ENGINEERING PROPERTIES OF LIGHTWEIGHT FOAMED CONCRETE INCORPORATED WITH PALM OIL FUEL ASH (POFA)

LIM OOI YUAN

A project report submitted in partial fulfilment of the
requirements for the award of Bachelor of Engineering
(Hons.) Civil Engineering

Faculty of Engineering and Science
Universiti Tunku Abdul Rahman

May 2012

DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

Signature : ____________________

Name : LIM OOI YUAN

ID No. : 08UEB05190

Date : 30 APRIL 2011

APPROVAL FOR SUBMISSION

I certify that this project report entitled **"ENGINEERING PROPERTEIS OF LIGHWEIGHT FOAMED CONCRETE INCORPORATE WITH PALM OIL FUEL ASH (POFA)"** was prepared by **LIM OOI YUAN** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Engineering (Hons.) Civil Engineering at Universiti Tunku Abdul Rahman.

Approved by,

Signature : _________________________

Supervisor : Dr. LIM SIONG KANG

Date : _________________________

Specially dedicated to
my beloved late grandfather, father and mother

ACKNOWLEDGEMENTS

I would like to thanks everyone who had contributed to the successful completion of this study. Throughout this study, I have received so much help, cooperation and encouragement from so much party that need to be duly acknowledged.

Firstly, I would like to express utmost gratitude to my study supervisor, Dr. Lim Siong Kang for his fruitful advice, guidance and his enormous patience throughout the study, which has lead to the smooth finishing of this study. Lab officers, which have been so friendly and cooperative, deserve a note of thanks from me as well. A word of gratitude is extended to Mr. Lim Eng Choon from Southern Edible Oil Industries (M) Sdn. Bhd. for the supply of palm oil fuel ash (POFA). Lastly, I'm thankful to have countless blessing from my friends and family which has always been the source of inspiration to the smooth finishing of the study.

ENGINEERING PROPERTIES OF LIGHTWEIGHT FOAMED CONCRETE INCORPORATED WITH PALM OIL FUEL ASH (POFA)

ABSTRACT

Malaysia is well known as the main crude palm oil producer and exporter in the world. Million tonnes of agro wastes such as palm oil fuel ash (POFA) is being produced every year with no commercial return on it. Due to the pozzolanic behaviour possessed by POFA, it could be significance when the POFA is being recycled and used in production of lightweight foamed concrete (LFC). Thus, the aim of this research is to study the effects of Palm Oil Fuel Ash (POFA) on engineering properties of LFC with 1300kg/m^3 of density in terms of compressive strength, flexural strength, splitting tensile strength, durability, Poisson's ratio, Poisson's ratio toughness and thermal conductivity. Three types of foamed concrete were prepared, namely i) LFC with 100 % sand as filler as control mix (LFC-CM), ii) LFC with 10 % POFA replacement as part of filler (LFC-PF10) and iii) LFC with 20 % POFA replacement as part of filler (LFC-PF20). All the specimens were water cured before being tested. Except Poisson's ratio, the laboratory results showed that the incorporation of POFA into lightweight foamed concrete has increased its compressive strength, flexural strength, splitting tensile strength, thermal conductivity, durability and Poisson's toughness. Besides, it was found that the microstructure of LFC was denser and the pore size of the structure was refined with the presences of POFA, compared with that of control mix.

TABLE OF CONTENTS

CHAPTER

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS / ABBREVIATIONS

A	cross-sectional area, mm^2
A_c	cross-sectional area of the cube, mm^2
d	diameter of specimen, mm
D	no. of scale division during the period
f	flow, $ml/m^2/s$
h	depth of specimen, mm
k	thermal conductivity, W/mK
l	length of specimen, mm
P	maximum load at failure, N
PI	performance index, MPa per 1000 kg/m^3
R	flexural strength, MPa
S_c	compressive strength, Mpa
t	period, s
T	splitting tensile strength,MPa
T_1	average temperature of hot plate, K
T_2	average temperature of cold plate, K
Φ	heat conduction, J/s

C-S-H	calcium silicate hydrate
LFC-CM	Control mix (LFC with 100 % sand as filler)
OPC	Ordinary Portland Cement
POFA	Palm Oil Fuel Ash
LFC-PF10	lightweight foamed concrete with 10% POFA replacement as part of filler
LFC-PF20	lightweight foamed concrete with 20% POFA replacement as part of filler
SEM	Scanning Electron Microscope
w/b	water-to-binder ratio

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Introduction

Concrete is one of the oldest manufactured construction material and it has been use extensively in the construction of various structures since ancient day. The continuous research and development of concrete has resulted in the production of many types of concrete. Each of the concrete possesses their own unique characteristic to meet and suit the demand of industry. One of the concrete that it popularity increase drastically in recent year is lightweight concrete. The classification of type of concrete is mainly depending on the concrete density. The practical range of concrete density for lightweight concrete is between 300 kg/m^3 and 1850 kg/m^3 (Neville, 2006).

Due to the practical and economic advantages it possesses, the demand for lightweight concrete has increasing over the years and has been partially used as structures such as panel wall, roof slab and etc. Using a lower density concrete can, therefore, significantly reduce the self-weight of concrete structure with a consequence allowing the reduction of columns and foundation size and other load bearing elements and a corresponding reduction in term of cost. Other advantages of lightweight concrete included it good thermal insulation properties, better fire resistance and more convenience in handling the concrete as the total mass of materials to be handled is reduced, which then lower the haulage and handling cost and increase the productivity.

1.2 Background of Study

Malaysia is one of the main palm oil producer and exporter in the world. As framed in Tenth Malaysian Plan (RMK-10), palm oil is listed as one of the main commodities to be exported internationally due to high demand of crude palm oil in the world. In 2010, the Malaysian Palm Oil Board (MPOB) estimated that the total oil palm planted area in Malaysia is 4.85 million hectares. Over 400 palm oil mills are operating and producing large amounts of solid waste in the form of fibers, kernels and empty fruit bunches annually (MPOB, 2010). The combustion of palm oil husk and palm kernel shell in the steam boiler produces approximately 5% of POFA (Tangchirapat et al., 2007).

Due to high silica oxide contents found in POFA chemical composition, which met the pozzolanic properties criteria, it has potential to be used as cement replacement or as filler to produce strong and durable concrete (Hussin and Awal, 1997).

1.3 Objectives of Study

The objectives of this study are:

1. To produce lightweight foamed concrete with 1300 kg/m^3 of density.
2. To obtain optimum w/c ratios for various types of LFC.
3. To study the effects of Palm Oil Fuel Ash (POFA) on engineering properties of lightweight foamed concrete in terms of compressive strength, flexural strength, splitting tensile strength, initial surface absorption test (ISAT), Poisson’s ratio, Poisson’s ratio toughness and thermal conductivity.

1.4 Scopes of Study

The study focuses on the effects of POFA on engineering properties of lightweight foamed concrete in term of compressive strength, splitting tensile strength, flexural strength, Poisson's ratio, ISAT and thermal conductivity. The targeted density of the foamed concrete is 1300 kg/m^3 with tolerance of ± 50 kg/m^3. Three types of foamed concrete were prepared, namely i) LFC with 100 % sand filler as control mix (LFC-LFC-CM), ii) LFC with 10 % POFA replacement as part of filler (LFC-PF10) and iii) LFC with 20 % POFA replacement as part of filler (LFC-PF20). The optimum w/c for LFC-LFC-CM, LFC-PF10 and LFC-PF20 was determined based on screening results of trial mixes. During trial mixes, the trial w/c ratio for respective mix ranging from 0.52 to 0.60 was increased by an interval of 0.02. Two tests were carried out, namely inverted slump test and compressive strength to determine the optimum w/c ratio for each mix proportion. The concrete cubes were cured in water and tested for 7 days, 14 days and 28 days compressive strength. Inverted slump test, on the other hand, were carried out to measure the workability of fresh concrete. Performance index of lightweight foamed concrete incorporated with POFA was then calculated. The optimum w/c ratios for respective mixes were determined based on screening results of trial mixes respectively.

Specimens including cubes, cylinders and prisms were cured in water and tested for 7 days, 28 days, 56 days and 90 days compressive strength, splitting tensile strength and flexural strength respectively. On the other hand, specimens such as cubes and block panel were cured in water for 28 days and oven dried for a day before undergoing ISAT and thermal conductivity test. For Poisson's ratio test, cylinders were water cured for 28 days before undergoing testing. For foamed concrete at 90 days, crushed pieces were used for microstructure studies using Scanning Electron Microscope (SEM). The engineering properties of LFC-LFC-CM, LFC-PF10 and LFC-PF20 were then studied and discussed.

1.5 Significance of Study

The significances of this study are as follows:

1. Incorporating POFA as partial sand replacement material in the mix as to encourage the use of agriculture waste and create a more sustainable environment besides its own ability to enhance the compressive strength of the concrete.
2. Developing the mix proportion to produce lightweight foamed concrete incorporated with POFA and study the engineering properties in term of compressive strength, splitting tensile strength, flexural strength, Poisson's ratio, Poisson's ratio toughness, initial surface absorption and thermal conductivity.

1.6 Layout of Report

This report consists of 5 chapters. Chapter 1 discusses the introduction of the study, background of the research, objectives of the research, scopes of research, significance of research and finally the layout of report.

Chapter 2 discusses the review of lightweight foamed concrete incorporated with POFA. This includes the review on materials used such as POFA, sand, cement and foam. Besides, the properties of lightweight foamed concrete are also discussed in this chapter.

Chapter 3 discusses the methodologies used in this study. The material preparation, method to get the mix proportion and mixing procedure are discussed in this chapter. Besides, the testing methods used in testing the specimens are also discussed in this chapter.

Chapter 4 mainly presents and discusses the results of trial mixes. The w/c ratio ratio for LFC-CM, LFC-PF10 and LFC-PF20 were determined based on screening of trial mixes results, respectively.

Chapter 5 mainly presents and discusses about the laboratory results of lightweight foamed concrete incorporated with POFA in term of compressive strength, splitting tensile strength, flexural strength, initial surface absorption, thermal conductivity, Poisson’s ratio and Poisson’s ratio toughness.

Chapter 6 concludes the whole study. Few conclusions have been drawn with respective objectives listed based on the results obtained from this study. Besides that, there are few recommendations listed in this chapter for future studies

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Lightweight foamed concrete is made of mixture of raw materials such as fine aggregate, Ordinary Portland Cement and water with pore structure created by air-voids, which are entrapped in mortar or cement paste by suitable foaming agent (Ramamurthy et al., 2009).

By proper control in dosage of foam, a wide range of densities of foamed concrete ranging from 400 kg/m3 to 1600 kg/m3 can be obtained for application to structural, partition, insulation and filling grades. The production of stable foam concrete mix depends on many factors viz., selection of foaming agent, method of foam preparation and addition for uniform air-voids distribution, material section and mixture design strategies, production of foamed concrete and performance with respect to fresh and hardened state are of greater significance (Ramamurthy et al., 2009).

Incorporation of pozzolans, either naturally occurring or artificially made into concrete has been in practise since the early civilisation (Hussin and Awal, 2009). Besides its economic advantages, the main reason for their use is that they can give useful modification or enhancements to concrete properties. Many researchers have studied the use of agricultural waste as constituents in concrete, namely rice-husk ash (Mehta, 1977) and sawdust ash (Udoeyo and Dashibil, 2002). Their study have revealed that agricultural waste ashes contained high amount of silica in amorphous form and could be used as a pozzolanic material (Tangchirapat et al., 2007). POFA is one of the potential agricultural wastes from palm oil industry as constituents in concrete due to the pozzolanic properties it possesses.

2.2 Advantages of Lightweight Foamed Concrete

Lightweight foamed concrete has been preferred over normal weight concrete due to a number of improved properties. Although the compressive strength of lightweight foamed concrete is compensated with its density, the utilization of lightweight foamed concrete as non-load bearing components has decreased the structural dead load. The decrease of dead load could lead to reduce concrete costs, since it can decrease the size of the foundation and structural members such as columns and thickness of walls. On the other hand, another prevailing benefit of lightweight foamed concrete is the excellent thermal insulation properties it possesses due to higher porous structure contained in lightweight foamed concrete (Kim et al., 2011). Excellent thermal insulation ensures the hot weather will not penetrate into a building easily, keeping the building at relatively lower temperature compared to temperature at outside. Other than that, other properties possessed by lightweight foamed concrete such as good acoustical properties and high workability also the advantages of lightweight foamed concrete.

2.3 Compressive Strength

Compressive strength is the most important mechanical properties of every concrete, including lightweight foamed concrete. Ramamurthy and Nambiar (2009) summarized the compressive strength of lightweight foamed concrete for various mixture composition and densities reported in literature. The compressive strength decreases exponentially with a reduction in density of lightweight foamed concrete (Kearsley, 1996). Besides the concrete density, the specimen shape and size, method of pore formation, direction of loading, curing age, water content, characteristic of ingredients used and the method of curing are reported to influence the strength of lightweight foamed concrete as well (Valore, 1954). Other parameters such as the cement-sand and water-cement ratios, curing regime, type and particle size distribution of sand and type of foaming agent used can be the factors that affecting the strength of lightweight concrete as well (Aldridge, 2005; Hamidah et al., 2005).

2.4 Flexural and Splitting Tensile Strengths

According to Ramamurthy and Nambiar (2009), the ratio of flexural strength to compressive strength of lightweight foamed concrete is in the range of 0.25-0.35 (Valore, 1954). On the other hand, the splitting tensile strength of lightweight foamed concrete is lower than normal weight concrete (Ramamurthy et al., 2009).

2.5 Thermal Conductivity

Lightweight foamed concrete possesses excellent thermal insulation properties due to it pore structure content in it. A study by Aldridge and Ansell (2001) showed that the thermal conductivity of lightweight foamed concrete of density 1000kg/m^3 is approximately one-sixth the value of typical cement-sand mortar. Another study by Jones and McCarthy (2005) proved that the thermal conductivity of lightweight foamed concrete is 5 to 30 % of those measured on normal weight concrete. The range of thermal conductivity for dry densities value of 600-1600 kg/m3 is between 0.1 and 0.7 W/mK, reducing with decreasing densities (Jones et al., 2005)

Besides the density of concrete, moisture content in concrete is another parameter which affects the thermal conductivity significantly, since water has conductivity about 25 times that of air. So, when the air in the pores has been partially displaced by water or moisture, the concrete will have greater thermal conductivity (Schnider, 1982). Study by Steiger and Hurd (1978) reported that the thermal conductivity of concrete increase 5 % with every increment of 1 % of concrete unit weight due to water absorption.

2.6 Foam

According to Ramamurthy and Nambiar (2009), lightweight foamed concrete is produced either by pre-foaming method or mixed foaming method. Pre-foaming method comprises of producing base mix and stable preformed aqueous foam separately and then thoroughly blending foam into the base mix. In mixed foaming, the surface active agent is mixed along with base mix ingredients and during the process of mixing; foam is produced resulting in cellular structure in concrete (Byun et al., 1998). The foam must be firm and stable so that it resists the pressure of the mortar until the cement takes its initial set and a strong skeleton of concrete is built up around the void filled with air (Koudriashoff, 1949). The preformed foam can be either wet or dry foam. The wet foam is produced by spraying a solution of foaming agent over a fine mesh, has 2–5 mm bubble size and is relatively less stable. Dry foam is produced by forcing the foaming agent solution through a series of high density restrictions and forcing compressed air simultaneously into mixing chamber. Dry foam is extremely stable and has size smaller than 1 mm, which makes it easier for blending with the base material for producing a pump able foam concrete (Aldridge, 2005).

2.7 Ordinary Portland Cement

Ordinary Portland Cement (OPC) was classified as Type I cement as according to ASTM C150 (2005). OPC was the most common cement in use in construction industry in the world when there is no exposure to sulphates in soil or groundwater (Neville, 2010).

2.7.1 Chemical Composition of Portland Cement

Generally, the chemical compositions of Portland cement are varying due to supply from different manufacturers. However, OPC mostly contained limestone, alumina and silica as these chemical compositions are important for the formation of calcium silicate hydrate gel during hydration process. A general idea of the composition of cement is presented in Table 2.1 (Neville, 2010).

Table 2.1: General Composition Limits of Portland Cement (Neville, 2010)

Oxide	Content, %
CaO	60 - 67
SiO_2	17 – 25
Al_2O_3	3 – 8
Fe_2O_3	0.5 – 6.0
MgO	0.5 – 4.0
Na_2O	0.3 – 1.2
SO_3	2.0 – 3.5

2.7.2 Compound Composition of Portland Cement

Generally, raw materials used in manufacturing Portland cement mainly are lime, silica, alumina and iron oxide. These four main raw materials interact with each other to form compounds, which usually regarded as major constituents of cement. These compounds are presented in Table 2.2.

Table 2.2: Main Compounds of Portland Cement (Neville, 2010)

Name of Compound	Oxide Composition	Abbreviation	Compound Composition, %
Tricalcium Silicate	3CaO.SiO2	C3S	42 – 67
Dicalcium Silicate	2CaO.SiO2	C2S	8 – 31
Tricalcium Silicate	3CaO.Al2O3	C3A	5 – 14
Tetracalcium Aluminoferrite	4CaO.Al2O3.Fe2O3	C4AF	6 - 12

2.8 Pozzolanic Material

ASTM C618 (2008) describes pozzolanic materials as a siliceous or siliceous and aluminous material which in itself possesses little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties.

2.8.1 Pozzolanic Reaction

POFA contained high amount of silicon dioxide in amorphous form that can react with calcium hydroxide generated from the hydration process to produce more calcium silicate hydrate, C-S-H gel compound (Karim et al., 2011).

$$2S + 3CH \rightarrow C_3S_2H_3 \tag{2.1}$$

The products of the pozzolanic reaction cannot be distinguished from those of the primary cement hydration and therefore make their own contribution to the strength and other properties of the hardened cement paste and concrete (Eldagal, 2008).

2.8.2 Origin of POFA

As discussed in previous chapter, Malaysia is one of the main palm oil producer and exporter in the world. In 2010, the Malaysian Palm Oil Board (MPOB) estimated that the total oil palm planted area in Malaysia is 4.85 million hectares. The total amount of fresh fruit bunches processes by over four hundred palm oil mills are approximately 87.5 million tonnes. Approximated 61.1 million tonnes of solid waste by-products in the form of fibers, kernels and empty fruit bunches are produced, which is about 70 % of fresh fruit bunches processed (MPOB, 2010). The combustion of palm oil husk and palm kernel shell in the steam boiler produces POFA, which is approximately 5 % of solid waste by-product, equivalent to 3.1 million tonnes in Malaysia in 2010 (Tangchirapat et al., 2006).

While the amount of POFA produced increase annually, allocation of transportation cost and landfills for the disposal of POFA is not an effective way to manage the waste as POFA has no commercial return value and it may lead to environmental problems in the future (Tangchirapat et al., 2006). Studies from researchers such as Tay (1995), Hussin and Awal (1997) and Tangchirapat et al. (2006) have proved that POFA can be reutilised as cement replacement material or as aggregate in concrete due to the pozzolanic properties it possesses. .

2.8.3 Chemical Properties of POFA

Supply of POFA from different palm oil mill will have separate chemical properties. However, silica is still the major chemical composition in POFA. The chemical composition of different POFA used in various research works are shown in Table 2.3.

Table 2.3: Chemical Composition of POFA Used In Various Researches (Awal, 1997; Tangchirapat, 2007; Eldagal, 2008)

Chemical Composition	Awal	Tangchirapat	Eldagal
Silicon dioxiode (SiO_2)	43.60	57.71	48.99
Aluminum oxide (Al_2O_3)	11.50	4.56	3.78
Ferric oxide (Fe_2O_3)	4.70	3.30	4.89
Calcium oxide (CaO)	8.40	6.55	11.69
Magnesium oxide (MgO)	4.80	4.23	1.22
Sulphur oxide (SO_3)	2.80	0.25	-
Sodium oxide (Na_2O)	0.39	0.50	0.73
Potassium oxide (K_2O)	3.50	8.27	4.01
Loss of ignition (LOI)	18.00	10.52	10.51

*All values are in percentage

According to ASTM C618 (2008), fly ash can be divided into three class, namely Class N fly ash, Class F fly ash and Class C fly ash. Based on the chemical composition of different POFA used in various research works, it shows that generally POFA is classified as Class F fly ash as complied with ASTM C618 (2008).

2.8.4 Effect of Fineness of POFA on Concrete Strength

The strength of concrete is influenced by the fineness of POFA. For same replacement of POFA in concrete, finer POFA would lead to greater strength development than the coarser one (Awal, 1998). This is due to higher total surface area of POFA particle that increase the pozzolanic activity and hence increase the concrete strength.

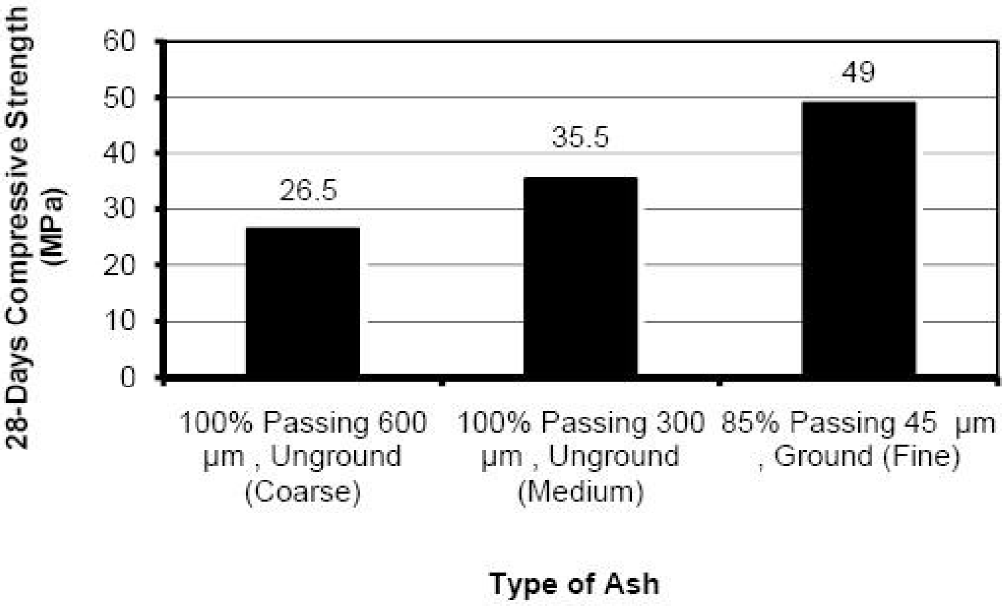

Figure 2.1: Effect of Fineness of Ash on Concrete Compressive Strength (Awal, 1998)

2.8.5 Strength Development of Normal Weight Concrete Incorporated with POFA

Concrete incorporated with POFA tend to have slow strength gain at early age as compared with OPC concrete, but at later ages, the compressive strength is found to be higher than of OPC concrete as shown in Figures 2.2 and 2.3 (Sata, 2010). This is due to the pozzolanic characteristic possessed by POFA, which extended the hydration process. The additional calcium silicate hydrate gel formed improves the interfacial bonding between the aggregates and pastes at later ages (Karim, 2011). Consequently, the compressive strength of concrete incorporated POFA is improved.

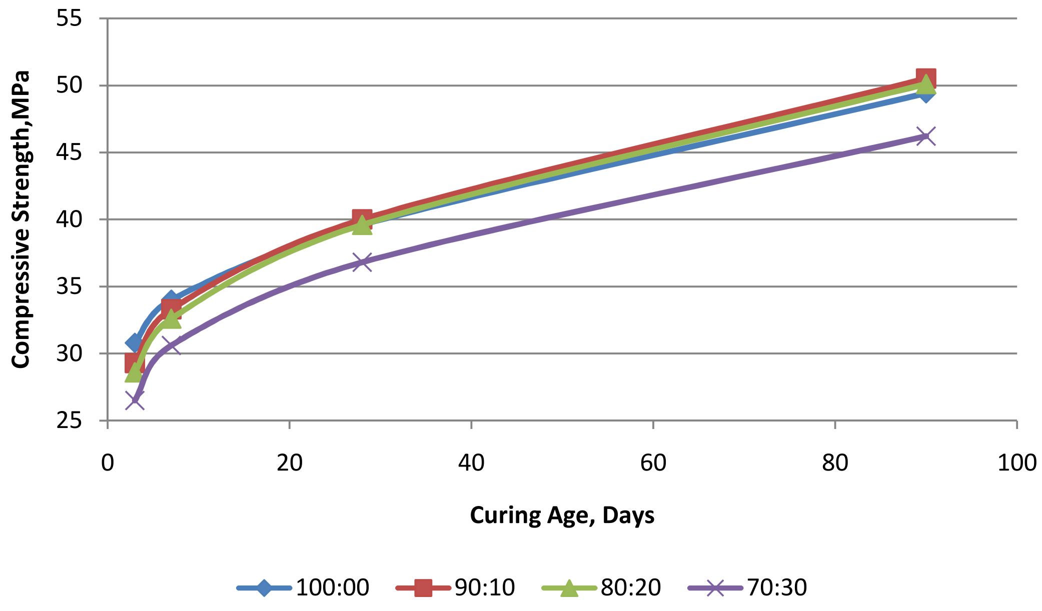

Figure 2.2: Compressive Strength for OPC : POFA Mixes (Sata, 2010)

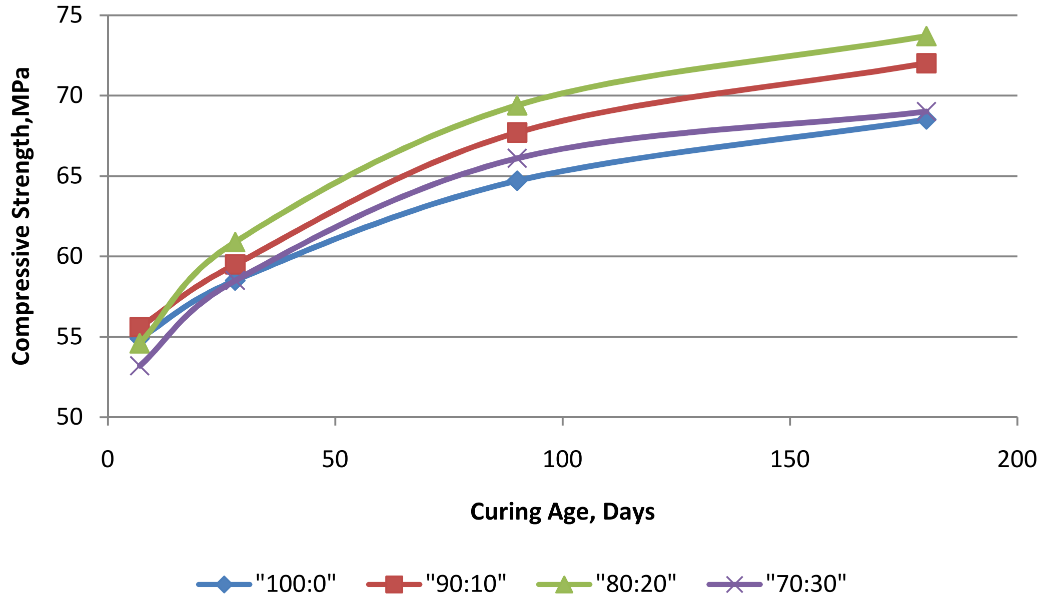

Figure 2.3: Compressive Strength for OPC : POFA Mixes (Tangchirapat et al., 2009)

2.9 Summary

Lightweight foamed concrete is made of mixture of fine aggregates, cement, water and incorporation of homogenous air-void into fresh concrete by the form of bubble. Lightweight foamed concrete can be produced by either pre-foaming method or mixed foaming method. Although the compressive strength of lightweight foamed concrete is compensated with its density, under certain situation, lightweight foamed concrete is still preferred over normal weight concrete due to a number of improved characteristic and advantages.

Lightweight foamed concrete can be used as non-load bearing members, which reduced the dead load of the structures. Hence, the size of the foundation and structural members such as beam and column can be reduced. The ease of handling the lightweight foamed concrete due to its high workability has save labour cost and speed up the construction process.

Besides, the improved characteristic such as thermal insulation and acoustical insulation has contributed in terms of energy saving. Excellent thermal insulation prevents the heat penetrates into building easily. Thus, the room temperature has relatively low temperature compared with temperature outside the building.

POFA is an agro waste, which do not have any commercial return. As POFA possesses pozzolanic characteristic, the incorporation of POFA into lightweight foamed concrete will ensure the continuous development of concrete strength as the reactive silica content in POFA will react with calcium hydroxide to produce more C-S-H gel.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter describes the materials used, the mixing procedures and the test methods followed in conducting various experimental investigations. The strength and density of lightweight foamed concrete incorporated with POFA are the two major areas of study in determining the optimum mix proportions. At the beginning, the collection and preparation of materials are presented in details, followed by presentation of the mixing procedures and test procedures for the lightweight foamed concrete specimens with POFA as part of filler.

3.2 Materials Used

The making of lightweight foamed concrete incorporated with POFA consist of five types of raw material, namely ordinary Portland cement, POFA, sand, water and foam.

3.2.1 Ordinary Portland Cement

Ordinary Portland cement (OPC) of “ORANG KUAT” branded from YTL Cement Sdn. Bhd. was used throughout the study. The OPC used complied with Type I Portland Cement in accordance with ASTM C150 (2005). The details chemical composition of OPC is given in Table 3.1. The OPC was sieved through 300μm sieve. The sieved OPC was kept in an airtight container to prevent air moisture contact as hydrated cement particle would affect the formation of calcium silicate hydrate gel.

3.2.2 Palm Oil Fuel Ash (POFA)

As mentioned earlier, Palm oil fuel ash (POFA) is solid waste by-product of palm oil industry. POFA is obtained in the form of ash when the burning of palm oil husk and palm kernel shell as fuel in palm oil mill steam boiler. For this study, the POFA was obtained from Southern Edible Oil Industries (M) Sdn. Bhd. at Kapar, Selangor. The chemical composition of POFA is listed in Table 3.1 and sieve analysis of POFA is illustrated in Figure 3.1. The fineness modulus for POFA is 2.64. Based on the chemical composition, POFA is classified as Class F Fly Ash in accordance with ASTM C618 (2008).

The POFA obtained was dried in an oven at temperature of 105 °C ± 5 °C for two hours to remove the moisture content in it. The dried POFA was then sieved through a 600 μm sieve in order to remove bigger size particles and any other foreign materials. The treated and sieved POFA were kept in airtight container.

Table 3.1: Chemical composition of OPC (SGS analysis report, 2007) and POFA (Tangchirapat et al., 2006)

Chemical Composition	OPC	POFA
Silicon dioxiode (SiO_2)	20.10	57.71
Aluminum oxide (Al_2O_3)	4.90	4.56
Ferric oxide (Fe_2O_3)	2.50	3.30
Calcium oxide (CaO)	65.00	6.55
Magnesium oxide (MgO)	3.10	4.23
Sulphur oxide (SO_3)	2.30	0.25
Sodium oxide (Na_2O)	0.20	0.50
Potassium oxide (K_2O)	0.40	8.27
Titanium Oxide (TiO_2)	0.20	-
Phosphorus Oxide (P_2O_2)	<0.90	-
Loss of ignition (LOI)	2.40	10.52

*All values are in percentage

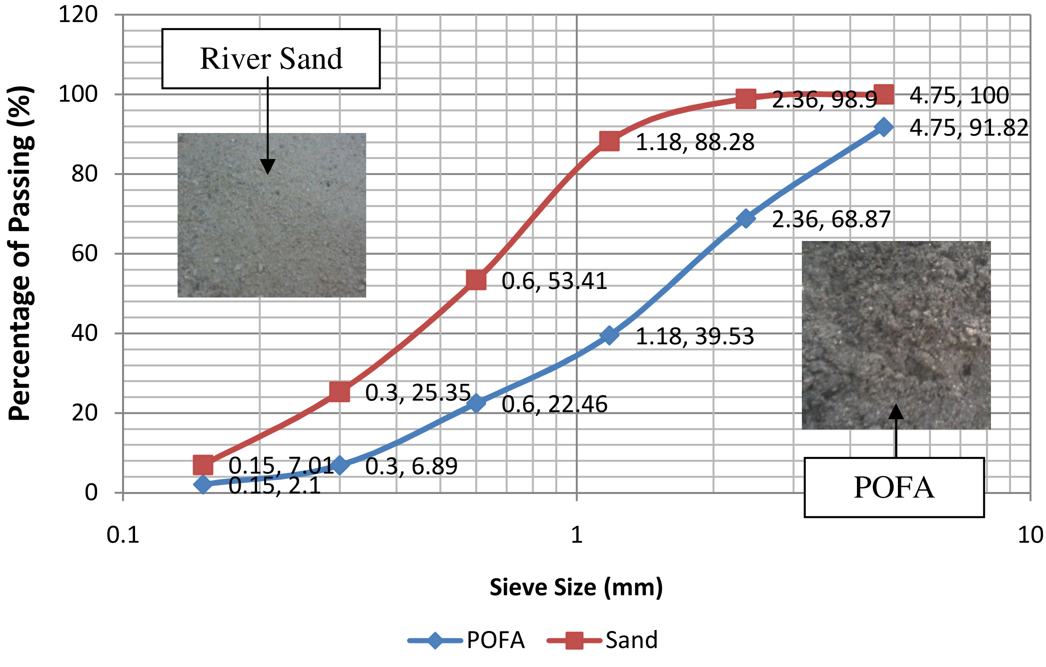

Figure 3.1: Sieve Analysis of Raw POFA and Sand

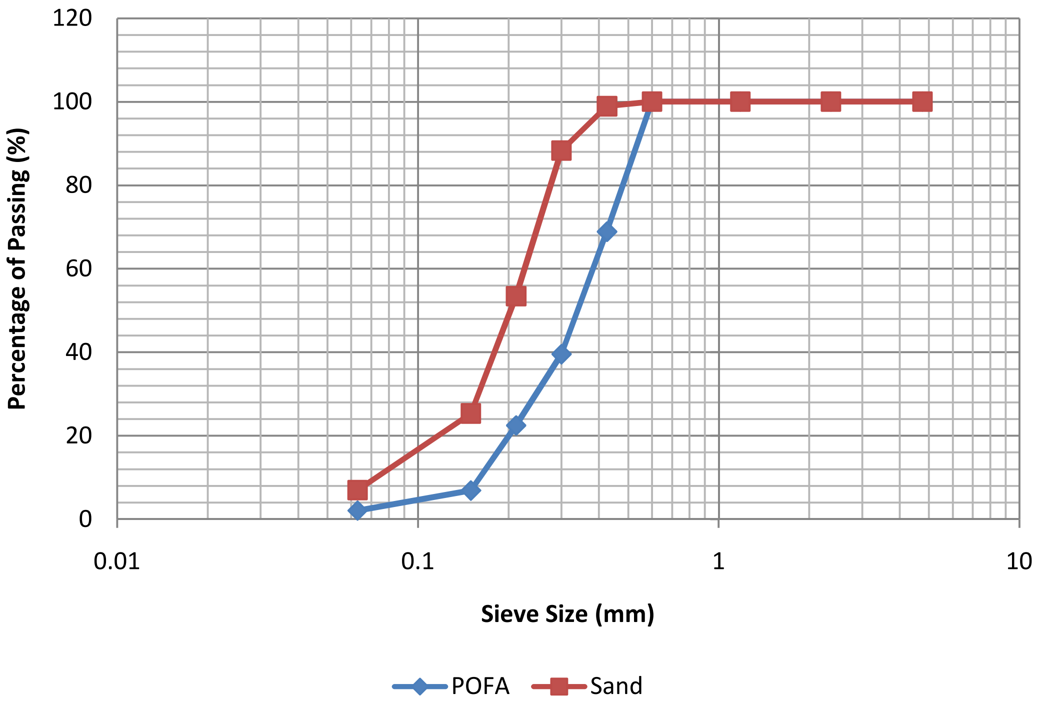

Figure 3.2: Sieve Analysis of Refined POFA and Sand

3.2.3 Sand

Only fine sand was used in producing the lightweight foamed concrete incorporated with POFA. The sand was dried in an oven at the temperature of 105 °C ± 5 °C for at least 24 hours to remove the moisture in it. The dried sand was then sieved through a 600 µm sieve.

3.2.4 Water

Water is one of the most important constituents to produce lightweight foamed concrete. The water used shouldn’t contain any substance as the presence of any other substance can be harmful to the process of hydration of cement and durability of concrete. In this study, tap water was used to cast lightweight foamed concrete incorporated with POFA.

3.2.5 Foaming Agent

Foam is a form of stable bubbles, produced by mixing foaming agent and water in foam generator. The purpose of the foam is to control the density of lightweight foamed concrete by incorporating dry preformed stable foam into fresh lightweight foamed concrete. For this study, the ratio of foaming agent to water is 1:30 by volume. The will have foam density of 45 kg/m^3.

Figure 3.3: Foam Generator

3.3 Mix Proportions

The mix proportion of the lightweight foamed concrete incorporated with POFA was determined based on trial and error method. Trial mixes with various w/c ratio were carried out. The optimum mix proportion was determined based on density and strength of lightweight foamed concrete incorporated with POFA.

3.4 Trial Mix

During the trial mix stage, three types of mix proportion, namely LFC with 100 % sand as filler (LFC-CM), 10 % POFA replacement as part of filler (LFC-PF10) and 20 % POFA replacement as part of filler (LFC-PF20). The water to cement ratio for each type of mix proportion was tried from the range of 0.52 to 0.60 with the increment of 0.02 for each mix. Density for every mix was controlled to 1300 kg/m^3 ± 50 kg/m^3.

3.5 Mixing Procedure

OPC, Sand and POFA were weighted and mixed in a concrete mixer until the dry mix was uniformly mixed. Next, water was weighted and added into the dry mix. The mix was mixed until the wet mix was uniformly mixed. Follow by that, an amount of foam was weighted and added into the wet mix repeatedly until the desired density, 1300 kg/m^3 ± 50 kg/m^3 was achieved. Lastly, inverted slump test was carried out before fresh lightweight foamed concrete was poured into the mould.

3.6 Curing

Curing condition is very important in gaining the strength of lightweight foamed concrete. For this study, specimens were cure in water curing after demould for 7, 28, 56 and 90 days until testing age, respectively.

Figure 3.4: Water Curing

3.7 Fresh Concrete Testing Method

3.7.1 Fresh Density Test (ASTM C796, 2004)

A 1 liter capacity container was tared to zero at weight machine and overfilled with fresh lightweight foamed concrete. The fresh lightweight foamed concrete was compacted by slight tapping at the sides of the container to allow consolidation of fresh lightweight foamed concrete. The excess lightweight foamed concrete was struck off and any excess lightweight foamed concrete found on container surface was wiped off. The 1 liter container was then weighted to obtain the fresh density of LFC.

3.7.2 Inverted Slump Test (ASTM C995, 2001)

The inverted slump test was conducted by using a slump cone and flat base plate as complied with ASTM C995 (2001). Slump cone was inverted and placed at the center of the base plate and filled with fresh lightweight foamed concrete until it was fully filled. Excessive fresh lightweight foamed concrete was struck off and the inverted slump cone was lifted to 1 ft height. The four angle of dimension of spread was measured and recorded.

Figure 3.5: Inverted Slump Test

3.8 Hardened Concrete Testing

3.8.1 Compression Test (BS EN 12390-3, 2002)

The compression test was conducted by using compressive strength machine. The test was performed in accordance with BS EN 12390-3 (2002). An axial compressive load with a specified rate of loading was applied to 100mm cube until failure occurred. INSTRON 5582 Testing Machine was used to conduct the compressive strength test on the cubes. Mean value obtained from three cubes was then taken as cube compressive strength for each lightweight foamed concrete mix.

Figure 3.6: INSTRON 5582 Testing Machine

The cubes were taken out from water tank and air-dried for two hours before the test was performed. Dimension of specimen was measured before the testing. This is to determine the cross-sectional area of specimen. Followed by that, the test specimen was placed at the center of the testing machine. Test specimen was loaded gradually with constant rate of loading of 0.02 mm/s until the specimen fails. The maximum load carried by the specimen was recorded and compressive strength was calculated based on Equation 3.1.

$$\text{Sc} = \frac{\text{P}}{\text{width} \times \text{thickness}} \quad (3.1)$$

where

Sc = compressive strength, MPa

P = maximum load carried by specimen, N

width = width of specimen, mm

thickness = thickness of specimen, mm

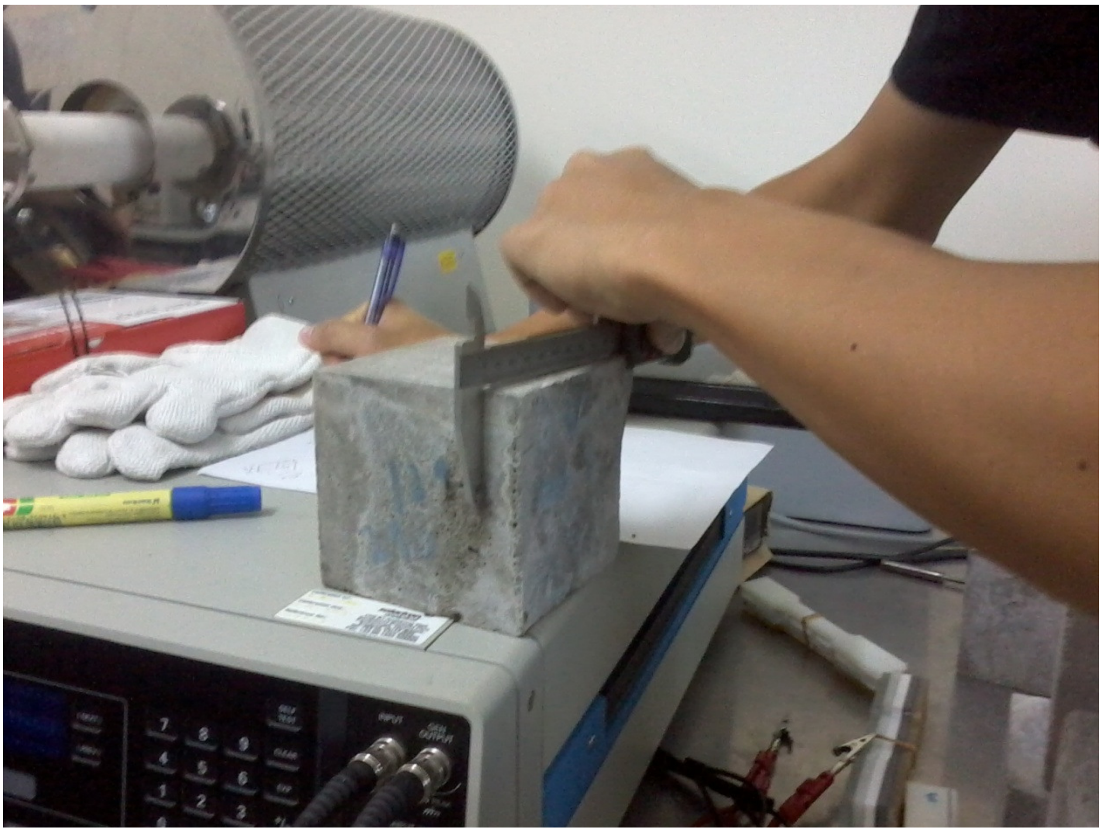

Figure 3.7: Specimen Dimension is being Measured and Recorded

3.8.2 Splitting Tensile Test (ASTM C496, 2004)

The test was performed in accordance with ASTM C496 (2004). An axial load with a specified rate of loading was applied to cylinder with diameter of 100 mm and height of 200 mm until failure occurred. INSTRON 5582 Testing Machine was used to conduct the splitting tensile test on the cylinder. Mean value obtained from three cylinders was then taken as splitting tensile strength for each lightweight foamed concrete mix.

The cylinders were taken out from water tank and air-dried for two hours before the test was performed. Test specimen was placed in a steel mould and a thin plywood bearing strip was placed at the bottom and top of the cylinder. This thin plywood bearing strips are used to distribute the load applied along the length of the cylinder. Test specimen was loaded gradually with constant rate of loading of 1.2 mm/min until the specimen fails. The maximum load carried by the specimen was recorded and splitting tensile strength was calculated based on Equation 3.2.

$$\mathrm{T} = \frac{2\mathrm{P}}{\pi \mathrm{ld}} \tag{3.2}$$

where

T = splitting tensile strength, MPa

P = maximum load carried by specimen, N

l = length of specimen, mm

d = diameter of specimen, mm

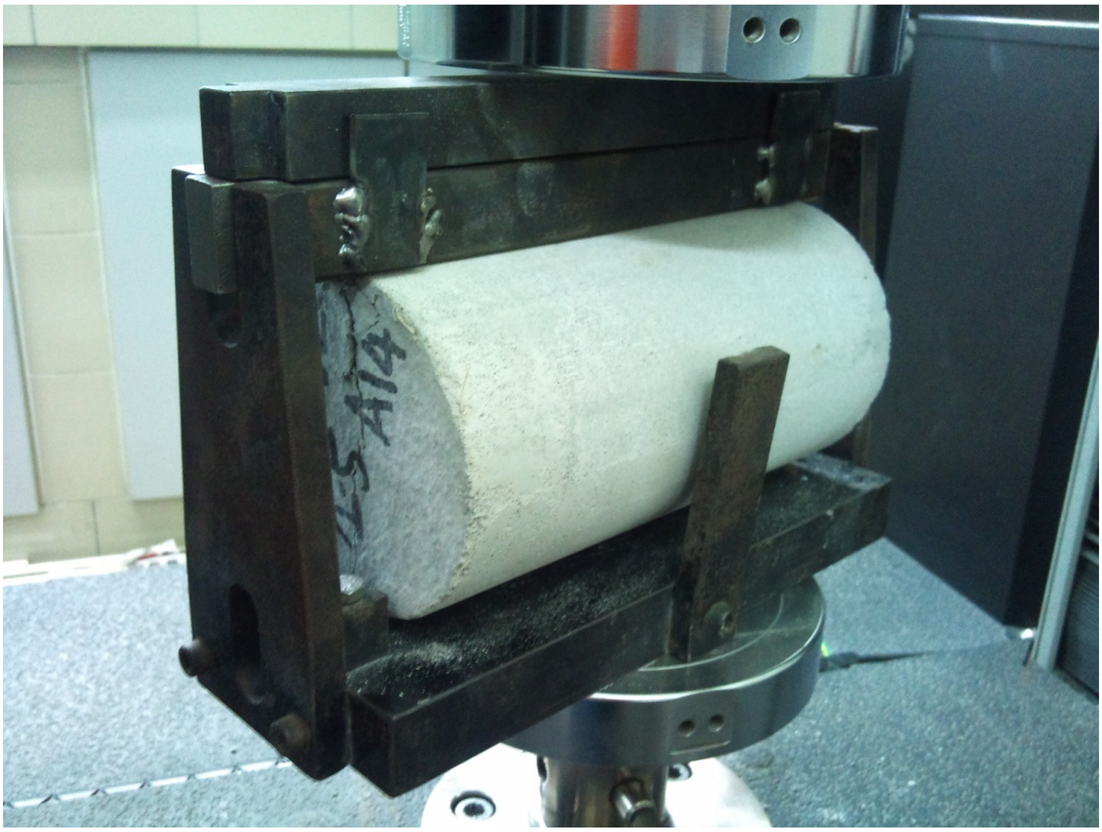

Figure 3.8: Splitting Tensile Strength Test of Lightweight Foamed Concrete

3.8.3 Flexural Strength Test (ASTM C293, 2002)

Flexural test was performed in accordance with ASTM C293 (2002). A center-point loading with a specified rate of loading was applied to prism with dimension of 25 mm x 25 mm x 250 mm until failure occurred. INSTRON 5582 Testing Machine was used to conduct the flexural strength test on the prism. Mean value obtained from three prisms was then taken as flexural strength for each lightweight foamed concrete mix.

The prisms were taken out from water tank and air-dried for two hours before the test was performed. An offset of 10 mm from both sides of prism was marked and the prism was placed on the support block. Test specimen was loaded gradually with constant rate of loading of 0.1 mm/min until the specimen fails. The maximum load carried by the specimen was recorded and flexural strength was calculated based on Equation 3.3.

$$R = \frac{3PL}{2bd^2} \tag{3.3}$$

where

R = flexural strength, MPa

P = maximum load carried by specimen, N

l = length of specimen, mm

h = thickness of specimen, mm

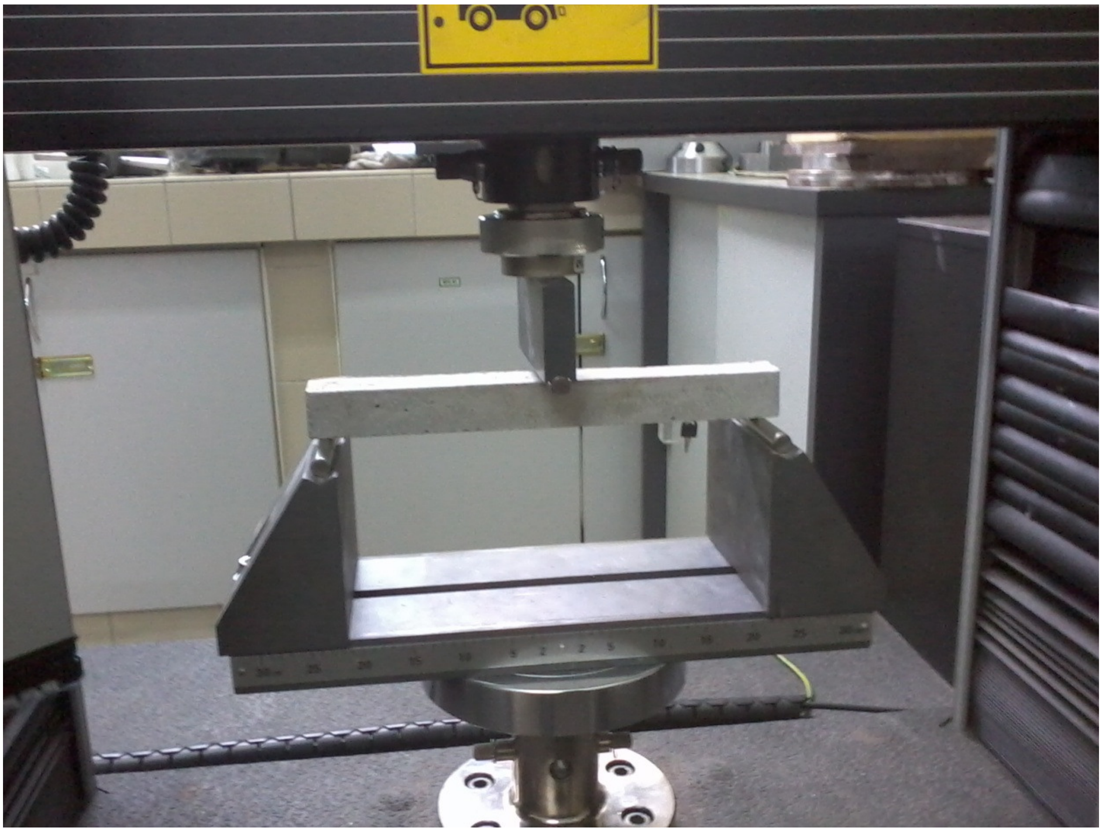

Figure 3.9: Flexural Strength Test of Lightweight Foamed Concrete

3.8.4 Poisson’s Ratio Test (ASTM C469, 2002)

Poisson’s ratio was performed in accordance with ASTM C469 (2002). An axial load with a specified rate of loading was applied to cylinder with diameter of 100 mm and height of 200 mm until failure occurred. INSTRON 5582 Testing Machine was used to conduct the Poisson’s ratio test on the cylinder. Mean value obtained from two cylinders was then taken as Poisson’s ratio for each lightweight foamed concrete mix.

The cylinders were taken out from water tank and air-dried for two hours before the test was performed. The dimension of cylinder was measured and the centroid of cylinder at side was marked. Two LVDTs connected to Data Logger were adjusted and pointed on the centroid of the cylinder. Test specimen was loaded gradually with constant rate of loading of 0.01 mm/s until the specimen fails. The strains for every 0.5 MPa were recorded until the specimens failed. The Poisson’s ratio can be calculated based on Equation 3.4.

$$\mu = \frac{\varepsilon_{t2} - \varepsilon_{t1}}{\varepsilon_2 - 0.000050} \tag{3.4}$$

where

ε_{t2}= tranverse strain at midheight of the specimen produced by stress corresponding to 40 % of ultimate load

ε_{t1}= tranverse strain at midheight of the specimen produced by stress corresponding to a longitudinal strain of 50 millionths

ε_2= longitudinal strain produced by stress corresponding to 40 % of ultimate load

Figure 3.10: Poisson's Ratio Test of Lightweight Foamed Concrete

3.8.5 Poisson's Ratio Toughness

The Poisson's ratio toughness is determined based on Poisson's ratio stress-strain diagrams plotted. The areas under the vertical deformation of Poisson's ratio stress-strain diagrams that represented the total energy to fracture each specimen, also termed as toughness of the material were computed by using integration method as shown in Equation 3.5.

$$\mu_t = \int_0^{\varepsilon_f} \sigma \, d\varepsilon \qquad (3.5)$$

where,

u_t = toughness (J/m^3)

ε = strain (10^{-6} mm/mm)

ε_f = strain upon failure (10^{-6} mm/mm)

σ = Maximum compressive strength (MPa)

3.8.6 Thermal Conductivity Test (BS EN 12664, 2001)

Thermal Conductivity test was performed in accordance with BS EN 12664 (2001). The block panel was taken out from water tank and oven dried in oven at temperature of 105 °C ± 5 °C for 24 hours to remove the moisture content in it. The present of moisture in block panel will affect the result significantly as moisture increase the heat transfer rate. The block panel was taken out from oven and cooled down to room temperature, approximately 28 °C ± 2 °C. A hot plate with temperature of 40°C was placed on top of a 300 mm x 300 mm x 100 mm block panel while a cold plate with temperature of 25°C was placed at the base of the block panel. Heat transfer between the hot plate, block panel and cold plate was automatically recorded by Logger Net every minute for approximately 20 hours. Mean value obtained from three block panels was then taken as thermal conductivity for each lightweight foamed concrete mix. The thermal conductivity, k can be calculated based on Equation 3.6.

$$k = \frac{\Phi h}{A(T_1 - T_2)} \tag{3.6}$$

where

k = Thermal Conductivity, W/mK

Φ = Heat Conduction, J/s

h = thickness of specimen, m

A = Cross sectional area, m^2

T_1 = Average temperature of hot plate, K

T_2 = Average temperature of cold plate, K

3.8.7 ISAT, Initial Surface Absorption Test (BS 1881-Part 5, 1970)

ISAT is a non-destructive test which was performed in accordance with BS 1881-Part 5 (1970). This is the test to indicate the rate of flow of water into concrete per unit area after a stated interval from the start of the test and at constant applied head and temperature. The purpose of the test is to obtain an indication of durability of concrete subjected to external chemical attack. Mean value obtained from three 100 mm cubes were then taken as initial surface absorption for each lightweight foamed concrete mix.

As shown in Figure 3.10, a clear reservoir is connected to the ‘inlet’ of the 100 mm cube. The ‘outlet’ of the cell is connected to a capillary tube with an affixed scale. A valve is fitted to the inlet side to isolate the reservoir and allow for recording the time taken for the capillary tube to move back 86 divisions.

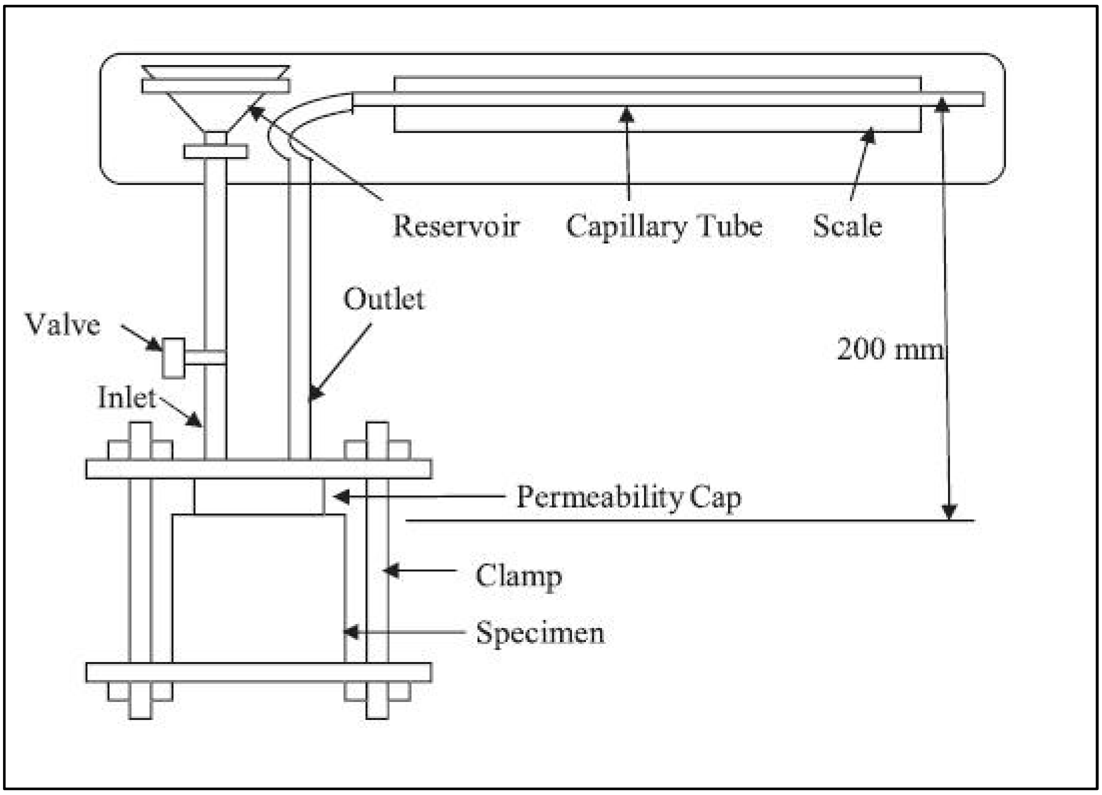

Figure 3.11: Setting Up of ISAT

The cube was taken out from water tank and oven dried in oven at temperature of 105 °C ± 5 °C for 24 hours to remove the moisture content in it. The cube was then taken out from oven and allowed to cool down to room temperature, approximately 28 °C ± 2 °C. Cooled oven dried cube was clamped to test surface so as to ensure an even pressure and good seal around the perimeter. The capillary tube and reservoir were mounted 200 mm above the cube. The test started when the water fully filled the reservoir, the permeability cap and the capillary tube. The time taken for the capillary tube to move back 86 divisions was taken for every 10, 30, 60 and 120 minutes. The flow, f can be calculated based on Equation 3.7.

$$f = 60 \times D \times \frac{0.01}{t} \tag{3.7}$$

where
f = flow, $ml/m^2/s$
D = no. of scale division during the period
t = period, s

Figure 3.12: ISAT of Lightweight Foamed Concrete

3.9 Consistency and Stability

The fresh density and hardened density was used to check the stability and consistency of the mix. The mix is said to be stable if the ratio of fresh density to hardened density is close to one. On the other hand, the mix is aid to be very consistent if the ratio of fresh density to designated density is close to one. The consistency of the mix is determined by Equation 3.8 (Ramamurthy, 2009) while the stability is determined by Equation 3.9.

$$\text{Consistency} = \frac{\text{Fresh Density}}{\text{Designated Density}} \tag{3.8}$$

$$\text{Stability} = \frac{\text{Fresh Density}}{\text{Hardened Density}} \tag{3.9}$$

3.10 Performance Index

The compressive strength and density of concrete has correlated relationship. Theoretically, higher density of concrete will have higher compressive strength. The density of lightweight foamed concrete for this research was control to within 1300 kg/m^3 ± 50 kg/m^3. As the density for each specimen was varying, performance index of concrete was calculated to increase the accuracy of the results obtained. The equation for performance index is shown in Equation 3.10.

$$\text{PI} = \frac{\text{Sc}}{\text{hardened density}/1000} \tag{3.10}$$

where

PI = Performance Index, MPa per 1000 kg/m^3

Sc = Compressive Strength, MPa

3.11 Microstructure Image Analysis

Microstructural image analysis was carried out in accordance with ASTM C1723 (2010) and by the mean of Scanning Electron Microscope (SEM). The imaging was performed in high vacuum with the application of a conductive coating. Hitachi VP-SEM S-3700N was used in this study for microstructure study. SEM imaging was carried out on 90-day foamed concrete only. A small piece of crushed cube was used for microstructure analysis. Specimens for each mix proportion were coated with a gold layer before the analysis being carried out. The accelerating voltage of the SEM was set to 15 kV and image with 50×, 100×, 250×, 500×, 1000×, 2000× and 5000× of magnifications were selected for analysis.

Figure 3.13: Coating of Specimen Before SEM Analysis

Figure 3.14: Hitachi VP-SEM S-3700N

3.12 Summary

Lightweight foamed concrete incorporated with POFA with density of 1300 kg/m3 was produced by the pre-foaming method, where the stable and dry foam was mixed into fresh lightweight foamed concrete until the desired density achieved. A density of 45 kg/m3 stable and dry foam was produced by the mixture of liquid synthetic foaming agent diluted with water with ratio of 1:30 in a foam generator. Three mix proportions were prepared in this study; namely LFC-CM, LFC-PF10 and LFC-PF20. A total of fifteen 100 mm cubes, fifteen cylinders with height of 200 mm and diameter of 100 mm, twelve 25 mm × 25 mm × 250 mm prisms and three 300 mm × 300 mm × 100 mm block panels were produced for each mix proportions. The specimens were cured in water for 7, 28, 56 and 90 days before undergoing several test sessions; namely compression test, splitting tensile test, flexural strength test, Poisson's ratio test, thermal conductivity test and ISAT. A small piece of crushed 90-day cube for each mix proportion was undergoing SEM for microstructural analysis.

The accelerating voltage of the SEM was set to 15 kV and image with 50×, 100×, 250×, 500×, 1000×, 2000× and 5000× of magnifications were selected for analysis.

CHAPTER 4

TRIAL MIXES

4.1 Introduction

This chapter discusses and screens trial mixes results for lightweight foamed concrete incorporated with POFA in obtaining the mix proportion for LFC-CM, LFC-PF10 and LFC-PF20. The specimens for each mix proportions were water cured for 7, 14 and 28 days before undergoing compression test.

4.2 Mix Proportions

Table 4.1 presented the mix proportions used during trial mixes for LFC-CM, LFC-PF10, LFC-PF20.

Table 4.1: Mix Proportions

Mix details	Binder: Sand	Sand: POFA	Foam volume per m^3 (liters)	w/b[1]	Inverted slump cone spread value (mm)
LFC-CM[2]-0.54[5]	1:1	100:0	454 ± 10	0.54	540-550
LFC-CM-0.56	1:1	100:0	444 ± 10	0.56	580-590
LFC-CM-0.58	1:1	100:0	373 ± 10	0.58	650-660
LFC-CM-0.60	1:1	100:0	296 ± 10	0.60	680-685
LFC-PF10[3]-0.52	1:1	90:10	356 ± 10	0.52	460-480
LFC-PF10-0.54	1:1	90:10	395 ± 10	0.54	470-500
LFC-PF10-0.56	1:1	90:10	454 ± 10	0.56	470-525
LFC-PF10-0.58	1:1	90:10	365 ± 10	0.58	490-540
LFC-PF10-0.60	1:1	90:10	336 ± 10	0.60	505-540
LFC-PF20[4]-0.54	1:1	80:20	356 ± 10	0.54	390-420
LFC-PF20-0.56	1:1	80:20	296 ± 10	0.56	410-440
LFC-PF20-0.58	1:1	80:20	395 ± 10	0.58	420-460
LFC-PF20-0.60	1:1	80:20	494 ± 10	0.60	485-525

Note:

[1] w/b = water-to-binder ratio

[2] LFC-CM = LFC with 100 % sand as filler

[3] LFC-PF10 = LFC with 10 % POFA replacement as part of filler

[4] LFC-PF20 = LFC with 20 % POFA replacement as part of filler

[5] 0.52 to 0.60 is the water to cement ratio

4.3 Compression Test Results

Compressive strength test results for LFC-CM, LFC-PF10 and LFC-PF20 were illustrated in Figures 4.1 to 4.3.

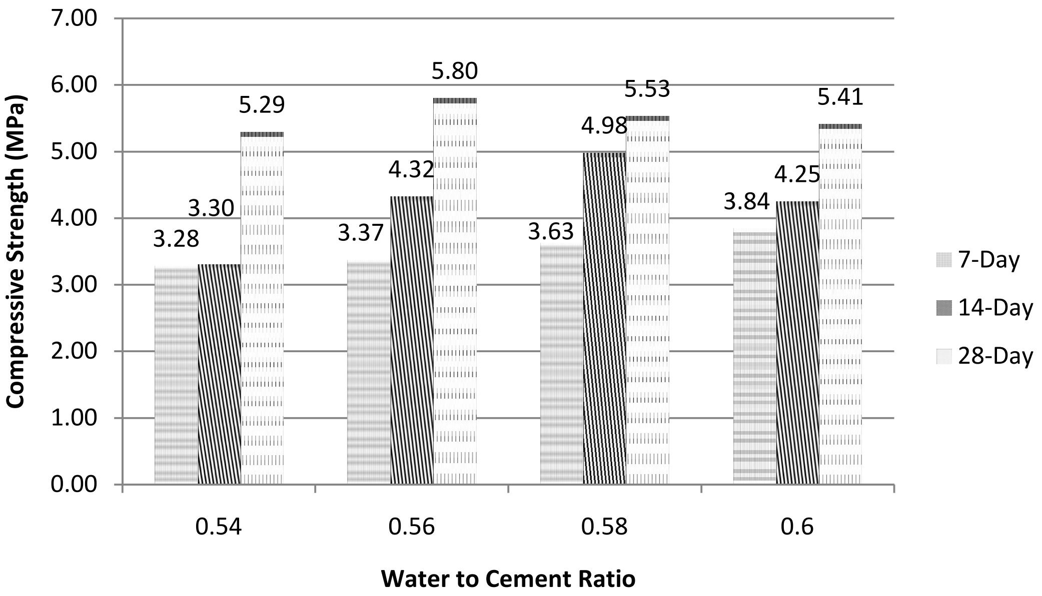

Figure 4.1: Compressive Strength of LFC-CM

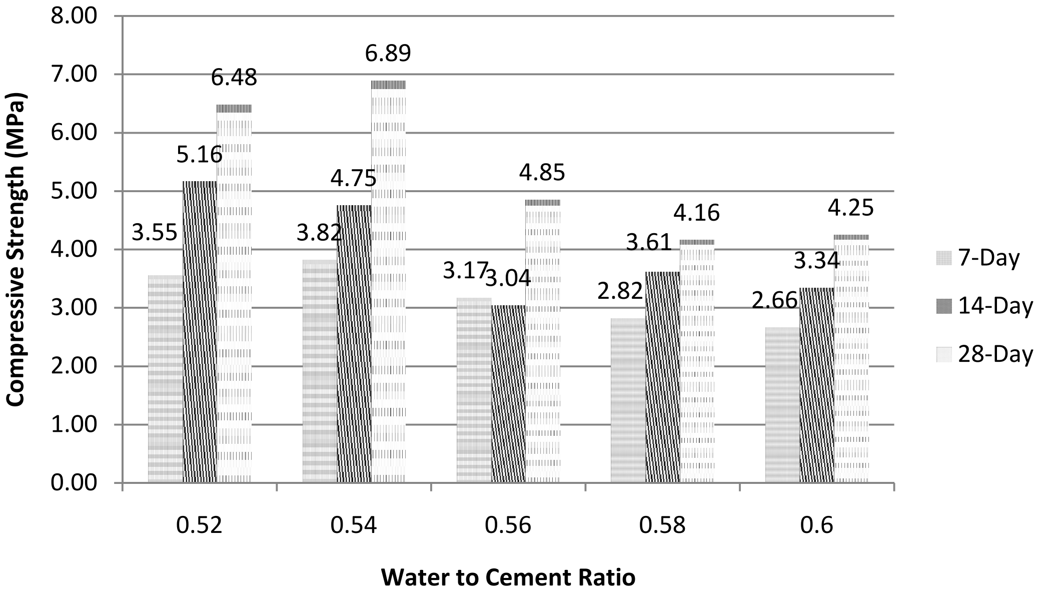

Figure 4.2: Compressive Strength of LFC-PF10

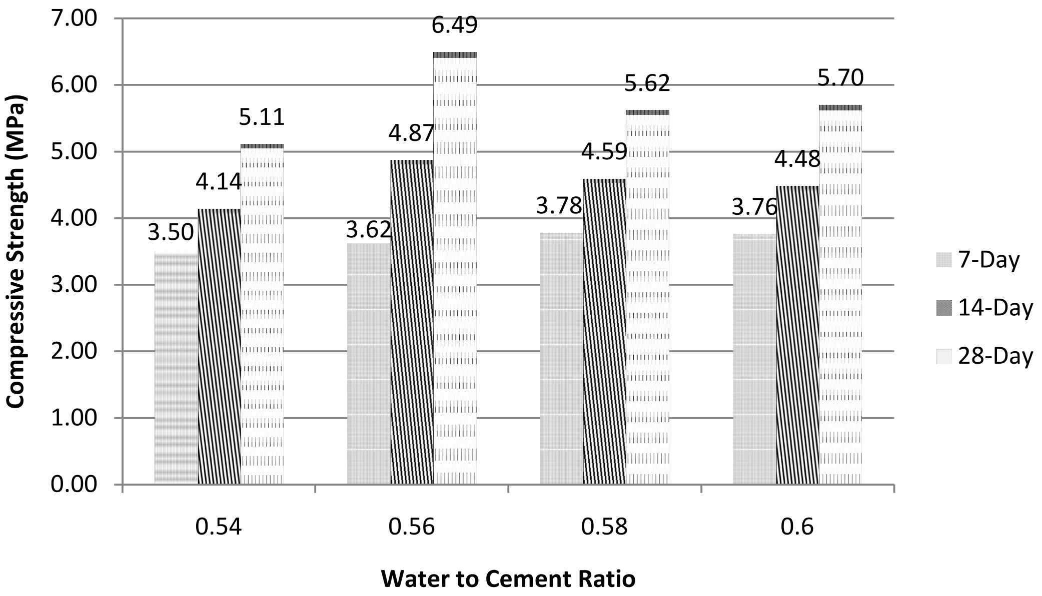

Figure 4.3: Compressive Strength of LFC-PF20

Figures 4.1 to 4.3 showed that the compressive strength is directly proportional to curing age. For LFC-CM, the highest 28-day compressive strength was achieved by 0.56 w/c mix proportion, which is 5.80 MPa. For LFC-PF10, 0.54 w/c mix proportion achieved the highest 28-day compressive strength, which is 6.89 MPa. For LFC-PF20, 0.56 w/c mix proportion achieved the highest 28-day compressive strength which is 6.49 MPa.

4.4 Performance Index

Specimen's performance index was calculated based on Equation 3.8. Performance index LFC-CM, LFC-PF10 and LFC-PF20 are illustrated in Figures 4.4 to 4.6.

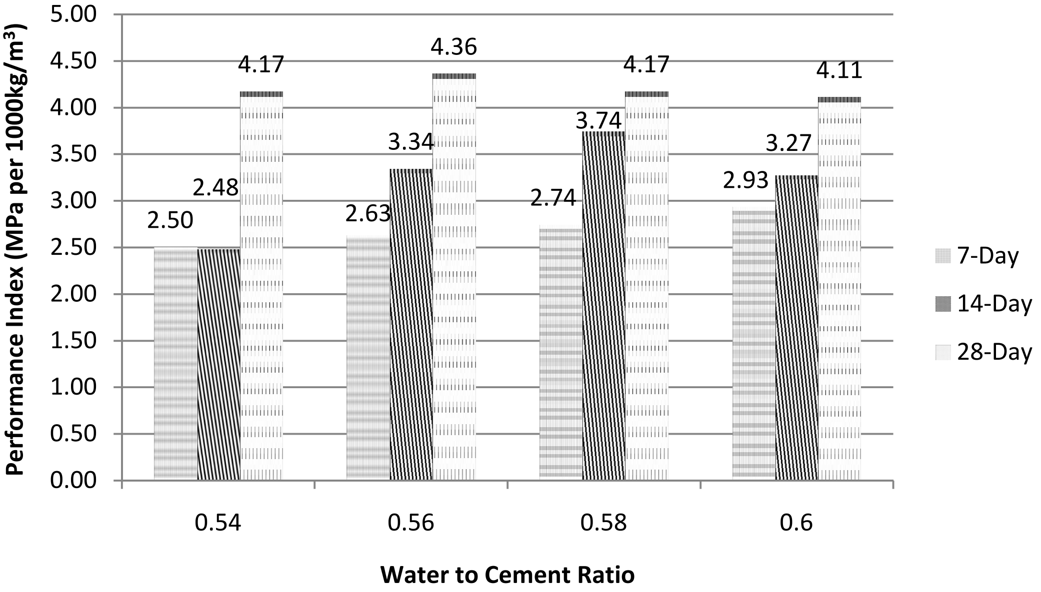

Figure 4.4: Performance Index LFC-CM

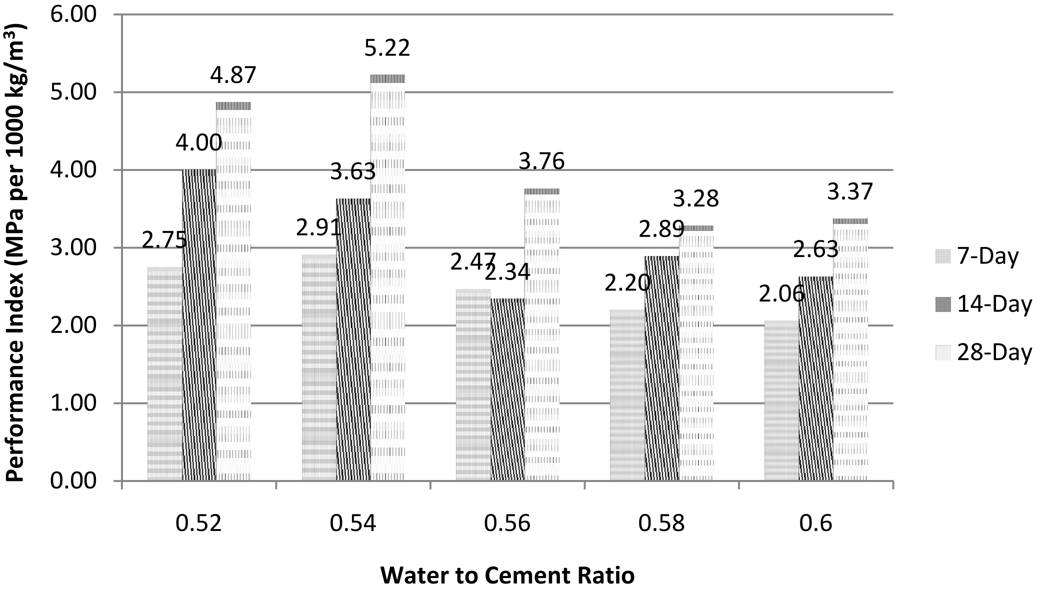

Figure 4.5: Performance Index of LFC-PF10

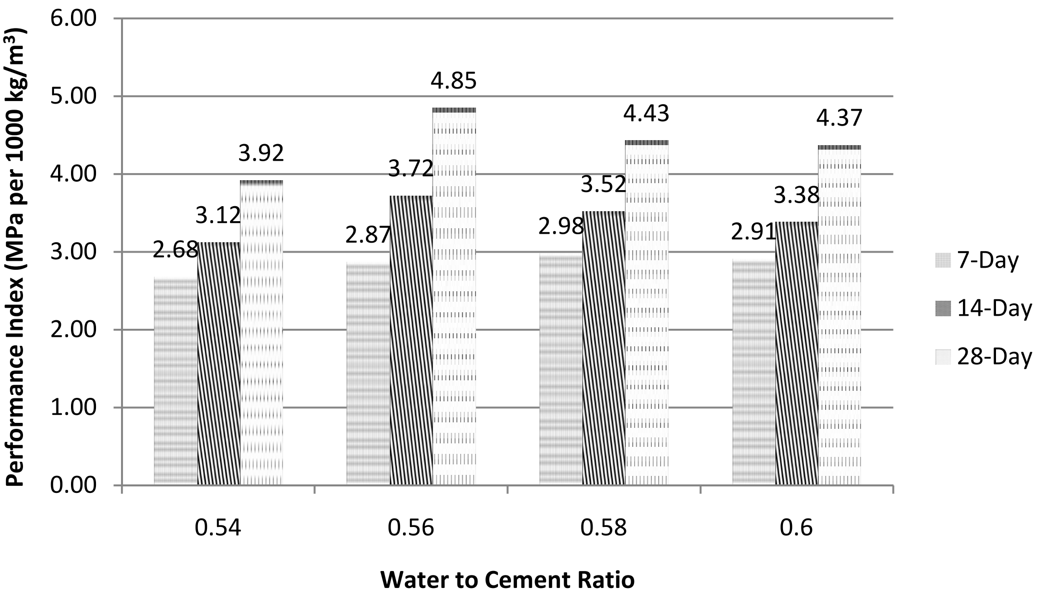

Figure 4.6: Performance Index of LFC-PF20

Similar trend obtained by performance index, where the performance index is directly proportional to the specimen’s curing age. For LFC-CM, the highest 28-day performance index was achieved by 0.54 w/c mix, which is 4.36 MPa per 1000 kg/m^3. On the other hand, highest 28-day performance index achieved by LFC-PF10 is 0.54 w/c mix. For LFC-PF20, the highest 28-day performance index was achieved by 0.56 w/c mix, 4.85 MPa per 1000 kg/m^3.

4.5 Summary

Incorporation of POFA into lightweight foamed concrete has increase its compressive strength. This mainly due to the pozzolanic process happened in lightweight foamed concrete incorporated with POFA. The pozzolanic process ensures continuous development of strength due to addition reactive silica content by the incorporation of POFA, which more C-S-H was produced.

Generally, compressive strength and performance index of lightweight foamed concrete shared the same trend, where the compressive strength and performance index are directly proportional to curing age. For LFC-CM, the highest 28-day compressive strength and performance index was achieved by 0.56 w/c mix proportion, which is 5.80 MPa and 4.36 MPa per 1000 kg/m^3 respectively. For LFC-PF10, 0.54 w/c mix proportion achieved the highest 28-day compressive strength and performance index, which are 6.89 MPa and 5.22 MPa per 1000 kg/m^3 respectively. For LFC-PF20, 0.56 w/c mix proportion achieved the highest 28-day compressive strength and performance index, which are 6.49 MPa and 4.85 MPa per 1000 kg/m^3 respectively.

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Introduction

This chapter discusses about the results of tests carried out on lightweight foamed concrete incorporated with POFA namely compression test, splitting tensile test, flexural strength test, Poisson’s ratio test, thermal conductivity test and ISAT. Specimens were water cured for 7, 28, 56 and 90 days before undergoing test sessions. The effects of incorporation of POFA into lightweight foamed concrete on its engineering properties in terms of compressive strength, splitting tensile strength, flexural strength, thermal conductivity, Poisson’s ratio, Poisson’s ratio toughness and initial water absorption was discussed at the later part of the chapter.

5.2 Mix Proportions

Table 5.1 presents the mix proportions used in this study for LFC-CM, LFC-PF10 and LFC-PF20.

Table 5.1: Mix Proportions

Mix details	Binder : Sand	Sand: POFA	Foam volume per m^3 (liters)	w/b[1]	Inverted slump cone spread value (mm)	Consistency	Stability
LFC-CM[2]-0.56[5]	1:1	100:0	545 ± 10	0.56	600-610	1.00	1.06
LFC-PF10[3]-0.54	1:1	90:10	588 ± 10	0.54	550-560	0.99	1.03
LFC-PF20[4]-0.56	1:1	80:20	652 ± 10	0.56	520-540	1.00	1.03

Note:

[1] w/b = water-to-binder ratio

[2] LFC-CM = LFC with 100 % sand as filler

[3] LFC-PF10 = LFC with 10 % POFA replacement as part of filler

[4] LFC-PF20 = LFC with 20 % POFA replacement as part of filler

[5] 0.54 to 0.60 is the water to cement ratio

5.3 Compressive Strength

The compressive strengths for LFC-CM, LFC-PF10 and LFC-PF20 are illustrated in Figure 5.1.

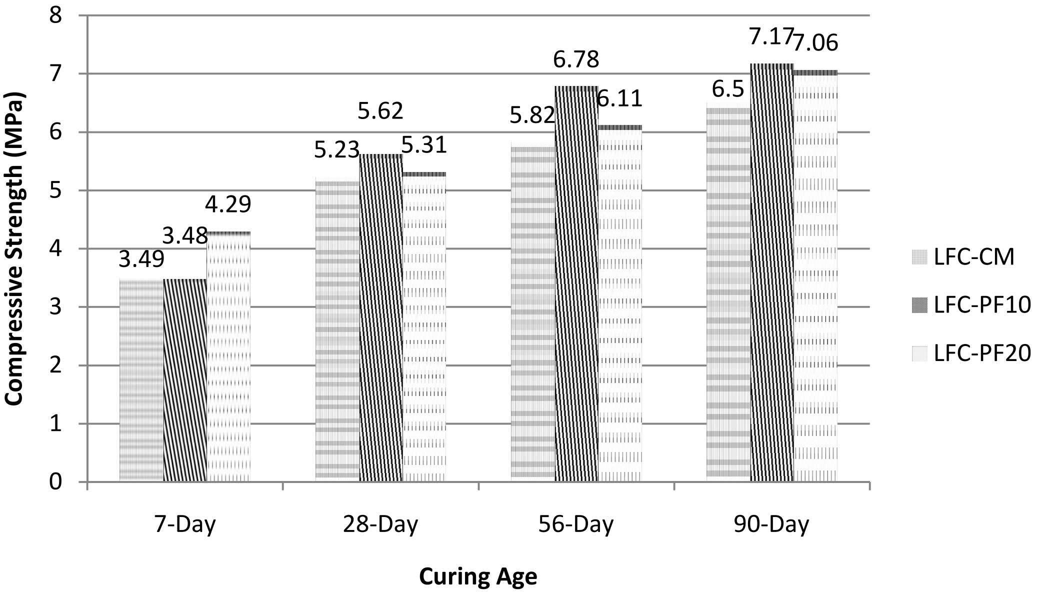

Figure 5.1: Compressive Strength Development up To 90 days of Age for LFC-CM, LFC-PF10 and LFC-PF20

Figure 5.1 shows the compressive strength of each mix proportion increased along with the curing age. At 7-day curing age, LFC-PF10 has the lowest compressive strength which is 3.48 MPa. The incorporation of POFA ensured the continuous strength development of LFC-PF10, this lead the LFC-PF10 to achieve the highest compressive strength at 90-day of age which is 7.17 MPa. Figure 5.1 also shows both LFC-PF10 and LFC-PF20 have higher compressive strength than of control mix at 90-day of age.

Incorporation of POFA into lightweight foamed concrete has increased the compressive strength of lightweight foamed concrete. This is mainly due to the high reactive silica content in POFA itself. This silica content allow the occurrence of pozzolanic process in lightweight foamed concrete, where additional C-S-H gel was produced due to the reaction of reactive silica with calcium hydroxide. This additional C-S-H gel caused the lightweight foamed concrete denser. The additional calcium silicate hydrate gel formed improves the interfacial bonding between the aggregates and pastes at later ages (Karim, 2011). Thus, the compressive strength increased. Table 5.2 shows the compressive strength of LFC-PF10 at 90 days of age was 10 % higher than that of LFC-CM. On the other hand, compressive strength of LFC-PF20 at 90 days of age was 9 % higher than of LFC-CM.

Table 5.2: Effect of Incorporation of POFA in LFC on its Compressive Strength Development at 90 Days of Age

Age	Mix	Strength development as percentage of control mix at 90 days of age
90 days	LFC-CM	100
	LFC-PF10	110
	LFC-PF20	109

5.4 Splitting Tensile Strength

The splitting tensile strength for LFC-CM, LFC-PF10 and LFC-PF20 are illustrated in Figure 5.2.

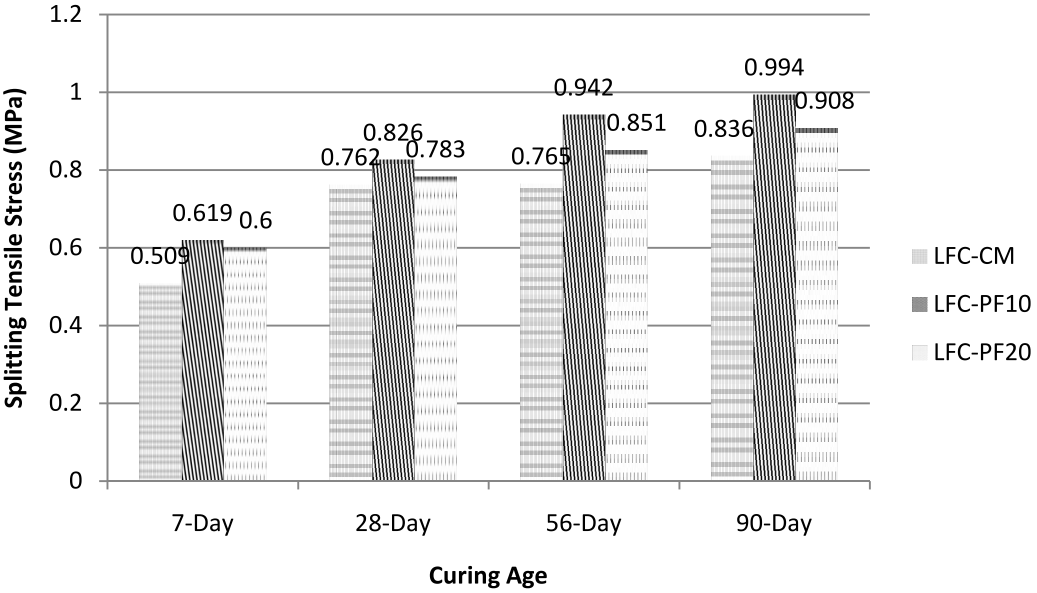

Figure 5.2: Splitting Tensile Strength Development Up To 90 days of Age for LFC-CM, LFC-PF10 and LFC-PF20

Figure 5.2 shows the splitting tensile strength of each mix proportion increased along with the curing age. Both LFC-PF10 and LFC-PF20 have higher splitting tensile strength than that of LFC-CM. LFC-PF10 achieved the highest splitting tensile strength which is 0.994 MPa at 90-day curing age.

Generally, the splitting tensile strength development shared the same trend with compressive strength development. Lightweight foamed concrete incorporated with POFA shows higher splitting tensile strength than pure sand based lightweight foamed concrete. Theoretically, splitting tensile strength is related to compressive strength, although this relationship depends on multiple factors namely aggregate type, particle size distribution, age of concrete, curing process and air content (Parra, 2011). Based on splitting tensile strength-compressive strength relationship illustrated in Figure 5.3, the splitting tensile strength is directly proportional to compressive strength. Referring to Table 5.3, the splitting tensile strength of LFC-PF10 at 90 days of age was 19 % higher than that of LFC-CM. On the other hand, spitting tensile strength of LFC-PF20 at 90 days of age was 9 % higher than that of LFC-CM.

Generally, splitting tensile strength is much lower than compressive strength. This is because in this test, the cylinder specimen is placed with its axis horizontal between the platens of a testing machine. The load is increased until failure by indirect tension in the form of splitting along the vertical diameter takes places. It can be seen that a high horizontal compressive stress exists in the vicinity of the loads but, as this is accompanied by a vertical compressive stress of comparable magnitude, thus producing a state of biaxial stress. Hence, the cylinder will fail at tension rather than failure in compression (Neville, 2010).

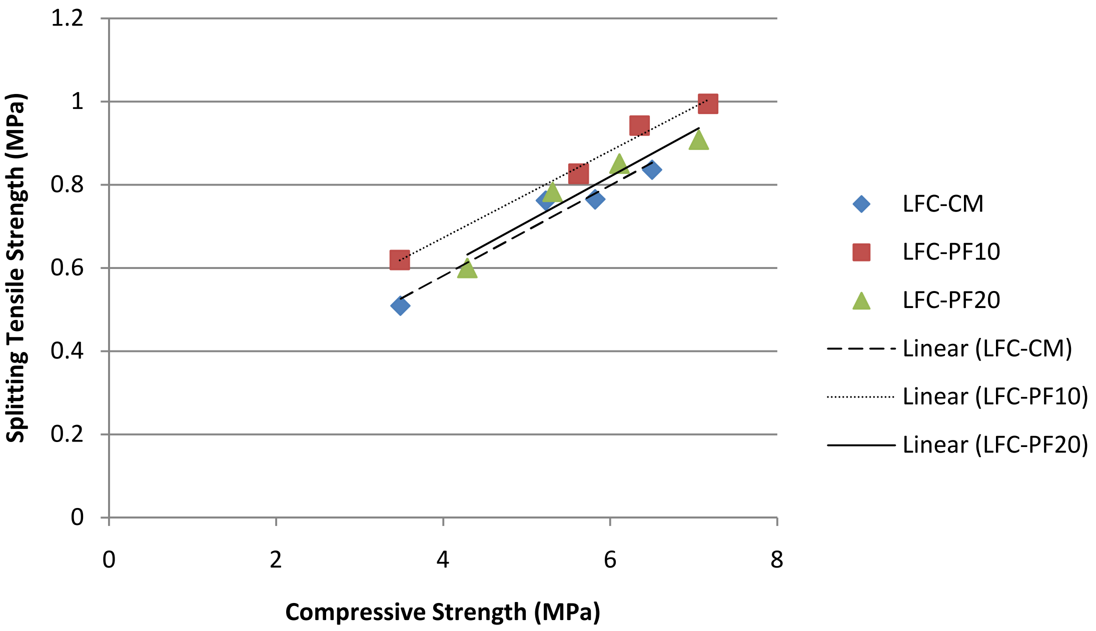

Figure 5.3: Relationship of Splitting Tensile Strength-Compressive Strength for LFC-CM, LFC-PF10 and LFC-PF20 Up to 90 days of Age

Table 5.3: Effect of Incorporation of POFA in LFC on its Splitting Tensile Strength Development at 90 Days of Age

Age	Mix	Strength development as percentage of control mix at 90 days of age
90 days	LFC-CM	100
	LFC-PF10	119
	LFC-PF20	109

5.5 Flexural Strength

The flexural strengths for LFC-CM, LFC-PF10 and LFC-PF20 are illustrated in Figure 5.4.

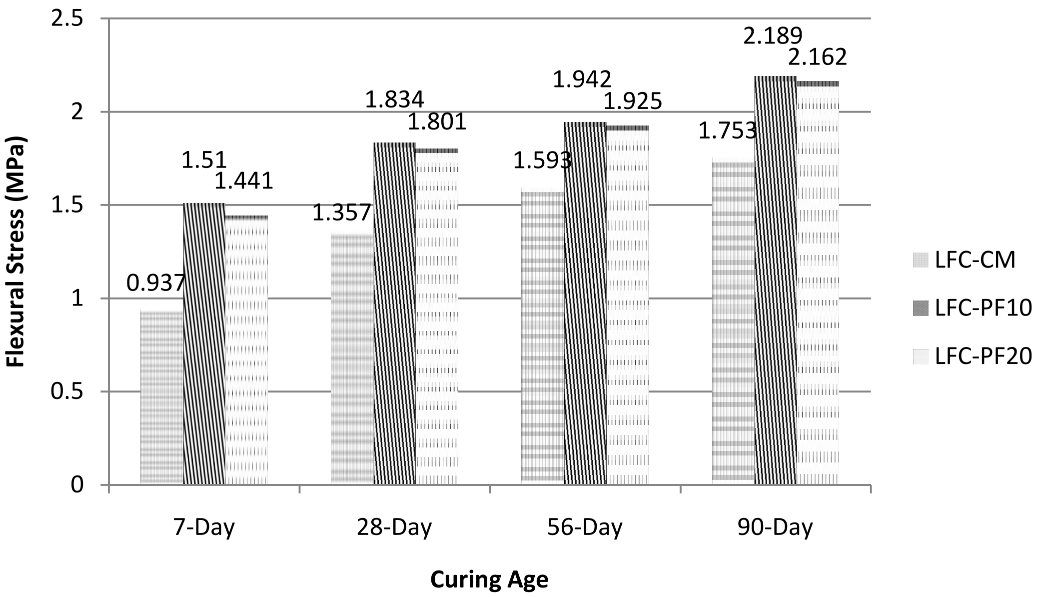

Figure 5.4: Flexural Strength Development up To 90 days of Age for LFC-CM, LFC-PF10 and LFC-PF20

Figure 5.4 shows the flexural strength of each mix proportion increased along with the curing age. Both LFC-PF10 and LFC-PF20 has higher flexural strength than that of LFC-CM at 90-day of age. LFC-PF10 achieved the highest flexural strength at 90 days of age which is 2.189 MPa.

In general, the flexural strength development has same trend with compressive strength development. Lightweight foamed concrete incorporated with POFA shows higher flexural strength than that of pure sand based lightweight foamed concrete. Based on flexural strength-compressive strength relationship illustrated in Figure 5.5, the flexural strength is directly proportional to compressive strength. Table 5.4 shows the flexural strength of LFC-PF10 at 90 days of age was 25 % higher than that of LFC-CM. On the other hand, flexural strength of LFC-PF20 at 90 days of age was 23 % higher than that of LFC-CM.

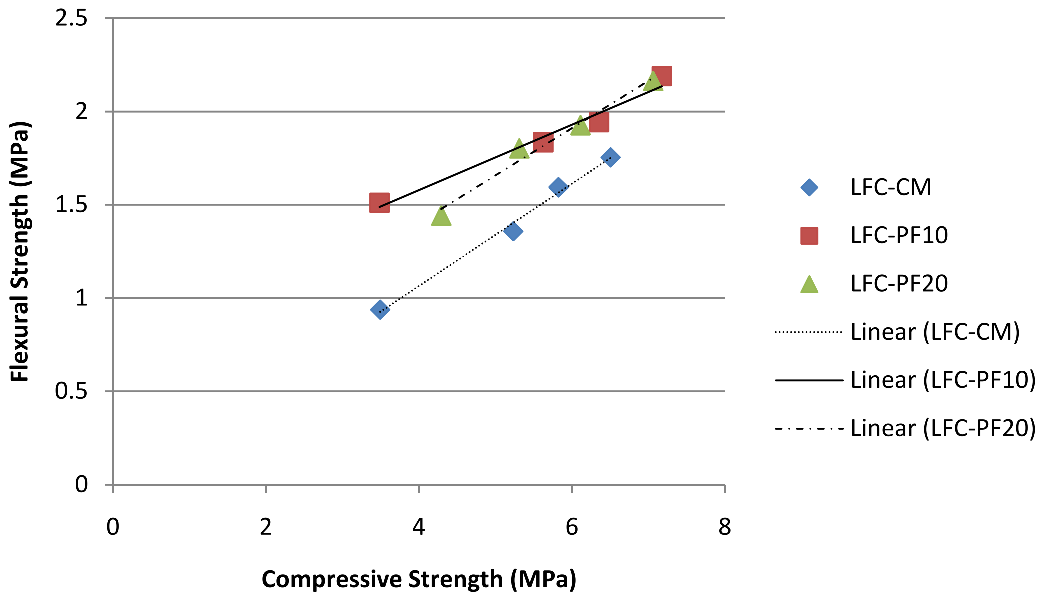

Figure 5.5: Relationship of Flexural Strength-Compressive Strength of LFC-CM, LFC-PF10 and LFC-PF20 Up to 90 days of Age

Table 5.4: Effect of Incorporation of POFA in LFC on its Flexural Strength Development at 90 Days of Age

Age	Mix	Strength development as percentage of control mix at 90 days
90 days	LFC-CM	100
	LFC-PF10	125
	LFC-PF20	123

5.6 Poisson's Ratio

The Poisson's ratios for 28-Day LFC-CM, LFC-PF10 and LFC-PF20 are illustrated in Table 5.5.

Table 5.5: 28-Day Poisson's ratio for LFC-CM-0.56, LFC-PF10-0.54 and LFC-PF20-0.56

Specimens Series No.	40 % of Maximum Compressive Strength (MPa)	ε_{t2}[1]	ε_{t1}[2]	ε_2[3]	Poisson's ratio, μ[4]
LFC-CM -0.56	1.88	0.000641	0.0000181	0.00196	0.327
LFC-PF10 -0.54	2.13	0.001239	0.0000111	0.00573	0.216
LFC-PF20 -0.56	2.53	0.000977	0.0000034	0.00378	0.261

Note:

[1] ε_{t2}= tranverse strain at midheight of the specimen produced by stress corresponding to 40 % of ultimate load

[2] ε_{t1}= tranverse strain at midheight of the specimen produced by stress corresponding to a longitudinal strain of 50 millionths

[3] ε_2= longitudinal strain produced by stress corresponding to 40 % of ultimate load

[4] $\mu = (\varepsilon_{t2} - \varepsilon_{t1})/(\varepsilon_2 - 0.000050)$

Table 5.5 shows that the LFC incorporated with POFA as part of filler have lower Poisson's ratio than that of LFC with 100 % sand filler at 28 days of age. The trends of Poisson's ratio were totally opposite than that of the compressive strength development. The results shows that LFC specimens with lower compressive strength tend to have more deformation at horizontal and vertical axis than that of higher compressive strength LFC specimens.

5.7 Poisson's Ratio Toughness

The 28-day Poisson's ratio stress-strain relationship for LFC-CM-0.56, LFC-PF10-0.54 and LFC-PF20-0.56 are illustrated in Figure 5.6, 5.7 and 5.8, respectively.

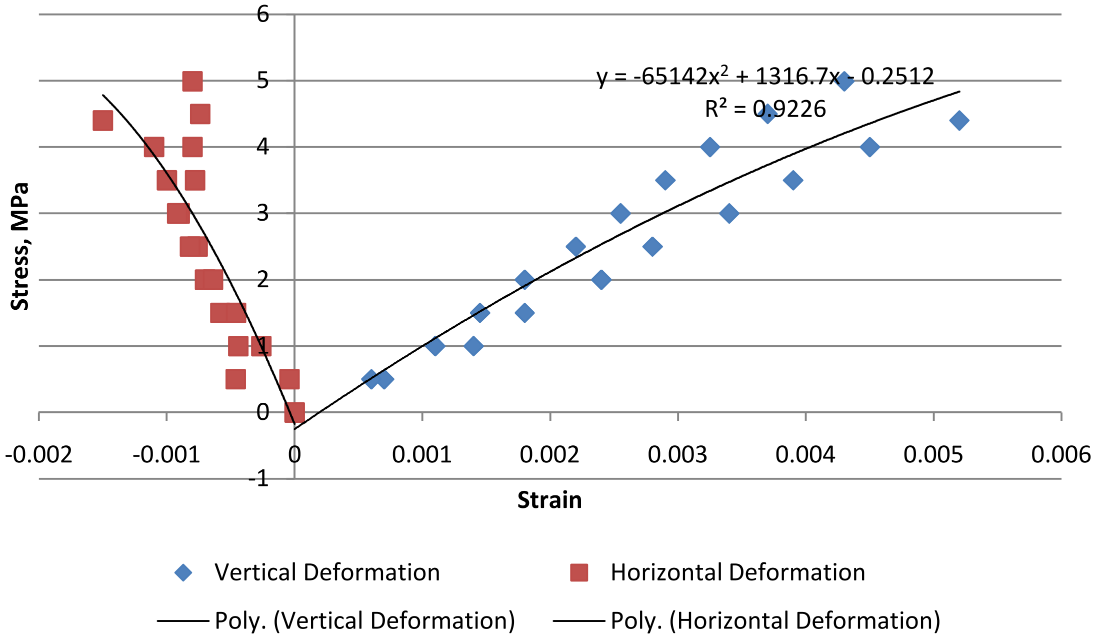

Figure 5.6: 28-Day stress-strain relationship of LFC-CM-0.56

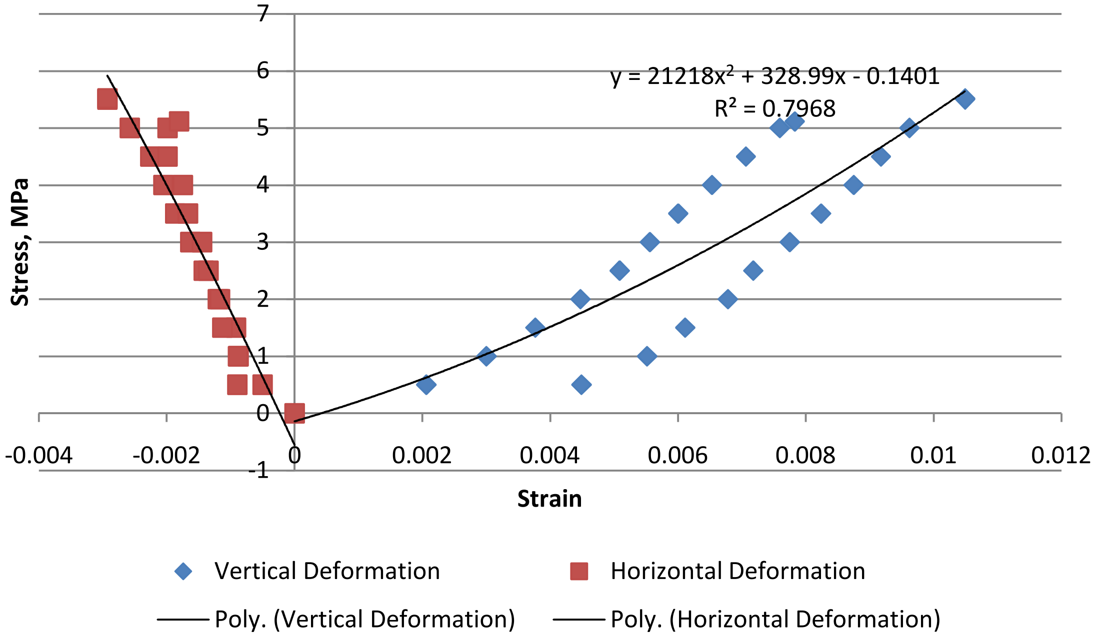

Figure 5.7: 28-Day stress-strain relationship of LFC-PF10-0.54

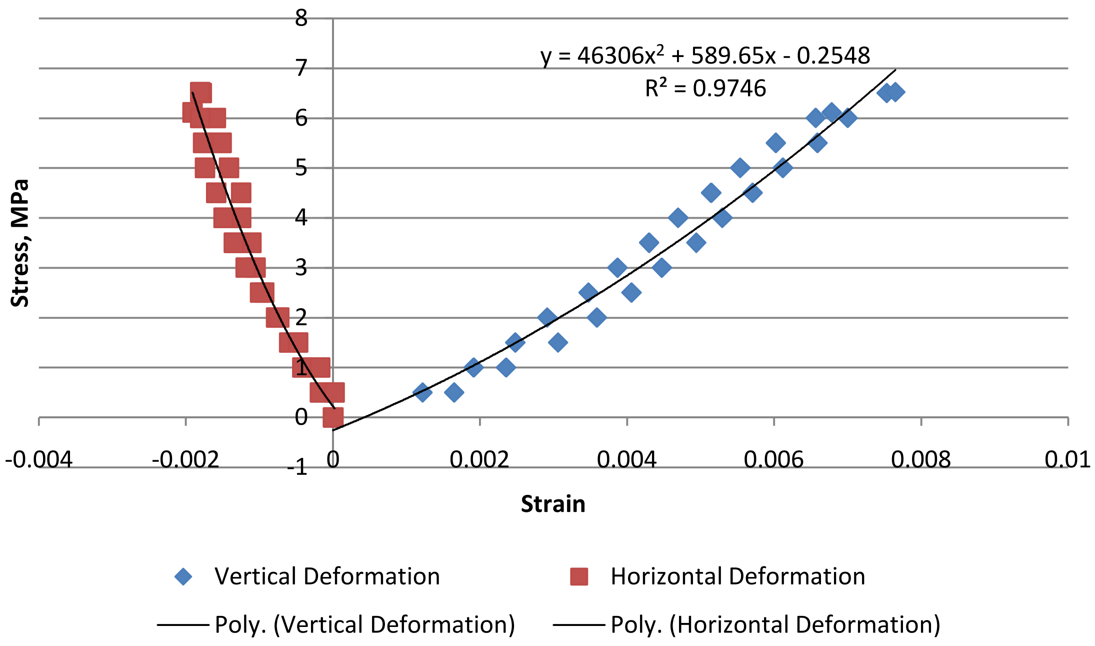

Figure 5.8: 28-Day stress-strain relationship of LFC-PF20-0.56

Table 5.6 shows the 28-day Poisson's ratio toughness value of each LFC cylinder specimen which computed by integrates the vertical deformation's curve's trend line equation obtained from Figure 5.6, 5.7 and 5.8. The toughness values of LFC-CM-0.56, LFC-PF10-0.54 and LFC-PF20-0.54 are 2.33×10^{15} J/m^3, 5.43×10^{15} J/m^3 and 5.79×10^{15} J/m^3, respectively. In general, incorporation of POFA as part of filler enhanced the Poisson's ratio toughness than that of specimens with 100 % sand filler. Specimen incorporated with POFA as part of filler able to withstand more loads with lesser deformation than that of 100 % sand as filler specimen.

Table 5.6: Poisson's ratio toughness of LFC-CM-0.56, LFC-PF10-0.54 and LFC-PF20-0.56 at 28 days of age

Specimen Series No.	Curves' Trend line Equation	R^2	Maximum Compressive Stress, σ (MPa)	Corresponding Vertical Strain, ε x 10^{-6}	Total Flexural Toughness (J/m^3)
LFC-CM-0.56	$\sigma = 65142\varepsilon^2 + 1317\varepsilon - 0.251$	0.9226	4.70	4750	2.33×10^{15}
LFC-PF10-0.54	$\sigma = 21218\varepsilon^2 + 329\varepsilon - 0.14$	0.7968	5.32	9156	5.43×10^{15}
LFC-PF20-0.56	$\sigma = 46306\varepsilon^2 + 590\varepsilon – 0.255$	0.9746	6.31	7214	5.79×10^{15}

5.8 Thermal Conductivity

The thermal conductivity for 28-Day LFC-CM), LFC-PF10 and LFC-PF20 are presented in Table 5.7.

Table 5.7: Thermal Conductivity of LFC-CM-0.56, LFC-PF10-0.54 and LFC-PF20-0.56 at 28 days of age

Specimen Series No.	Oven Dried Density (kg/m^3)	28-Day Compressive Strength (MPa)	Thermal Conductivity (W/mk)
LFC-CM-0.56	1076	5.23	0.65
LFC-PF10-0.54	1197	5.62	0.74
LFC-PF20-0.56	1188	5.31	0.67

Table 5.7 shows that the LFC incorporated with POFA as part of filler gained higher 28-day thermal conductivity than that of LFC with 100 % sand filler. This circumstance is due to densification of microstructure in LFC-PF10-0.54 and LFC-

PF20-0.56 by the additional C-S-H gel produced through pozzolanic reaction. In addition, the fineness of POFA also contributed densification of LFC's microstructure as the micro-fine fillers have efficiently filled up the macro-pores in the LFC, increases the strength. This is justified by the higher compressive strength obtained by LFC-PF10-0.54 and LFC-PF20-0.56 than that of LFC with 100 % sand filler. Table 5.8 shows the thermal conductivity of LFC-PF10 was 13 % higher than that of LFC-CM while LFC-PF20 was 3 % higher than that of LFC-CM.

Table 5.8: Effect of Incorporation of POFA on Thermal Conductivity at 28 Days

Age	Mix	Thermal Conductivity as percentage of control mix at 28 days
28 days	LFC-CM	100
	LFC-PF10	113
	LFC-PF20	103

5.9 Initial Surface Absorption Test (ISAT)

The ISAT for 28-Day LFC-CM, LFC-PF10 and LFC-PF20 were illustrated in Figure 5.9.

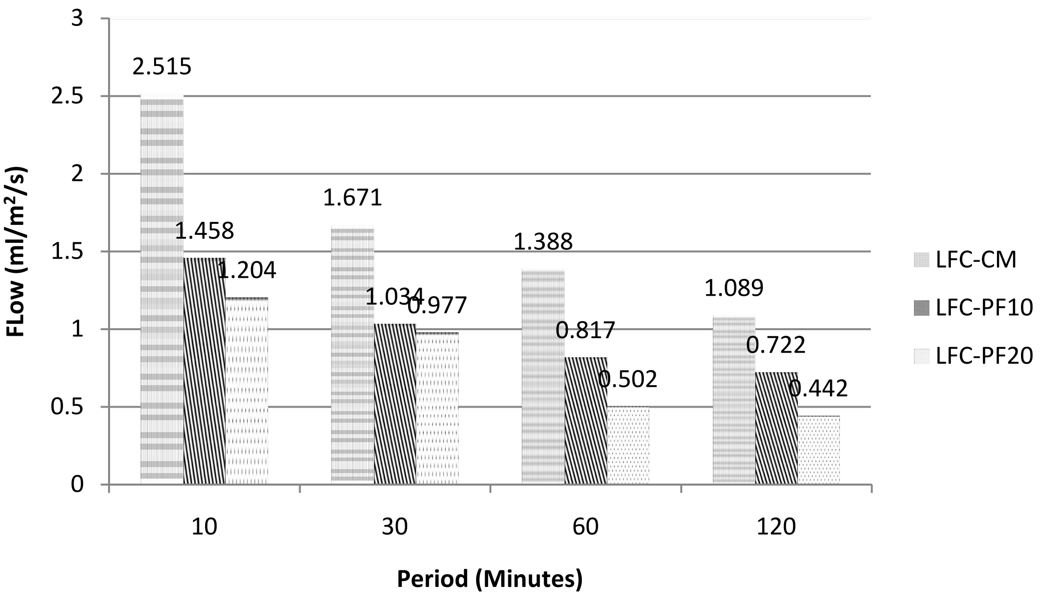

Figure 5.9: 28-day Initial Surface Absorption Test for LFC-CM, LFC-PF10 and LFC-PF20

The incorporation of POFA into lightweight foamed concrete has resulted a decrease of initial surface absorption of concrete. This is possible due to the reduction in the average pore radius of concrete with the formations of C-S-H gel by the pozzolanic reaction that gradually fill the original water filled space. Another possible reason is the high fineness of POFA that would become as filler between cement particles (Kartini, 2010). Table 5.9 shows the initial surface absorption of LFC-PF10 was 34 % lower than that of LFC-CM while LFC-PF20 was 59 % lower than that of LFC-CM. Although LFC-PF20 has slightly lower compressive strength than that of LFC-PF10, LFC-PF20 has lower concrete surface absorption. Consequently, LFC-PF20 has better durability than that of LFC-PF10.

Table 5.9: Effect of Incorporation of POFA in LFC on its ISAT at 28 Days of Age

Age	Mix	ISAT as percentage of control mix at 28 days of age for 120 minutes
28 days	LFC-CM	100
	LFC-PF10	66
	LFC-PF20	41

5.10 Performance Index

Table 5.10 presents the performance index of the lightweight foamed concrete. The trend of performance index of lightweight foamed concrete is same as compressive strength development, where the performance index is directly proportional to curing age. The highest performance index was achieved by LFC-PF10 and followed by LFC-PF20 at 90 days of age.

Table 5.10: Performance Index of Lightweight Foamed Concrete

Age	Mix	Performance Index
7 days	LFC-CM	2.72
	LFC-PF10	2.68
	LFC-PF20	3.25
28 days	LFC-CM	4.04
	LFC-PF10	4.34
	LFC-PF20	4.13
56 days	LFC-CM	4.42
	LFC-PF10	5.31
	LFC-PF20	4.64
90 days	LFC-CM	4.96
	LFC-PF10	5.58
	LFC-PF20	5.45

5.11 Summary

The incorporation of POFA into lightweight foamed concrete as sand replacement plays vital role in improving the engineering properties of lightweight foamed concrete in terms of compressive strength, splitting tensile strength, flexural strength, thermal conductivity, initial surface absorption, Poisson’s ratio and Poisson’s ratio toughness.

LFC-PF10 has lowest compressive strength at 7-day which is 3.48 MPa. However, at later stage, LFC-PF10 shows the highest compressive strength at 90 days of age, which is 7.17 MPa when compared with LFC-PF20 and LFC-CM. Generally, specimens with POFA as part of filler have higher compressive strength than that of 100 % sand as filler specimen. This is due to the pozzolanic behaviour possessed by POFA. The reactive silica content in POFA allows the reaction of pozzolanic to happen. With the presence of moisture, the reactive silica reacts with calcium hydroxide to produce additional C-S-H gel. In this study, the performance index share the same trend with compressive strength trend.

A common trend can be obtained for flexural and splitting tensile strengths, where the flexural and splitting tensile strengths are directly proportional to its curing ages. Besides that, specimen incorporated with POFA has higher flexural and splitting tensile strengths than that of pure sand based specimens. Incorporation of POFA in LFC has reduced its Poisson's ratio. However, the Poisson's ratio toughness of specimens with POFA has increased. This shows that specimens with POFA able to withstand more loads with lesser deformation that that of 100 % sand as filler specimens.

The thermal conductivity of specimen incorporated with POFA increased as compared with pure sand based concrete. This is justified by the densification of microstructure of lightweight foamed concrete incorporated with POFA and the increase of the compressive strength due to pozzolanic reaction. LFC-PF10 has highest thermal conductivity and this was justified by the highest compressive strength achieved by LFC-PF10.

The initial surface absorption test showed that LFC-PF20 has the lowest initial surface absorption as compared with LFC-PF10 and LFC-CM. Incorporation of POFA into specimen reduced the initial surface absorption than that of 100 % sand as filler specimen. This is due to the refinement of pore by the POFA and the pores have been filled up by the C-S-H gel formed by pozzolanic reaction.

CHAPTER 6

CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

Based on the laboratory results, the following conclusions can be drawn corresponding to the respective objective that are listed out at the beginning of this study.

The first objective is to produce lightweight foamed concrete incorporated with POFA with dry-bulk density of 1300 kg/m^3. This was achieved as three types of foamed concrete were prepared, which included LFC-CM, LFC-PF10 and LFC-PF20.

The second objective is to obtain optimum w/c ratios for LFC-CM, LFC-PF10 and LFC-PF20. This was achieved through trial mixes, where the optimum w/c ratios for LFC-CM, LFC-PF10 and LFC-PF20 are 0.56, 0.54 and 0.56, respectively.

The third objective is to study the effects of Palm Oil Fuel Ash (POFA) on engineering properties of lightweight foamed concrete in terms of compressive strength, flexural strength, splitting tensile strength, Poisson's ratio, Poisson's ratio toughness, initial surface absorption and thermal conductivity. Except Poisson's ratio, incorporation of POFA into lightweight foamed concrete has increased its compressive strength, flexural strength, splitting tensile strength, Poisson's ratio toughness, initial surface absorption and thermal conductivity than that of 100 % sand as filler specimen.

6.2 Recommendation

The research work on lightweight foamed concrete incorporated with POFA is still limited. But it promises a great scope for future studies. Following aspects related to the properties of lightweight foamed concrete need to be further study and investigate:

1. The effect of higher replacement level of sand with POFA on engineering properties of LFC.
2. The effect of longer period of curing age on engineering properties of LFC in terms of compressive strength, splitting tensile strength, flexural strength, initial surface absorption, Poisson's ratio, Poisson's ratio toughness and thermal conductivity.
3. The effect of other curing methods on engineering properties of LFC in term of compressive strength, splitting tensile strength, flexural strength, initial surface absorption, Poisson's ratio, Poisson's ratio toughness and thermal conductivity.

REFERENCES

Aldridge, D., (2005), Introduction to Foamed Concrete What, Why, and How?. *Use of Foamed Concrete in Construction*. London: Thomas Telford, 1005: 1-14.

Aldridge, D., Ansell, T., (2001), Foamed Concrete: Production and Equipment Design, Properties, Applications and Potential. *Proceedings of One Day Seminar on Foamed Concrete: Properties, Applications and Latest Technology Developments*. Loughborough University.

American Society for Testing and Materials (2005). Standard Specification for Portland Cement (ASTM C150 – 05)

American Society for Testing and Materials (2008). Standard Specification for Flow Table for Use in Tests of Hydraulic Cement (ASTM C230-08)

American Society for Testing and Materials (2002). Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Center-Point Loading) (ASTM C292-02)

American Society for Testing and Materials (2002). Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression (ASTM C469-02)

American Society for Testing and Materials (2004). Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens (ASTM C496-04)

American Society for Testing and Materials (2008). Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete (ASTM C618 – 08a)

American Society for Testing and Materials (2001). Standard Test Method for Time of Flow of Fiber-Reinforced Concrete Through Inverted Slump Cone (ASTM C995-01)

American Society for Testing and Materials (2007). Standard Test Method for Flow of Hydraulic Cement Mortar (ASTM C1437-07)

American Society for Testing and Materials (2010). Standard Guide for Examination of Hardened Concrete Using Scanning Electron Microscopy (ASTM C1723-10)

Awal, A.S.M. and Hussin, M.W. (1997). Some Aspects of Durability Performances of Concrete Incorporating Palm Oil Fuel Ash, *Proceedings of 5th International Conference on Structural Failure, Durability and Retrofitting*, Singapore, 210 – 217

Awal, A.S.M. (1998). A Study of Strength and Durability Performances of Concrete Containing Palm Oil Fuel Ash, PhD Thesis, Universiti Teknologi Malaysia.

British Standards Institution (1970). Testing hardened concrete–Part 5: Method of Testing Hardened Concrete for Other Than Strength. London: BS 1885-5:1970

British Standards Institution (2002). Testing hardened concrete–Part 3: Compressive strength of test specimens. London: BS EN 12390-3:2002

British Standards Institution (2001). Thermal Performance of Building Materials and Products. Determination of Thermal Resistance by Means of Guarded Hot Plate and Heat Flow Meter Methods. Dry and Moist Products of Medium and Low Thermal Resistance. London: BS EN 12664:2001

Byun, K.J., Song, H.W., Park, S.S. (1998). Development of Structural Lightweight Foamed Concrete Using Polymer Foam Agent. *ICPIC-98: 9.*

Eldagal, O.E.A. (2008). Study On The Behaviour of High Strength Palm Oil Fuel Ash (POFA) Concrete, Master Thesis, Universiti Teknologi Malaysia.

Hamidah, M.S, Azmi, I., Ruslan, M.R.A., Kartini, K., Fahil, N.M. (2005). Optimisation of Foamed Concrete Mix of Different Sand – Cement Ratio and Curing Conditions. *Use of Foamed Concrete in Construction*. London: Thomas.

Jones, M.R., McCarthy, A., Dhir, R.K. (2005). Recycled and Secondary Aggregate in Foamed Concrete. *WRAP Research Report, The Waste and Resources Action Programme*. Banbury, Oxon.

Karim, M. R., Zain, M. F. M., Jamil, M., Islam, M. N. (2011). Strength of Concrete as Influenced by Palm Oil Fuel Ash. *Australian Journal of Basic and Applied Sciences*, 5(5): 990 – 997.

Kearsley, E.P. (1996). The Use of Foamed Concrete for Affordable Development in Third World Countries. *Appropriate Concrete Technology*. London: E&FN Spon. 233-234.

Kim, H.K., Jeon, J.H., Lee, H.K (2011). Workability, and Mechanical, Acoustic and Thermal Properties of Lightweight Aggregate Concrete with A High Volume of Entrained Air. *Construction and Building Material*, 29: 193-200.

Koudriashoff, I.T., (1942), Manufacture of Reinforced Foam Concrete Roof Slabs. *J Am Concrete Institution*. 21(1): 37-48

Mehta, P. K., (1977), Properties of blended cements made from rice-husk ash. *ACI Journal*, 74: 440-442.

Malaysia Palm Oil Board. (2010). Overview of the Malaysian Oil Palm Industry 2010. Kajang.

Neville, A. M. (2010). *Properties of Concrete* (4th ed.). London: Pearson, 10 – 17, 65 – 71, 83 – 86, 598-599, 688.

Parra, C., Valcuende, M., and Gomez, F. (2011) Splitting tensile and modulus of elasticity of self-compacting concrete. *Construction and Building Materials*. 25: 201-207.

Ramamurthy, K., Kunhanandan Nambiar, E.K., Indu Siva Ranjani, G. (2009). A Classification of Studies on Properties of Foam Concrete. *Cement & Concrete Composite*, 31: 388-396.

Sata, V., Jaturapitakkul, C., and Chaiyanunt, R. (2010). Compressive Strength and Heat Evolution of Concretes Containing Palm Oil Fuel Ash. *Journal of Materials in Civil Engineering*, 22(10): 1033-1038.

Schnider, U. (1982). Behavior of Concrete at High Temperature. Deutscher Aussehuss fur Stahlbeton, Heft 337, Berlin.

Steiger, R.W., Hurd, M.K. (1978). Lightweight Insulating Concrete for Floors and Roof Decks. *Concrete Construction.* 23(7): 411-422.

Tangchirapat, W., Saeting, T., Jaturapitakkul, C., Kiattikomol, K., and Siripanichgorn, A. (2007). Use of waste ash from palm oil industry in concrete, *Waste Management*, 27: 81 – 88.

Tangchirapat, W., Jaturapitakkul, C., and Chindaprasirt, P. (2009). Use of Palm Oil Fuel Ash as a Supplementary Cementitous Material for Producing High-strength Concrete. *Construction and Building Materials*, 23(7): 2641-2646.

Udoeyo, F. F., Dashibil, P. U. (2002). Sawdust ash as concrete material. *Journal of Materials in Civil Engineering*, 173 – 176.

Valore, R.C. (1954). Cellular Concrete Part 1: Composisiton and Method of Production, *ACI Journal*, 50: 773-796.

APPENDICES

APPENDIX A: Compressive Strength of Various Types LFC Specimens

Age (days)	Mix	Dry Bulk Density (kg/m^3)	Compressive Strength (MPa)	Performance Index	Consistency
7	LFC-CM	1284	3.49	2.72	0.987
	LFC-PF10	1297	3.48	2.68	0.994
	LFC-PF20	1319	4.29	3.25	1.019
28	LFC-CM	1294	5.23	4.04	1.000
	LFC-PF10	1295	5.62	4.34	0.996
	LFC-PF20	1289	5.31	4.13	0.992
56	LFC-CM	1316	5.82	4.42	1.013
	LFC-PF10	1276	6.78	5.31	0.981
	LFC-PF20	1318	6.12	4.64	1.014
90	LFC-CM	1310	6.50	4.96	1.008
	LFC-PF10	1287	7.17	5.58	0.990
	LFC-PF20	1297	7.06	5.45	0.998

APPENDIX B: Splitting Tensile and Flexural Strengths of Various Types of LFC Specimens

Age (days)	Mix	Splitting Tensile Strength (MPa)	Flexural Strength (MPa)	Vertical Deformation (mm)	Elongation	Flexural Strain
7	LFC-CM	0.509	0.937	0.185	0.002	1.314×10^{-6}
	LFC-PF10	0.619	1.501	0.333	0.005	4.219×10^{-6}
	LFC-PF20	0.600	1.441	0.294	0.004	3.291×10^{-6}
28	LFC-CM	0.762	1.357	0.240	0.003	2.187×10^{-6}
	LFC-PF10	0.826	1.834	0.343	0.005	4.463×10^{-6}
	LFC-PF20	0.783	1.801	0.314	0.004	3.745×10^{-6}
56	LFC-CM	0.765	1.593	0.267	0.003	2.702×10^{-6}
	LFC-PF10	0.942	1.942	0.361	0.006	4.931×10^{-6}
	LFC-PF20	0.851	1.925	0.345	0.005	4.517×10^{-6}
90	LFC-CM	0.836	1.753	0.282	0.003	2.999×10^{-6}
	LFC-PF10	0.994	2.189	0.387	0.007	5.764×10^{-6}
	LFC-PF20	0.908	2.162	0.372	0.006	5.254×10^{-6}

APPENDIX C: Thermal Conductivity Values of Various Types of LFC Specimens

Table C1: Thermal Conductivity Value of LFC-CM-0.56-1 (9.00kg) at 28 days of Age

Hours	Heat conduction, H = Q/t (W) or (J/s)	Avg Hot Plate Temp	AvgCold Plate Temp	Avg Temp Different, ΔT (K)	Area, A (m2)	Thickness, L (m)	Thermal Conductivity, K (W·K−1·m−1)
1	15.57	39.99	25.90	14.08	0.09	0.1	1.23
2	7.82	40.07	26.24	13.83	0.09	0.1	0.63
3	7.88	40.04	26.00	14.04	0.09	0.1	0.62
4	7.87	40.07	26.24	13.83	0.09	0.1	0.63
5	7.85	40.19	26.40	13.79	0.09	0.1	0.63
6	7.82	40.23	26.72	13.51	0.09	0.1	0.64
7	7.92	40.12	26.05	14.08	0.09	0.1	0.62
8	7.70	40.03	26.47	13.56	0.09	0.1	0.63
9	7.92	40.10	26.21	13.90	0.09	0.1	0.63
10	7.69	40.04	26.14	13.90	0.09	0.1	0.61
11	7.81	40.02	26.52	13.51	0.09	0.1	0.64
12	7.87	39.98	25.89	14.08	0.09	0.1	0.62
13	7.94	40.03	26.35	13.68	0.09	0.1	0.64
14	7.68	39.99	25.91	14.09	0.09	0.1	0.61
15	7.86	39.96	26.22	13.75	0.09	0.1	0.64
16	7.77	39.98	26.05	13.93	0.09	0.1	0.62
17	7.78	39.91	26.07	13.84	0.09	0.1	0.62
18	7.93	39.88	26.16	13.72	0.09	0.1	0.64
19	7.91	39.92	25.89	14.03	0.09	0.1	0.63
20	7.97	39.83	26.21	13.62	0.09	0.1	0.65
AVG	-	40.02	26.18	-	-	-	0.66

Table C2: Thermal Conductivity Value of LFC-CM-0.56-2 (10.00kg) at 28 days of Age

Hours	Heat conduction, H = Q/t (W) or (J/s)	Avg Hot Plate Temp	AvgCold Plate Temp	Avg Temp Different, ΔT (K)	Area, A (m2)	Thickness, L (m)	Thermal Conductivity, K (W·K−1·m−1)
1	7.80	40.60	26.00	14.60	0.09	0.1	0.59
2	7.93	40.33	26.09	14.24	0.09	0.1	0.62
3	7.81	40.34	25.63	14.72	0.09	0.1	0.59
4	7.79	40.27	26.07	14.20	0.09	0.1	0.61
5	7.84	40.26	25.72	14.53	0.09	0.1	0.60
6	7.77	40.22	25.77	14.45	0.09	0.1	0.60
7	8.04	40.25	26.01	14.23	0.09	0.1	0.63
8	7.82	40.14	25.61	14.53	0.09	0.1	0.60
9	7.81	40.15	26.01	14.14	0.09	0.1	0.61
10	7.65	40.14	25.61	14.53	0.09	0.1	0.59
11	7.87	40.06	25.75	14.31	0.09	0.1	0.61
12	11.74	40.10	25.77	14.33	0.09	0.1	0.91
13	7.67	40.15	25.58	14.57	0.09	0.1	0.59
14	8.02	40.12	25.90	14.21	0.09	0.1	0.63
15	7.74	40.09	25.45	14.63	0.09	0.1	0.59
16	7.91	40.09	25.96	14.13	0.09	0.1	0.62
17	7.88	40.09	25.29	14.80	0.09	0.1	0.59
18	7.81	40.11	25.77	14.35	0.09	0.1	0.60
19	7.76	40.10	25.96	14.13	0.09	0.1	0.61
20	7.61	40.21	25.69	14.52	0.09	0.1	0.58
AVG	-	40.19	25.78	-	-	-	0.62

Table C3: Thermal Conductivity Value of LFC-CM-0.56-3 (10.06kg) at 28 days of Age

Hours	Heat conduction, H = Q/t (W) or (J/s)	Avg Hot Plate Temp	AvgCold Plate Temp	Avg Temp Different, ΔT (K)	Area, A (m2)	Thickness, L (m)	Thermal Conductivity, K (W·K−1·m−1)
1	11.70	40.16	26.26	13.90	0.09	0.1	0.94
2	11.72	39.99	26.45	13.54	0.09	0.1	0.96
3	7.76	40.13	26.08	14.04	0.09	0.1	0.61
4	8.04	40.05	26.32	13.73	0.09	0.1	0.65
5	7.91	40.09	26.37	13.72	0.09	0.1	0.64
6	7.90	40.10	25.96	14.15	0.09	0.1	0.62
7	7.82	40.07	26.31	13.76	0.09	0.1	0.63
8	7.84	40.04	26.11	13.93	0.09	0.1	0.63
9	7.91	40.05	26.02	14.03	0.09	0.1	0.63
10	8.00	40.02	26.42	13.60	0.09	0.1	0.65
11	7.89	40.00	25.84	14.16	0.09	0.1	0.62
12	7.88	39.95	26.36	13.58	0.09	0.1	0.64
13	7.75	39.95	25.83	14.12	0.09	0.1	0.61
14	7.94	39.93	26.21	13.72	0.09	0.1	0.64
15	7.80	39.90	25.94	13.96	0.09	0.1	0.62
16	7.82	39.90	26.10	13.80	0.09	0.1	0.63
17	11.58	39.95	26.10	13.85	0.09	0.1	0.93
18	7.80	39.94	26.01	13.93	0.09	0.1	0.62
19	7.76	39.95	26.27	13.68	0.09	0.1	0.63
20	7.86	39.94	25.93	14.00	0.09	0.1	0.62
AVG	-	40.00	26.14	-	-	-	0.68

Table C4: Thermal Conductivity Value of LFC-PF10-0.54-1 (10.60kg) at 28 days of Age

Hours	Heat conduction, H = Q/t (W) or (J/s)	Avg Hot Plate Temp	AvgCold Plate Temp	Avg Temp Different, ΔT (K)	Area, A (m2)	Thickness, L (m)	Thermal Conductivity, K (W·K−1·m−1)
1	15.87	39.86	26.09	13.77	0.09	0.1	1.28
2	7.88	40.03	25.78	14.25	0.09	0.1	0.61
3	11.67	39.93	25.95	13.98	0.09	0.1	0.93
4	7.68	40.12	26.16	13.96	0.09	0.1	0.61
5	7.76	40.12	26.41	13.70	0.09	0.1	0.63
6	7.83	40.10	26.13	13.97	0.09	0.1	0.62
7	7.89	40.16	26.09	14.07	0.09	0.1	0.62
8	11.83	40.12	26.39	13.73	0.09	0.1	0.96
9	7.99	40.21	25.97	14.24	0.09	0.1	0.62
10	7.80	40.13	26.06	14.07	0.09	0.1	0.62
11	7.98	40.08	26.24	13.85	0.09	0.1	0.64
12	8.02	40.07	25.75	14.33	0.09	0.1	0.62
13	7.80	40.01	26.24	13.77	0.09	0.1	0.63
14	7.98	39.94	25.78	14.15	0.09	0.1	0.63
15	11.98	40.11	25.94	14.17	0.09	0.1	0.94
16	8.06	40.04	26.00	14.04	0.09	0.1	0.64
17	7.92	40.03	25.79	14.23	0.09	0.1	0.62
18	7.84	39.98	26.18	13.80	0.09	0.1	0.63
19	11.93	39.90	25.64	14.26	0.09	0.1	0.93
20	7.89	40.10	26.29	13.81	0.09	0.1	0.63
AVG	-	40.05	26.04	-	-	-	0.72

Table C5: Thermal Conductivity Value of LFC-PF10-0.54-2 (10.85kg) at 28 days of Age

Hours	Heat conduction, H = Q/t (W) or (J/s)	Avg Hot Plate Temp	AvgCold Plate Temp	Avg Temp Different, ΔT (K)	Area, A (m2)	Thickness, L (m)	Thermal Conductivity, K (W·K−1·m−1)
1	15.52	40.26	25.51	14.75	0.09	0.1	1.17
2	11.68	40.22	25.97	14.25	0.09	0.1	0.91
3	7.85	40.17	26.25	13.92	0.09	0.1	0.63
4	11.80	40.34	26.26	14.08	0.09	0.1	0.93
5	7.81	40.37	26.02	14.35	0.09	0.1	0.60
6	7.88	40.38	26.07	14.31	0.09	0.1	0.61
7	11.66	40.57	26.38	14.19	0.09	0.1	0.91
8	7.81	40.47	26.18	14.29	0.09	0.1	0.61
9	7.81	40.44	26.05	14.39	0.09	0.1	0.60
10	10.48	40.39	26.33	14.07	0.09	0.1	0.83
11	9.02	40.56	26.27	14.29	0.09	0.1	0.70
12	7.73	40.45	26.01	14.43	0.09	0.1	0.59
13	7.82	40.35	26.26	14.09	0.09	0.1	0.62
14	11.63	40.34	26.12	14.22	0.09	0.1	0.91
15	7.93	40.51	25.93	14.59	0.09	0.1	0.60
16	7.78	40.35	26.35	14.01	0.09	0.1	0.62
17	7.84	40.25	25.89	14.36	0.09	0.1	0.61
18	11.93	40.41	25.99	14.42	0.09	0.1	0.92
19	7.84	40.38	26.21	14.16	0.09	0.1	0.61
20	7.87	40.26	25.72	14.53	0.09	0.1	0.60
AVG	-	40.37	26.09	-	-	-	0.73

Table C6: Thermal Conductivity Value of LFC-PF10-0.54-3 (10.88kg) at 28 days of Age

Hours	Heat conduction, H = Q/t (W) or (J/s)	Avg Hot Plate Temp	AvgCold Plate Temp	Avg Temp Different, ΔT (K)	Area, A (m2)	Thickness, L (m)	Thermal Conductivity, K (W·K−1·m−1)
1	15.48	40.28	25.63	14.65	0.09	0.1	1.17
2	11.68	40.15	26.09	14.06	0.09	0.1	0.92
3	7.93	40.09	25.57	14.52	0.09	0.1	0.61
4	11.78	40.14	25.91	14.23	0.09	0.1	0.92
5	7.83	40.03	25.82	14.21	0.09	0.1	0.61
6	7.88	39.94	25.70	14.24	0.09	0.1	0.61
7	11.58	40.16	26.18	13.98	0.09	0.1	0.92
8	7.96	40.02	25.69	14.33	0.09	0.1	0.62
9	11.84	40.00	26.11	13.90	0.09	0.1	0.95
10	7.92	40.15	25.72	14.43	0.09	0.1	0.61
11	7.87	40.01	25.97	14.05	0.09	0.1	0.62
12	11.74	40.03	25.91	14.11	0.09	0.1	0.92
13	7.97	40.12	25.79	14.32	0.09	0.1	0.62
14	7.94	39.94	25.98	13.96	0.09	0.1	0.63
15	11.89	40.11	25.69	14.42	0.09	0.1	0.92
16	8.01	40.00	26.02	13.99	0.09	0.1	0.64
17	11.91	39.89	25.66	14.23	0.09	0.1	0.93
18	7.94	40.11	26.15	13.96	0.09	0.1	0.63
19	8.08	39.94	25.50	14.44	0.09	0.1	0.62
20	11.76	40.07	26.06	14.00	0.09	0.1	0.93
AVG	-	40.06	25.86	-	-	-	0.77

Table C7: Thermal Conductivity Value of LFC-PF20-0.56-1 (10.40kg) at 28 days of Age

Hours	Heat conduction, H = Q/t (W) or (J/s)	Avg Hot Plate Temp	AvgCold Plate Temp	Avg Temp Different, ΔT (K)	Area, A (m2)	Thickness, L (m)	Thermal Conductivity, K (W·K−1·m−1)
1	7.88	40.10	24.18	15.93	0.09	0.1	0.55
2	7.86	40.08	25.51	14.58	0.09	0.1	0.60
3	7.79	40.16	26.69	13.48	0.09	0.1	0.64
4	7.82	40.20	26.29	13.91	0.09	0.1	0.62
5	7.83	40.21	26.46	13.75	0.09	0.1	0.63
6	7.84	40.19	26.85	13.33	0.09	0.1	0.65
7	7.96	40.21	26.56	13.65	0.09	0.1	0.65
8	7.83	40.21	26.46	13.75	0.09	0.1	0.63
9	7.77	40.13	26.85	13.28	0.09	0.1	0.65
10	7.89	40.12	26.05	14.07	0.09	0.1	0.62
11	7.94	40.13	26.50	13.63	0.09	0.1	0.65
12	7.61	40.11	26.23	13.88	0.09	0.1	0.61
13	7.94	40.07	26.29	13.77	0.09	0.1	0.64
14	7.77	40.07	26.46	13.62	0.09	0.1	0.63
15	8.02	40.08	26.01	14.07	0.09	0.1	0.63
16	7.70	40.06	26.56	13.50	0.09	0.1	0.63
17	8.04	40.06	25.89	14.16	0.09	0.1	0.63
18	7.79	40.05	26.54	13.51	0.09	0.1	0.64
19	7.73	39.99	25.89	14.11	0.09	0.1	0.61
20	7.88	39.97	26.42	13.55	0.09	0.1	0.65
AVG	-	40.11	26.23	-	-	-	0.63

Table C8: Thermal Conductivity Value of LFC-PF20-0.56-2 (10.90kg) at 28 days of Age

Hours	Heat conduction, H = Q/t (W) or (J/s)	Avg Hot Plate Temp	AvgCold Plate Temp	Avg Temp Different, ΔT (K)	Area, A (m2)	Thickness, L (m)	Thermal Conductivity, K (W·K−1·m−1)
1	11.80	40.02	25.79	14.23	0.09	0.1	0.92
2	11.96	40.20	25.80	14.40	0.09	0.1	0.92
3	7.93	40.15	26.06	14.09	0.09	0.1	0.63
4	11.78	40.21	26.13	14.08	0.09	0.1	0.93
5	7.99	40.35	26.04	14.31	0.09	0.1	0.62
6	7.92	40.40	26.13	14.27	0.09	0.1	0.62
7	7.89	40.30	26.32	13.98	0.09	0.1	0.63
8	7.92	40.32	26.13	14.18	0.09	0.1	0.62
9	7.83	40.25	26.00	14.25	0.09	0.1	0.61
10	7.83	40.27	26.21	14.06	0.09	0.1	0.62
11	7.83	40.26	25.99	14.27	0.09	0.1	0.61
12	7.90	40.25	25.97	14.28	0.09	0.1	0.61
13	7.76	40.20	26.29	13.91	0.09	0.1	0.62
14	11.87	40.27	25.77	14.50	0.09	0.1	0.91
15	7.87	40.29	26.03	14.26	0.09	0.1	0.61
16	7.64	40.29	26.16	14.13	0.09	0.1	0.60
17	7.94	40.26	25.78	14.48	0.09	0.1	0.61
18	7.85	40.22	26.23	13.99	0.09	0.1	0.62
19	7.78	40.20	25.73	14.47	0.09	0.1	0.60
20	7.88	40.11	26.01	14.10	0.09	0.1	0.62
AVG	-	40.24	26.03	-	-	-	0.68

Table C9: Thermal Conductivity Value of LFC-PF20-0.56-3 (10.77kg) at 28 days of Age

Hours	Heat conduction, H = Q/t (W) or (J/s)	Avg Hot Plate Temp	AvgCold Plate Temp	Avg Temp Different, ΔT (K)	Area, A (m2)	Thickness, L (m)	Thermal Conductivity, K (W·K−1·m−1)
1	11.86	40.01	25.77	14.24	0.09	0.1	0.93
2	11.63	39.99	25.93	14.06	0.09	0.1	0.92
3	7.89	40.03	26.19	13.84	0.09	0.1	0.63
4	7.90	39.97	25.83	14.15	0.09	0.1	0.62
5	11.86	40.07	26.24	13.83	0.09	0.1	0.95
6	7.79	40.15	25.99	14.16	0.09	0.1	0.61
7	7.93	40.17	26.11	14.06	0.09	0.1	0.63
8	7.80	40.11	26.39	13.72	0.09	0.1	0.63
9	7.98	40.14	25.74	14.40	0.09	0.1	0.62
10	7.70	40.16	26.23	13.93	0.09	0.1	0.61
11	7.92	40.14	25.87	14.26	0.09	0.1	0.62
12	7.96	40.08	25.96	14.12	0.09	0.1	0.63
13	8.66	40.00	25.97	14.03	0.09	0.1	0.69
14	10.78	40.11	25.81	14.29	0.09	0.1	0.84
15	7.84	40.11	25.99	14.12	0.09	0.1	0.62
16	7.60	40.05	25.72	14.33	0.09	0.1	0.59
17	7.84	40.02	25.98	14.04	0.09	0.1	0.62
18	7.67	39.91	25.77	14.14	0.09	0.1	0.60
19	11.92	39.97	26.08	13.89	0.09	0.1	0.95
20	8.01	40.09	25.61	14.48	0.09	0.1	0.61
AVG	-	40.06	25.96	-	-	-	0.70

APPENDIX D: Microstructural Analysis

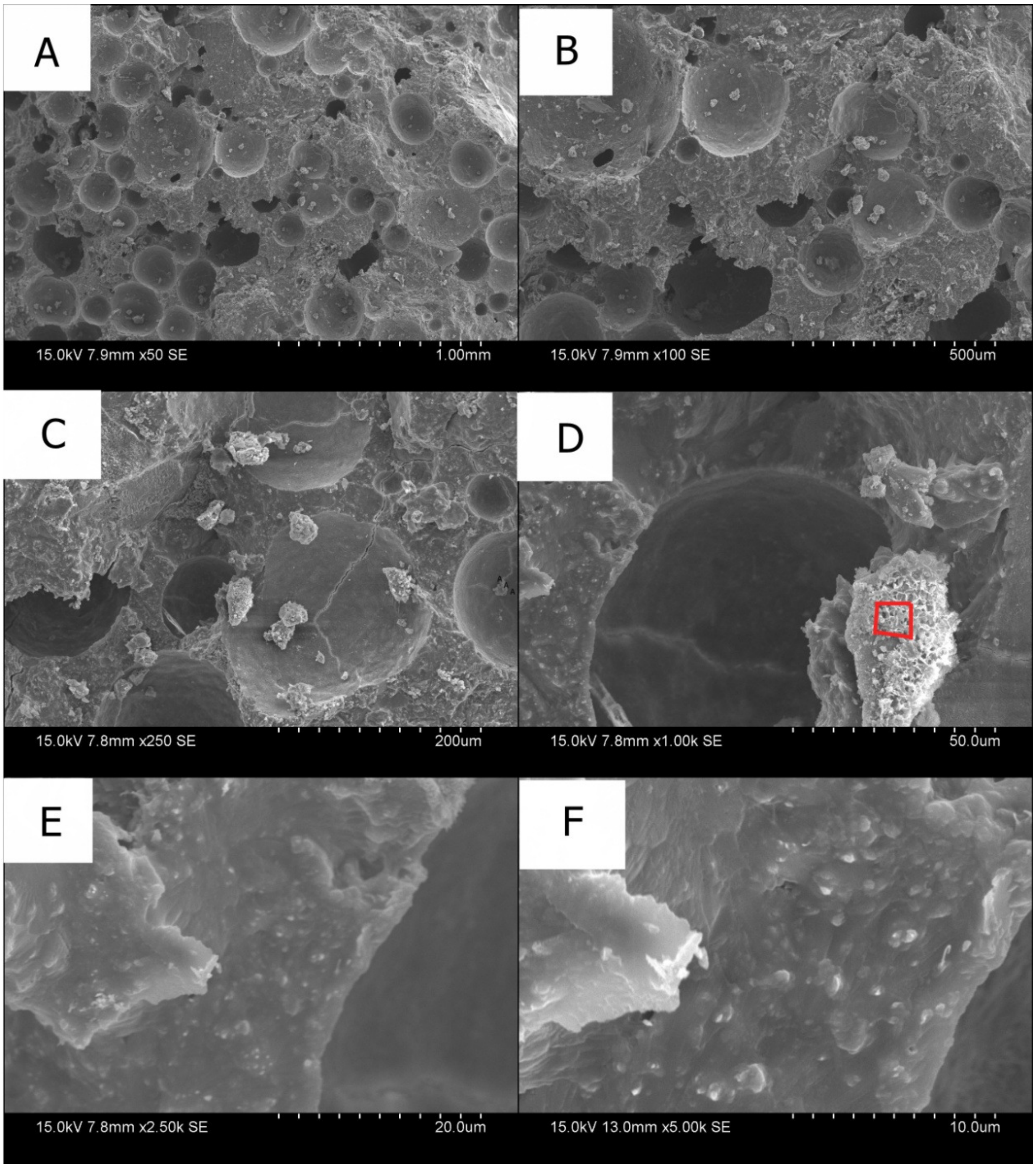

Figure D1: Microstructural Images of LFC-PF10 at 90 days of age with: (a) 50x, (b) 100x, (c) 250x, (d) 1000x, (e) 2500x, (f) 5000x of magnification

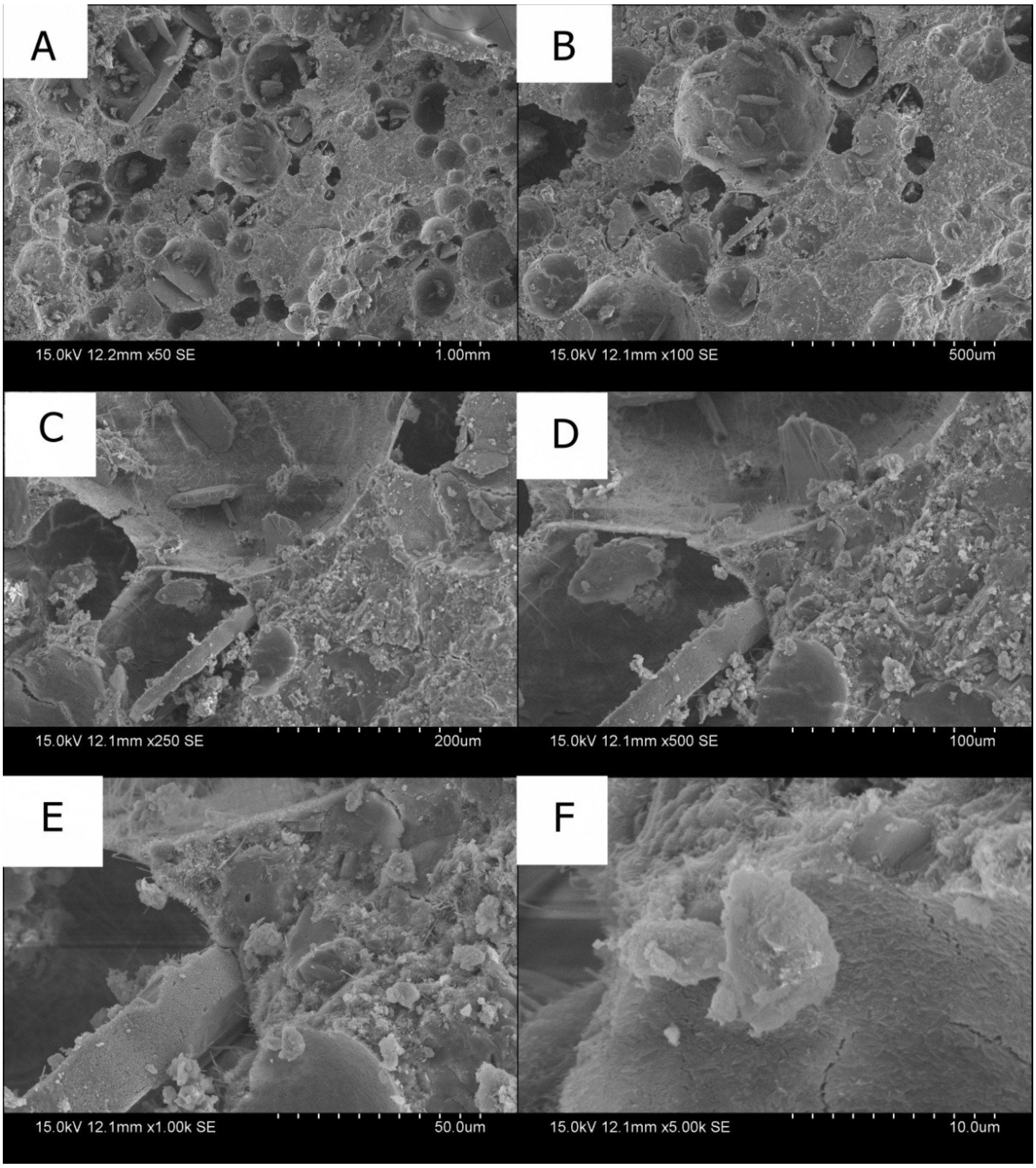

Figure D2: Microstructural Images of LFC-PF20 at 90 days of age with: (a) 50x, (b) 100x, (c) 250x, (d) 500x, (e) 1000x, (f) 5000x of magnification