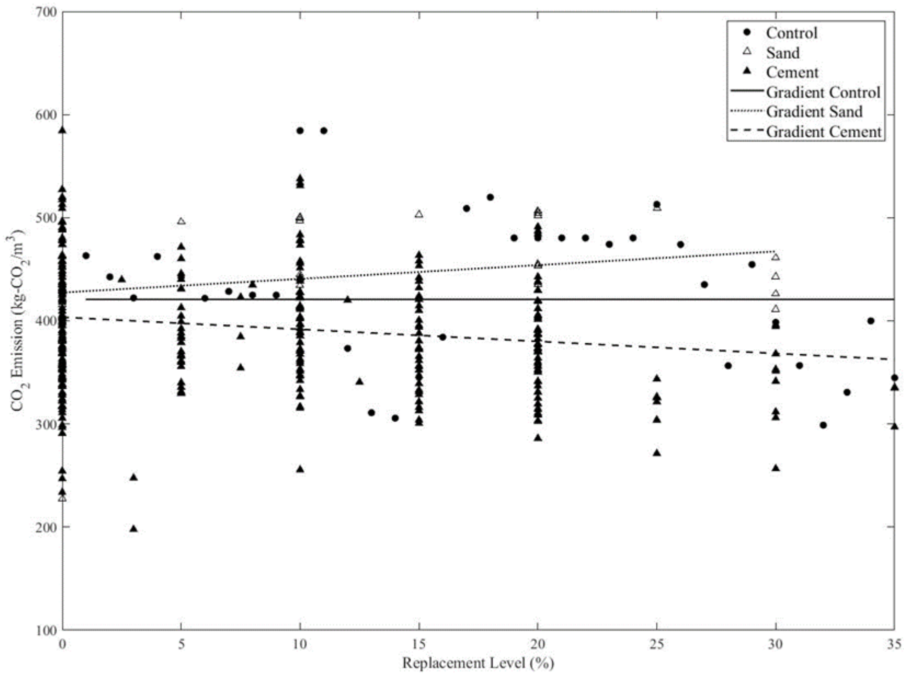

Figure 7.2: CO2 emissions of ●; concrete control (87 data points), ▲; concrete containing RHA as cement replacement (455 data points), ∆; concrete containing RHA as sand replacement (45 data points).

Figure 7.2 demonstrates the CO_2 emissions of concrete containing RHA used both as cement and sand replacements. It is clearly shown in Figure 7.2 that the utilisation of RHA as a binder substitution considerably reduces the CO_2 emissions of concrete due to the reasons aforementioned. The incorporation of RHA as a sand replacement, however does not positively influence in reducing the CO_2 emissions of concrete and, in fact, accelerates the CO_2 emissions further when compared to the control concrete. Although the use of RHA as a sand replacement may appear to adversely influence the CO_2 emissions of concrete, demolition and destruction of natural resources to acquire the necessary aggregates in concrete making have negative impact on environmental sustainability. Replacing fine and coarse aggregates with RHA enables a great reduction on the natural resources and hence reduces the ecological deprivation and sustains environmental conservation.

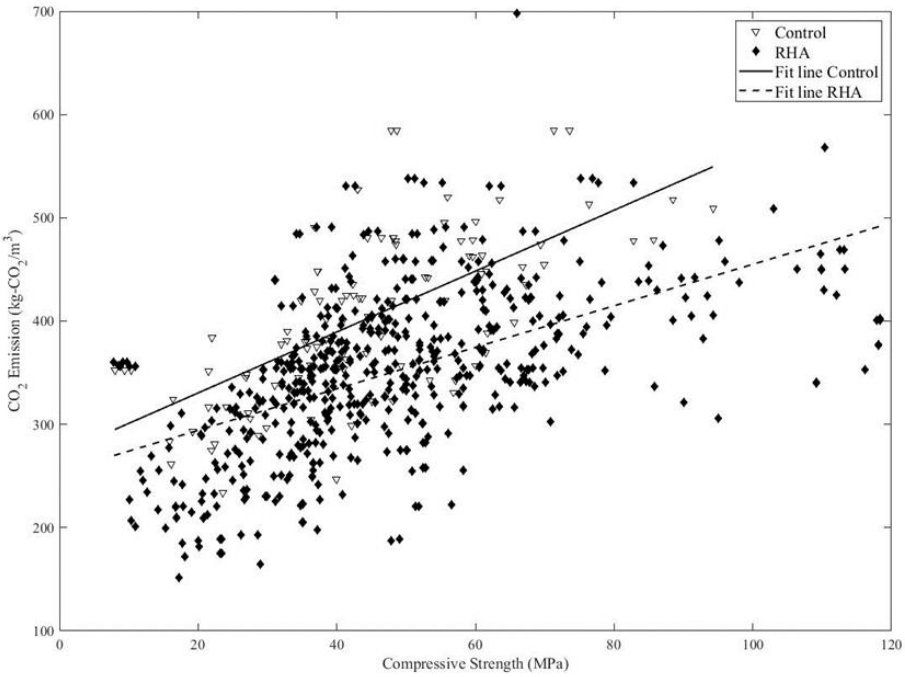

Figure 7.3: CO_2 emissions of; concrete control (103 data points), ♦; concrete containing RHA as cement replacement (580 data points).

CO_2 emissions are plotted versus the compressive strength of concrete and concrete containing RHA in Figure 7.3. It is evidently exhibited in Figure 7.3 that the concrete (the control concrete) provided high CO_2 emissions at all ranges of compressive strength examined in the database when compared to the concrete comprising RHA.

This is expected as the control concrete contains higher amount of cement than that of the concrete comprising RHA at all strength ranges, which yields high CO_2 emissions to be generated. In addition to the substantial decrease attained in CO_2 emissions when RHA is used at all ranges of compressive strength of concrete, Figure 7.3 also exhibited that increase in the compressive strength of concrete both control and concrete comprising RHA demonstrated a considerable increase in the CO_2 emissions. The higher CO_2 emissions attained in these particular cases are attributed to the increased amount of binder and the raw materials used in making high-strength concrete.

It must be noted that the considerable amount of CO_2 emissions generated during the production of the raw materials are reabsorbed during the carbonation of cement-based materials (Guo et al., n.d.; Xi et al., 2016; Yang et al., 2014). Although there are conflicting rates reported by individual researchers in the literature, the average reabsorption rate is stated to be 43% between 1930 to 2013 (Xi et al., 2016). This is attributing that the significant amount of CO_2 emitted during the production of the raw materials is reabsorbed during the lifespan of cement-based materials.

7.2 Cost Efficiency Factor

The cost efficiency factor of concrete containing RHA as well as concrete containing both RHA and pozzolans are shown in Figure 7.4. The cost efficiency factor of control concrete is also added in Figure 7.4 for comparison. It is previously shown in the paper that the incorporation of RHA as cement replacement increases the strength of concrete. The use of pozzolans in conjunction with the RHA further results in the additional formation of calcium-silicate-hydrate gels and hence improves the hydraulic binding capacity of the matrix. Replacing the binder with RHA and pozzolans also reduces the total cost of the mixture as these materials have usually lower unit prices than the cement binder itself. It is revealed in Figure 7.4

that the cost efficiency of concrete containing RHA is systematically rising with the increased substitution level of RHA. The increase in the cost efficiency of concrete containing RHA is attributed to the significant increase in the strength of concrete and an accompanying reduction in the total cost of the mixture. The use of pozzolans that further enhanced the strength of concrete and resulted in a further reduction in the cost of such mixtures led to a 65% increase in the cost efficiency of concrete.

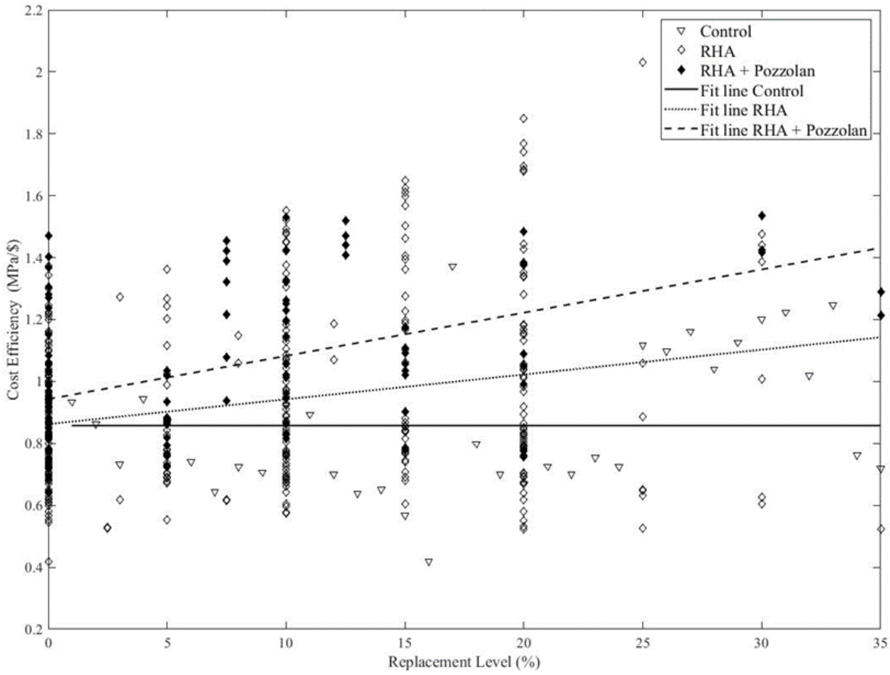

Figure 7.4: Cost efficiency factor of; concrete control (87 data points), ◊; concrete containing RHA (314 data points), ♦; concrete containing RHA and pozzolans (141 data points).

Figure 7.5 demonstrates the cost efficiency of concrete containing RHA used both as cement and sand replacements. It is clearly shown in Figure 7.5 that the utilisation of RHA as a binder substitute noticeably increases the cost efficiency of concrete due to the substantial increase in strength in conjunction with the decrease in the overall cost of these mixtures. The incorporation of RHA as a sand replacement does not improve the cost efficiency of concrete as in the case of binder replacement. The reduction in the cost efficiency of concrete containing RHA as sand replacement, compared to the case of binder replacement, is mainly attributed to the lower increase attained in the strength as well as the lower reduction conquered in total cost of the mixture. It must be emphasized in the paper that the performance of the replacement type of RHA is already examined in Section 5.2 and that cement replacements of RHA were reported to have more influential results on the strength of concrete. It is, therefore, unsurprising to observe that the utilisation of RHA as cement replacement has significantly improved the cost efficiency of concrete and that the adverse performance is exhibited in the case of sand replacement.

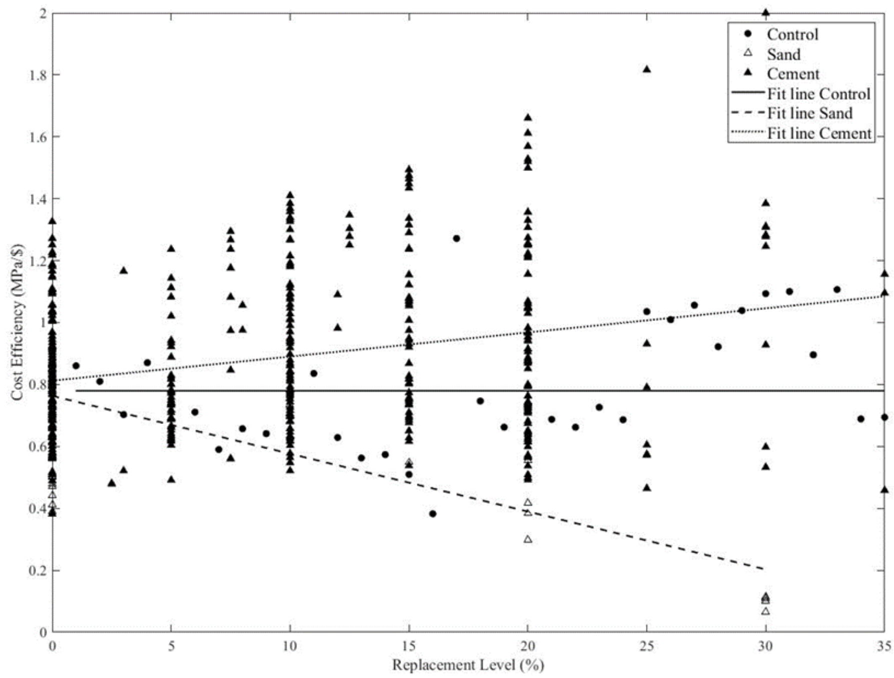

Figure 7.5: Cost efficiency of ●; concrete control (87 data points), ▲; concrete containing RHA as cement replacement (455 data points), Δ; concrete containing RHA as sand replacement (45 data points).

7.3 Eco-Strength Efficiency Factor

The eco-strength efficiency factor of concrete containing RHA and concrete containing both RHA and pozzolans are shown in Figure 7.6. The eco-strength efficiency factor of control concrete is also added in Figure 7.6 for comparison. The results shown in Figure 7.6 eminently demonstrated that the rise in the substitution level of RHA, used as cement replacement, resulted in a systematic increase in the eco-strength efficiency of concrete. The substantial increase in strength as well as the associated reductions in the CO_2 emissions of the mixture, previously reported in the paper, simultaneously played a determining role on the rise in the eco-strength efficiency of concrete. The utilisation of pozzolans has already been shown to result in a substantial increase in strength and further reduction in the overall cost of the mixtures. These prominent factors further enhanced the eco-strength efficiency of pozzolanic concrete containing RHA.

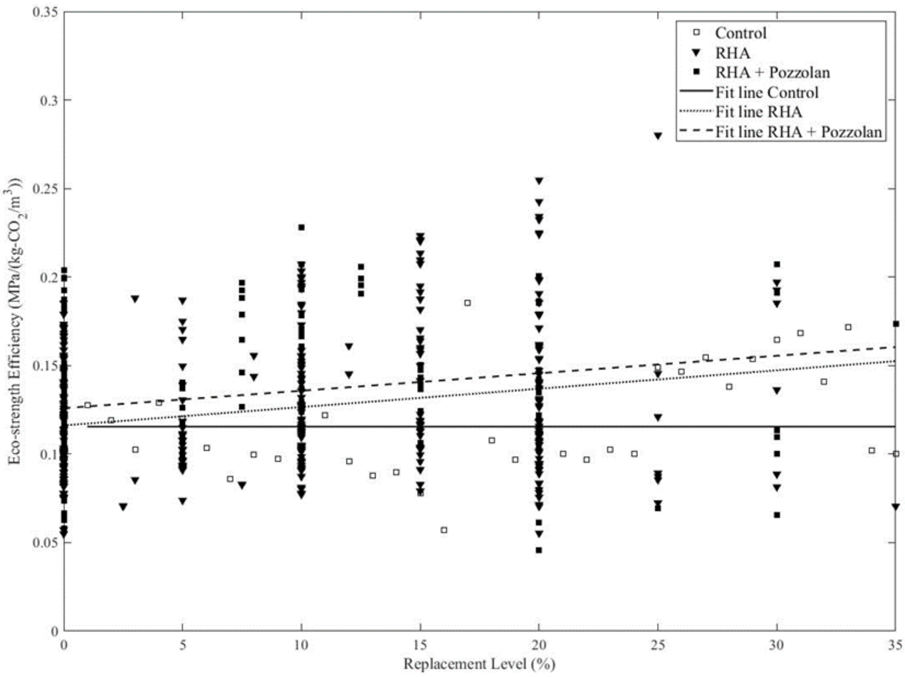

Figure 7.6: Eco-strength efficiency factor of □; concrete control (87 data points), ▼; concrete containing RHA (314 data points), ■; concrete containing RHA and pozzolans (141 data points).

It is shown in Figure 7.7 that use of RHA as sand replacements did also not improve the eco-strength efficiency of concrete as much as in the case of the cement replacement. The results demonstrated in Figure 7.7 are in a good correlation with the results demonstrated in Figure 7.5. The reduction in the eco-strength efficiency of concrete containing RHA as sand replacement, compared to the case of binder replacement, is mainly attributed to the lower increase attained in the strength as well as the lower decrease conquered in total CO2 emissions of the mixture.

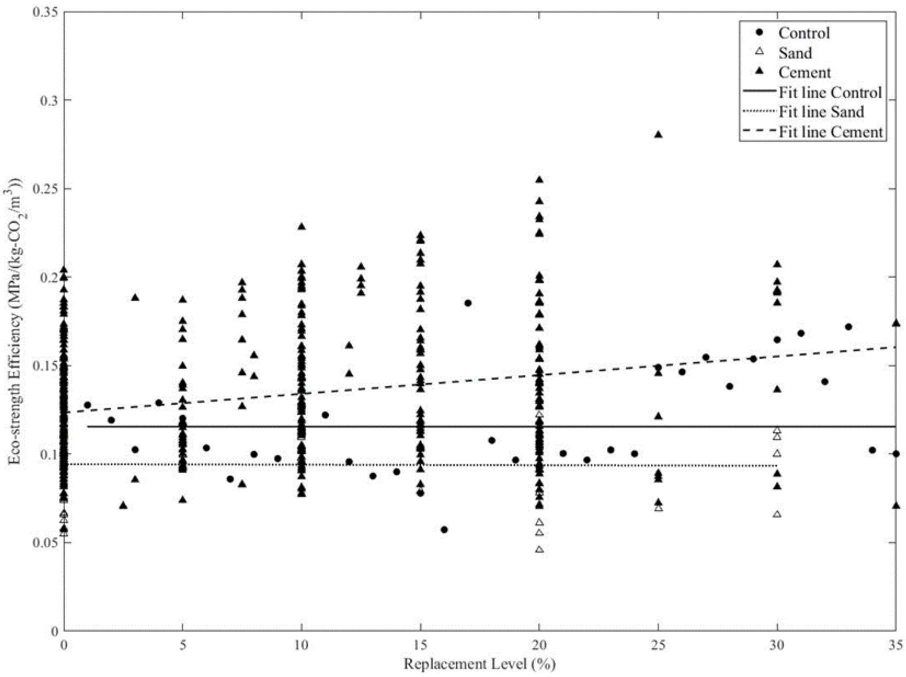

Figure 7.7: Eco-strength efficiency of ●; concrete control (87 data points), ▲; concrete containing RHA as cement replacement (455 data points), Δ; concrete containing RHA as sand replacement (45 data points).

CHAPTER 8

LIFE CYCLE ASSESSMENT OF POZZOLANIC CONCRETE CONTAINING RICE HUSK ASH

8.1 Introduction

In this chapter, life cycle analysis are conducted according to the results and boundary conditions attained in Chapters 5 and 6. Models, concrete comprising RHA and pozzolanic replacements, are defined using the boundary conditions to conduct the analysis in openLCA 1.10.3 software. The majority of the steps adapted for the analysis in LCA are briefly reported in Chapter 4. The essential steps in defining materials’ embodied energy and the stages that were taken into account in this approach are clearly defined. The openLCA software is used to assess the impact of RHA utilisation in concrete on climate change (GWP100), human toxicity level (HTPinf), marine ecotoxicity (METPinf), ozone depletion (ODPinf), and water depletion (WDP).

As it is already stated in Chapter 4, raw materials such as cement, sand, gravel are already defined in Chapter 4. A new flow and process have been defined on the model for RHA, which is the study's primary objective. Some of the studies suggested that, since rice husk is used as a biomass source, only the energy arising from transportation has been taken into account (Gursel et al., 2016; Şahan Arel & Aydin, 2018). Another study reported that rice husk should be burned in designated conditions to have favorable properties, such as fineness and chemical composition (Muthadhi & Kothandaraman, 2010). These processes require a certain amount of energy (Karim et al., 2011). On the other hand, it is stated in some publications that energy gained by the incineration of rice husk should be considered (Zerbino et al., 2011b). Considering the aforementioned statements, it was determined to take transportation of RHA into account in the analysis.

Silica fume is a byproduct of silicon and ferrosilicon alloys in smeltering process (Sandeep Kauthsa Sharma et al., 2021; Siddique & Chahal, 2011). Although there are aforementioned production differences in the literature, it has been observed that the substitution of silica fume into concrete increases its strength due to its pozzolanic properties. According to the Jamieson et al. (2015), it was seen that the range for silica fume production was 0.05-0.1 MJ/kg in the literature (by considering the capture and mining processes), and it was accepted as 0.1 MJ/kg for this study (McLellan et al., 2011, 2012). It was, therefore, determined to take into account the production and the transportation activities into account for silica fume.

Fly ash is a byproduct of a coal-burning process. Although the process for fly ash is slightly different from the silica fume, 0.1 MJ/kg as a production considering capture and separation processes, and transportation energy is used in the analysis to be conservative (Jamieson et al., 2015; McLellan et al., 2011, 2012).

For metakaolin, activities such as crushing, calcination, milling, and sieving are taken into account to estimate the energy consumption, which brought 63 kWh (~226.8 MJ) per tonne (Abbas et al., 2020). Transportation is also taken into account for this pozzolanic material.

In the same way, preparation, drying, and grinding processes are taken into account for slag production in this study. 95 kWh/t (~342 MJ/t) total energy is used for slag along with the transportation activity (Dunlap, 2003).

Input flows and flow properties are summarised in Table 8.1

Table 8.1: Flow types and properties defined in openLCA

Flow name	Flow type	Flow property
Cement	Product	Mass
Sand	Product	Mass
Gravel	Product	Mass
Water	Product	Mass

Silica Fume	Product	Mass
Fly Ash	Product	Mass
Metakaolin	Product	Mass
Slag	Product	Mass
RHA	Product	Mass
Transportation of raw materials	Product	Mass
Concrete	Product	Volume

After that, processes were created using the flows adapted from the approach of de Fatima Dias (2019) as shown in Table 8.2. The ELCD data as well as the data carefully determined from the literature are defined for the assessment of sustainability indices.

Table 8.2: Processes involving data of the functional unit

Process	Quantitive reference	Input flows
Cement Production	Cement	Portland cement
Sand Production	Sand	Sand
Gravel Production	Gravel	Gravel
RHA Production	RHA	RHA
Silica fume production	Silica Fume	Silica Fume Electricity mix
Metakaolin production	Metakaolin	Metakaolin Electricity mix
Fly ash production	Fly Ash	Fly Ash Electricity mix
Slag Production	Slag	Slag

		Electricity mix
Raw material transported	Transportation of raw materials	Chosen raw materials for the model (e.g. cement, sand, RHA) Transportation (150 km assumed) Water
Model Concrete	Concrete	Transported raw materials Electricity (2775 MJ assumed) (Singh et al., 2020)

8.1.1 Models Defined for Life Cycle Assessment

Models were established to evaluate the performance of RHA and pozzolans used as a replacement material in concrete on the life cycle assessment. To attain the raw materials for model 1, concrete control (the data points that do not involve RHA and pozzolans) is taken into account. The raw materials specifically are determined by taking the average of each raw material in the database. The quantities of the raw materials used to define each model are given in Table 8.3.

Model 2 mainly considered concrete specimens that comprise RHA without the use of pozzolanic material. Model 2a was then established using concrete specimens with RHA utilised only as cement replacement. The optimum replacement level of RHA using as a cement replacement is determined to be 30-40% previously in Chapters 5 and 6. However, replacement levels of RHA used as cement replacement is taken to be 30% to be more conservative. Model 2b is established on concrete specimens comprising RHA only as fine aggregate. Likewise, it was found appropriate to determine the optimum replacement level of RHA as to be 20%.

Model 3 generally specifies concrete specimens comprising both RHA and pozzolanic replacement materials. Pozzolanic replacement levels are initially determined in Chapters 5 and 6. The most commonly used pozzolans are determined to be metakaolin, fly ash, slag, and silica fume, similarly in previous Chapters 5 and 6. The determination of optimum replacement levels of each pozzolan initially is studied in detail in Chapters 5 and 6. These are now summarised in Table 8.3. Although analysis in Chapter 6 might slightly provide varying optimum replacement levels for these pozzolans, a conservative approach is taken in this thesis. Therefore, the smallest percentages of the optimum replacement levels attained through Chapters 5 and 6 are used in the analysis. Models are defined in openLCA as shown in Appendix B.

Table 8.3: Model names and ingredients

Model Name	Code	Ingredients
Control	Model 1	
RHA Cement Replacement	Model 2a	30% RHA
RHA Sand Replacement	Model 2b	20% RHA
RHA cement replacement with silica fume	Model 3a1	30% RHA + 15% silica fume
RHA cement replacement with fly ash	Model 3a2	30% RHA + 30% fly ash
RHA cement replacement with metakaolin	Model 3a3	30% RHA + 15% metakaolin
RHA cement replacement with slag	Model 3a4	30% RHA + 30% slag

RHA sand replacement with silica fume	Model 3b1	20% RHA + 15% silica fume
RHA sand replacement with fly ash	Model 3b2	20% RHA + 30% fly ash
RHA sand replacement with metakaolin	Model 3b3	20% RHA + 15% metakaolin
RHA sand replacement with slag	Model 3b4	20% RHA + 30% slag

8.2 Life Cycle Impact Assessment (LCIA)

Life cycle impact assessment of concrete comprising RHA is detailed in this section of the thesis. First of all, the use of RHA as a cement and sand replacements are considered. Afterward, the use of RHA along with the pozzolanic replacements are assessed in the thesis within the impact categories that are global warming potential (GWP 100), freshwater ecotoxicity (FETPinf), human ecotoxicity (HTPinf), marine ecotoxicity (METPinf), ozone depletion (ODPinf), water depletion (WDPinf).

8.2.1 Influence of the use of RHA

The impact assessment is conducted with the ReCiPe midpoint approach on the models determined considering the results obtained in Chapters 5 and 6. Global warming potential is the calculation for the measurement of heat capture in terms of CO_2.

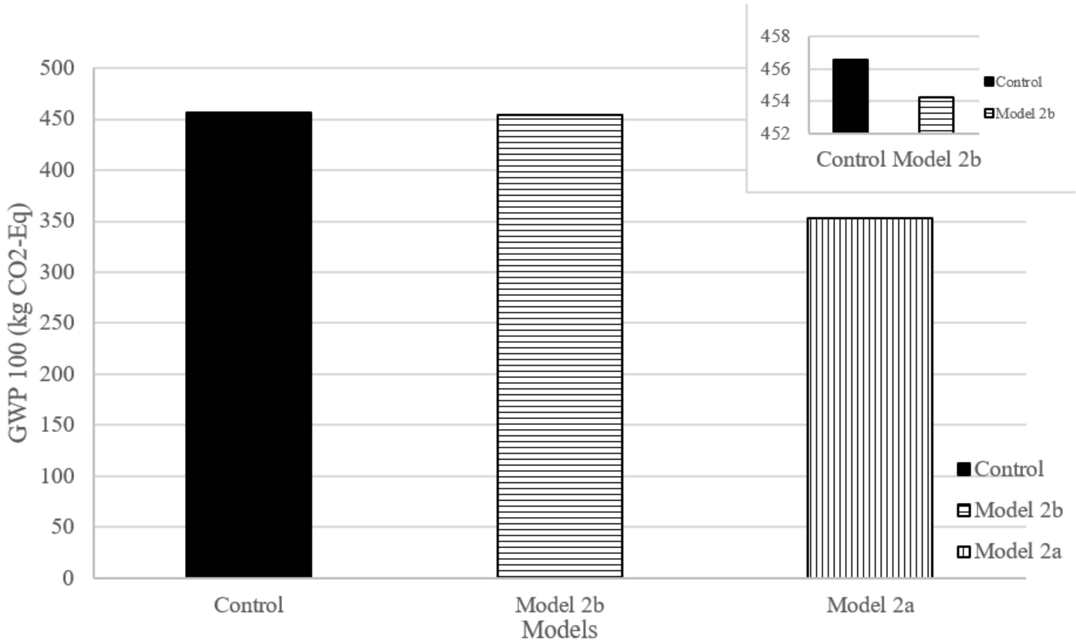

Figure 8.1: Global warming potential of Models Concrete, 2a and 2b

It is shown in Figure 8.1 that the RHA is used both as cement and sand replacement in concrete. It is evidently shown in Figure 8.1 that the incorporation of 30% RHA used as cement replacement dramatically reduced the global warming potential in 100-year horizon (GWP 100). Incorporation of 20% RHA used as sand replacement, on the other hand, resulted in a slight reduction in the global warming potential. Although the decrease attained in global warming potential in 100-year horizon (GWP 100) might look much smaller when RHA is used as sand replacement, the impact of the use of RHA as sand replacement should not be underestimated. Replacing fine aggregates, basic raw materials using with RHA is an important action in terms of conserving the natural resources, and avoiding environmental degradation (Ahmad et al., 2021; Yunus et al., 2016).

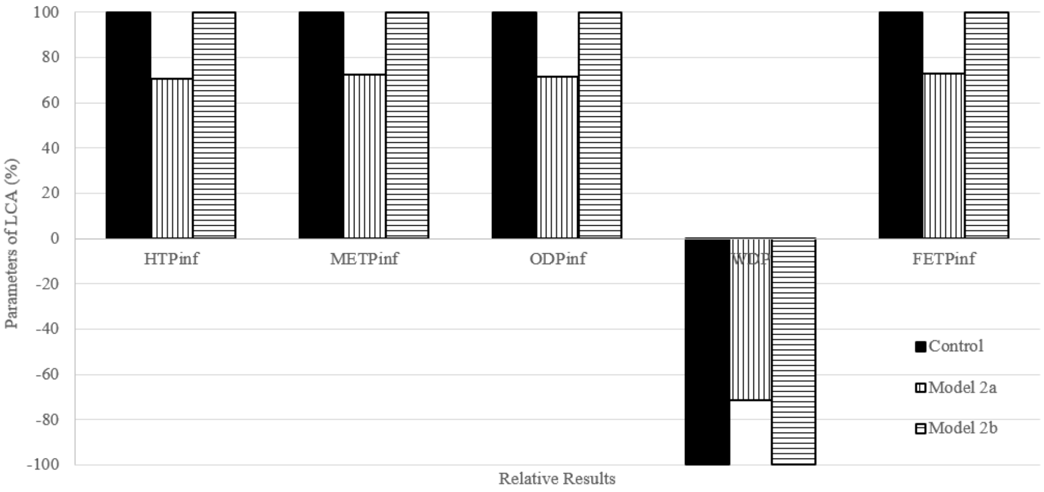

Figure 8.2: Relative results of life cycle impact categories of Models control, 2a and 2b

Parameters such as global warming potential (GWP 100), freshwater ecotoxicity (FETPinf), human ecotoxicity (HTPinf), marine ecotoxicity (METPinf), ozone depletion (ODPinf), water depletion (WDPinf) are examined to assess the life cycle impact of the RHA used as a substitute material in concrete. Similar to the results already shown in Figure 8.2, the use of RHA as a cement replacement dramatically reduced the global warming potential (GWP 100), freshwater ecotoxicity (FETPinf), human ecotoxicity (HTPinf), marine ecotoxicity (METPinf), ozone depletion (ODPinf), water depletion (WDPinf). Human toxicity, an index related to the harm based on the dose and toxicity of a compound (Hertwich et al., 2001), has been closely associated with freshwater ecotoxicity. Results have indicated that almost 30% reduction in human toxicity is achieved with the nearly 27% reduction in freshwater ecotoxicity. Although the reduction attained on global warming potential (GWP 100), freshwater ecotoxicity (FETPinf), human ecotoxicity (HTPinf), marine ecotoxicity (METPinf), ozone depletion (ODPinf), water depletion (WDPinf) parameters, are much smaller compared to the case when RHA is used as cement replacement, the significance of this practice should not also be underestimated.

8.2.2 Influence of the use of pozzolans on concrete containing RHA as cement replacement

The influence of the RHA along with the utilisation of the pozzolans are investigated with respect to mechanical properties and durability characteristics of concrete in associated sections in Chapters 5 and 6. Based on these investigations, the boundary conditions that state the optimum replacement level and type of the RHA and the most commonly used pozzolans are determined previously. Model 3 states concrete comprising RHA and the incorporation of pozzolans. Model 3a1, 3a2, 3a3 and 3a4 indicate the utilisation of silica fume, fly ash, metakaolin, and slag, respectively.

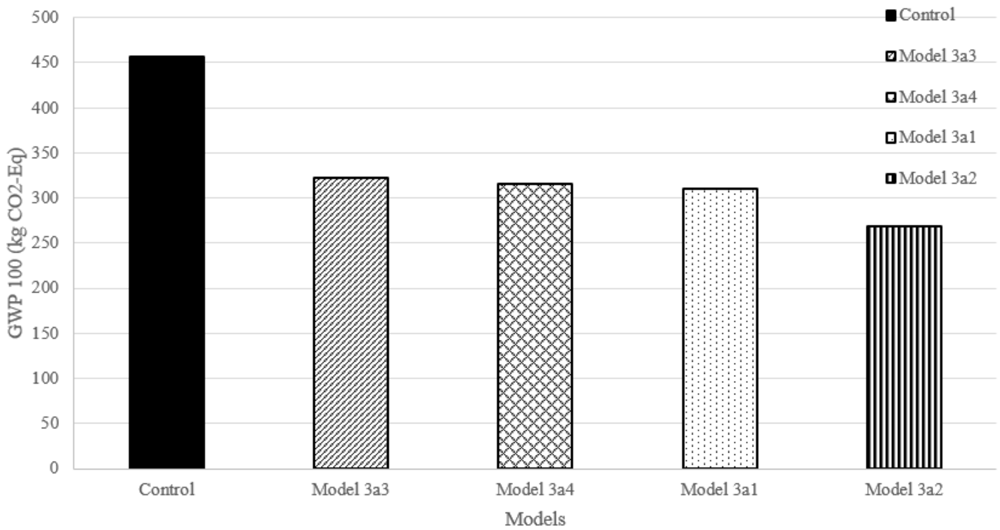

Figure 8.3: Global warming potential of Models control, 3a1, 3a2, 3a3 and 3a4

The results shown in Figure 8.3 attributes that the utilisation of RHA along with the pozzolans results in a substantial decrease in the global warming potential. When the results shown in Figure 8.3 is clearly studied, it can be easily seen that the use of fly ash along with the RHA resulted in the greatest decrease in the global warming potential. This must be associated with the low CO2 emission rates of fly ash. It is common knowledge in the literature (Shine, 2009) that the global warming potential, an index for greenhouse gas emissions, is closely associated with climate change (Boucher et al., 2009). The reduction in the global warming potential is in the range of 30% to 40% with respect to the silica fume, fly ash, metakaolin, and slag in concrete making. This great achievement is mainly due to the replacement of a carbon intensive binder, cement, with the RHA and the pozzolanic materials.

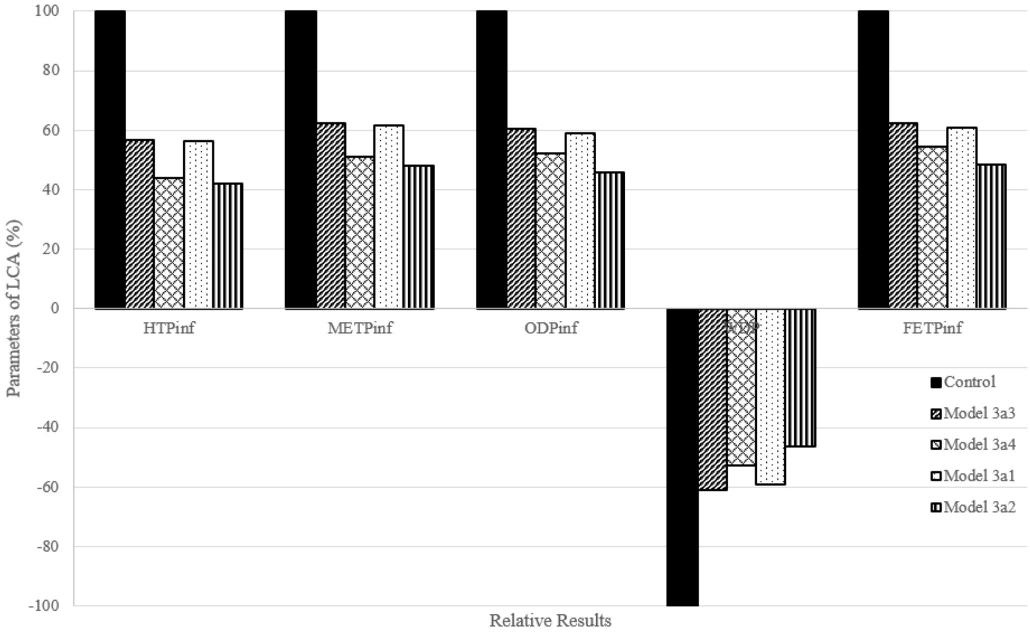

Figure 8.4: Relative results of life cycle impact categories of Models control, 3a1, 3a2, 3a3 and 3a4

The relative results of global warming potential (GWP 100), freshwater ecotoxicity (FETPinf), human ecotoxicity (HTPinf), marine ecotoxicity (METPinf), ozone depletion (ODPinf), water depletion (WDPinf) of concrete comprising RHA and pozzolans are shown in Figure 8.4. The results shown in Figure 8.4 exhibit that the reduction in the cement binder yielded a significant reduction in these sustainable indices, and that utilisation of pozzolans further enhanced the decrease in these sustainability indices. The results shown in Figure 8.4 must be emphasized as the great reduction in global warming potential is also leading, for instance, a great reduction in ozone depletion, that depends on the temperature, weather, etc. (Boyes & Stanisstreet, 1997; Shine, 2009). The decrease attained in ozone depletion would essentially avoid the associated health and skin problems (Norval et al., 2007) on humans. It must also be pointed out that the utilisation of both RHA and pozzolans also yielded a 50% reduction in human toxicity along with the 40% reduction. These are associated parameters that globally improve the sustainability perspectives of the environment.

8.2.3 Influence of the use of pozzolans on concrete containing RHA as sand replacement

The influence of the use of RHA as sand replacement along with the pozzolans on the sustainability impact categories of concrete is assessed in this section. As aforementioned, replacement types and levels of RHA and pozzolans using concrete making are previously determined, and necessary boundary conditions are established. Model 3b1, 3b2, 3b3, and 3b4 associates the utilisation of silica fume, fly ash, metakaolin, and slag, respectively.

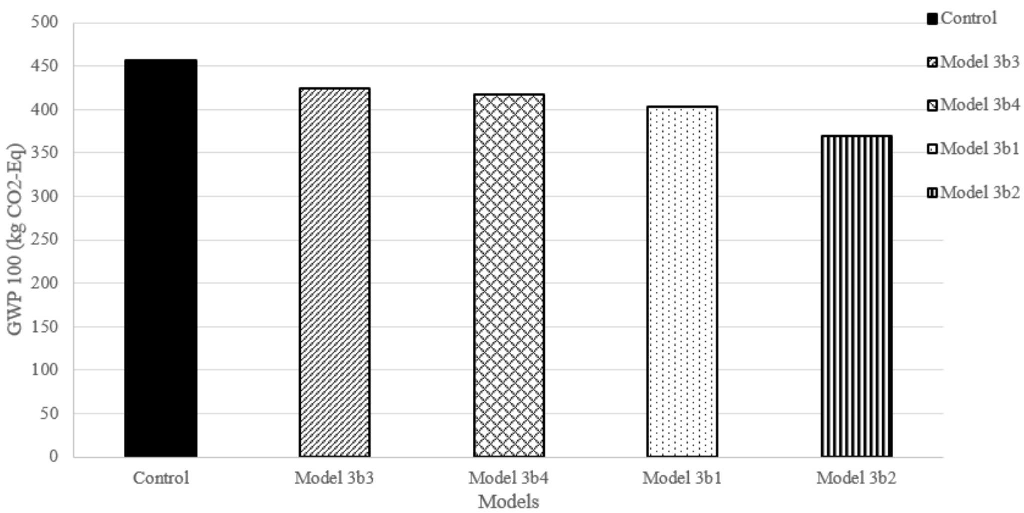

Figure 8.5: Global warming potential of Models: Control, 3b1, 3b2, 3b3 and 3b4

It is demonstrated in Figure 8.5 that the utilisation of RHA as sand replacement along with the pozzolans resulted in a considerable in global warming potential. The results have shown that utilisation of fly ash generated the greatest reduction on GWP on concrete incorporating RHA. When the results shown in Figure 8.5 are compared with concrete comprising RHA and pozzolans used as cement replacement, it can be easily seen that the use of RHA as sand replacement resulted in a lesser decrease in the global warming potential of concrete. It is common knowledge that excessive use of sand, a nonrenewable natural resource, has been the practice for years (Bartlett, 1980). Although the results stated that the use of sand yielded a lesser reduction in the index categories compared to that of the cement replacement, it must be emphasized that these resources should be efficiently used to preserve to avoid environmental degradation and maintain the environmental sustainability.

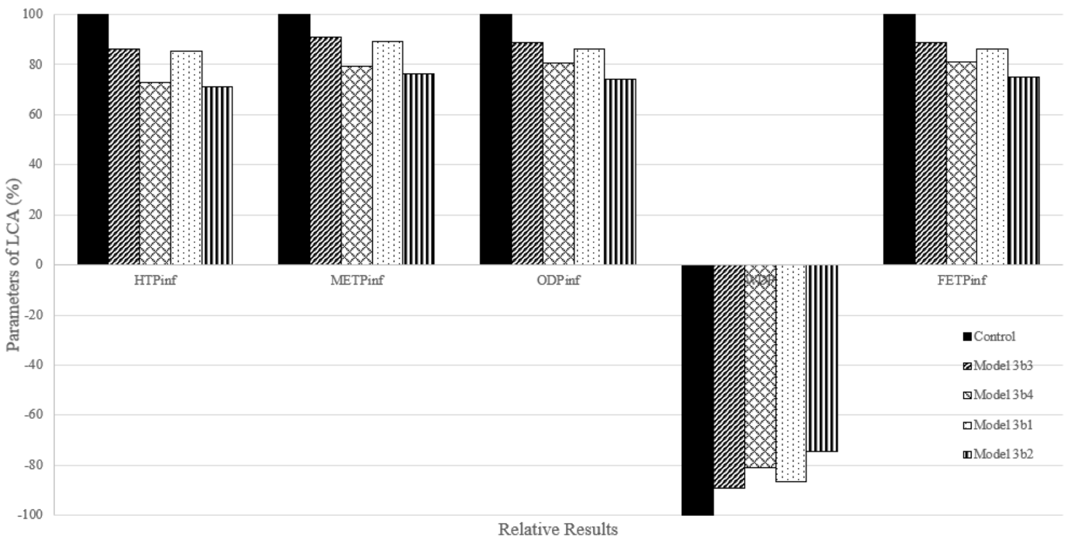

Figure 8.6: Relative results of life cycle impact categories of Models control, 3b1, 3b2, 3b3 and 3b4

When the associated parameters of life cycle impact categories such as global warming potential (GWP 100), freshwater ecotoxicity (FETPinf), human ecotoxicity (HTPinf), marine ecotoxicity (METPinf), ozone depletion (ODPinf), water depletion (WDPinf) are studied in Figure 8.6, it is shown that the utilisation of RHA as sand replacement along with the pozzolans in concrete yields in the range of 7 to 29% reduction in these indices. Similar to Figure 8.5 above, utilisation of 30% fly ash also resulted in the greatest reduction in the associated indexes analysed in this thesis. For instance, when these indices are studied independently, it is shown that approximately 25% of water depletion is achieved by the use of 20% RHA utilisation as sand replacement along with the most commonly used pozzolans. It was essentially important to decrease freshwater ecotoxicity and marine ecotoxicity that are the two important factors associated with the toxic substances. Results have already shown that 25% reduction can be observed in freshwater ecotoxicity along with the 24% reduction in marine ecotoxicity. These are important achievements, and it must be emphasized in the thesis that these substantial reductions on the sustainability indices are only attained by replacing the raw materials such as cement and sand with RHA and most commonly used pozzolans.

CHAPTER 9

CONCLUSION

The thesis begins with an assessment on the key factors that have eminent influences on the mechanical and durability properties of concrete incorporating RHA. Comprising a large database was vital to gain an insight into the actual performance of RHA in concrete as well as to determine the boundary conditions that were essential to implement in the sustainability analysis in the former section. The sustainability components such as CO_2 emissions, cost efficiency, and eco-strength efficiency attained during this practice are investigated in the thesis for the first time. In addition, life cycle assessment is performed by considering the boundary conditions found in Chapters 5 and 6. Life cycle impact categories such as global warming potential (GWP 100), freshwater ecotoxicity (FETPinf), human ecotoxicity (HTPinf), marine ecotoxicity (METPinf), ozone depletion (ODPinf), water depletion (WDPinf) are used for the analysis. The key findings of this research are summarised herein:

It is shown in the thesis that the water:binder ratio played a vital role in determining the optimal replacement level of RHA. The results have revealed that the water:binder ratio in the range of 0.3 to 0.6 were found to provide the most accomplished strength values of concrete containing RHA. The database study also indicated that the compressive strength values lower than 20MPa and greater than 100MPa were not practically acceptable and applicable on-site, respectively, and therefore were disregarded from the study. The most effective replacement type was found to be the binder replacement of RHA when used up to 35% replacement level. The use of pozzolans demonstrated a clear enhancement on the strength of concrete containing RHA. The fly ash, silica fume, metakaolin, and slag were designated as the most commonly used and effective pozzolanic additions to concrete containing RHA.

Durability characteristics of concrete containing RHA and pozzolans are studied in Chapter 6. Similar to Chapter 5, the major aspect of studying the performance of concrete comprising RHA and pozzolans was to determine the optimum replacement level and type of these materials. It was established that 30% RHA could be used as cement substitute, whereas 20% RHA was convenient to be used as sand substitute. The results associated with the pozzolanic additions were in line with the results attained in Chapter 5, and hence, 15% silica fume, 15% metakaolin, 30% fly ash, and 30% slag are found to be conservative to consider as a pozzolanic addition in concrete along with the associated RHA replacements, and therefore, these limits form the boundary conditions of this thesis. It was, therefore, important to perform the sustainability indices as well as the life cycle assessment of concrete comprising RHA and pozzolans using the carefully determined values in the boundary conditions.

The results have shown that the use of RHA in conjunction with the pozzolans as cement replacement had a dramatic influence in reducing the carbon footprint significantly, which is shown in Chapter 7. This is attributed to the reduced demand for cement that results in a substantial decrease in the process-related emissions as well as fuel combustion and therefore essentially contributes to reducing the carbon footprints.

Cost efficiency and eco-strength efficiency of concrete have shown to improve significantly when incorporated with RHA and pozzolans. The substantial increase in strength and the associated reduction in the CO_2 emissions, as well as the reduction in the total cost of such mixtures, were the decisive mechanism responsible for this phenomenon.

Life cycle assessment, conducted using openLCA software, demonstrated that the use of RHA and the pozzolans substantially resulted in an essential decrease in (GWP 100), freshwater ecotoxicity (FETPinf), human ecotoxicity (HTPinf), marine ecotoxicity (METPinf), ozone depletion (ODPinf), water depletion (WDPinf) parameters. The greatest achievement is attained when RHA is used as cement replacement with fly ash. In this case, 41% reduction in the global warming potential and 54% reduction in ozone depletion is attained, which serves the global development of sustainable ecology. The results obtained using life cycle assessment have shown great agreement with the previously attained results on sustainability indices. Similar reductions in the CO2 emissions already attained in Chapter 7, which are preliminary results have already indicated that 25% reduction in the CO_2 emissions using manual approaches.) Results attained from life cycle assessment have validated the presence of sustainability indices previously assessed in the thesis.

Although reducing the clinker-to-cement ratio and the deploying innovative technologies could dramatically improve the sustainable manufacture of cement, the latter often is not the optimal case in developing countries. This thesis reports important results with regards to the reduced clinker-to-cement ratio and hence contributes to the reduction of the most direct emissions in this context.

Considering that the rice industry generates approximately 156 million tons of rice husk annually, the waste disposal method, addressed in the thesis, should not be underestimated, particularly when compared to the existing waste management alternatives that often cause contamination and pollution.

The research results reported in this thesis reinforce the recourses that can basically be implemented for the sustainable development of concrete in construction practice.

REFERENCES

Abbas, R., Khereby, M. A., Hanaa, ·, Ghorab, Y., Elkhoshkhany, · N, Ghorab, H. Y., & Elkhoshkhany, N. (2020). Preparation of geopolymer concrete using Egyptian kaolin clay and the study of its environmental effects and economic cost. *Clean Technologies and Environmental Policy*, *22*, 669–687. https://doi.org/10.1007/s10098-020-01811-4

Agarwal, S. K., & Gulati, D. (2006). Utilization of industrial wastes and unprocessed micro-fillers for making cost effective mortars. *Construction and Building Materials*, *20*(10), 999–1004. https://doi.org/10.1016/J.CONBUILDMAT.2005.06.009

Agricultural Development Economics Division Economic and Social Development Department, F. (2009). *Global agriculture towards 2050*.

Ahmad, W., Ahmad, A., Ostrowski, K. A., Aslam, F., & Joyklad, P. (2021). A scientometric review of waste material utilization in concrete for sustainable construction. *Case Studies in Construction Materials*, *15*, e00683. https://doi.org/10.1016/J.CSCM.2021.E00683

AlBiajawi, M. I., Embong, R., & Muthusamy, K. (2022). An overview of the utilization and method for improving pozzolanic performance of agricultural and industrial wastes in concrete. *Materials Today: Proceedings*, *48*, 778–783. https://doi.org/10.1016/J.MATPR.2021.02.260

Algren, M., Fisher, W., & Landis, A. E. (2021). Machine learning in life cycle assessment. *Data Science Applied to Sustainability Analysis*, 167–190. https://doi.org/10.1016/B978-0-12-817976-5.00009-7

Alnahhal, M. F., Alengaram, U. J., Jumaat, M. Z., Abutaha, F., Alqedra, M. A., & Nayaka, R. R. (2018). Assessment on engineering properties and CO2 emissions of recycled aggregate concrete incorporating waste products as supplements to Portland cement. *Journal of Cleaner Production*, *203*, 822–835. https://doi.org/10.1016/J.JCLEPRO.2018.08.292

Alston, J. M., & Pardey, P. G. (2014). Agriculture in the Global Economy. *Journal of Economic Perspectives*, *28*(1), 121–146. https://doi.org/10.1257/JEP.28.1.121

Ambedkar, B., Alex, J., & Dhanalakshmi, J. (2017). Enhancement of mechanical properties and durability of the cement concrete by RHA as cement replacement: Experiments and modeling. *Construction and Building Materials*, *148*, 167–175. https://doi.org/10.1016/J.CONBUILDMAT.2017.05.022

Ampadu, K. O., & Torii, K. (2002). Chloride ingress and steel corrosion in cement mortars incorporating low-quality fly ashes. *Cement and Concrete Research*, *32*(6), 893–901. https://doi.org/10.1016/S0008-8846(02)00721-4

Bahri, S., Mahmud, H. B., & Shafigh, P. (2018). Effect of utilizing unground and ground normal and black rice husk ash on the mechanical and durability properties of high-strength concrete. *Sadhana - Academy Proceedings in Engineering Sciences*, *43*(2), 1–12. https://doi.org/10.1007/S12046-018-0795-0/FIGURES/13

Balapour, M., Ramezanianpour, A. A., & Hajibandeh, E. (2017). An investigation on mechanical and durability properties of mortars containing nano and micro RHA. *Construction and Building Materials*, *132*, 470–477. https://doi.org/10.1016/J.CONBUILDMAT.2016.12.017

Bartlett, A. A. (1980). Comments on long-term aspects of renewable vs nonrenewable resource substitution. *American Journal of Physics*, *54*(5), 398–402. https://doi.org/10.1119/1.14600

Bhuvaneshwari, S., Hettiarachchi, H., & Meegoda, J. N. (2019). Crop Residue Burning in India: Policy Challenges and Potential Solutions. *International Journal of Environmental Research and Public Health 2019, Vol. 16, Page 832*, *16*(5), 832. https://doi.org/10.3390/IJERPH16050832

Bolla, R. K., Ratnam, M. K. M. V., & Raju, U. R. (2015). Experimental Studies on Concrete with Rice Husk Ash as a Partial Replacement of Cement Using Magnesium Sulphate Solution. *IJIRST-International Journal for Innovative Research in Science & Technology*|, *1*. www.ijirst.org

Boucher, O., Friedlingstein, P., Collins, B., & Shine, K. P. (2009). The indirect global warming potential and global temperature change potential due to methane oxidation. *Environmental Research Letters*, *4*(4), 044007. https://doi.org/10.1088/1748-9326/4/4/044007

Boyes, E., & Stanisstreet, M. (1997). *Children's Models of Understanding of Two Major Global Environmental Issues (Ozone Layer and Greenhouse Effect)*. https://doi.org/10.1080/0263514970150102

Brown, D. K. (2012). *Unprocessed rice husk ash as a partial replacement of cement for low-cost concrete* [Massachusetts Institute of Technology]. https://dspace.mit.edu/handle/1721.1/78143

Büchs, M., & Schnepf, S. v. (2013). Who emits most? Associations between socio-economic factors and UK households' home energy, transport, indirect and total CO2 emissions. *Ecological Economics*, *90*, 114–123. https://doi.org/10.1016/J.ECOLECON.2013.03.007

Chao-Lung, H., Anh-Tuan, B. le, & Chun-Tsun, C. (2011). Effect of rice husk ash on the strength and durability characteristics of concrete. *Construction and Building Materials*, *25*(9), 3768–3772. https://doi.org/10.1016/J.CONBUILDMAT.2011.04.009

Chatveera, B., & Lertwattanaruk, P. (2011). Durability of conventional concretes containing black rice husk ash. *Journal of Environmental Management*, *92*(1), 59–66. https://doi.org/10.1016/J.JENVMAN.2010.08.007

Chau, C. K., Leung, T. M., & Ng, W. Y. (2015). A review on Life Cycle Assessment, Life Cycle Energy Assessment and Life Cycle Carbon Emissions Assessment on buildings. *Applied Energy*, *143*(1), 395–413. https://doi.org/10.1016/J.APENERGY.2015.01.023

Chopra, D., Siddique, R., & Kunal. (2015). Strength, permeability and microstructure of self-compacting concrete containing rice husk ash. *Biosystems Engineering*, *130*, 72–80. https://doi.org/10.1016/J.BIOSYSTEMSENG.2014.12.005

Collins, F. (2010). Inclusion of carbonation during the life cycle of built and recycled concrete: Influence on their carbon footprint. *International Journal of Life Cycle Assessment*, *15*(6), 549–556. https://doi.org/10.1007/S11367-010-0191-4/TABLES/5

Cook, J. D. (1986). Rice husk ash. In R. N. Swamy (Ed.), *Concrete technology and design. Cement replacement materials.* (Vol. 3, pp. 171–195). Surrey University Press.

Cordeiro, G. C., Toledo Filho, R. D., & de Moraes Rego Fairbairn, E. (2009). Use of ultrafine rice husk ash with high-carbon content as pozzolan in high performance concrete. *Materials and Structures/Materiaux et Constructions*, *42*(7), 983–992. https://doi.org/10.1617/S11527-008-9437-Z/FIGURES/12

Danjuma, T., Yohanna Adamu, A., Mbishida, M. A., Yusuf Mailafiya, B., & Building, N. (2021). Assessment of Concrete Elements of A Collapsed Building Using Ultrasonic Pulse Velocity Test. *SSRG International Journal of Recent Engineering Science*, *8*, 16–19. https://doi.org/10.14445/23497157/IJRES-V8I2P103

de Fatima Dias, J. (2019). *Reuse of Construction Materials*. http://urn.kb.se/resolve?urn=urn:nbn:se:du-30024

de Sensale, G. R., Ribeiro, A. B., & Gonçalves, A. (2008). Effects of RHA on autogenous shrinkage of Portland cement pastes. *Cement and Concrete Composites*, *30*(10), 892–897. https://doi.org/10.1016/J.CEMCONCOMP.2008.06.014

Della, V. P., Junkes, J. A., Oliveira, N., & Hotza, D. (2010). Heteromorphic Hematite Pigments Obtained from Steel Scrap and Encapsulated in Amorphous Silica for Porcelainized Stoneware. *Journal of Materials Science and Engineering*, *4*(5). https://www.researchgate.net/publication/209118604

Dollente, I. J. R., Tan, R. R., & Promentilla, M. A. B. (2021). Life Cycle Assessment of Precast Geopolymer Products. *Chemical Engineering Transactions*, *88*, 799–804. https://doi.org/10.3303/CET2188133

Dong, Y. H., & Ng, S. T. (2014). Comparing the midpoint and endpoint approaches based on ReCiPe - A study of commercial buildings in Hong Kong. *International Journal of Life Cycle Assessment*, *19*(7), 1409–1423. https://doi.org/10.1007/S11367-014-0743-0/FIGURES/8

Dunlap, R. (2003). *Life cycle inventory of slag cement manufacturing process: project CTL.*

EPA. (n.d.). *National Overview: Facts and Figures on Materials, Wastes and Recycling*. Retrieved January 8, 2022, from https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/national-overview-facts-and-figures-materials

Ezcurra, A., Ortiz De Zárate, I., Dhin, P. V., & Lacaux, J. P. (2001). Cereal waste burning pollution observed in the town of Vitoria (northern Spain). *Atmospheric Environment*, *35*(8), 1377–1386. https://doi.org/10.1016/S1352-2310(00)00393-9

FAO. (2015). *Food Outlook: biannual report on global food markets*. www.fao.org/

FAO. (2017). *Strategic Work of FAO for Sustainable Food and Agriculture*.

FAO, & OECD. (2019). Background Notes on Sustainable, Productive and Resilient Agro-Food Systems. In *Background Notes on Sustainable, Productive and Resilient Agro-Food Systems*. OECD. https://doi.org/10.1787/DCA82200-EN

Feng, Q. G., Lin, Q. Y., Yu, Q. J., Zhao, S. Y., Yang, L. F., & Sugita, S. (2004). Concrete with highly active rice husk ash. *Journal of Wuhan University of Technology-Mater. Sci. Ed. 2004 19:3*, *19*(3), 74–77. https://doi.org/10.1007/BF02835067

Fernandes, I. J., Calheiro, D., Kieling, A. G., Moraes, C. A. M., Rocha, T. L. A. C., Brehm, F. A., & Modolo, R. C. E. (2016). Characterization of rice husk ash produced using different biomass combustion techniques for energy. *Fuel*, *165*, 351–359. https://doi.org/10.1016/J.FUEL.2015.10.086

Flower, D. J. M., & Sanjayan, J. G. (2007). Green house gas emissions due to concrete manufacture. *The International Journal of Life Cycle Assessment 2007 12:5*, *12*(5), 282–288. https://doi.org/10.1065/LCA2007.05.327

Font, A., Soriano, L., Tashima, M. M., Monzó, J., Borrachero, M. V., & Payá, J. (2020). One-part eco-cellular concrete for the precast industry: Functional features and life cycle assessment. *Journal of Cleaner Production*, *269*, 122203. https://doi.org/10.1016/J.JCLEPRO.2020.122203

Foong, K. Y., Alengaram, U. J., Jumaat, M. Z., & Mo, K. H. (2015). Enhancement of the mechanical properties of lightweight oil palm shell concrete using rice husk ash and manufactured sand. *Journal of Zhejiang University: Science A*, *16*(1), 59–69. https://doi.org/10.1631/JZUS.A1400175/TABLES/8

Gastaldini, A. L. G., da Silva, M. P., Zamberlan, F. B., & Mostardeiro Neto, C. Z. (2014). Total shrinkage, chloride penetration, and compressive strength of concretes that contain clear-colored rice husk ash. *Construction and Building Materials*, *54*, 369–377. https://doi.org/10.1016/J.CONBUILDMAT.2013.12.044

Gastaldini, A. L. G., Isaia, G. C., Hoppe, T. F., Missau, F., & Saciloto, A. P. (2009). Influence of the use of rice husk ash on the electrical resistivity of concrete: A technical and economic feasibility study. *Construction and Building Materials*, *23*(11), 3411–3419. https://doi.org/10.1016/J.CONBUILDMAT.2009.06.039

Gastaldini, A. L. G., Isaia, G. C., Saciloto, A. P., Missau, F., & Hoppe, T. F. (2010). Influence of curing time on the chloride penetration resistance of concrete containing rice husk ash: A technical and economical feasibility study. *Cement and Concrete Composites*, *32*(10), 783–793. https://doi.org/10.1016/J.CEMCONCOMP.2010.08.001

Gill, A. S., & Siddique, R. (2018). Durability properties of self-compacting concrete incorporating metakaolin and rice husk ash. *Construction and Building Materials*, *176*, 323–332. https://doi.org/10.1016/J.CONBUILDMAT.2018.05.054

Guinée, J. B., Gorreé, M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., van Oers, L., Wegener Sleeswijk, A., Suh, S., Udo de Haes, H. A., de Bruijn, H., van Duin, R., & Huijbregts, M. A. J. (2002). *Handbook on life cycle assessment: operational guide to the ISO standards* (Vol. 7). Springer Science & Business Media.

Guo, R., Wang, J., Bing, L., Tong, D., Ciais, P., Davis, S. J., Andrew, R. M., Xi, F., & Liu, Z. (n.d.). *Global CO 2 uptake of cement in 1930-2019 Earth System Science Data Discussions*. https://doi.org/10.5281/zenodo.4064803

Gursel, A. P., Maryman, H., & Ostertag, C. (2016). A life-cycle approach to environmental, mechanical, and durability properties of "green" concrete mixes with rice husk ash. *Journal of Cleaner Production*, *112*, 823–836. https://doi.org/10.1016/J.JCLEPRO.2015.06.029

Hammond, G. P., & Jones, C. I. (2008). Embodied energy and carbon in construction materials. *Proceedings of Institution of Civil Engineers: Energy*, *161*(2), 87–98. https://doi.org/10.1680/ENER.2008.161.2.87/ASSET/IMAGES/SMALL/ENER161-087-F8.GIF

Hasbullah, M. A., Yusof, R., & Rahman, M. N. Y. A. (2016). Evaluating the strength of concrete structure on terrace houses. *AIP Conference Proceedings, 1761*(1), 020043. https://doi.org/10.1063/1.4960883

He, Z. hai, Li, L. yuan, & Du, S. gui. (2017). Creep analysis of concrete containing rice husk ash. *Cement and Concrete Composites*, *80*, 190–199. https://doi.org/10.1016/J.CEMCONCOMP.2017.03.014

Hegg, D. A., Radke, L. F., Hobbs, P. v., Brock, C. A., & Riggan, P. J. (1987). Nitrogen and sulfur emissions from the burning of forest products near large urban areas. *Journal of Geophysical Research: Atmospheres*, *92*(D12), 14701–14709. https://doi.org/10.1029/JD092ID12P14701

Hertwich, E. G., Mateles, S. F., Pease, W. S., & McKone, T. E. (2001). Human toxicity potentials for life-cycle assessment and toxics release inventory risk screening. *Environmental Toxicology and Chemistry*, *20*(4), 928–939. https://doi.org/10.1002/ETC.5620200431

Hossain, K. M. A. (2005). Correlations between porosity, chloride diffusivity and electrical resistivity in volcanic pumice-based blended cement pastes. *Advances in Cement Research*, *17*(1), 29–37. https://doi.org/10.1680/ADCR.2005.17.1.29/ASSET/IMAGES/SMALL/ADCR17-029-F9.GIF

Huerta, A. (2020). *Sustainability and viability assessment of returnable transport item approaches in e-Commerce*.

ILCD. (2011). *Recommendations for life cycle impact assessment in the European context-based on existing environmental impact assessment models and factors*.

Ince, C. (2019). Reusing gold-mine tailings in cement mortars: Mechanical properties and socio-economic developments for the Lefke-Xeros area of Cyprus. *Journal of Cleaner Production*, *238*, 117871. https://doi.org/10.1016/J.JCLEPRO.2019.117871

Ince, C., Derogar, S., Gurkaya, K., & Ball, R. J. (2021). Properties, durability and cost efficiency of cement and hydrated lime mortars reusing copper mine tailings of Lefke-Xeros in Cyprus. *Construction and Building Materials*, *268*, 121070. https://doi.org/10.1016/J.CONBUILDMAT.2020.121070

Ince, C., Hamza, A., Derogar, S., & Ball, R. J. (2020). Utilisation of waste marble dust for improved durability and cost efficiency of pozzolanic concrete. *Journal of Cleaner Production*, *270*, 122213. https://doi.org/10.1016/J.JCLEPRO.2020.122213

ISO - ISO 14040:2006 - Environmental management — Life cycle assessment — Principles and framework. (2006). https://www.iso.org/standard/37456.html

Issa Khassaf, S., Talib Jasim, A., Kurdi Mahdi, F., Khassaf, S. I., Jasim, A. T., & Mahdi, F. (2014). Investigation The Properties Of Concrete Containing Rice Husk Ash To Reduction The Seepage In Canals. *Article in International Journal of Scientific & Technology Research*, *3*. www.ijstr.org

James, J., & Subba Rao, M. (1986). Reactivity of rice husk ash. *Cement and Concrete Research*, *16*(3), 296–302. https://doi.org/10.1016/0008-8846(86)90104-3

Jamieson, E., McLellan, B., van Riessen, A., & Nikraz, H. (2015). Comparison of embodied energies of Ordinary Portland Cement with Bayer-derived geopolymer products. *Journal of Cleaner Production*, *99*, 112–118. https://doi.org/10.1016/J.JCLEPRO.2015.03.008

Kannan, V., & Ganesan, K. (2014). Chloride and chemical resistance of self compacting concrete containing rice husk ash and metakaolin. *Construction and Building Materials*, *51*, 225–234. https://doi.org/10.1016/J.CONBUILDMAT.2013.10.050

Karim, M. R., Zain, M. F. M., Jamil, M., & Lai, F. C. (2011). Significance of Waste Materials in Sustainable Concrete and Sustainable Development. *International Conference on Biotechnology and Environment Management*.

Kaur, R., Kothiyal, N. C., & Arora, H. (2020). Studies on combined effect of superplasticizer modified graphene oxide and carbon nanotubes on the physico-mechanical strength and electrical resistivity of fly ash blended cement mortar. *Journal of Building Engineering*, *30*, 101304. https://doi.org/10.1016/J.JOBE.2020.101304

Kaza, S., Yao, L., Bhada-Tata, P., & Woerden, F. van. (2018). *WHAT A WASTE 2.0 A Global Snapshot of Solid Waste Management to 2050 OVERVIEW*. https://openknowledge.worldbank.org/handle/10986/2174

King, D. (2012). The effect of silica fume on the properties of concrete as defined in concrete society report 74, cementitious materials. *37th Conference on Our World in Concrete and Structures*, 29–31.

Kizhakkumodom Venkatanarayanan, H., Rangaraju, P. R., & Asce, M. (2013). Evaluation of Sulfate Resistance of Portland Cement Mortars Containing Low-Carbon Rice Husk Ash. *Journal of Materials in Civil Engineering*, *26*(4), 582–592. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000868

Koushkbaghi, M., Kazemi, M. J., Mosavi, H., & Mohseni, E. (2019). Acid resistance and durability properties of steel fiber-reinforced concrete incorporating rice husk ash and recycled aggregate. *Construction and Building Materials*, *202*, 266–275. https://doi.org/10.1016/J.CONBUILDMAT.2018.12.224

Lacaux, J. P., Loemba-Ndembi, J., Lefeivre, B., Cros, B., & Delmas, R. (1992). Biogenic emissions and biomass burning influences on the chemistry of the fogwater and stratiform precipitations in the African equatorial forest. *Atmospheric Environment. Part A. General Topics*, *26*(4), 541–551. https://doi.org/10.1016/0960-1686(92)90167-J

Le, H. T., Nguyen, S. T., & Ludwig, H. M. (2014). A Study on High Performance Fine-Grained Concrete Containing Rice Husk Ash. *International Journal of Concrete Structures and Materials*, *8*(4), 301–307. https://doi.org/10.1007/S40069-014-0078-Z/FIGURES/5

Lehne, J., & Preston, F. (2018). *Chatham House Report Making Concrete Change Innovation in Low-carbon Cement and Concrete #ConcreteChange*. www.chathamhouse.org

Liu, Y., Guo, Y., Gao, W., Wang, Z., Ma, Y., & Wang, Z. (2012). Simultaneous preparation of silica and activated carbon from rice husk ash. *Journal of Cleaner Production*, *32*, 204–209. https://doi.org/10.1016/J.JCLEPRO.2012.03.021

Lopes, J. (2012). Construction in the economy and its role in socio-economic development: role of construction in economic development. *New Perspectives on Construction in Develops Countries, first edition*, 41–71. https://bibliotecadigital.ipb.pt/handle/10198/11220

Madandoust, R., Ranjbar, M. M., Moghadam, H. A., & Mousavi, S. Y. (2011a). Mechanical properties and durability assessment of rice husk ash concrete. *Biosystems Engineering*, *110*(2), 144–152. https://doi.org/10.1016/J.BIOSYSTEMSENG.2011.07.009

Madandoust, R., Ranjbar, M. M., Moghadam, H. A., & Mousavi, S. Y. (2011b). Mechanical properties and durability assessment of rice husk ash concrete. *Biosystems Engineering*, *110*(2), 144–152. https://doi.org/10.1016/J.BIOSYSTEMSENG.2011.07.009

Mahmud, H. (2010). *Properties of high strength concrete incorporating black rice husk ash*.

Mahmud, H. B., Bahri, S., Yee, Y. W., & Yeap, Y. T. (2016). Effect of Rice Husk Ash on Strength and Durability of High Strength High Performance Concrete. *International Journal of Civil and Environmental Engineering*, *10*(3), 390–395. https://doi.org/10.5281/ZENODO.1123585

Malhotra, V. M., & Mehta, P. K. (1996). Pozzolanic and Cementitious Materials. In *Pozzolanic and Cementitious Materials*. CRC Press. https://doi.org/10.1201/9781482296761

Marchand, J., Odler, I., & Skalny, J. P. (2001). Sulfate Attack on Concrete. In *Sulfate Attack on Concrete*. CRC Press. https://doi.org/10.4324/9780203301623

McCarter, W. J., & Tran, D. (1996). Monitoring pozzolanic activity by direct activation with calcium hydroxide. *Construction and Building Materials*, *10*(3), 179–184. https://doi.org/10.1016/0950-0618(95)00089-5

McLellan, B. C., Corder, G. D., Giurco, D. P., & Ishihara, K. N. (2012). Renewable energy in the minerals industry: a review of global potential. *Journal of Cleaner Production*, *32*, 32–44. https://doi.org/10.1016/J.JCLEPRO.2012.03.016

McLellan, B. C., Williams, R. P., Lay, J., van Riessen, A., & Corder, G. D. (2011). Costs and carbon emissions for geopolymer pastes in comparison to ordinary portland cement. *Journal of Cleaner Production*, *19*(9–10), 1080–1090. https://doi.org/10.1016/J.JCLEPRO.2011.02.010

Mehta, P. K., & Monterio, P. J. M. (2014). *Concrete: microstructure, properties and materials* (4th ed.). McGraw-Hill Education.

Mi, Z., Meng, J., Guan, D., Shan, Y., Song, M., Wei, Y. M., Liu, Z., & Hubacek, K. (2017). Chinese CO2 emission flows have reversed since the global financial crisis. *Nature Communications 2017 8:1*, *8*(1), 1–10. https://doi.org/10.1038/s41467-017-01820-w

Mohamad, N., Tahir Lakhiar, M., Aziz Abdul Samad, A., Othuman Mydin, M. A., Ahmed Jhatial, A., Anis Sofia, S., Inn Goh, W., & Ali, N. (2019). Innovative and sustainable green concrete–A potential review on utilization of agricultural waste. *IOP Conference Series: Materials Science and Engineering*, *601*(1), 012026. https://doi.org/10.1088/1757-899X/601/1/012026

Msinjili, N. S., Schmidt, W., Rogge, A., & Kühne, H. C. (2017). Performance of rice husk ash blended cementitious systems with added superplasticizers. *Cement and Concrete Composites*, *83*, 202–208. https://doi.org/10.1016/J.CEMCONCOMP.2017.07.014

Muthadhi, A., & Kothandaraman, S. (2010). Optimum production conditions for reactive rice husk ash. *Materials and Structures/Materiaux et Constructions*, *43*(9), 1303–1315. https://doi.org/10.1617/S11527-010-9581-0/FIGURES/17

Muthadhi, A., & Kothandaraman, S. (2013). Experimental Investigations of Performance Characteristics of Rice Husk Ash–Blended Concrete. *Journal of Materials in Civil Engineering*, *25*(8), 1115–1118. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000656

Nair, D. G., Fraaij, A., Klaassen, A. A. K., & Kentgens, A. P. M. (2008). A structural investigation relating to the pozzolanic activity of rice husk ashes. *Cement and Concrete Research*, *38*(6), 861–869. https://doi.org/10.1016/J.CEMCONRES.2007.10.004

Norval, M., Cullen, A. P., de Gruijl, F. R., Longstreth, J., Takizawa, Y., Lucas, R. M., Noonan, F. P., & van der Leun, J. C. (2007). The effects on human health from stratospheric ozone depletion and its interactions with climate change. *Photochemical & Photobiological Sciences*, *6*(3), 232–251. https://doi.org/10.1039/B700018A

Padhi, R. S., Patra, R. K., Mukharjee, B. B., & Dey, T. (2018). Influence of incorporation of rice husk ash and coarse recycled concrete aggregates on properties of concrete. *Construction and Building Materials*, *173*, 289–297. https://doi.org/10.1016/J.CONBUILDMAT.2018.03.270

Passuello, A., Rodríguez, E. D., Hirt, E., Longhi, M., Bernal, S. A., Provis, J. L., & Kirchheim, A. P. (2017). Evaluation of the potential improvement in the environmental footprint of geopolymers using waste-derived activators. *Journal of Cleaner Production*, *166*, 680–689. https://doi.org/10.1016/J.JCLEPRO.2017.08.007

Pathak, N., & Siddique, R. (2012). Properties of self-compacting-concrete containing fly ash subjected to elevated temperatures. *Construction and*

Building Materials, *30*, 274–280. https://doi.org/10.1016/J.CONBUILDMAT.2011.11.010

Patil, S. B., & Khan, M. K. (2011). Germinated brown rice as a value added rice product: A review. *Journal of Food Science and Technology*, *48*(6), 661–667. https://doi.org/10.1007/S13197-011-0232-4/TABLES/1

Pode, R. (2016). Potential applications of rice husk ash waste from rice husk biomass power plant. *Renewable and Sustainable Energy Reviews*, *53*, 1468–1485. https://doi.org/10.1016/J.RSER.2015.09.051

Pomakhina, E., Deneele, D., Gaillot, A. C., Paris, M., & Ouvrard, G. (2012). 29Si solid state NMR investigation of pozzolanic reaction occurring in lime-treated Ca-bentonite. *Cement and Concrete Research*, *42*(4), 626–632. https://doi.org/10.1016/J.CEMCONRES.2012.01.008

Prasara-A, J., & Gheewala, S. H. (2017). Sustainable utilization of rice husk ash from power plants: A review. *Journal of Cleaner Production*, *167*, 1020–1028. https://doi.org/10.1016/J.JCLEPRO.2016.11.042

Purmessur, B., & Surroop, D. (2019). Power generation using landfill gas generated from new cell at the existing landfill site. *Journal of Environmental Chemical Engineering*, *7*(3), 103060. https://doi.org/10.1016/J.JECE.2019.103060

Ramírez-García, R., Gohil, N., & Singh, V. (2019). Recent Advances, Challenges, and Opportunities in Bioremediation of Hazardous Materials. *Phytomanagement of Polluted Sites: Market Opportunities in Sustainable Phytoremediation*, 517–568. https://doi.org/10.1016/B978-0-12-813912-7.00021-1

Rêgo, J. H. S., Nepomuceno, A. A., Figueiredo, E. P., & Hasparyk, N. P. (2015). Microstructure of cement pastes with residual rice husk ash of low amorphous silica content. *Construction and Building Materials*, *80*, 56–68. https://doi.org/10.1016/J.CONBUILDMAT.2014.12.059

Rodríguez de Sensale, G., & Rodríguez Viacava, I. (2018). A study on blended Portland cements containing residual rice husk ash and limestone filler. *Construction and Building Materials*, *166*, 873–888. https://doi.org/10.1016/J.CONBUILDMAT.2018.01.113

Roper, H. (1994). Mineral admixtures in cements for general use and special purposes. In *Advances in Cement and Concrete* (pp. 236–242). ASCE.

Sabiiti, E. (2011). Utilising agricultural waste to enhance food security and conserve the environment. *African Journal of Food, Agriculture, Nutrition and Development*. https://www.ajol.info/index.php/ajfand/article/view/72668

Safiuddin, M., West, J. S., & Soudki, K. A. (2010a). Hardened properties of self-consolidating high performance concrete including rice husk ash. *Cement and Concrete Composites*, *32*(9), 708–717. https://doi.org/10.1016/J.CEMCONCOMP.2010.07.006

Safiuddin, M., West, J. S., & Soudki, K. A. (2010b). Hardened properties of self-consolidating high performance concrete including rice husk ash. *Cement and Concrete Composites*, *32*(9), 708–717. https://doi.org/10.1016/J.CEMCONCOMP.2010.07.006

Şahan Arel, H., & Aydin, E. (2018). Use of Industrial and Agricultural Wastes in Construction Concrete. *ACI Materials Journal*. https://doi.org/10.14359/51700991

Sandeep Kauthsa Sharma, M., Umadevi, S., Sai Sampath, Y., Vasugi, K., Sai Nitesh, K. J. N., Swamy Nadh, V., & Natrayan, L. (2021). Mechanical Behavior of Silica Fume Concrete Filled with Steel Tubular Composite Column. *Advances in Materials Science and Engineering*, *2021*. https://doi.org/10.1155/2021/3632991

Saraswathy, V., & Song, H. W. (2007). Corrosion performance of rice husk ash blended concrete. *Construction and Building Materials*, *21*(8), 1779–1784. https://doi.org/10.1016/J.CONBUILDMAT.2006.05.037

Sathiparan, N., & de Zoysa, H. T. S. M. (2018). The effects of using agricultural waste as partial substitute for sand in cement blocks. *Journal of Building Engineering*, *19*, 216–227. https://doi.org/10.1016/J.JOBE.2018.04.023

Shine, K. P. (2009). The global warming potential-the need for an interdisciplinary retrial An editorial comment. *Climatic Change*, *96*, 467–472. https://doi.org/10.1007/s10584-009-9647-6

Siddika, A., Mamun, M. A. al, Alyousef, R., & Mohammadhosseini, H. (2021). State-of-the-art-review on rice husk ash: A supplementary cementitious material in concrete. *Journal of King Saud University - Engineering Sciences*, *33*(5), 294–307. https://doi.org/10.1016/J.JKSUES.2020.10.006

Siddique, R., & Chahal, N. (2011). Use of silicon and ferrosilicon industry by-products (silica fume) in cement paste and mortar. *Resources, Conservation and Recycling*, *55*(8), 739–744. https://doi.org/10.1016/J.RESCONREC.2011.03.004

Singh, A., Sampath, P. V., & Biligiri, K. P. (2020). A review of sustainable pervious concrete systems: Emphasis on clogging, material characterization, and environmental aspects. *Construction and Building Materials*, *261*, 120491. https://doi.org/10.1016/J.CONBUILDMAT.2020.120491

Sousa-Coutinho, J., & Papadakis, V. G. (2011, April). *Rice Husk Ash-Importance of Fineness for its Use as a Pozzolanic and Chloride-Resistant Material*.

Standard test method for electrical indication of concrete's ability to resist chloride ion penetration, ASTMC 1202-97 (Vol. 4, pp. 639–644). (2006). Annual book of ASTM standards.

Sua-iam, G., & Makul, N. (2012). Effect of limestone powder on the properties of self-consolidating concrete mixed with rice husk ash. *Research and Development Journal*, *23*(4). https://ph02.tci-thaijo.org/index.php/eit-researchjournal/article/view/113192/88113

Sua-Iam, G., & Makul, N. (2014). Utilization of high volumes of unprocessed lignite-coal fly ash and rice husk ash in self-consolidating concrete. *Journal of Cleaner Production*, *78*, 184–194. https://doi.org/10.1016/J.JCLEPRO.2014.04.060

Tahwia, A. M., El-Far, O., & Amin, · Mohamed. (2022). *Characteristics of sustainable high strength concrete incorporating eco-friendly materials*. *7*(8). https://doi.org/10.1007/s41062-021-00609-7

Tuck Lun, L. (2015). *EFFECTS OF RICE HUSK ASH (RHA) PRODUCED FROM DIFFERENT TEMPERATURES ON THE PERFORMANCE OF CONCRETE*.

Tumidajski, P. J. (2005). Relationship between resistivity, diffusivity and microstructural descriptors for mortars with silica fume. *Cement and Concrete Research*, *35*(7), 1262–1268. https://doi.org/10.1016/J.CEMCONRES.2004.10.007

Turk, J., Cotič, Z., Mladenovič, A., & Šajna, A. (2015). Environmental evaluation of green concretes versus conventional concrete by means of LCA. *Waste Management*, *45*, 194–205. https://doi.org/10.1016/J.WASMAN.2015.06.035

Turner, L. K., & Collins, F. G. (2013). Carbon dioxide equivalent (CO2-e) emissions: A comparison between geopolymer and OPC cement concrete. *Construction and Building Materials*, *43*, 125–130. https://doi.org/10.1016/J.CONBUILDMAT.2013.01.023

United Nations Environmental Programme (UNEP). (2007). *United Nations Environment Programme - Buildings and climate clange, status, challenges and opportunities*.

Vadiveloo, J., Nurfariza, B., & Fadel, J. G. (2009). Nutritional improvement of rice husks. *Animal Feed Science and Technology*, *151*(3–4), 299–305. https://doi.org/10.1016/J.ANIFEEDSCI.2009.03.002

van Gijlswijk, R. N., Pascale, S., de Vos, S. E., & Urbano, G. (2015). *Carbon footprint of concrete based on secondary materials*. *60*(1).

Van, V. T. A., Rößler, C., Bui, D. D., & Ludwig, H. M. (2013). Mesoporous structure and pozzolanic reactivity of rice husk ash in cementitious system. *Construction and Building Materials*, *43*, 208–216. https://doi.org/10.1016/J.CONBUILDMAT.2013.02.004

Varadharajan, S., Jaiswal, A., & Verma, S. (2020). Assessment of mechanical properties and environmental benefits of using rice husk ash and marble dust in concrete. *Structures*, *28*, 389–406. https://doi.org/10.1016/J.ISTRUC.2020.09.005

WWF. (2019). *Climate protection in the concrete and cement industry Background and possible courses of action*. www.mkuesters.com

Xi, F., Davis, S. J., Ciais, P., Crawford-Brown, D., Guan, D., Pade, C., Shi, T., Syddall, M., Lv, J., Ji, L., Bing, L., Wang, J., Wei, W., Yang, K. H., Lagerblad, B., Galan, I., Andrade, C., Zhang, Y., & Liu, Z. (2016). Substantial global carbon uptake by cement carbonation. *Nature Geoscience 2016 9:12*, *9*(12), 880–883. https://doi.org/10.1038/ngeo2840

Xu, W., Lo, T. Y., & Memon, S. A. (2012). Microstructure and reactivity of rich husk ash. *Construction and Building Materials*, *29*, 541–547. https://doi.org/10.1016/J.CONBUILDMAT.2011.11.005

Yang, K. H., Seo, E. A., & Tae, S. H. (2014). Carbonation and CO2 uptake of concrete. *Environmental Impact Assessment Review*, *46*, 43–52. https://doi.org/10.1016/J.EIAR.2014.01.004

Yu, Q., Sawayama, K., Sugita, S., Shoya, M., & Isojima, Y. (1999). The reaction between rice husk ash and Ca(OH)2 solution and the nature of its product. *Cement and Concrete Research*, *29*(1), 37–43. https://doi.org/10.1016/S0008-8846(98)00172-0

Yunus, M., Karim, Y., Khan, Z., Alsoufi, M. S., & Review, " A. (2016). A Review on Recycled Aggregates for the Construction Industry. *American Journal of Civil Engineering and Architecture*, *4*(1), 32–38. https://doi.org/10.12691/ajcea-4-1-5

Yuzer, N., Cinar, Z., Akoz, F., Biricik, H., Gurkan, Y. Y., Kabay, N., & Kizilkanat, A. B. (2013). Influence of raw rice husk addition on structure and properties of concrete. *Construction and Building Materials*, *44*, 54–62. https://doi.org/10.1016/J.CONBUILDMAT.2013.02.070

Zerbino, R., Giaccio, G., & Isaia, G. C. (2011a). Concrete incorporating rice-husk ash without processing. *Construction and Building Materials*, *25*(1), 371–378. https://doi.org/10.1016/J.CONBUILDMAT.2010.06.016

Zerbino, R., Giaccio, G., & Isaia, G. C. (2011b). Concrete incorporating rice-husk ash without processing. *Construction and Building Materials*, *25*(1), 371–378. https://doi.org/10.1016/J.CONBUILDMAT.2010.06.016

Zhang, M. H., Lastra, R., & Malhotra, V. M. (1996). Rice-husk ash paste and concrete: Some aspects of hydration and the microstructure of the interfacial zone between the aggregate and paste. *Cement and Concrete Research*, *26*(6), 963–977. https://doi.org/10.1016/0008-8846(96)00061-0

APPENDICES

A. Database Reference List

Abalaka, A. E. (2013). Strength and Some Durability Properties of Concrete Containing Rice Husk Ash Produced in a Charcoal Incinerator at Low Specific Surface. *International Journal of Concrete Structures and Materials*, 7(4), 287–293. https://doi.org/10.1007/S40069-013-0058-8/TABLES/13

Ameri, F., Shoaei, P., Bahrami, N., Vaezi, M., & Ozbakkaloglu, T. (2019). Optimum rice husk ash content and bacterial concentration in self-compacting concrete. *Construction and Building Materials*, 222, 796–813. https://doi.org/10.1016/J.CONBUILDMAT.2019.06.190

Amin, M. N., Hissan, S., Shahzada, K., Khan, K., & Bibi, T. (2019). Pozzolanic reactivity and the influence of rice husk ash on early-age autogenous shrinkage of concrete. *Frontiers in Materials*, 6, 150. https://doi.org/10.3389/FMATS.2019.00150/BIBTEX

Anwar, M., Miyagawa, T., & Gaweesh, M. (2000a). Using rice husk ash as a cement replacement material in concrete. *Waste Management Series*, 1(C), 671–684. https://doi.org/10.1016/S0713-2743(00)80077-X

Bahri, S., Mahmud, H. B., Shafigh, P., & Majuar, E. (2019). Mechanical and Durability Properties of High Strength High Performance Concrete Incorporating Rice Husk Ash. *IOP Conference Series: Materials Science and Engineering*, 536(1), 012028. https://doi.org/10.1088/1757-899X/536/1/012028

Brown, D. K. (2012). Unprocessed rice husk ash as a partial replacement of cement for low-cost concrete [Massachusetts Institute of Technology]. https://dspace.mit.edu/handle/1721.1/78143

Bui, D. D., Hu, J., & Stroeven, P. (2005). Particle size effect on the strength of rice husk ash blended gap-graded Portland cement concrete. *Cement and Concrete*

Composites, 27(3), 357–366. https://doi.org/10.1016/J.CEMCONCOMP.2004.05.002

Chalee, W., Sasakul, T., Suwanmaneechot, P., & Jaturapitakkul, C. (2013). Utilization of rice husk–bark ash to improve the corrosion resistance of concrete under 5-year exposure in a marine environment. *Cement and Concrete Composites*, 37(1), 47–53. https://doi.org/10.1016/J.CEMCONCOMP.2012.12.007

Chao-Lung, H., Anh-Tuan, B. le, & Chun-Tsun, C. (2011). Effect of rice husk ash on the strength and durability characteristics of concrete. *Construction and Building Materials*, 25(9), 3768–3772. https://doi.org/10.1016/J.CONBUILDMAT.2011.04.009

Chatveera, B., & Lertwattanaruk, P. (2009). Evaluation of sulfate resistance of cement mortars containing black rice husk ash. *Journal of Environmental Management*, 90(3), 1435–1441. https://doi.org/10.1016/J.JENVMAN.2008.09.001

Chatveera, B., & Lertwattanaruk, P. (2011). Durability of conventional concretes containing black rice husk ash. *Journal of Environmental Management*, 92(1), 59–66. https://doi.org/10.1016/J.JENVMAN.2010.08.007

Chatveera, B., & Lertwattanaruk, P. (2014). Evaluation of nitric and acetic acid resistance of cement mortars containing high-volume black rice husk ash. *Journal of Environmental Management*, 133, 365–373. https://doi.org/10.1016/J.JENVMAN.2013.12.010

Chindaprasirt, P., Homwuttiwong, S., & Jaturapitakkul, C. (2007). Strength and water permeability of concrete containing palm oil fuel ash and rice husk–bark ash. *Construction and Building Materials*, 21(7), 1492–1499. https://doi.org/10.1016/J.CONBUILDMAT.2006.06.015

Chopra, D., Siddique, R., & Kunal. (2015). Strength, permeability and microstructure of self-compacting concrete containing rice husk ash. *Biosystems Engineering, 130, 72–80*. https://doi.org/10.1016/J.BIOSYSTEMSENG.2014.12.005

Cordeiro, G. C., Toledo Filho, R. D., & de Moraes Rego Fairbairn, E. (2009). Use of ultrafine rice husk ash with high-carbon content as pozzolan in high performance concrete. *Materials and Structures/Materiaux et Constructions*, 42(7), 983–992. https://doi.org/10.1617/S11527-008-9437-Z/FIGURES/12

Cordeiro, G. C., Toledo Filho, R. D., Tavares, L. M., & Fairbairn, E. M. R. (2012). Experimental characterization of binary and ternary blended-cement concretes containing ultrafine residual rice husk and sugar cane bagasse ashes. *Construction and Building Materials*, 29, 641–646. https://doi.org/10.1016/J.CONBUILDMAT.2011.08.095

Das, S. K., Mishra, J., Singh, S. K., Mustakim, S. M., Patel, A., Das, S. K., & Behera, U. (2020). Characterization and utilization of rice husk ash (RHA) in fly ash – Blast furnace slag based geopolymer concrete for sustainable future. Materials Today: *Proceedings*, 33, 5162–5167. https://doi.org/10.1016/J.MATPR.2020.02.870

Effect of limestone powder on the properties of self-consolidating concrete mixed with rice husk ash | *Engineering Journal of Research and Development*. (n.d.). Retrieved January 9, 2022, from https://ph02.tci-thaijo.org/index.php/eit-researchjournal/article/view/113192

Foong, K. Y., Alengaram, U. J., Jumaat, M. Z., & Mo, K. H. (2015). Enhancement of the mechanical properties of lightweight oil palm shell concrete using rice husk ash and manufactured sand. *Journal of Zhejiang University: Science A*, 16(1), 59–69. https://doi.org/10.1631/JZUS.A1400175/TABLES/8

Ganesan, K., Rajagopal, K., & Thangavel, K. (2008). Rice husk ash blended cement: Assessment of optimal level of replacement for strength and permeability properties of concrete. *Construction and Building Materials*, 22(8), 1675–1683. https://doi.org/10.1016/J.CONBUILDMAT.2007.06.011

Gastaldini, A. L. G., da Silva, M. P., Zamberlan, F. B., & Mostardeiro Neto, C. Z. (2014). Total shrinkage, chloride penetration, and compressive strength of concretes that contain clear-colored rice husk ash. *Construction and Building Materials*, 54, 369–377. https://doi.org/10.1016/J.CONBUILDMAT.2013.12.044

Gastaldini, A. L. G., Isaia, G. C., Hoppe, T. F., Missau, F., & Saciloto, A. P. (2009). Influence of the use of rice husk ash on the electrical resistivity of concrete: A technical and economic feasibility study. *Construction and Building Materials*, 23(11), 3411–3419. https://doi.org/10.1016/J.CONBUILDMAT.2009.06.039

Gastaldini, A. L. G., Isaia, G. C., Saciloto, A. P., Missau, F., & Hoppe, T. F. (2010). Influence of curing time on the chloride penetration resistance of concrete containing rice husk ash: A technical and economical feasibility study. *Cement and Concrete Composites*, 32(10), 783–793. https://doi.org/10.1016/J.CEMCONCOMP.2010.08.001

Gill, A. S., & Siddique, R. (2018). Durability properties of self-compacting concrete incorporating metakaolin and rice husk ash. *Construction and Building Materials*, 176, 323–332. https://doi.org/10.1016/J.CONBUILDMAT.2018.05.054

Givi, A. N., Rashid, S. A., Aziz, F. N. A., & Salleh, M. A. M. (2010). Assessment of the effects of rice husk ash particle size on strength, water permeability and workability of binary blended concrete. *Construction and Building Materials*, 24(11), 2145–2150. https://doi.org/10.1016/J.CONBUILDMAT.2010.04.045

Gursel, A. P., Maryman, H., & Ostertag, C. (2016). A life-cycle approach to environmental, mechanical, and durability properties of "green" concrete mixes with rice husk ash. *Journal of Cleaner Production*, 112, 823–836. https://doi.org/10.1016/J.JCLEPRO.2015.06.029

Horsakulthai, V., Phiuvanna, S., & Kaenbud, W. (2011). Investigation on the corrosion resistance of bagasse-rice husk-wood ash blended cement concrete by impressed voltage. *Construction and Building Materials*, 25(1), 54–60. https://doi.org/10.1016/J.CONBUILDMAT.2010.06.057

Huang, H., Gao, X., Wang, H., & Ye, H. (2017). Influence of rice husk ash on strength and permeability of ultra-high performance concrete. *Construction and*

Building Materials, 149, 621–628. https://doi.org/10.1016/J.CONBUILDMAT.2017.05.155

Hussain, Z., Noor, N. M., & Caronge, M. A. (2019). Workability and Compressive Strength of Seawater-Mixed Concrete Containing Rice Husk Ash as Supplementary Cementitious Material. *International Journal of Integrated Engineering*, 11(9), 192–200.

https://doi.org/10.30880/ijie.2019.11.09.021

Issa Khassaf, S., Talib Jasim, A., Kurdi Mahdi, F., Khassaf, S. I., Jasim, A. T., & Mahdi, F. (2014). Investigation The Properties Of Concrete Containing Rice Husk Ash To Reduction The Seepage In Canals. Article in *International Journal of Scientific & Technology Research*, 3. www.ijstr.org

Jindal, A., & Ransinchung, G. D. (2018). Behavioural study of pavement quality concrete containing construction, industrial and agricultural wastes. *International Journal of Pavement Research and Technology*, 11(5), 488–501. https://doi.org/10.1016/J.IJPRT.2018.03.007

Kannan, V. (2018). Strength and durability performance of self compacting concrete containing self-combusted rice husk ash and metakaolin. *Construction and Building Materials*, 160, 169–179. https://doi.org/10.1016/J.CONBUILDMAT.2017.11.043

Kannan, V., & Ganesan, K. (2014). Chloride and chemical resistance of self compacting concrete containing rice husk ash and metakaolin. *Construction and Building Materials,* 51, 225–234. https://doi.org/10.1016/J.CONBUILDMAT.2013.10.050

Kizhakkumodom Venkatanarayanan, H., & Rangaraju, P. R. (2015). Effect of grinding of low-carbon rice husk ash on the microstructure and performance properties of blended cement concrete. *Cement and Concrete Composites,* 55, 348–363. https://doi.org/10.1016/J.CEMCONCOMP.2014.09.021

Koushkbaghi, M., Kazemi, M. J., Mosavi, H., & Mohseni, E. (2019). Acid resistance and durability properties of steel fiber-reinforced concrete incorporating rice husk ash and recycled aggregate. *Construction and Building Materials*, 202, 266–275. https://doi.org/10.1016/J.CONBUILDMAT.2018.12.224

Krishna, N. K., Sandeep, S., & Mini, K. M. (2016). Study on concrete with partial replacement of cement by rice husk ash. IOP Conference Series: *Materials Science and Engineering*, 149(1), 012109. https://doi.org/10.1088/1757-899X/149/1/012109

Kunchariyakun, K., Asavapisit, S., & Sinyoung, S. (2018). Influence of partial sand replacement by black rice husk ash and bagasse ash on properties of autoclaved aerated concrete under different temperatures and times. *Construction and Building Materials*, 173, 220–227. https://doi.org/10.1016/J.CONBUILDMAT.2018.04.043

Kusbiantoro, A., Nuruddin, M. F., Shafiq, N., & Qazi, S. A. (2012). The effect of microwave incinerated rice husk ash on the compressive and bond strength of fly ash based geopolymer concrete. *Construction and Building Materials*, 36, 695–703. https://doi.org/10.1016/J.CONBUILDMAT.2012.06.064

Le, H. T., & Ludwig, H. M. (2016). Effect of rice husk ash and other mineral admixtures on properties of self-compacting high performance concrete. *Materials & Design*, 89, 156–166. https://doi.org/10.1016/J.MATDES.2015.09.120

Le, H. T., Nguyen, S. T., & Ludwig, H. M. (2014). A Study on High Performance Fine-Grained Concrete Containing Rice Husk Ash. *International Journal of Concrete Structures and Materials*, 8(4), 301–307. https://doi.org/10.1007/S40069-014-0078-Z/FIGURES/5

Lertwattanaruk, P., Sua-iam, G., & Makul, N. (2018). Effects of calcium carbonate powder on the fresh and hardened properties of self-consolidating concrete incorporating untreated rice husk ash. *Journal of Cleaner Production*, 172, 3265–3278. https://doi.org/10.1016/J.JCLEPRO.2017.10.336

Madandoust, R., & Ghavidel, R. (2013). Mechanical properties of concrete containing waste glass powder and rice husk ash. *Biosystems Engineering*, 116(2), 113–119. https://doi.org/10.1016/J.BIOSYSTEMSENG.2013.07.006

Madandoust, R., Ranjbar, M. M., Moghadam, H. A., & Mousavi, S. Y. (2011). Mechanical properties and durability assessment of rice husk ash concrete. *Biosystems Engineering*, 110(2), 144–152. https://doi.org/10.1016/J.BIOSYSTEMSENG.2011.07.009

Mahmud, H. bin, Malik, M. F. A., Kahar, R. A., Zain, M. F. M., & Raman, S. N. (2009). Mechanical Properties and Durability of Normal and Water Reduced High Strength Grade 60 Concrete Containing Rice Husk Ash. *Journal of Advanced Concrete Technology*, 7(1), 21–30. https://doi.org/10.3151/JACT.7.21

Mahmud, H. B., Bahri, S., Yee, Y. W., & Yeap, Y. T. (2016). Effect of Rice Husk Ash on Strength and Durability of High Strength High Performance Concrete. *International Journal of Civil and Environmental Engineering*, 10(3), 390–395. https://doi.org/10.5281/ZENODO.1123585

Makul, N. (2019). Combined use of untreated-waste rice husk ash and foundry sand waste in high-performance self-consolidating concrete. *Results in Materials*, 1, 100014. https://doi.org/10.1016/J.RINMA.2019.100014

Makul, N., & Sua-iam, G. (2018). Effect of granular urea on the properties of self-consolidating concrete incorporating untreated rice husk ash: Flowability, compressive strength and temperature rise. *Construction and Building Materials*, 162, 489–502. https://doi.org/10.1016/J.CONBUILDMAT.2017.12.023

Mehta, A., & Siddique, R. (2018). Sustainable geopolymer concrete using ground granulated blast furnace slag and rice husk ash: Strength and permeability properties. *Journal of Cleaner Production*, 205, 49–57. https://doi.org/10.1016/J.JCLEPRO.2018.08.313

Modarres, A., & Hosseini, Z. (2014). Mechanical properties of roller compacted concrete containing rice husk ash with original and recycled asphalt pavement material. *Materials & Design*, 64, 227–236. https://doi.org/10.1016/J.MATDES.2014.07.072

Mohseni, E., Khotbehsara, M. M., Naseri, F., Monazami, M., & Sarker, P. (2016). Polypropylene fibre reinforced cement mortars containing rice husk ash and nano-alumina. *Construction and Building Materials*, 111, 429–439. https://doi.org/10.1016/J.CONBUILDMAT.2016.02.124

Molaei Raisi, E., Vaseghi Amiri, J., & Davoodi, M. R. (2018a). Mechanical performance of self-compacting concrete incorporating rice husk ash. *Construction and Building Materials*, 177, 148–157. https://doi.org/10.1016/J.CONBUILDMAT.2018.05.053

Molaei Raisi, E., Vaseghi Amiri, J., & Davoodi, M. R. (2018b). Influence of rice husk ash on the fracture characteristics and brittleness of self-compacting concrete. *Engineering Fracture Mechanics*, 199, 595–608. https://doi.org/10.1016/J.ENGFRACMECH.2018.06.025

Muthadhi, A., & Kothandaraman, S. (2013). Experimental Investigations of Performance Characteristics of Rice Husk Ash–Blended Concrete. *Journal of Materials in Civil Engineering*, 25(8), 1115–1118. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000656

Muthukrishnan, S., Gupta, S., & Kua, H. W. (2019). Application of rice husk biochar and thermally treated low silica rice husk ash to improve physical properties of cement mortar. *Theoretical and Applied Fracture Mechanics*, 104, 102376. https://doi.org/10.1016/J.TAFMEC.2019.102376

Nair, D. G., Sivaraman, K., & Thomas, J. (2013). Mechanical Properties of Rice Husk Ash (RHA) - High strength Concrete.

Najimi, M., Sobhani, J., Mirgozar, A., Alireza Zareei, S., Ameri, F., Bahrami, N., & Dorostkar, F. (2017). Experimental Evaluation of Eco-friendly Light Weight Concrete with Optimal Level of Rice Husk Ash Replacement Cite this paper Civil Engineering Journal Experimental Evaluation of Eco-friendly Light Weight

Concrete with Optimal Level of Rice Husk Ash Replacement. 3(10). https://doi.org/10.28991/cej-030930

Naseri, F., Mohseni, E., Amjadi, R., Khotbehsara, M. M., & Ranjbar, M. M. (n.d.). Microstructure and durability properties of cement mortars containing nano-TiO 2 and rice husk ash Related papers Microstructure and durability properties of cement mortars containing nano-TiO 2 and rice husk ash. https://doi.org/10.1016/j.conbuildmat.2016.03.136

Naveen, Bansal, S., & Antil, Y. (2015). Effect of Rice Husk on Compressive Strength of Concrete. *International Journal on Emerging Technologies*, 6(1), 144–150.

Nehdi, M., Duquette, J., & el Damatty, A. (2003). Performance of rice husk ash produced using a new technology as a mineral admixture in concrete. *Cement and Concrete Research*, 33(8), 1203–1210. https://doi.org/10.1016/S0008-8846(03)00038-3

Olutoge, F. A., & Adesina, P. A. (2019). Effects of rice husk ash prepared from charcoal-powered incinerator on the strength and durability properties of concrete. *Construction and Building Materials*, 196, 386–394. https://doi.org/10.1016/J.CONBUILDMAT.2018.11.138

Padhi, R. S., Patra, R. K., Mukharjee, B. B., & Dey, T. (2018). Influence of incorporation of rice husk ash and coarse recycled concrete aggregates on properties of concrete. *Construction and Building Materials*, 173, 289–297. https://doi.org/10.1016/J.CONBUILDMAT.2018.03.270

Patel, Y. J., & Shah, N. (2018). Enhancement of the properties of Ground Granulated Blast Furnace Slag based Self Compacting Geopolymer Concrete by incorporating Rice Husk Ash. *Construction and Building Materials*, 171, 654–662. https://doi.org/10.1016/J.CONBUILDMAT.2018.03.166

Praveenkumar, T. R., Vijayalakshmi, M. M., & Meddah, M. S. (2019). Strengths and durability performances of blended cement concrete with TiO2 nanoparticles and rice husk ash. *Construction and Building Materials*, 217, 343–351. https://doi.org/10.1016/J.CONBUILDMAT.2019.05.045

Prayuda, H., Monika, F., & Cahyati, M. D. (2020). Fresh properties and compressive strength of self compacting concrete with fines aggregate replacement using red brick powder and rice husk ash. *World Journal of Engineering*, 17(4), 473–480. https://doi.org/10.1108/WJE-08-2019-0236/FULL/PDF

Rattanachu, P., Toolkasikorn, P., Tangchirapat, W., Chindaprasirt, P., & Jaturapitakkul, C. (2020). Performance of recycled aggregate concrete with rice husk ash as cement binder. *Cement and Concrete Composites*, 108, 103533. https://doi.org/10.1016/J.CEMCONCOMP.2020.103533

Rodríguez De Sensale, G. (2006). Strength development of concrete with rice-husk ash. *Cement and Concrete Composites*, 28(2), 158–160. https://doi.org/10.1016/J.CEMCONCOMP.2005.09.005

Safiuddin, M., West, J. S., & Soudki, K. A. (2010). Hardened properties of self-consolidating high performance concrete including rice husk ash. *Cement and Concrete Composites*, 32(9), 708–717. https://doi.org/10.1016/J.CEMCONCOMP.2010.07.006

Sakr, K. (2006). Effects of Silica Fume and Rice Husk Ash on the Properties of Heavy Weight Concrete. *Journal of Materials in Civil Engineering*, 18(3), 367–376. https://doi.org/10.1061/(ASCE)0899-1561(2006)18:3(367)

Salas, A., Delvasto, S., de Gutierrez, R. M., & Lange, D. (2009). Comparison of two processes for treating rice husk ash for use in high performance concrete. *Cement and Concrete Research*, 39(9), 773–778. https://doi.org/10.1016/J.CEMCONRES.2009.05.006

Sathawane, S. H., Vairagade, V. S., & Kene, K. S. (2013). Combine Effect of Rice Husk Ash and Fly Ash on Concrete by 30% Cement Replacement. *Procedia Engineering*, 51, 35–44. https://doi.org/10.1016/J.PROENG.2013.01.009

Siddharth Talsania, E., Mukeshkumar Vyas, C., Talsania, S., Pitroda, J., & Vyas, C. M. (2015). EFFECT OF RICE HUSK ASH ON PROPERTIES OF PERVIOUS CONCRETE. International Journal of Advanced Engineering Research and Studies. https://www.researchgate.net/publication/281639934

Siddique, R., Singh, K., Kunal, P., Singh, M., Corinaldesi, V., & Rajor, A. (2016). Properties of bacterial rice husk ash concrete. *Construction and Building Materials*, 121, 112–119. https://doi.org/10.1016/J.CONBUILDMAT.2016.05.146

Sua-iam, G., & Makul, N. (2013). Use of Unprocessed Rice Husk Ash and Pulverized Fuel Ash in the Production of Self-compacting Concrete. *IERI Procedia*, 5, 298–303. https://doi.org/10.1016/J.IERI.2013.11.107

Sua-Iam, G., & Makul, N. (2013). Utilization of limestone powder to improve the properties of self-compacting concrete incorporating high volumes of untreated rice husk ash as fine aggregate. *Construction and Building Materials*, 38, 455–464. https://doi.org/10.1016/J.CONBUILDMAT.2012.08.016

Sua-iam, G., Makul, N., Cheng, S., & Sokrai, P. (2019). Workability and compressive strength development of self-consolidating concrete incorporating rice husk ash and foundry sand waste – A preliminary experimental study. *Construction and Building Materials*, 228, 116813. https://doi.org/10.1016/J.CONBUILDMAT.2019.116813

Sua-iam, G., Sokrai, P., & Makul, N. (2016). Novel ternary blends of Type 1 Portland cement, residual rice husk ash, and limestone powder to improve the properties of self-compacting concrete. *Construction and Building Materials*, 125, 1028–1034. https://doi.org/10.1016/J.CONBUILDMAT.2016.09.002

Tangchirapat, W., Buranasing, R., Jaturapitakkul, C., & Chindaprasirt, P. (2008). Influence of rice husk–bark ash on mechanical properties of concrete containing high amount of recycled aggregates. *Construction and Building Materials*, 22(8), 1812–1819. https://doi.org/10.1016/J.CONBUILDMAT.2007.05.004

Tuck Lun, L. (2015). EFFECTS OF RICE HUSK ASH (RHA) PRODUCED FROM DIFFERENT TEMPERATURES ON THE PERFORMANCE OF CONCRETE.

Vieira, A. P., Toledo Filho, R. D., Tavares, L. M., & Cordeiro, G. C. (2020). Effect of particle size, porous structure and content of rice husk ash on the hydration process and compressive strength evolution of concrete. *Construction and Building Materials*, 236, 117553. https://doi.org/10.1016/J.CONBUILDMAT.2019.117553

Zareei, S. A., Ameri, F., Dorostkar, F., & Ahmadi, M. (2017). Rice husk ash as a partial replacement of cement in high strength concrete containing micro silica: Evaluating durability and mechanical properties. *Case Studies in Construction Materials*, 7, 73–81. https://doi.org/10.1016/J.CSCM.2017.05.001

Zerbino, R., Giaccio, G., & Isaia, G. C. (2011). Concrete incorporating rice-husk ash without processing. *Construction and Building Materials*, 25(1), 371–378. https://doi.org/10.1016/J.CONBUILDMAT.2010.06.016

Zhang, M. H., Lastra, R., & Malhotra, V. M. (1996). Rice-husk ash paste and concrete: Some aspects of hydration and the microstructure of the interfacial zone between the aggregate and paste. *Cement and Concrete Research*, 26(6), 963–977. https://doi.org/10.1016/0008-8846(96)00061-0

Zubairu, I., Ibrahim, H., & Kabir, N. (2018). Investigation Into The Use Of Rice Husk Ash And Local Dye Residue (Katsi) As Partial Replacement For Cement. *Global Scientific Journals*, 6 (6)

B. openLCA Model