CHARACTERIZATION OF DURABILITY AND MECHANICAL PROPERTIES OF ‘*COCOS NUCIFERA LINN*’ FIBRE (CNF) REINFORCED FOAMCRETE AND ITS PERFORMANCE AT ELEVATED TEMPERATURES

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by

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LIST OF ABBREVIATIONS

LF	Lightweight Foamcrete
CNF	Cocos Nucifera Linn Fibre
SCM's	Supplementary Cementitious Materials
ASTM	American Society for Testing Materials
ACI	American Concrete Institute
UPV	Ultrasonic Pulse Velocity
LVDT	Linear Variation Differential Transformer
SCC	Self Compacting Concrete
OPC	Ordinary Portland Cement
NaOH	Sodium Hydroxide
HSC	High Strength Concrete
SEM	Scanning Electron Microscopy
GBI	Green Building Index
CLSM	Controlled Low Strength Material
pH	Potential of Hydrogen
CO_2	Carbon Dioxide
CaO	Calcium Oxide
CSP	Coconut Shell Powder
BS	British Standard
PSC	Pre-Stressed Concrete
PUNDIT	Portable Ultrasonic Non-destructive Digital Indicating Tester
C-S-H	Calcium-Silicate-Hydrate
$Ca(OH)_2$	Calcium Hydroxide

RH	Relative Humidity
R^2	coefficient of determination
kg	kilogram
mm	millimeter
°C	celsius
kg/m^3	kilogram per meter cube
%	percentage
g/cm^3	gram per centimeter cube
N/mm^2	newton per millimeter square
GPa	gigapascal
cm^2	centimeter square
kHz	kilohertz
KN	kilonewton
N/sec	newton per second
m/s	meter per second
kJ	kilojoule
cc	cubic centimeters

LIST OF NOMENCLATURE

w/c	water to cement ratio
W_a	water absorption of hardened foamcrete sample (%)
W_{sat}	saturated surface dry weight of foamcrete sample (kg)
W_{dry}	oven-dried weight of specimen (kg)
W_{wat}	weight of foamcrete sample (kg) in water (kg)
P_r	porosity of hardened foamcrete sample (%)
ϕ	porosity of foamcrete (%)
x	CNF volume fraction in %
UPV	ultrasonic pulse velocity in m/s
CD	carbonation depth of foamcrete in %
F_c	compressive strength in N/mm^2
F_l	flexural strength in N/mm^2
S_t	flexural strength in N/mm^2

PENCIRIAN SIFAT KETAHANAN DAN MEKANIKAL KONKRIT RINGAN BERBUSA DIPERKUAT DENGAN GENTIAN *'COCOS NUCIFERA LINN'* (CNF) DAN PRESTASINYA PADA SUHU TINGGI

ABSTRAK

Permintaan terhadap pengunaan konkrit ringan berbusa adalah semakin meluas yang didorong oleh garis panduan dan peraturan dengan tujuan untuk mengurangkan pelepasan gas rumah hijau dan mengurangkan pelepasan karbon. Penggunaan gentian semulajadi dalam konkrit ringan berbusa dianggap sebagai satu usaha yang mampan. Oleh yang demikian, kajian ini telah dilaksanakan bagi tujuan untuk mengenalpasti sifat ketahanan dan mekanikal gentian *cocos nucifera linn* (CNF) sebagai bahan tetulang dalam konkrit ringan berbusa serta prestasinya pada suhu tinggi. CNF diperoleh dari sisa pertanian atau produk sampingan yang dihasilkan melalui proses pengagihan minyak kelapa terkumpul dalam kuantiti yang banyak di Malaysia. Kajian ini dijalankan untuk mengenalpasti tindakbalas enam peratusan CNF yang berlainan (0.1%, 0.2%, 0.3%, 0.4%, 0.5% dan 0.6%) dengan jumlah campuran. Tiga ketumpatan berbeza iaitu 650, 1050, dan 1450 kg/m³ telah diuji dalam kajian ini. Nisbah simen, pasir dan air yang digunakan adalah 1:1.5:0.45. Hasil kajian menunjukkan bahawa CNF memainkan peranan yang penting untuk meningkatkan sifat ketahanan seperti penyerapan air, keliangan, pengecutan pengeringan, kedalaman karbonisasi dan kelajuan denyut ultrasonik konkrit ringan berbusa. Penambahan CNF juga telah meningkatkan kekuatan mampatan, lenturan dan tegangan konkrit ringan berbusa. CNF bertindak sebagai agen retak anti mikro yang menghalang keretakan pada konkrit ringan berbusa. CNF juga mempunyai kelebihan dari aspek ikatan yang baik antara zarah-zarah dan meningkatkan kekuatan

konkrit ringan berbusa. Pada suhu tinggi, CNF berperanan penting dalam mewujudkan struktur konkrit yang lebih mulur berbanding dengan konkrit ringan berbusa biasa tanpa sebarang gentian. Penggunaan CNF meningkatkan sifat mekanikal pada setiap suhu yang telah ditetapkan untuk semua ketumpatan yang diselidiki. Hal ini menunjukkan bahawa CNF mempunyai ikatan yang kukuh dan sifat kimia yang sangat baik. Peratusan optimum CNF yang memberikan peningkatan yang terbaik dalam sifat ketahanan, sifat mekanikal dan prestasi suhu tinggi adalah 0.3% untuk 650 kg/m^3 dan 0.4% untuk 1050kg/m^3 dan 0.5% untuk 1450kg/m^3.

CHARACTERIZATION OF DURABILITY AND MECHANICAL PROPERTIES OF '*COCOS NUCIFERA LINN*' FIBRE (CNF) REINFORCED FOAMCRETE AND ITS PERFORMANCE AT ELEVATED TEMPERATURES

ABSTRACT

The call for lightweight foamcrete technology is impelled by the amplified rules and guidelines with the aim of minimizing greenhouse gas emission and reducing carbon footprint. The use of natural fibres in foamcrete is considered as a useful option in making concrete as a sustainable material. Therefore, the aim of the present study is to characterize the durability and mechanical properties of foamcrete reinforced with *cocos nucifera linn* fibres (CNF) as well as its performance at elevated temperatures. CNF refer to agricultural waste or by-products that can be obtained through the distribution of coconut oil and can be accumulated in a large amount in Malaysia. This study aimed to identify the response of CNF towards six different contents (0.1%, 0.2%, 0.3%, 0.4%, 0.5%, and 0.6%) by mix volume. Three different densities of 650, 1050 and 1450 kg/m^3 were tested in this study. The proportion of foamcrete was cement, sand, and water which were represented by the ratio of 1:1.5:0.45. Results showed that, CNF plays a vital role to improve the durability properties such as water absorption, porosity, drying shrinkage, carbonation depth and ultrasonic pulse velocity of foamcrete. Addition of CNF also had enhanced the compressive, flexural and splitting tensile strengths of foamcrete. CNF acts as an anti-micro crack agent by preventing cracks from forming on the foamcrete. CNF are multi-fibre empowering enhancement for the bonding between the particles materials and minimized void proportion. At high temperatures, CNF strengthened foamcrete offer progressively ductile structure contrasted with plain

foamcrete. The incorporation of CNF enhanced the mechanical properties at each predetermined temperature for all densities investigated. This demonstrates that CNF has strong bonding and good quality of chemical properties that are unique to itself. The optimum volume fraction of CNF that gave the best improvement in durability, mechanical and high temperature properties were 0.3% for 650 kg/m^3 and 0.4% for 1050 kg/m^3 and 0.5% for 1450 kg/m^3.

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Green environment is a puzzling and stimulating concern that has received a considerable attention in today's construction industry. The call for green concrete technology is impelled by the amplified rules and guidelines with the aim of minimizing greenhouse gas emission and reducing carbon footprint. In regard to this matter, the construction industry in Malaysia is seen to embrace green construction due to the project requirements that need to be adhered to achieve the certification for Green Building Index (GBI). It is important to note that the GBI rating tool was first introduced in Malaysia back in the year 2005 with the main objective of enhancing awareness among industrial players and encouraging sustainable construction in built environment.

Furthermore, it should be noted that global apprehension and governance on carbon footprint emissions have driven a considerable amount of research on green concrete around the world. In particular, special attention has been given on environmental deliberations with respect to base mix material sourcing, concrete mix design, design of structural component, construction method, construction technology, and the aspect of concrete structure maintenance. Therefore, it can be stated that concrete industry players in Malaysia play a significant role in achieving a holistic and sustainable development of the society.

In the present day, it should be acknowledged that most of the construction products are produced using materials that require a high amount of energy and not naturally sustainable which can lead to global problem. Hence, the use of natural fibres in lightweight foamcrete is considered as a useful option in making concrete as a sustainable material to overcome this problem. In regard to this matter, it should be understood that there are various advantages in using foamcrete which include lightweight, able to deliver good thermal insulation, and influent savings of several materials such as cement, fine aggregate, stable foam, and water. These materials are the basic components of foamcrete but there are other types of admixture that can be used to enhance the strength of foamcrete.

Moreover, the low density of foamcrete is caused by the absence of coarse aggregate which subsequently leads to lower self-weight. On another note, foamcrete can be used for structural elements, semi-structural, non-structural partitions, and thermal insulating materials. In addition, foamcrete are usually developed in various densities ranging from 400 kg/m^3 to 1800 kg/m^3 (Jalal *et al.*, 2017). More importantly, foamcrete are ecologically clean, inflammable, and easy to produce compared to other materials despite the fact that the mixing time of foamcrete is longer than the conventional one to ensure proper mixing.

Generally, foamcrete is known to have a good compression but poor tension strength, thus making it fragile. Meanwhile, the access of air bubbles and the interrelation between them tend to increase significantly due to the reduction of density. As a result, the increase of water vapor will lead to the reduction in foamcrete strength. However, the weakness in tension can be reduced by adding a sufficient volume of certain fibres. In this case, it should be understood that the use of fibres are able to arrest cracks formation and improve strength and ductility with the overall aim of improving its toughness.

Furthermore, a considerable amount of studies has proven the effectiveness of fibres into mixtures in terms of durability and the enhancement of mechanical properties. According to Awang *et al.*, (2015), fibres have their own advantages and disadvantages and it can be categorized into two, namely synthetic fibres known as man-made fibres and natural fibres that are more environmental-friendly. Nevertheless, the finest fibres tend to have a very good essence which is able to assist in the enhancement of the strength and properties of concrete. Apart from that, the use of natural fibre can help to improve shrinkage and ductility (Falliano *et al.*, 2018).

In regard to this matter, natural fibres are known as sustainable resources which is the main reason why they are currently getting a lot of attention in replacing synthetic fibre (Pickering *et al.*, 2016). Unlike synthetic fibres, there are numerous benefits of natural fibres which include low density, biodegradable, and hard to melt on heating. More importantly, natural fibres are capable of strengthening cementitious material, particularly in the invention and fabrication of building materials. Currently, the most commonly used natural fibres are bamboo, coir, sisal, cane, jute, and henequen fibres (Ibrahim *et al.*, 2016).

According to Rahman *et al.* (2015), there has been a wide application of natural fibres in producing lightweight concrete due to the increasing interest in natural fibres in adhering to a more environmental and cost-effective value in construction industries. Nevertheless, it should be understood from a structural standpoint that the primary purpose of adding fibre in cementitious material is to improve the durability of engineering properties. Specifically, it is believed that the fibre could enhance the matrix bond that will help to develop the tensile strength and structural integrity of the concrete (Narayanan and Ramamurthy, 2000).

Cocos nucifera linn fibres (CNF) refer to agricultural waste or by-products that can be obtained through the distribution of coconut oil and can be accumulated in a large amount in Malaysia. Moreover, it should be understood that CNF fibres are often discarded as agricultural wastes. Nevertheless, numerous schemes concentrating on the lower cost of materials have been recommended despite the important need of green concrete production and reasonably priced housing system for both whom live at the countryside and metropolitan areas in Malaysia. As a result, it has been recommended that agricultural wastes and residues should be utilized as partial or full replacement of building materials. Accordingly, it is crucial to note that CNF fibres have the potential to be utilized as substitute coarse aggregate in foamcrete for the purpose of improving the strength and durability (Amran *et al.*, 2015).

It should be pointed out that there is a large volume of published studies that were conducted to further expand the understanding and applications of CNF these days in concrete based materials all over the world. In this case, these undertakings embrace the progress of new and stronger fibres, or in other words, a new alternative of fibre that can strengthen concrete. In addition, it is crucial to understand that concrete and mortar strength and durability performance can be holistically improved using CNF (Hilal *et al.*, 2015). However, there is a need to solver the issue of long-term durability. In regard to this matter, it should be clearly understood that the level of concrete improvement with the assistance of CNF relies on the type of the species and ages of the fibre itself. Apart from that, the capability of fibres can be defined based on their act, particularly when they receive force from compression, flexural, and tensile strength.

The research findings will address the knowledge gap in the subject of CNF reinforced foamcrete and will provide an improved understanding of the high-temperature properties of with the inclusion of CNF.

1.2 Research Problem Statement

On another note, it is important to understand that a lot of energy required to produce concrete with synthetic fibres such as fibre glass, sawdust, straw and others makes it unnaturally sustainable despite the fact that they are easily accessible low in cost. In addition, there are several disadvantages of these materials, specifically in terms of durability because the materials tend to readily absorb water and lose insulating value in wet condition (Falliano *et al.*, 2018).

Despite the fact that foamcrete mechanical properties are low in comparison to normal weight concrete, foamcrete has a potential to be used as in-fill material, partition and light load bearing panel in low rise residential construction. The first stage to realize the potential of foamcrete for application as a load-bearing material in building construction is to obtain reliable mechanical properties at ambient and elevated temperatures. The major factor limiting the use of foamcrete in the building construction is inadequate knowledge and information of the material performance at elevated temperatures. Fire resistance of foamcrete is highly dependent on its constituent materials, particularly the pozzolans. The effect of elevated temperatures on CLM not been investigated in detail (Hilal *et al.*, 2015).

Nowadays, it has been widely agreed that construction needs materials that are durable, light, and simple to use but are more naturally sustainable. Additionally, natural fibres have the potentials to perform equally as synthetic fibres. Moreover, this alternative does not need a high amount of energy and considered as ultimate green products because it utilizes some agricultural wastes as construction materials. However, there is a minimum potential for the plain concrete to prevent cracking. Cracks are a significant issue as suggested by Gowri and Anand (2018) because it will lead to negative impression of quality, durability and serviceability but they are only regarded as aesthetic problems in most cases.

CNF has always been disposed as wastes instead of being utilized as construction materials. The use of foamcrete with CNF is able to reduce the weaknesses of foamcrete which include low tensile strength, shrinkage problem, and serious crack propagation, especially in low densities foamcrete. In addition, the addition of CNF is a practical way to improve the bending performance as well as tensile cracking considering that foamcrete is generally weak in tension compared to its capacity in compression (Yalley and Kwan, 2012).

In addition, the capability of fibres is dependent on the amount of fibres used in the mixture. According to Rai and Joshi (2014), higher percentage of fibre will lead to segregation and roughness of concrete and mortar. Moreover, fibres that are lengthy in the mix will create workability problems that can be discovered using the flow table test and during the pouring of the concrete into the mold. Therefore, the aim of the present study is to perform experimental studies in order to characterize the durability and mechanical properties of foamcrete reinforced with CNF as well as its performance at elevated temperatures.

Foamcrete is a heterogeneous multi-phase material that is held together by the hydrated Portland cement paste. When foamcrete is exposed to elevated temperatures, changes in durability occur. Non-linearities in material properties, the disparity of physical properties with temperature, tensile cracking, and creep effects affect the buildup of thermal forces, the load-carrying capacity, and the deformation capability (i.e., ductility) of the structural members will take place. The property variations result principally because of changes in the moisture condition of the concrete constituents and the progressive deterioration of the cement paste-aggregate bond, which is especially critical where thermal expansion values for the cement paste and fillers diverge significantly

1.3 Research Aim and Objectives

The objectives of the current research are as follows:

i. To determine the durability properties of foamcrete that contains different percentages of CNF.

ii. To identify the mechanical properties of foamcrete which encompasses different portions of CNF

iii. To determine the elevated temperature strengths of foamcrete reinforced with CNF.

1.4 Significance of the Study

A considerable amount of studies has investigated foamcrete involving two types of fibres, namely synthetic fibres and natural resources fibres (alternative option to make concrete naturally sustainable). In this case, it should be understood that fibre reinforced concrete has the potential to reduce the problem of concrete fracture. Therefore, the aim of the current research is to observe the potential utilization of CNF for foamcrete engineering and durability properties enhancement. Apart from that, the purpose of this experimental study is to produce something that has a value of sustainability.

Accordingly, the present study will also focus on the performance of foamcrete reinforced with CNF at elevated temperature. Hence, the results from this project will allow a reappraisal use of these fibres that will perform well as additive in foamcrete. Therefore, the current research aims to fill the gaps of knowledge, specifically concerning the properties and performance at elevated temperature. As previously mentioned, only minimum amount of energy is required to produce natural fibres which makes it the ultimate green products that can be used as alternate option to make concrete more naturally sustainable.

Overall, the purpose of the present study is to motivate other researchers to carry out research on natural fibres and its application to any structural system because the findings of this study will provide understandable and accurate information of foamcrete with different percentages of CNF and its performance at ambient and elevated temperatures.

1.5 Scope of Study

The present study investigates the potential of using natural fibres as additive in foamcrete. In addition, the current research is designed to explore the durability and mechanical properties of CNF reinforced lightweight foamcrete as well as its performance at elevated temperature. Nevertheless, it is crucial to note that there are restrictions of study and experimental work set for the current research. In the case of this study, lightweight foamcrete mix proportions are designed to achieve the target density. The foamcrete mix proportions of sand: cement: water is fixed at the ratio of 1:1.5:0.45 because the main emphasis of this research is to observe the influence of CNF addition on durability and mechanical properties at ambient and high temperatures. In turn to attain sufficient strength, a constant cement-sand ratio of 1:1.5 and water cement ratio of 0.45 were used for all mixes. Due to concern of the environment, the cement content was lower than the amount of sand added.

According to Ede and Agbede (2015), it was verified that CNF content in the excess of 0.75% reduces the workability and drastically weakens the compressive and flexural strength. The presence of CNF significantly improves the toughness and the ductility behavior of concrete. The test results have shown that CNF at 0.5% content is optimal for enhancing the rheological and mechanical properties of concrete. Hence for this research, CNF contents of 0.1%, 0.2%, 0.3%, 0.4%, 0.5%, and 0.6% by mix volume fraction will be added in the foamcrete mixes. This CNF was extracted from the outer shell of a young coconut.

Apart from that, three densities of 650 kg/m^3, 1050 kg/m^3, and 1450 kg/m^3 will be cast and tested to expansively characterize the durability, engineering, and high temperature properties. Moreover, it should be noted that all foamcrete samples cast for the current research will be sealed curing.

Certainly, the present study aims to identify the response of these CNF in terms of durability properties, mechanical performance, and high temperature properties. In this case, the durability properties of the mixtures can be determined by measuring the depth of carbonation, water absorption, porosity, ultrasonic pulse velocity and drying shrinkage. In addition, it is equally important to evaluate the mechanical properties of the mixtures by testing their compressive strength, flexural strength, and splitting tensile strength and SEM analysis. Finally, the current research will investigate the elevated temperature performance of foamcrete reinforced with CNF at different heating temperatures of 20°C, 105°C, 200°C, 400°C, 600°C, and 800°C.

1.6 Thesis Organization

The overall structure of this thesis takes the form of five chapters which covers the characterization of durability, engineering properties, and performance of foamcrete reinforced with CNF at elevated temperature.

Chapter One

This chapter acts as an introduction chapter that demonstrates the general aims and objectives of the current research. This chapter also provides a deliberate and in-depth overview of the present study along with the problem statements that highlight the durability problems faced by the plain foamcrete. Meanwhile, the potential use of CNF as reinforcement in foamcrete will also be highlighted. Apart from that, this chapter also defines the research objective, significance of the study, and research limitations.

Chapter Two

This chapter presents an in-depth literature review of the present study. More specifically, this chapter will discuss a considerable amount of studies on durability and engineering properties of foamcrete that is added with fibre which is believed to prevent cracks formation as well as improve strength and ductility. Moreover, foamcrete behavior at elevated temperatures will also be discussed, while the boundaries discovered in former studies will be acknowledged and additional information will be delivered as a platform to provide a better understanding of this research project. This chapter ends with a summary that explicitly describes the framework of the current research.

Chapter Three

The third chapter is concerned with the methodology employed in the present study involving the relevant experiments and investigations. This chapter provides a detailed discussion about the basic materials that can be used to fabricate foamcrete, mix design, mix procedure, laboratory works as well as the process to accomplish the objectives of the present study which will be achieved by a systematic process throughout this study.

Chapter Four

Chapter 4 analyses the data gathered and addresses each of the research questions of the present study. This chapter presents and discusses the results obtained from experimental works on durability performance, mechanical properties, regression models for predicting durability and mechanical properties of foamcrete as well as the elevated temperatures strengths of foamcrete reinforced with CNF. The analysis of the results and the discussions will be further explained in this chapter. Hence, this allows the strength, weakness, and the opportunity to utilize CNF in concrete based materials to be determined explicitly.

Chapter Five

The purpose of the final chapter is to reflect on the extent to which this study has managed to be conducted. A summary for the entire study will be presented in this chapter based on the results acquired throughout the laboratory investigation. Apart from that, all of the results, discussions, and contents discussed in the previous chapters will also be summarized in this chapter. Finally, the conclusion and recommendation for future plans are also presented at the end of this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The purpose of this chapter is to discuss past researches that investigated the mechanical and durability properties of CNF that is reinforced with lightweight foamcrete. The relevant topics and background studies of lightweight concrete are also being reviewed in this chapter. Furthermore, the elevated temperature properties and characteristics of foamcrete are discussed in accordance with competent standard.

In regard to this matter, it is important to note that the utilization of lightweight foamcrete in construction industry has increased significantly over the recent years due to its various advantages which include low self-weight, free flowing, good thermal insulation properties, and excellent acoustic resistance (Amran *et al.*, 2015), thus make it ideal for a wide range purposes, from insulating floors and roofs, to void filling. However, there are several drawbacks of foamcrete that must be considered such as extreme sensitivity to water content in the mixtures, which subsequently lead to extensive breakability as well as low bending strength (Narayanan and Ramamurthy, 2000). Therefore, the use of natural fibres is expected to strengthen the lightweight foamcrete and arrest the crack formation (Ramaswamy *et al.*, 1983).

Accordingly, the current research is motivated to investigate the influence of CNF as a reinforcement material in lightweight foamcrete with regards to environmental concerns. In addition, another purpose of this research is to perform experimental studies with the aim of characterizing the durability and engineering properties of CNF that is reinforced with lightweight foamcrete as well as assessing its performance at elevated temperatures. Besides, this study also intended to propose regression models for the purpose of predicting the durability and mechanical properties of foamcrete strengthened with CNF at ambient temperature.

2.2 Lightweight Foamcrete

Foamcrete is classified as a lightweight concrete (400 kg/m^3 to 1850 kg/m^3). In this case, the absence of coarse aggregate causes the foamcrete to have low density, which consequently leads to lower self-weight. More importantly, this type of lightweight concrete is recognized due to its low cement content, high workability, and low aggregate usage (Valore, 1954). Meanwhile, other characteristics of lightweight foamcrete include its ability to be attained ecologically clean, inflammable, and easy to produce. However, it is crucial to note that the mixing time is longer than normal concrete to ensure proper mixing for the purpose of attaining the target density and quality of lightweight foamcrete (Hilal *et al.*, 2015).

Furthermore, foamcrete can be categorized as a wider class of lightweight foamcrete which is made up of cement, water, fine sands, and trapped bubbles that stands in as an aggregate. More importantly, the mixture of lightweight foamcrete can be replaced or added with other materials in order to enhance the strength and durability; for example, replacing the sand with other sand-like materials such as silica fume and fly ash (Ramamurthy *et al.*, 2009). In addition, it should be noted that foamcrete encompasses of mortar matrix with at least 20% of entrapped air void which indicates that it can simply be produced with outstanding workability, high level of sound insulation, good thermal protection, excellent fire resistance, decent heat absorption, good flowability, and self-compatibility (Johnson and Li, 2012).

The past centuries had shown that the Romans were able to create the earliest concrete consisting well-mixed small gravel, coarse sands, with hot lime and water. Meanwhile, a few years following the innovation, it was found that the concrete can have better durability and workability through the addition of animal blood into the mix which tend to produce small air bubbles when it is stirred. Apart from that, horse hair was also added into the mixes as admixture with the aim of enhancing the strength and reducing the shrinkage which is more or less similar to the use of fibres today. Panesar (2013) reported that the incorporation of fibre into lightweight foamcrete is for the purpose of improving its durability properties. Meanwhile, low volumetric of short fibre has been demonstrated to decrease the effect of early age on concrete durability. On another note, the development in the eminence of surfactants (foaming agents) and foam generator further facilitates the utilization of foamcrete on a much greater scale such as roof insulation, concrete blocks, floor screed, and road sub-base in-fill material (Amran *et al.*, 2015).

2.3 Constituent Materials of Lightweight Foamcrete

Lightweight foamcrete is a blend comprising of water, cement, fine aggregate, and foam. Moreover, it should be noted that foamcrete has higher sand ratio compared to normal concrete, probably in the range of 40% to 50%, thus leading to the reduction of size and reduced number of voids. In this case, smaller number of voids leads to better durability. The other fundamental factors that impact the quality of lightweight foamcrete are cement-sand proportion, water cement proportion, type of cement and substance, pore size and circulation, type of foaming agent, and curing regime (Gowri and Anand, 2018).

Furthermore, it is crucial to note that stable foam is the most important component in the production of lightweight foamcrete. Meanwhile, the purpose of using foaming agent is to ensure a good performance of the lightweight foamcrete, particularly in terms of workability, durability, and easy casting. Moreover, there are two types of foaming agents, namely natural and synthetic. In a research conducted by Bombatkar *et al.* (2017), it was found that foam that is protein based originates from environmental sources and has a load of 80g/liter. More importantly, natural foaming agents are progressively steady compared to the engineered ones, but have a shorter life span, particularly in open conditions. Apart from that, they additionally provide a higher quality of concrete in contrast to the manufactured foaming agents.

According to Zulkarnain and Ramli (2011), water is an essential constituent of mixing process whereby its ratio is dependent on the admixtures and other materials composition that may lead to the required consistency and stability. However, it should be noted that the reduction of water causes bubbles burst and segregation. (Kearsley and Visagie, 1999) stated that w/c ratio used range of 0.40-1.25. Liu *et al.* (2016) discovered that the water-cement ratio influences the size, shape, distribution, and connectivity of pores in foamcrete. Nevertheless, the power exponential relationship between 28-day strength and dry density of the foamcrete varies with different w/c ratios.

The utilization of fibres into foamcrete is able to reduce brittleness, breakability, and cost of production (Lim *et al.*, 2014). An appropriate selection of the type of fibre, w/c ratio, and air content of base mortar will produce the ideal blends of flexibility, thickness, usefulness, and quality of the mortar. Meanwhile, higher adjustment to water-cement ratio or reduction in foam leads to decreased uniformity and consistency of the mortar slurry (Amran *et al.*, 2015) .

2.3.1 Cement

Early strengthening of foamcrete is extremely significant. In regard to this matter, cement should be hydrated adequately before defoaming due to the action of gravity, extrusion. and drying shrinkage for the purpose of preventing the occurrences of breakdown of pore connection in the matrix. In addition, the selection of suitable types of cement is important to achieve the required characterization, particularly in terms of the physical and chemical properties of foamcrete such as gaining strength, low rate of heat hydration, or the ability to resist sulphate attack (Kim *et al.*, 2012). According to Yang *et al.* (2014), Portland cement is comprised of silicate and calcium silicate hydrolysis that are naturally included in the material arrange tie (generally gypsum), while cement works are performed by sticking the fragments and occupying the air holes between the aggregate grain. Kearsley and Wainwright (2001) stated that the main binder for lightweight foamcrete is typically Portland cement. In regard to this matter, supplementary materials such as fly ash and silica fume were utilized as the cement substitute for the purpose of reducing the production cost of cement as well as to improve the mix design consistency. Other than that, it is crucial to note that each additional element may affect the properties of foamcrete in diverse ways. For example, the purpose of utilizing silica fume as cement replacement is to reinforce the foamcrete in a brief timeframe because of their filler physiognomies and pozzolanic comportment, whereas fly ash requires an extended time in order to achieve its maximum strength (Ramamurthy *et al.*, 2009).

2.3.2 Sand

Aggregate is a material that has the ability to bring about an effect to the strength, durability, and performance of concrete. Generally, there are two types of aggregates, namely coarse aggregate and fine aggregate. Fine aggregate is known as sand (British Standards Institution, 1992) which comprises of elements that are both sharp and hard (divided rocks and mineral particles), thus indicating that it cannot be damaged or shattered due to the weather such as sun and rain (Sivaraja *et al.*, 2010). Sach and Seifert (1999) reported that only finer sands that are around 4mm and with an even dispersion of sizes ought to be utilized for lightweight foamcrete. On the other hand, coarse aggregate may destruct the foam during the mixing process. Hence, from this statement, it can be concluded that finer sand is able to maintain the shape of foam in a uniformly regular shaped.

On another note, the uniformity and stability of foamcrete mixtures are primarily contingent on the filler quality and type. Meanwhile, the intensification in fineness of sand leads to greater strength to density ratio, better compressive and flexural strengths, and enhanced ductility and workability (Hilal *et al.*, 2015). In addition, finer sand encourages better air-void structure in the cement matrix as well as distribution in foamcrete. However, void pattern of smaller size that is evenly distributed is able to generate greater strength (Narayanan and Ramamurthy, 2012).

2.3.3 Water

The use of water is considered as part of the satisfaction process of mixing concrete. Falliano *et al.* (2018) highlighted that water is used in the mix for hydration process in order to stimulate the binding of cementitious material through chemical reaction. However, the performance with cement and aggregate will be affected if any chemical substances are added with water. In addition, the water used for mixing must be clean from debris and other materials (Talaei *et al.*, 2014) because the performance of concrete will be affected if the water is polluted. Essentially, the water ratio used in their studies was 0.45 because this ratio managed to achieve the required workability.

According to Kearsley (1999), the suitable value of water is dependent on the amount of cement in the mix including the chemicals and other consistent requirements. The author also described that plasticizers are not necessary in ensuring high workability of lightweight foamcrete because the paste itself has intrinsic high workability. Amran *et al.* (2015) mentioned that the disintegration of foam is caused by the extraction of water, thus causing the mix to collapse. However, excessive amount of water in the mix favors segregation which may cause the mix to collapse and increase the drying shrinkage of the specimens.

As suggested by Brady and Jones (2001), the water must be measured in order to assure perfect quality of foamcrete mixes. The role of water in lightweight foamcrete is well documented and differs from normal weight concrete in several aspects; for instance, the increase in strength as a result of the increase of water to cement ratio (Liu *et al.*, 2016).

2.3.4 Foaming Agent

Aqueous stable foam is one of the most essential ingredients in the production of foamcrete. Meanwhile, foaming agents that are synthetic and protein based have been commonly used and defined to create air bubbles that are adequately steady and ready to prevent physical and chemical force acted amid blending, casting, and hardening process (Ramamurthy *et al.*, 2009). According to Narayanan and Ramamurthy (2012), protein foaming agent are based from refined animal products such as horn, skin, and hoof, while synthetic foaming surfactants are man-made chemicals which include soap powders, shampoos, and soaps. In addition, Hilal *et al.,* (2015) stated that protein-based surfactants tend to produce smaller and uniformly bubble size which makes it more steady and durable bonding bubble in contrast to the man-made chemicals of surfactants. Overall, protein agent is considered as the best and suitable agent for the production of lightweight foamcrete.

A study by Liu *et al.* (2016) found that higher water-cement ratio would lead to lower relative viscosity and poorer ability to maintain bubble in cement paste. Moreover, Chen *et al.* (2014) in their study prepared foamcrete using circulating fluidized by fly ash. The results of the study found that bubbles in cement paste of high consistency are easily broken during stirring, while the density of the corresponding concrete tends to increase during the related process.

Meanwhile, Lim *et al.* (2014) analyzed the relationship between bubbles under natural and stress states during foamcrete coagulation as well as pores in hardened foamcrete. In that study, it was revealed that bubbles are combined during the stirring and coagulation of foamcrete; hence, it leads to the expansion of pore diameter distribution of the foamcrete as well as the decreased in foamcrete strength.

On another note, Moon and Varghese (2014) explained that the characteristics of lightweight foamcrete are significantly dependent on the quality of foam. In other words, the foam must be in good quality which include stable, firm, and uniformly in regular bonding shape to ensure that the concrete developed around the void is occupied with air. Figure 2.1 displays typical patterns of protein-based foamcrete with different dry densities of 800 kg/m^3 and 500 kg/m^3 correspondingly.

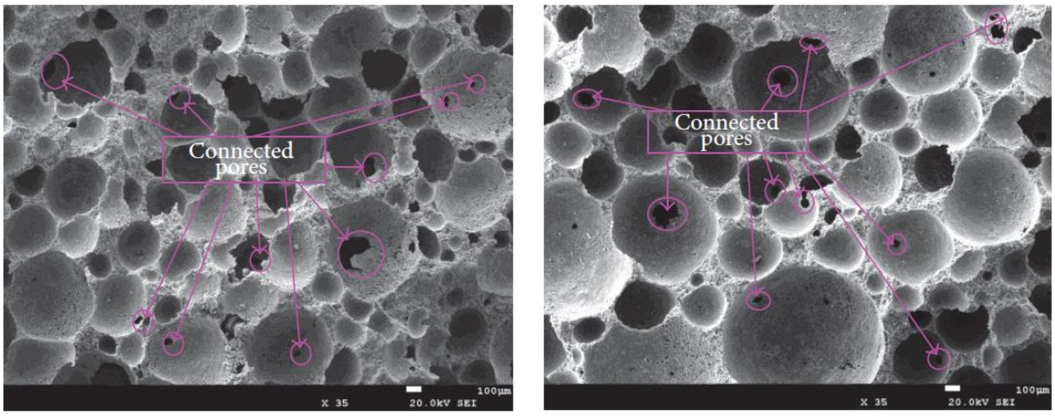

Figure 2.1 Bubble size formed by protein-based foamcrete with dry densities of 8000 kg/m^3 (left) and 500 kg/m^3 (right)

As can be clearly observed in Figure 2.1, a larger bubble size results in a thinner enclosed area that separates the neighboring bubbles. Furthermore, these thinner enclosed areas tend to comprise numerous additional small bubbles. Therefore, it should be pointed out that these small bubbles are caused by the entrapped air in the cementitious mix, which becomes more noticeable when restrained in thin enclosed area.

2.3.5 Additives

Moon and Varghese (2014) stated that resource and energy saving management through the advancement and execution of energy efficient building materials for building envelopes are particularly critical. Zhang *et al.*, 2014 also mentioned the necessary criteria for effectiveness in such materials which include thermal properties, ease of development, enhanced durability and reliability as well as the enhancement in the manufacturing of heat insulating foam concrete that is with particularly better quality. Apart from that, the authors also reported that energy efficiency can be further enhanced using natural hardening foam in construction as a result of its higher thermal resistance of the walls as well as weaker energy intensity in the building.

A study by Kudiakov *et al.* (2015) found that foamcrete with changing mineral and natural added substances tend to have higher plastic quality by early structure arrangement, progressively homogeneous structure, compressive and bending rigidity and lower thermal conductivity compared to regular foamcrete. Overall, it is suitable to be utilized in the development of thermal-efficient buildings.

Similar results were obtained by Hilal *et al.* (2015) which stated that additives in foamcrete can improve the pore structure and provide better strength. Hence, this reduces water absorption and slightly increases the thermal conductivity of foamcrete. However, it was found that additives with higher density would lead to the reduction of water absorption. Apart from that, additives are believed to be able to improve the strength properties of foamcrete and act as water reducer.

Overall, Hilal *et al.* (2015) concluded that the inclusion of additives helps to improve both the cement paste microstructure as well as air-void structure of foamcrete compared to the normal mixes, thus further contributing to the strength of foamcrete.

2.4 Design Procedure and Methods of Lightweight Foamcrete Production

Mix design is the process of selecting the accurate amount of cement, fine and coarse aggregates as well as clean water in the preparation of foamcrete mix. The finest mix must achieve the crucial foamcrete properties which include workability, strength, and durability. In regard to this matter, trial mixes and process are conducted a few times in order to obtain the proper mixes with the desired strength and properties (Richard and Ramli, 2013). As stated by Brady and Jones (2001), there is no standard method to measure or calculate the mix proportions of lightweight foamcrete.

However, the technique of calculating foam volume requires the target density to be achieved as suggested by American Society for Testing and Materials (2012). Kearsley and Mostert (2005) developed a set calculation and formula (density and volume of foamcrete) that are composed in terms of the mixture composition which allows the materials volume to be determined. Meanwhile, Nambiar and Ramamurthy (2006) determined the volume mixture of materials such as water content, cement content, and percentage of volume or any other admixtures or replacement that can affect the strength of foamcrete. For example, the strength of foamcrete can be enhanced by adjusting the constituent materials. In addition, the foam volume requirement is dependent on the mortar mix design and volume of constituents.

There are two stages of developing lightweight foamcrete: (1) preparation of base mix and design foam to obtain the target density. All dry materials such as cement and fine sand are mixed together with the measured water until the homogenous mortar contains no lumps (Thakrele, 2014).

Furthermore, the pre-formed foam is produced by the foam generator (include foam generator), while the designed foam quality is immediately added to the base mix or mortar. In this case, the mixer is gently allowed to rotate for some time until a uniform foam mix is obtained. Thakrele (2014) also stated that additional foam is added to obtain the designed density if the mix is higher than the target density. However, plastic density that is less than the designed density will be discarded, and the procedure is repeated with less foam to obtain the target plastic density.

Kim *et al.* (2012) reported that density has a strong effect on the properties of lightweight foamcrete, whether it is plastic density or dry density. Generally, it was also stated that ±50kg/m^3 on the target density is acceptable, which has been widely applied in industry practice for the purpose of producing lightweight foamcrete. In regard to this matter, it was also pointed out that achievement required target density of lightweight foamcrete is dependent on concrete fresh density, early curing regime, and exposure conditions.

According to Panesar (2013), foam collapse heads to increase target density may result in the modifications of the properties of the resultant concrete. Therefore, it is important to control the mix stability for the mix design of the required density with the aim of achieving the desired properties from the specified lightweight foamcrete.