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

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

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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.

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APPROVAL FOR SUBMISSION

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ABSTRACT

Malaysia is one of the main crude palm oil producer and exporter in the world. Meanwhile, million tonnes of agro wastes such as palm oil fuel ash (POFA) is being produced every year and it causes a problem in disposing POFA, a by-product of palm oil mill. However, POFA has the high potential to be used as recycle construction materials in production of lightweight foamed concrete (LFC) as it contains high content of silica which possesses pozzolanic behaviour. For strength activity index of POFA, it was observed that the specimen’s strength for incorporation of 20% POFA into a cement mortar as a part of binder has achieved and complied as Class F pozzolan in accordance with Specification C618. The main objective 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, flexural and splitting tensile strengths, Poisson’s ratio and compressive toughness. In this study, three types of foamed concrete were prepared, namely i) LFC with 100 % sand as filler as control mix (LFC-CM), ii) LFC with 25% POFA replacement as part of filler (LFC-PF25) and iii) LFC with 50% POFA replacement as part of filler (LFC-PF50). All the specimens were cured in water before being tested. The results indicated that lightweight foamed concrete incorporated with 25% and 50% POFA as a part of filler has improved its compressive, flexural and splitting tensile strengths, ductility as well as compressive toughness.

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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
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	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
OPC	Ordinary Portland Cement
POFA	Palm Oil Fuel Ash
LFC-CM	Control mix (LFC with 100 % sand as filler)
LFC-PF25	lightweight foamed concrete with 25% POFA replacement as part of filler
LFC-PF50	lightweight foamed concrete with 50% POFA replacement as part of filler
M-CM	Control mix (mortar cement paste with 100% cement as binder)
M-PF20	Mortar cement paste with 20% POFA replacement as part of binder
SEM	Scanning Electron Microscope
w/b	water-to-binder ratio

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Concrete is one of the composite construction material that composed primarily of aggregate, water and cement. It has been used widely in the field of construction for making various structures such as architectural structures, foundations, pavements, bridges and so forth. Therefore, the various concrete types available nowadays are attributed to the continuous research and development of concrete over the years to provide more alternative construction material for making construction structure. However, the popularly utilise of lightweight concrete, also known as aerated concrete in the European countries construction field due to its versatilities and lightness, which has brought a offer application of new alternative building material for the improvement of Malaysia building technology. The classification of concrete type is mainly depending on the concrete density. By using the lightweight concrete which possesses low density properties, it is capable of contributing towards the reduction of building dead load and resulting in more economic structural design (Short and Kinniburgh,1978; Narayanan and Ramamurthy, 2000b) as reduction of dead load may consequently the reduction of size of bearing load structure. The practical range of concrete density for lightweight concrete is between 300 kg/m^3 and 1850 kg/m^3 (Neville, 2006). Besides that, other than lightweight concrete possess the advantage of low density properties, it is also good in fire resistance and thermal insulation properties.

On the other hand, the continuous research of producing a new concrete material of palm oil fuel ash (POFA) was developed. Malaysia is a country with full of resources and it was being the largest producer and exporter of palm oil in the world, accounting for 52% of the total world oil and fats exports in year 2006 (Sumathi et al., 2008). Hence, it has led to higher volume of palm oil mill by-product such as POFA generated and being dumped in the landfill. In this scenario, it is predicted that larger amount of POFA will be discarded as environmental polluting waste in future. Therefore, POFA had been chosen in research as new concrete material to process this material for other applications in order to convert the environmentally polluting by-product problem into beneficial for the development of human civilization. In addition, success in producing palm oil fuel ash based aerated concrete not only could reduce the quantity of ashes as environmental waste but also introduce new agro based aerated concrete which is adequate for the use in tropical countries.

1.2 Background of Study

Malaysia, Indonesia and Thailand are the main palm oil producer and exporter in the world, which is a leading agricultural cash crop in these tropical countries. Malaysia is concentrating on bio-technology industry and its objective is to produce better and quality agriculture products. In addition, palm oil is listed as one of the main commodities to be exported internationally and consequently it will being generate bigger amount of palm oil fuel ash and being dumped in the landfill. Palm oil fuel ash (POFA) is an agro-waste or industry by-product resulting from the combustion of oil palm plant residue in palm oil industry. Approximately 5% of POFA is generated from the combustion of palm oil husks and kernel shell in steam boiler to generates electricity for use in palm oil mills (Tangchirapat et al., 2007).

Palm oil fuel ash (POFA) has the high potential to be used as recycle construction materials as pozzolans. It is because POFA possesses high contents of silica oxide, which met the pozzolanic properties criteria to react with calcium hydroxide (Ca(OH)) from the hydration process which is deteriorated to concrete and pozzolanic reaction produce more calcium silicate hydrate (C-S-H) which is a gel compound that contributes to the strength of the concrete and subsequently produce stronger and denser concrete as well as enhance the durability of the concrete. Therefore, POFA has potential to be used as cement replacement or as filler to produce strong and durable concrete (Awal and Hussin, 1997).

On the other hand, aerated concrete is also known as cellular concrete, cellular aerated concrete, gas concrete or foamed concrete. This type of concrete is essentially an aerated cement paste or mortar made by entraining air or gas in the form or small bubbles with diameter from 0.1 to 1.0mm into a plain cement paste or mortar mix during the mixing process (Tam et. al., 1987). The air bubbles are uniformly distributed in the plain cement paste and are retained in the matrix on setting and hardening to form a cellular structure (AAC 1.1, 1990). The classification of aerated concrete is based upon the method of formation (Narayanan & Ramamurthy, 2000b) and it can be, basically, divided into two types that are foamed concrete and gas concrete.

1.3 Objectives of Study

The objectives of this study are:

1. To produce lightweight foamed concrete with 1300 ±50 $kg/m^3$of density.
2. To obtain optimum w/c ratios for three types of LFC.
3. To study the effect of POFA on fresh properties in terms of workability and fresh density of concrete.
4. To study the effect of Palm Oil Fuel Ash (POFA) on engineering properties of lightweight foamed concrete in terms of compressive, flexural and splitting tensile strengths, Poisson’s ratio and compressive toughness.

1.4 Scopes of Study

The present research is to study the engineering properties of lightweight foamed concrete incorporated with palm oil fuel ash (POFA) in term of compressive, splitting tensile and flexural strength, Poisson's ratio, and strength activity index. On overall, this study has to produce a mix proportion for POFA cement based aerated concrete as well as producing a normal aerated concrete that was used as control subject with targeted density of 1300 kg/m^3 and 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 25 % POFA replacement as part of filler (LFC-PF25) and iii) LFC with 50 % POFA replacement as part of filler (LFC-PF20). During the laboratory work, flow table test were carried out before the plain mortar added with foam to measure the consistency of fresh concrete. Besides that, inverted slump test is also carried out to measure the workability of fresh concrete. However, in order to study the maximum compressive strength of foamed concrete produced, optimum w/c ratio must be determined through a trial mixes with various w/c ratio. In this study, the trial w/c ratio for respective mix ranging was started from 0.52 to 0.62 with increased by an interval of 0.02. The water curing method is used for further hydration process of concrete cubes. Then the water cured of concrete cubes for 7 days, 14 days and 28 days were tested by compressive strength test in order to calculate the performance index of POFA based aerated concrete and to obtain the optimum w/c ratio for each mix proportion respectively.

After obtained optimum w/c ratio, new set of specimens including cubes, cylinders and prisms were casted with optimum w/c ratio and cured in water for 7 days, 28 days, 56 days and 90 days. The specimens were then oven dried for a day before and tested in term of compressive strength, splitting tensile strength and flexural strength respectively. Besides that, another set of cube specimens was water cured for 7 and 28 days and oven dried for a day before undergoing Strength Activity Index test. Moreover, the cylinders were water cured for 28 days before undergoing testing by Poisson's ratio test. Lastly, the crushed pieces of foamed concrete at 90 days were used for microstructure studies by using Scanning Electron Microscope (SEM). The engineering properties of LFC-LFC-CM, LFC-PF25 and LFC-PF50 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 terms of compressive strength, splitting tensile strength, flexural strength, Poisson's ratio, compressive toughness and strength activity index.

1.6 Layout of Report

This report consists of 6 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, mix proportion of trial mixes and mixing procedure are discussed in this chapter. In addition, 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 for LFC-CM, LFC-PF25 and LFC-PF50 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 terms of compressive strength, splitting tensile strength, flexural strength, strength activity index, Poisson's ratio and compressive 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 categorized as one type of lightweight concrete. It is because, foamed concrete is containing no large aggregates, only fine sand and with extremely light weight materials containing cement, water and foam. In other words, it is one type of lightweight material consisting of Portland cement paste or cement filler matrix, with a homogeneous void or pore structure created by air-voids, which are entrapped in mortar or cement paste by suitable foaming agent (Ramamurthy et al., 2009). However, the pore-formation method in aerated concrete can affect the microstructure as well as its properties. The material structure of aerated concrete is characterised by its solid microporous matrix and macropores (Narayanan and Ramamurthy, 2000). Macropores is defined as pores with a diameter of more than 60 μm (Petrov and Schlegel, 1994). The formation of macropores is due to the expansion of the mass caused by aeration. Besides, the micropores also appear in the walls between the macropores (Alexanderson, 1979).

The properties of foamed concrete are low self-weight, high workability, consists of low compressive strength, minimum consumption of aggregate and good thermal insulation properties. Therefore, lightweight foamed concrete is famous to be used due to its lightness and versatility. By using the appropriate composition of foam, the range of densities between 400kg/m^3 to 1600kg/m^3 of foamed concrete can be achieved for application to structural, partition, insulation and filling grades (Ramamurthy et al., 2009).

On the other hand, palm oil fuel ash (POFA) is one of the potential recycles by-product from palm oil industry which possesses high content of siliceous compositions and reacted as pozzolans in order to produce a stronger and denser concrete. Therefore, there are many researches and experimental works were conducted for the use of variety of agro waste which contains high silica content in amorphous form as constituent in concrete and can be used as pozzolans (Tangchirapat et al., 2007). Other than POFA, slag (Hogan el al., 1981; Arreshvhina, 2002), fly ash (Metha, 1985; Chindaprasirt et al., 2004), rice-husk ash (Mehta, 1977) and sawdust ash (Udoeyo and Dashibil, 2002) also had been studied as a constituent in concrete to react as pozzolanic material.

Successful in production of POFA cement based aerated concrete not only can convert the environmentally polluting by-product problem into beneficial for the development of human civilization but it also enhance concrete properties in term of strength, thermal conductivity, fire resistance and so forth. Therefore, POFA has potential to be used as cement replacement or as filler to produce strong and durable concrete (Awal and Hussin, 1997).

2.2 Advantages of Lightweight Foamed Concrete

Lightweight foamed concrete is famous to be used nowadays because it possesses low density properties and consequently contribute towards the reduction of building dead load and resulting in more economic structural design in term of concrete cost due to reduction of size of bearing load structure, such as foundation, columns and thickness of walls. Moreover, it also possesses superior fire resistance and high workability. In addition, lightweight foamed concrete is also good in thermal insulation and acoustic insulation due to higher porous structure contained itself as the heat energy and sound wave are diffused much more slowly in medium of air compared to solid state (Kim et al., 2011). Besides, foam concrete can control the air humidity in a room by absorbing and releasing moisture during the day and night. Foam concrete also increases the construction speed several times compared to the normal concrete. On the other hand, foam concrete is also an eco-compatibility material as it does not produce any toxic substances. Last but not least, foam concrete is also a lot cheaper than the normal concrete in terms of transportation as well as reduction in manpower.

2.3 Disadvantages of Lightweight Foamed Concrete

Foamed concrete also carries a few disadvantages. First of all, it is very sensitive with water content in the mixtures. Besides, it is also very difficult to place and finish because of the porosity and angularity of the aggregate. In some mixes, the cement mortar may separate the aggregate and float towards the surface. In addition, the mixing time is longer than conventional concrete to assure proper mixing. One of the major disadvantages of foam concrete has been the inability to provide consistent compressive strengths and density throughout the entire area. (Neville, 1985)

2.4 Application of Lightweight Foamed Concrete

Foamed concrete can be used for a wide range of applications as insulation, infill and lightweight foundations. It is used in securing old mine-workings, shafts tunnels and other underground voids. Besides, it also can be used to fill redundant sewers, pipelines fuel-tanks, culverts and subways. Other than that, foam concrete is also used in rodent exclusion infill beneath railway station platforms, infill spandrel arches under bridges and viaducts, roof screeds and floor insulation, soil stabilization and replacement, harbour retaining wall backfill, airport aircraft arrestor beds, annulus fill of pipelines, tunnel-liner backfill, road foundations and many more. (Neville, 1985)

2.5 Compressive Strength

Compressive strength is the most important mechanical properties of every concrete including lightweight foamed concrete as it is playing a very important role in construction in order to sustain the load and transfer the entire load on top to the foundation and ground. The compressive strength decreases exponentially with a reduction in density of lightweight foamed concrete (Kearsley, 1996). Besides that, in general, there are also some factors will affect the strength of aerated concrete other than concrete's density, such as 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 (Valore, 1954). In addition, other factors such as the cement-sand and water-cement ratios, curing regime, type and particle size distribution of sand and type of foaming agent used also can affecting the compressive strength of lightweight concrete as well (Aldridge, 2005; Hamidah et al., 2005). On the other hand, compressive strength is inversely proportional to the void diameter, especially with a dry density foamed concrete between 500 and 1000 kg/m^3. The composition of the paste determines the compressive strength (Visagie and Kearsley, 2002) in densities higher than 1000 kg/m^3 because the air-void is far apart to have an effect on the compressive strength. On the other hand, compressive strength of lightweight foamed concrete is not affected by small changes in w/c ratio (Jones and McCarthy, 2006). Meanwhile, the increases in w/c ratio within the consistency and stability limit provide an increase in strength of foamed concrete (De Rose & Morris, 1999; Tam et al., 1987). The compressive strength of lightweight foamed concrete for various mixture composition and densities was summarized and reported in literature (Ramamurthy and Nambiar, 2009).

2.6 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).

2.7 Thermal Conductivity

Lightweight foamed concrete possesses good thermal insulation properties due to the air-void structure contained itself. 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. In addition, the range of thermal conductivity for dry densities value of 600-1600 kg/m^3 is between 0.1 and 0.7 W/mK, reducing with decreasing densities (Jones et al., 2005). Meanwhile, the thermal conductivity of lightweight foamed concrete is 5 to 30 % of those measured on normal weight concrete had been proved by Jones and McCarthy (2005).

2.8 Poisson's Ratio and Compressive Toughness

Poisson's ratio represents the ratio of the size change in the direction perpendicular to the applied force over the expanded length in the direction of the force. Poisson's ratio provides the essential metric by which to compare the performance of any material when strained elastically. Every materials has different Poisson's ratio as every material owns different capacity of distortion resistance under mechanical load. The numerical limits are set by 1/2 and -1, between which all stable isotropic materials are found. However, Poisson's ratio is intimately connected with the way structural elements are packed. For densest metal, the Poisson's ratio is greater than 0.5 due to the variety of atom sizes. For less densely packed like steel, Poisson's ratio is around 1/3. By contrast, the density of covalent solids is directly proportional to the Poisson's ratio. On the other hand, Poisson's ratio is inversely proportional to the connectivity of structures because the stiff arms in cross-linked structures against transverse contraction upon tensile loading. (Lakes, 2011)

Compressive toughness is the amount of energy per volume that a material can absorb before fracturing. There are two factors that affect the compressive toughness of a material, such as compressive strength and the ductility of the material. It is because a ductile material can absorb more energy than a brittle material as it can deform more under the same amount of mechanical forces. Therefore, a negative Poisson’s ratio can results enhanced in compressive toughness. (Michael, 2012)

2.9 Foam

According to Ramamurthy and Nambiar (2009), there are two different ways to produce foamed concrete in which it can produced by pre-foaming method or mixed foaming method. For pre-foaming method, base mix and stable preformed aqueous foam are produce individually and then the foam is added into the base mix and blended thoroughly. For mixed foaming method, the surface active agent is added and mixed into the base mix ingredient. Next, the foam is produced resulting the void structure develop in concrete during the mixing process (Byun et al., 1998). The foam produced must be stable and firm in order to resists the pressure of the mortar until the cement achieves its initial set and built up with a strong skeleton of concrete around the void filled with air (Koudriashoff, 1949). The pre-formed foam can be categorized as wet and dry foam. The wet foam is produced by spraying a solution of foaming agent over a fine mesh, has 2mm to5 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. this makes it easier application in base material required in producing a pump able foam concrete (Aldridge, 2005). There are some factors may affect the formation of stable foam concrete mix which are selection of foaming agent, material section and mixture design strategies, production of foam concrete, performance with respect to fresh and hardened state are of greater significance, method of foam preparation and addition for uniform air-voids distribution.

2.10 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).

2.10.1 Chemical Composition of Portland Cement

Generally, the chemical compositions of Portland cement are varying due to supply from different manufacturers. However, the main chemical compositions contains in OPC are limestone, alumina and silica because these chemical compositions are playing an important role in hydration process in order to form calcium silicate hydrate gel which contribute the main compressive strength on concrete. 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

2.10.2 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

2.11 Pozzolanic Material

ASTM C618 (2008) defines 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.

2.11.1 Pozzolanic Reaction

POFA contains 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).

$$2S + 3CH \rightarrow C_3S_2H_3 \quad (2.1)$$

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).

2.11.2 Origin of POFA

As discussed in previous chapter, Malaysia is being the largest palm oil producing and exporting country in the world. In 2011, the Malaysian Palm Oil Board (MPOB) predicted that the total oil palm planted area in Malaysia is 5 million hectares. Besides, the total amount of fresh fruit bunches processes are approximately 98.5 million tonnes and approximated 68.9 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, 2011). 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 3.5 million tonnes in Malaysia in 2011 (Tangchirapat et al., 2007).

Based on the MPOB annual report, it is clearly show that the amount of POFA produced had been increased compared to last year, which lead to increase in solid waste by-product were discarded as environmental polluting waste in future (Tangchirapat et al., 2007). However, POFA had been proved that can be recycled and reused as cement replacement material or as filler in concrete due to the pozzolanic properties it possesses (Tay, 1995; Hussin and Awal, 1997; Tangchirapat et al., 2007).

2.11.3 Chemical Properties of POFA

Generally, the chemical compositions of POFA are varying due to supply from different manufacturers. 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 classified 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).

2.11.4 Properties of Fineness of POFA on Concrete Strength

The strength of concrete and fineness of POFA has a correlation, such as the finer the POFA is used, the higher the concrete strength will developed. Therefore, for same replacement of POFA in concrete, finer POFA would lead to greater strength development than the coarser one (Awal, 1998). This is because finer particle of POFA possesses higher total surface area compared to the courser particle of POFA, and it had promoted and increased the chances of pozzolanic reaction occurred between the silica from POFA and calcium hydroxide generated from hydration process. Hence, more calcium silicate hydrate (C-S-H) gel was generated and increases the concrete strength.

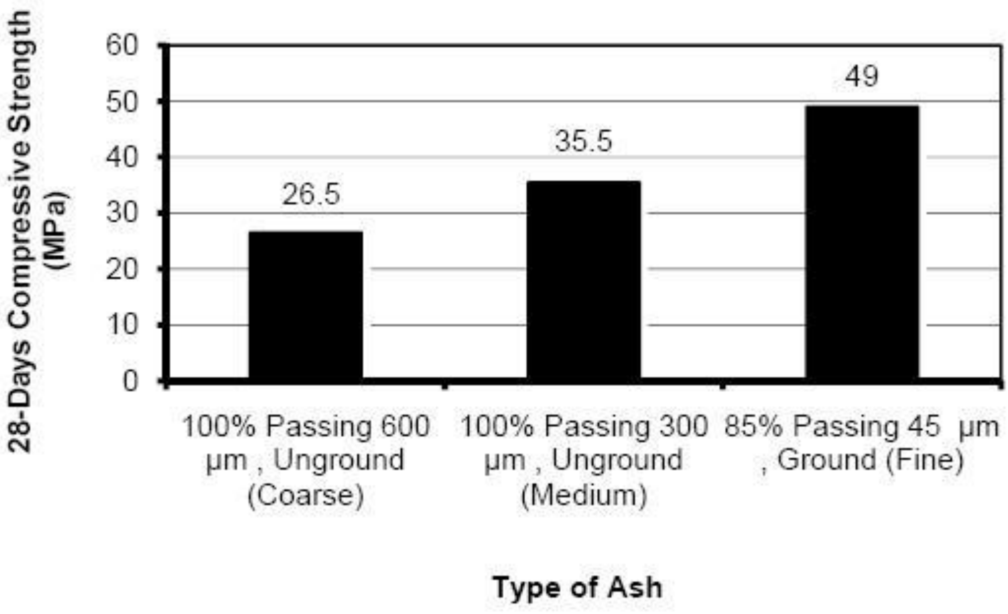

Figure 2.1: Effect of Fineness of Ash on Concrete Compressive Strength (Awal, 1998)

2.11.5 Strength Development of Normal Weight Concrete Incorporated with POFA

At early stage, concrete incorporated with POFA tend to have slow strength gained compared with OPC concrete. However, the compressive strength of concrete incorporated with POFA is found to be higher than of OPC concrete at later stage 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. Hence, the additional calcium silicate hydrate gel formed and it contribute more strength by improves the interfacial bonding between the aggregates and pastes at later ages (Karim, 2011). Consequently, the compressive strength of concrete incorporated POFA is improved.

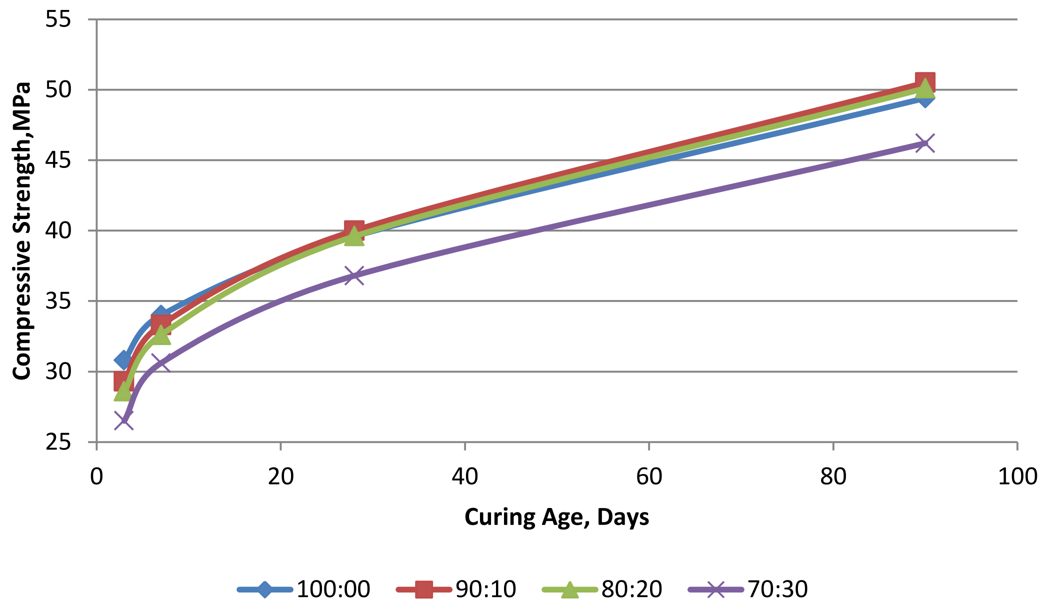

Figure 2.2: Compressive Strength for OPC : POFA Mixes (Sata, 2010)

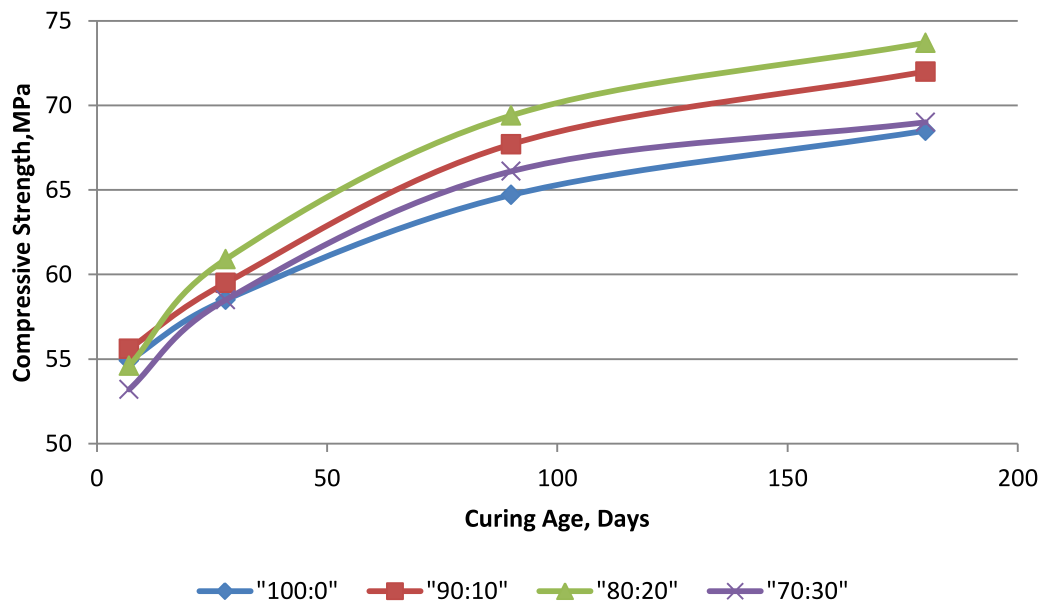

Figure 2.3: Compressive Strength for OPC : POFA Mixes (Tangchirapat et al., 2009)

2.12 Summary

Lightweight foamed concrete is categorized as one type of lightweight concrete as it is containing no large aggregates, only fine sand and with extremely light weight materials containing cement, water and incorporation of foam, where a homogeneous void or pore structure created by entraining the forming agent in a form of bubble in mortar or cement paste. Lightweight foamed concrete can be produced by either pre-foaming method or mixed foaming method.

Lightweight foamed concrete can be used to provide more economic structural design due to its low density properties and it may lead reduction of size of bearing load structure as well. The ease of handling the lightweight foamed concrete due to its high workability has save labour cost and speed up the construction process. Besides, lightweight foamed concrete is also good in thermal insulation and acoustical insulation due to its higher porous structure properties.

POFA is a by-product from palm oil industries which contains high amount of silicon dioxide in amorphous form. By incorporate of POFA with lightweight foamed concrete, it can react with calcium hydroxide generated from the hydration process to produce more calcium silicate hydrate, C-S-H gel compound and it contribute more strength to the concrete by improves the interfacial bonding between the aggregates and pastes at later ages. Consequently, the compressive strength of concrete incorporated POFA is improved.

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 Raw Materials

The specimen production for 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

The Ordinary Portland Cement (OPC) which is produced by YTL Cement Sdn. Bhd under the brand name of “ORANG KUAT” was used throughout the study. The OPC was sieved through 600µm sieve and was stored in an airtight container in order to maintain the quality of cement such as to prevent air moisture contact as hydrated cement particle would affect the formation of calcium silicate hydrate gel. According to ASTM C150 (2005), the OPC used throughout this research is complied with Type I Portland Cement and the details chemical composition of OPC is given in Table 3.1

3.2.2 Palm Oil Fuel Ash (POFA)

In this present study, POFA was obtained from Southern Edible Oil Industries (M) Sdn. Bhd. at Kapar, Selangor. The POFA is generated in the form of ash from the combustion of palm oil husks and kernel shell in steam boiler. The collected POFA was dried in an oven at temperature of 105 °C ± 5 °C for twenty four hours in order to remove the moisture content in it. Next, the dried POFA was sieved through a 600 μm sieve to remove bigger size particles and any other impurities. Only the fine ashes passing through 600 μm sieve were collected and stored in airtight container.

According to ASTM C618 (2008), the POFA is categorize as Class F Fly Ash based on its chemical composition. The chemical composition of POFA is stated in Table 3.1 and sieve analysis of POFA is illustrated in Figure 3.1. The fineness modulus for POFA is 2.64.

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

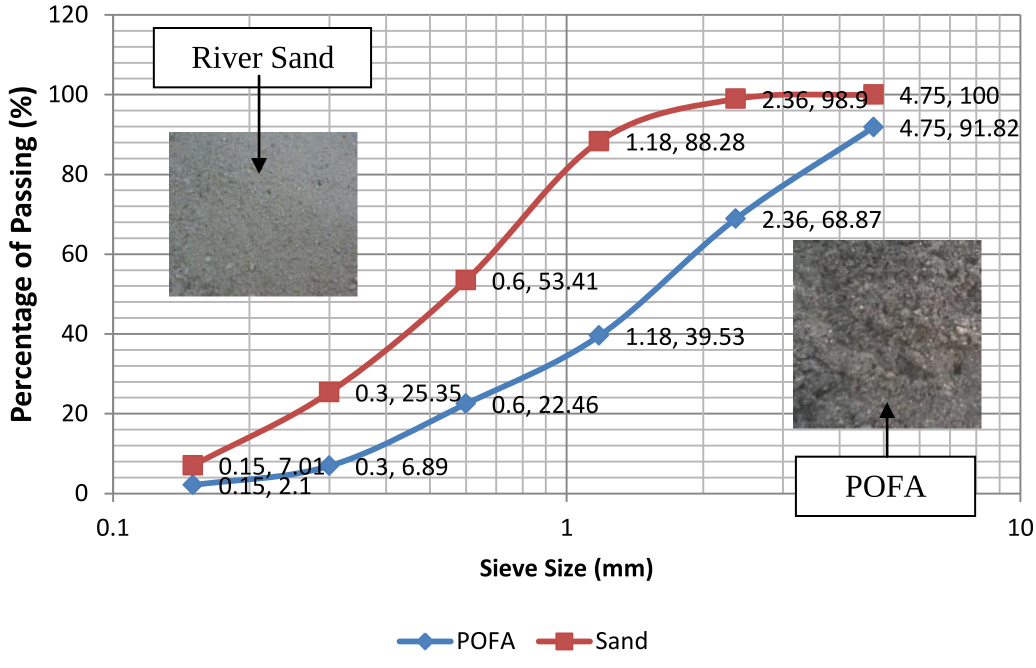

Figure 3.1: Sieve Analysis of Raw POFA and Sand

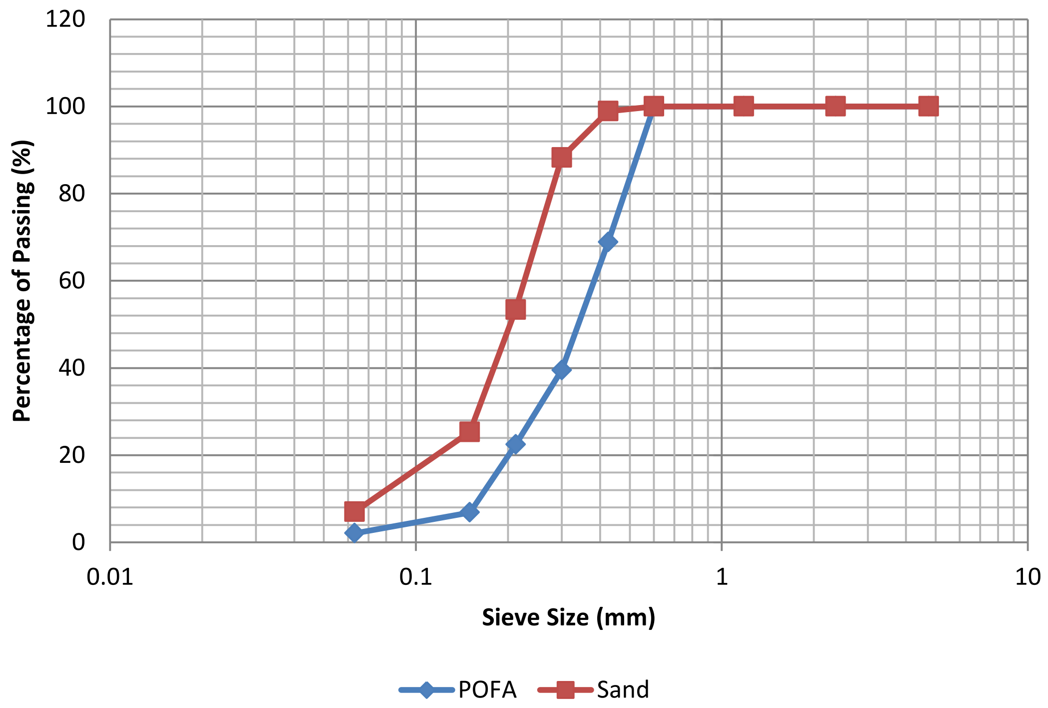

Figure 3.2: Sieve Analysis of Refined POFA and Sand

3.2.3 Sand

In this study, only fine sand was used in the production of POFA cement based aerated concrete. 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. Then, the dried sand was sieved through a 600 µm sieve before it stored in airtight container to prevent atmospheric humidity contact.

3.2.4 Water

In this study, tap water was used in the production of lightweight foamed concrete incorporated with POFA. The tap water used must not contain any impurities as the impurities may affect or harmful to the hydration process of cement and durability of concrete.

3.2.5 Foaming Agent

Foam is a form of stable bubbles, produced in foam generator by mixing foaming agent and water with a specific ratio in order to produce desired density of foam. In this study, the ratio of foaming agent to water is 1:30 by volume is used and the foam produced with density of 45 kg/m^3. Foaming agent is used by entraining the preformed stable foam into the fresh lightweight concrete in order to control the density of lightweight concrete and achieve desired density of lightweight concrete. In this study, the densities of specimens were controlled at 1300 ± 50 kg/m^3.

Figure 3.3: Foam Generator

3.3 Mix Proportions and Trial Mix

A trial and error process is commonly adopted to achieve foamed concrete with the desired properties (Nehdi et al., 2001). In this study, this method is adopted in term of w/c ratio in trial mixes in order to obtain the optimum mix proportion of the normal aerated concrete containing 100% of sand and lightweight foamed concrete incorporated with POFA. The optimum mix proportion was obtained based on density and strength of lightweight foamed concrete incorporated with POFA.

In this study, during trial mixing, three types of mix proportion were casted such as LFC with 100 % sand as filler (LFC-CM) which was used as control specimen, 25 % POFA replacement as part of filler (LFC-PF25) and 50 % POFA replacement as part of filler (LFC-PF50). 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.

3.4 Mixing Procedure

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

3.5 Curing Condition

Curing condition is very important in gaining the strength of lightweight foamed concrete as it provides good condition for hydration process of concrete specimens. In this study, water curing method was adopted and all specimens were cure in water curing after demould for 7, 28, 56 and 90 days until testing age, respectively. The temperature of water tank for curing of concrete is controlled in range of $25\ to\ 28^{o}C$.

Figure 3.4: Water Curing

3.6 Fresh Concrete Testing Method

3.6.1 Fresh Density Test (ASTM C796, 2004)

In this study, a 1 liter capacity container was tared to zero at an electronic weight machine. Next, it had been overfilled with fresh lightweight foamed concrete and slightly tapping at the sides of the container in order to compact in order to compact and allow consolidation of fresh lightweight foamed concrete. The excessive of lightweight foamed concrete was struck off and any lightweight foamed concrete found on container surface was wiped off. Lastly, the container was then weighted to obtain the fresh density of LFC.

3.6.2 Flow Table Test (ASTM C1437, 2007)

Flow table test was conducted by using a 2 inch tall conical brass mold and a flow table as complied with ASTM C1437 (2007). Mortar is placed and filled inside 2 inch conical brass mold. Next, the mold is removed and the mortar is being spread and vibrated by raising and dropping the flow table with 25 times in 15 seconds. Lastly, four angle of dimension of spread was measured and recorded.

Figure 3.5: Flow Table Test

3.6.3 Inverted Slump Test (ASTM C1611, 2005)

The inverted slump test was conducted by using a slump cone and flat base plate as complied with ASTM C1611 (2005). 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. The fresh lightweight foamed concrete was compacted by slightly vibrate the concrete to allow consolidation of fresh lightweight foamed concrete. Excessive fresh lightweight foamed concrete was struck off and the inverted slump cone was lifted to 1 ft height within 3 seconds. The four angle of dimension of spread was measured and recorded.

Figure 3.6: Inverted Slump Test

3.7 Hardened Concrete Testing

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

The compression test was conducted by using compressive strength machine. In this study, INSTRON 5582 Testing Machine was used to conduct the compression test on specimens. The test was performed in complied with BS EN 12390-3 (2002). Compression test was performing with an axial compressive load with a specified rate of loading was applied to 100mm cube until the failure of specimens occurred.

Before the test was being performed, the cubes were taken out from water tank and oven dried for 24 hours and the dimension of specimen was measured in order to obtain cross sectional area of specimen. Next, the specimen was placed at the center of the testing machine and it was subjected to an axial compressive load gradually with specified rate of loading of 0.02 mm/s until the specimen failed. The maximum load carried by the specimen was recorded and compressive strength was calculated based on Equation 3.1. Mean value of compressive strength obtained from three cubes was then taken as cube compressive strength for each lightweight foamed concrete mix.

$$Sc = \frac{P}{\text{width} \times \text{thickness}} \tag{3.1}$$

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: INSTRON 5582 Testing Machine

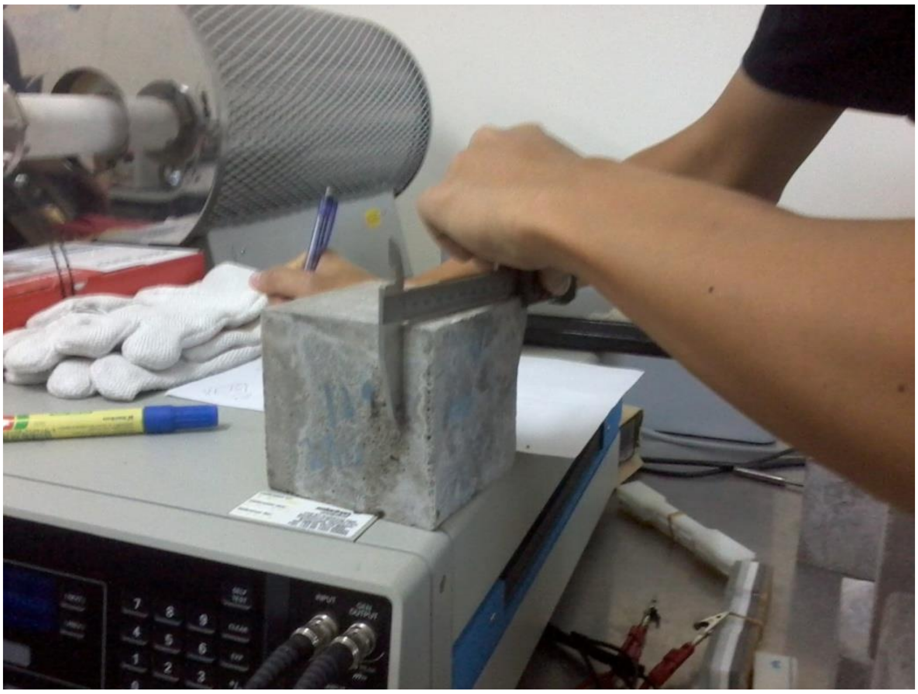

Figure 3.8: Specimen Dimension is being Measured and Recorded

3.7.2 Splitting Tensile Test (ASTM C496, 2004)

In this study, INSTRON 5582 Testing Machine was used to conduct the splitting tensile test on the cylinder specimens. The test was performed in accordance with ASTM C496 (2004). The test was performing with an axial load with a specified rate of loading was applied to cylinder with diameter of 100 mm and height of 200 mm until the failure of specimens occurred.

Before the test was being performed, the cylinders were taken out from water tank and air-dried for two hours. Next, the specimen was placed in a steel mould and a thin plywood bearing strip was placed at the bottom and top of the cylinder. After that, the cylinder specimen was subjected to an axial load gradually with a constant rate of loading of 1.2 mm/min until the specimen failed. The thin plywood bearing strips are used to distribute the load applied along the length of the cylinder. The maximum load sustained by the specimen was recorded and the splitting tensile strength was calculated based on Equation 3.2. Mean value of splitting tensile strength obtained from three cylinders was then taken as splitting tensile strength for each lightweight foamed concrete mix.

$$T = \frac{2P}{\pi l d} \tag{3.2}$$

Where,

T = splitting tensile strength, MPa

P = maximum load carried by specimen, N

l = length of specimen, mm

d = diameter of specimen, mm

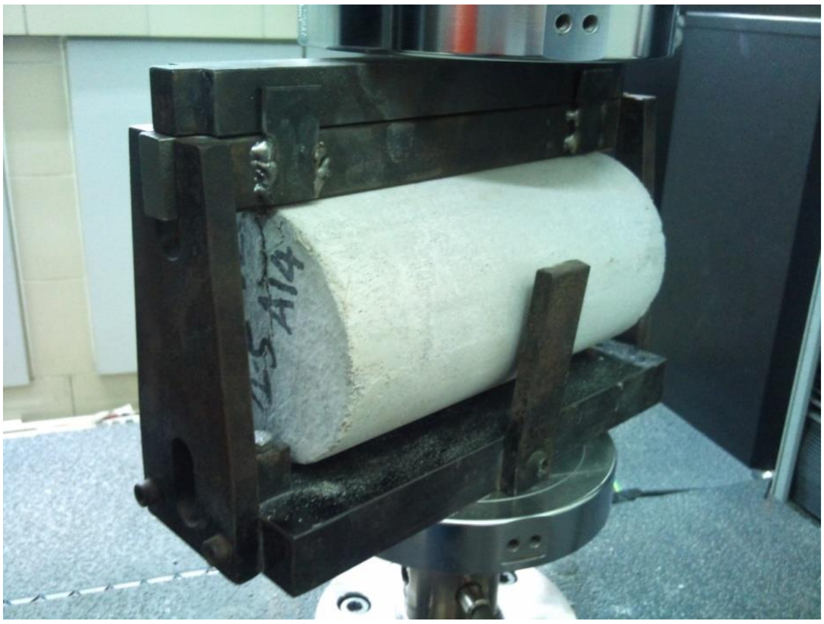

Figure 3.9: Splitting Tensile Strength Test of Lightweight Foamed Concrete

3.7.3 Flexural Strength Test (ASTM C293, 2002)

In this study, INSTRON 5582 Testing Machine was used to conduct the flexural strength test on the prism specimens. Flexural test was performed in accordance with ASTM C293 (2002). The test was performing with 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 of specimens occurred.

Before the test was being performed, the prisms were taken out from water tank and air-dried for two hours. Next, an offset of 10 mm from both sides of prism was marked and the prism was placed on the support block. After that, the specimen was subjected to a center-point load gradually with constant rate of loading of 0.1 mm/min until the specimen failed. The maximum load sustained by the specimen was recorded and flexural strength was calculated based on Equation 3.3. Mean value of flexural strength obtained from three prisms was then taken as flexural strength for each lightweight foamed concrete mix.

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

Where,

R = flexural strength, MPa

P = maximum load carried by specimen, N

l = length of specimen, mm

b = width of specimen, mm

d = thickness of specimen, mm

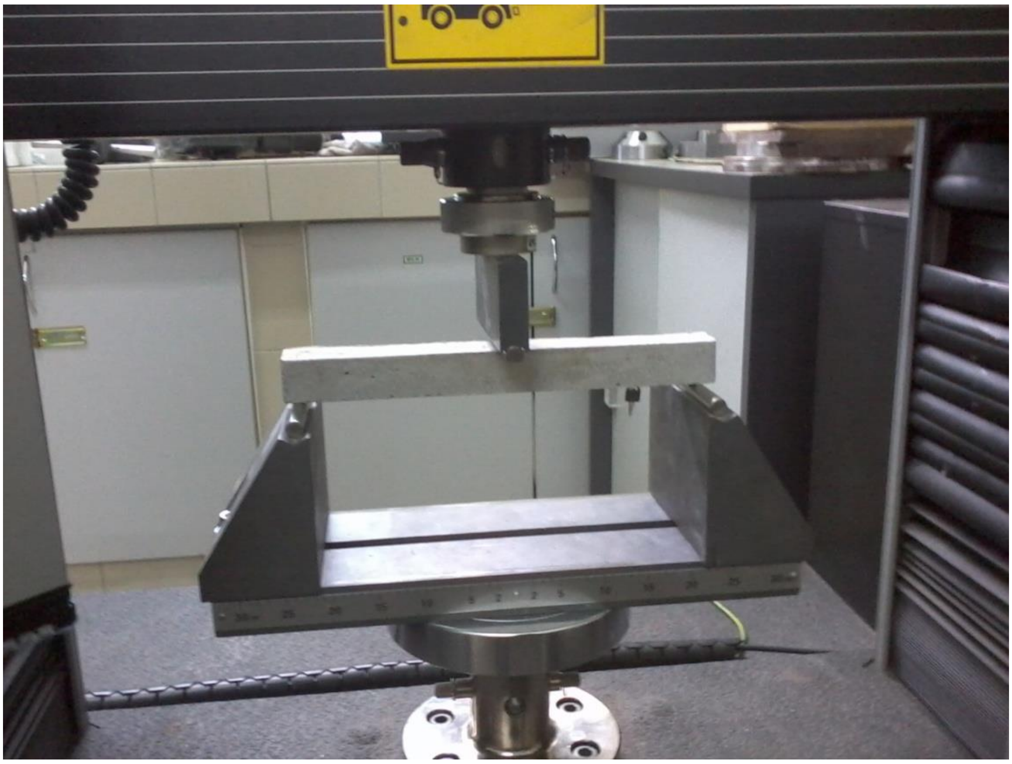

Figure 3.10: Flexural Strength Test of Lightweight Foamed Concrete

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

In this study, INSTRON 5582 Testing Machine was used to conduct the Poisson’s ratio test on the cylinder. Poisson’s ratio test was performed in accordance with ASTM C469 (2002). The test was performing with 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 of specimens occurred.

Before the test was being performed, the cylinders were taken out from water tank and air-dried for two hours and the dimension of cylinder specimen was measured and the centroid of cylinder at side was marked. Next, two LVDTs connected to Data Logger were adjusted and pointed on the centroid of the cylinder. After that, the specimen was subjected to an axial load gradually with constant rate of loading of 0.01 mm/s until the specimen failed. During the testing, 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. Mean value of Poisson ratio obtained from two cylinders was then taken as Poisson's ratio for each lightweight foamed concrete mix.

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

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 3.11: Poisson's Ratio Test of Lightweight Foamed Concrete

3.7.5 Compressive 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 known as toughness of the material were computed by using integration method as shown in Equation 3.5.

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

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)

3.7.6 Strength Activity Index Test

Strength Activity Index test is one of the compression test and it was performed with 50mm cubes in accordance with Test Method C 109/C 109M. Before the test was being performed, the cubes were taken out from water tank and oven dried for 24 hours and the dimension of specimen was measured in order to obtain cross sectional area of specimen. Next, the specimen was placed at the center of the testing machine and it was subjected to an axial compressive load gradually with a loading rate in range of 900 to 1800 N/s until the specimen failed. The maximum load carried by the specimen was recorded and compressive strength was calculated based on Equation 3.1. Mean value of compressive strength obtained from three cubes was then taken as cube compressive strength for each mortar concrete mix. For the strength activity index with Portland cement, it was calculated based on Equation 3.6.

$$Strenght\ activity\ index\ with\ portland\ cement = \left(\frac{A}{B}\right) \times 100 \qquad (3.6)$$

where,

A = average compressive strength of test mixture cubes (MPa), and

B = average compressive strength of control mix cubes (MPa).

3.8 Consistency and Stability

The fresh density and hardened density was used to check the stability and consistency of the mix. If the ratio of fresh density to designated density is approximately to one, then the mix is considered to be consistent. Meanwhile, if the ratio of fresh density to hardened density is approximately to one, the mix is considered to be stable. The consistency of the mix is determined by Equation 3.7 (Ramamurthy, 2009) while the stability of the mix is determined by Equation 3.8.

$$\text{Consistency} = \frac{\text{Fresh Density}}{\text{Designated Density}} \qquad (3.7)$$

$$\text{Stability} = \frac{\text{Fresh Density}}{\text{Hardened Density}} \qquad (3.8)$$

3.9 Performance Index

Theoretically, the density of concrete is directly proportional to compressive strength. In this study, the density of lightweight foamed concrete was controlled within 1300 ± 50 kg/m^3. Therefore, performance index of concrete was calculated to increase the accuracy of the results obtained due to the various density for each specimen was obtained. The equation for performance index is shown in Equation 3.9.

$$PI = \frac{Sc}{\text{hardened density}/_{1000}} \quad (3.9)$$

where

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

Sc = Compressive Strength, MPa

3.10 Microstructure Image Analysis

In this study, Hitachi VP-SEM S-3700N was used to conduct microstructure image analysis by using the mean of Scanning Electron Microscope (SEM). The analysis was carried out in accordance with ASTM C1723 (2010). Before the analysis was being performed, the specimens for each mix proportion were coated with a gold layer and the accelerating voltage of the SEM was set to 15 kV and image with 250×, 1000× and 5000× of magnifications were selected for analysis. Next, the analysis was performed with a small piece of crushed cube in high vacuum with the application of a conductive coating. SEM imaging and EDS were carried out on 90 days specimens only.

Figure 3.12: Coating of Specimen Before SEM Analysis

Figure 3.13: Hitachi VP-SEM S-3700N

3.11 Summary

Lightweight foamed concrete incorporated with POFA was produced by the pre-foaming method, where the stable and dry foam was entrained into fresh lightweight concrete until the desired density of 1300 kg/m^3 achieved. A density of 45 kg/m^3 stable and dry foam was produced in a foam generator by mixing the liquid synthetic foaming agent and water with ratio of 1:30. Three LFC mix proportions were prepared in this study namely LFC-CM, LFC-PF25 and LFC-PF50. A total of fifteen 100 mm cubes, eighteen cylinders with height of 200 mm and diameter of 100 mm, fifteen 25 mm × 25 mm × 250 mm prisms. Besides that, two mortar mix proportions were prepared in this study namely M-CM and M-PF20 for the purpose to investigate the strength activity index of POFA. A total three 50 mm × 50 mm × 50 mm cubes were produced for each mix proportions. Water curing method was adopted and the specimens were cured in water for 7, 28, 56 and 90 days before carry out the following test sessions, such as compression test, splitting tensile test, flexural strength test, Poisson's ratio test and strength activity index test. For microstructure image analysis, a small piece of crushed cube of LFC-PF50 at 90 days was undergoing SEM and EDS. The accelerating voltage of the SEM was set to 15 kV and image with 250×, 1000× and 5000× of magnifications were selected for analysis.

CHAPTER 4

TRIAL MIXES

4.1 Introduction

This chapter discusses the results about the strength activity index between the mortar cement paste (M-CM) and the test mixture with POFA (M-PF20). These specimens where cured in water for 7 and 28 days for testing. Besides that, this chapter also discusses and screens trial mixes results for lightweight foamed concrete incorporated with POFA in obtaining the mix proportion for LFC-CM, LFC-PF25 and LFC-PF50. The specimens for each mix proportions were cure in water for 7, 14 and 28 days before carry out compression test.

4.2 Strength Activity Index of POFA

The compressive strength and strength activity index for M-CM and M-PF20 are listed in Table 4.1.

Table 4.1: Compressive Strength and Strength Activity Index at 7 Days and 28 Days

Curing Age	Mix	Compressive Strength (MPa)	Strength Activity Index	Sieve analysis (% of POFA passing through 45μm within an hour)
7 days	M-CM	28.03	77.88	8.9%
	M-PF20	21.83		
28days	M-CM	44.23	75.70	
	M-PF20	33.48		

Table 4.1 shows that compressive strength is directly proportional to the curing age. The strength activity index was calculated based on equation 3.6 and the index for 7 days and 28 days are 77.88% and 75.70% respectively. In addition, these index results are proved and comply with ASTM C618 as the standard summarized that the test mixture with replacement 20% of cement with F-type fly ash has at least 75% as minimum strength development from control mix with 100% cement as binder. Therefore, it had been proved that the mix of M-PF20 (20% POFA replacement as part of binder in the mix) has developed at least 75% of compressive strength compared to the control mix (100% of cement as binder in the mix). On the other hand, a sieve analysis for 1kg of POFA to pass through 45μm within an hour was carried out and there is only 8.9% of POFA is successfully passing through of it.

4.3 Mix Proportions

Table 4.2 has shown the mix proportions used during trial mixes for LFC-CM, LFC-PF25, and LFC-PF50.

Table 4.2: Mix Proportions for Various Types of LFC

Mix details	Binder: Sand	Sand: POFA	Foam volume per m^3 (liters)	w/b[1]	Flow table-Spread value (mm)	Inverted slump cone spread value (mm)
LFC-CM[2]-0.52[5]	1:1	100:0	434 ± 10	0.52	>250/24times	530-540
LFC-CM-0.54	1:1	100:0	454 ± 10	0.54	>250/20times	540-550
LFC-CM-0.56	1:1	100:0	444 ± 10	0.56	>250/16times	580-590
LFC-CM-0.58	1:1	100:0	373 ± 10	0.58	>250/14times	650-660
LFC-CM-0.60	1:1	100:0	296 ± 10	0.60	>250/6times	680-685
LFC-PF25[3]-0.52	1:1	75:25	357 ± 10	0.52	230/25times	460-480
LFC-PF25-0.54	1:1	75:25	354 ± 10	0.54	240/25times	470-500
LFC-PF25-0.56	1:1	75:25	425 ± 10	0.56	>250/24times	470-525
LFC-PF25-0.58	1:1	75:25	415 ± 10	0.58	>250/23times	490-540
LFC-PF25-0.60	1:1	75:25	374 ± 10	0.60	>250/19times	505-540
LFC-PF50[4]-0.52	1:1	50:50	356 ± 10	0.52	200/25times	490-520
LFC-PF50-0.54	1:1	50:50	334 ± 10	0.54	225/25times	500-550
LFC-PF50-0.56	1:1	50:50	296 ± 10	0.56	230/25times	540-560
LFC-PF50-0.58	1:1	50:50	395 ± 10	0.58	>250/21times	580-600
LFC-PF50-0.60	1:1	50:50	494 ± 10	0.60	>250/15times	590-600

Note:

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

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

[3]LFC-PF25 = LFC with 25 % POFA replacement as part of filler

[4]LFC-PF50 = LFC with 50 % POFA replacement as part of filler

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

4.4 Compressive Strength

Compressive strength test results for LFC-CM, LFC-PF25 and LFC-PF50 were shown in Figures 4.1 to 4.3.

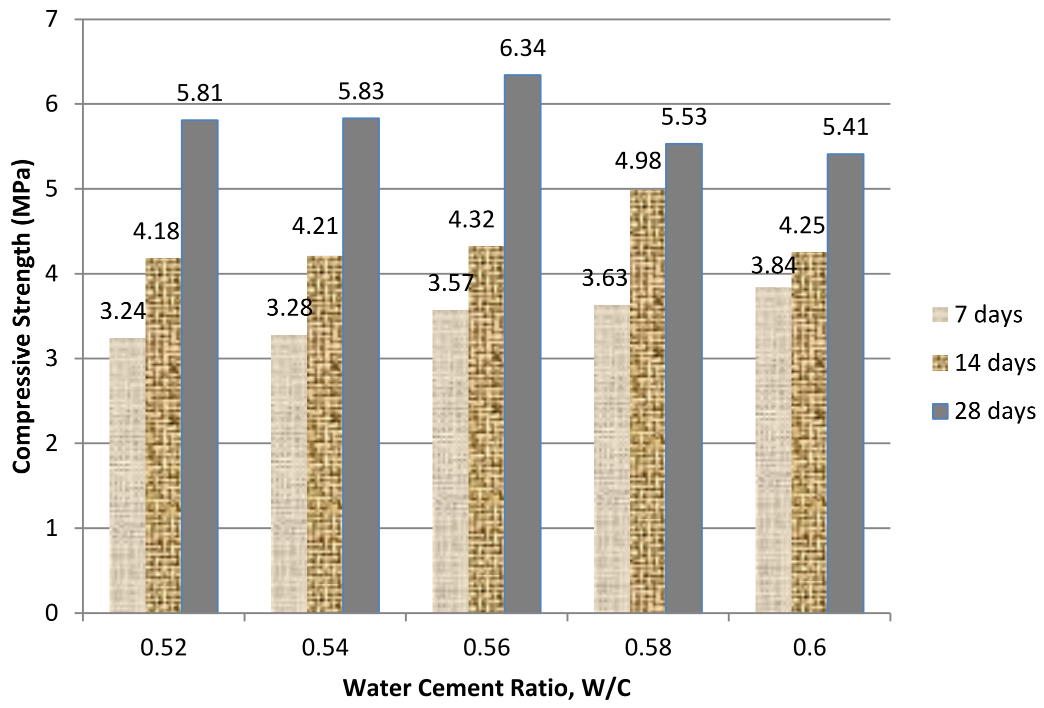

Figure 4.1: Compressive Strength of LFC-CM at various w/c ratios

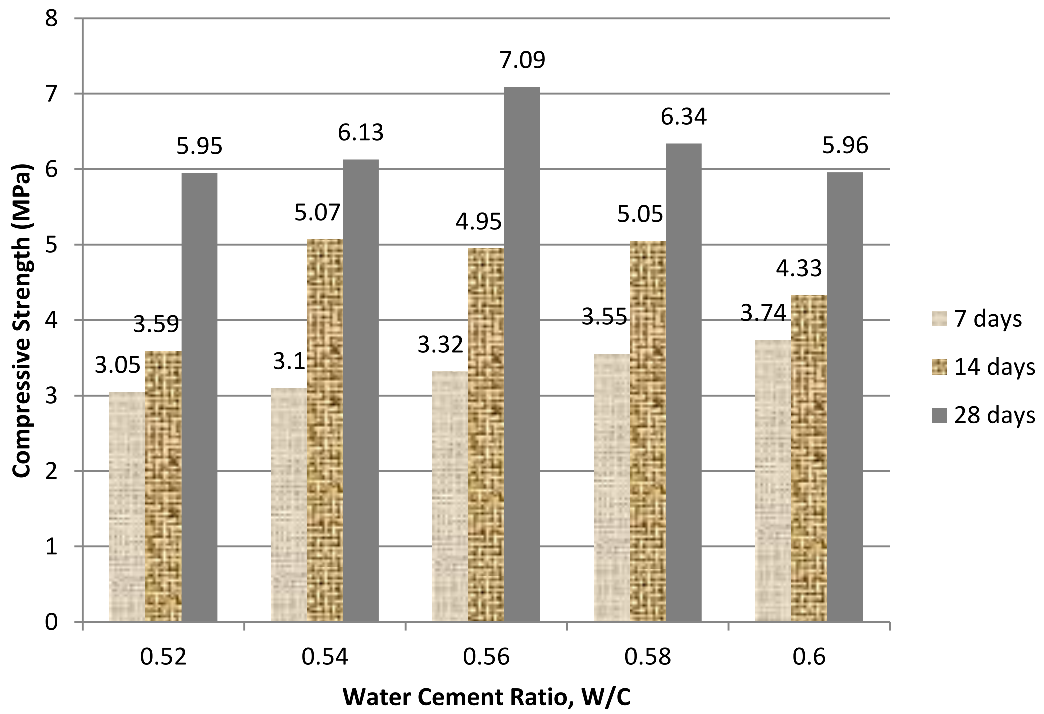

Figure 4.2: Compressive Strength of LFC-PF25 at various w/c ratios

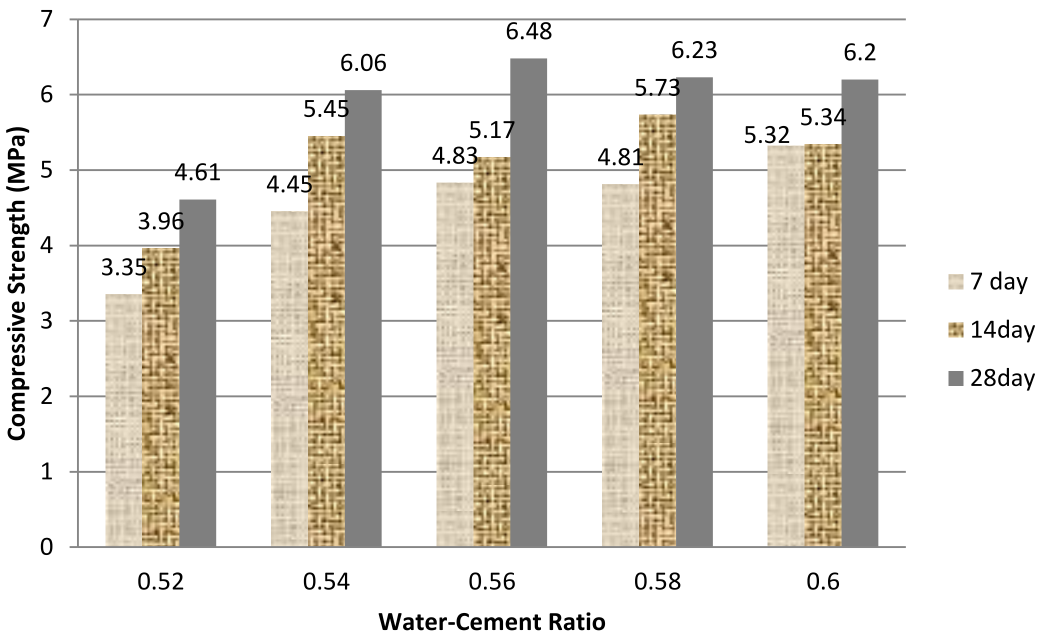

Figure 4.3: Compressive Strength of LFC-PF50 at various w/c ratios

Figures 4.1 to 4.3 show that the compressive strength is directly proportional to the curing age. Therefore, the longer the period of curing age, the higher the concrete strength is achieved. For LFC-CM, the highest 28-day compressive strength was achieved by 0.56 w/c mix proportion, which is 6.34 MPa. Besides, for LFC-PF25, the highest 28-day compressive strength was achieved by 0.56 w/c mix proportion as well, which is 7.09 MPa. For LFC-PF50, 0.56 w/c mix proportion achieves the highest 28-day compressive strength which is 6.48 MPa.

4.5 Performance Index

The performance index for LFC-CM, LFC-PF25, and LFC-PF50 were calculated and shown in Figures 4.4 to 4.6, respectively.

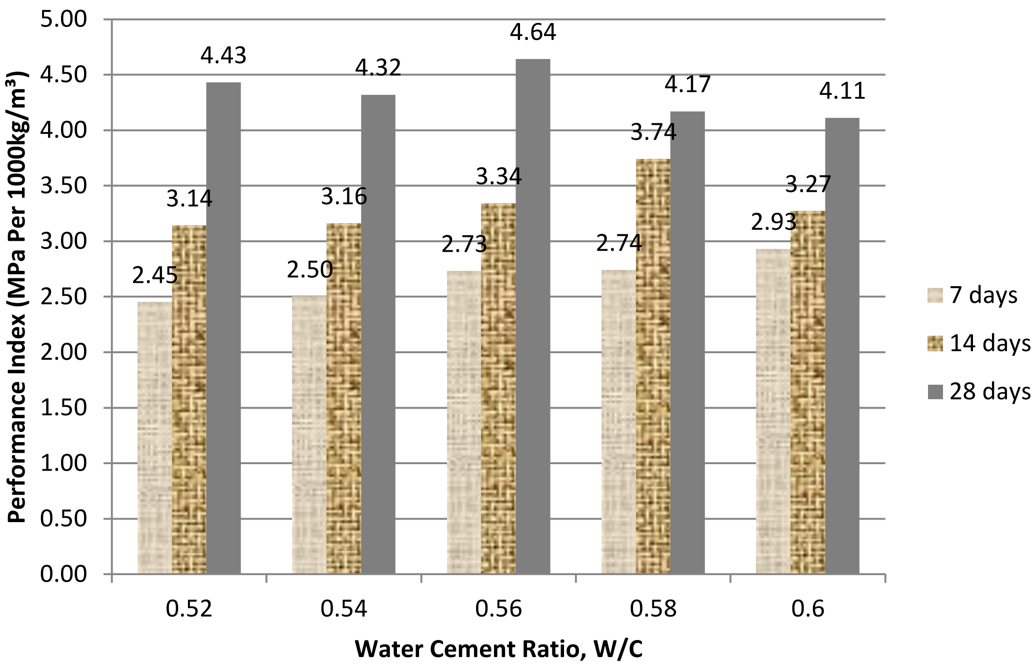

Figure 4.4: Performance Index of LFC-CM at various w/c ratios

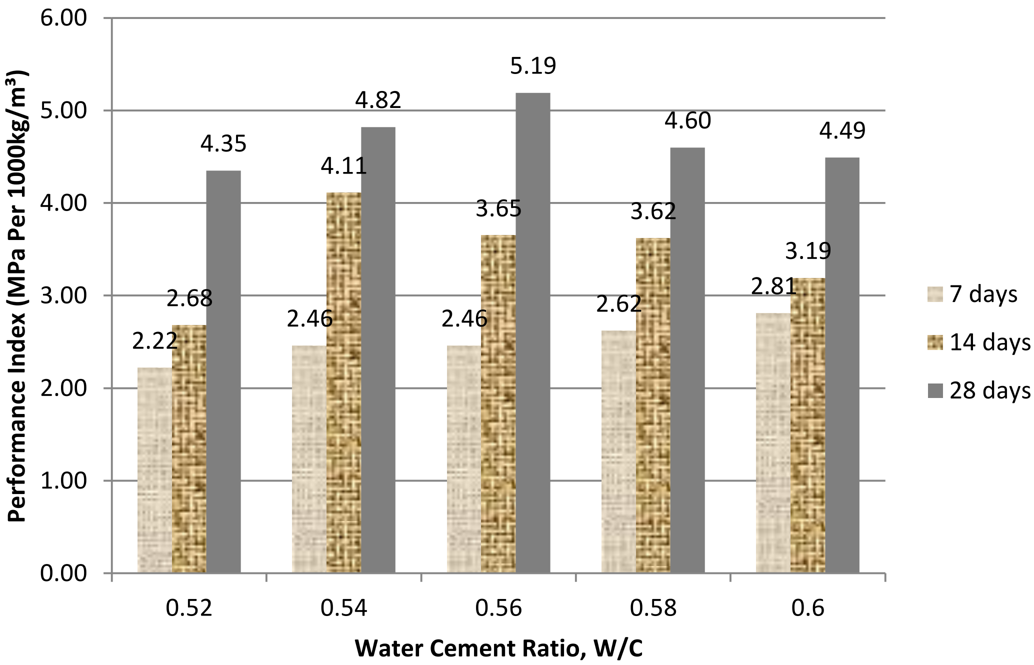

Figure 4.5: Performance Index of LFC-PF25 at various w/c ratios

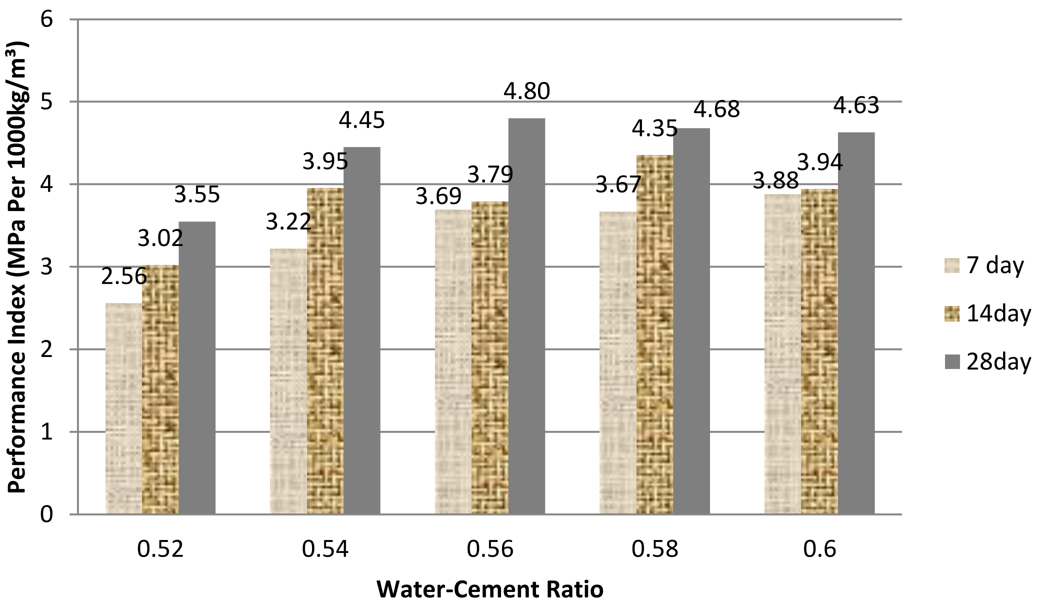

Figure 4.6: Performance Index of LFC-PF50 at various w/c ratios

Figures 4.4 to 4.6 show that the performance index is directly proportional to the curing age of specimen as well. For LFC-CM, the highest 28-day performance index was achieved by 0.56 w/c mix proportion, which is 4.64 MPa per 1000 kg/m^3. Besides, for LFC-PF25, the highest 28-day performance index was achieved by 0.56 w/c mix, which is 5.19 MPa per 1000 kg/m^3. For LFC-PF50, the highest 28-day performance index was achieved by 0.56 w/c mix, which has 4.80 MPa per 1000 kg/m^3.

4.6 Summary

According to ASTM C618, the standard has summarized that the test mixture with replacement 20% of cement with F-type fly ash has at least 75% as minimum strength development from control mix with 100% cement as binder. The strength activity index was calculated and the index for 7days and 28days are achieved 77.88% and 75.70% respectively. Therefore, these index results are proved and comply with ASTM C618. Therefore, it had been proved that the mix of M-PF20 (20% POFA replacement as part of binder in the mix) has developed at least 75% of compressive strength compared to the control mix (100% of cement as binder in the mix).

On the other hand, based on the results obtained and represented in bar chart, it had clearly shown that the compressive strength of lightweight foamed concrete incorporated with POFA has increased compared to the control specimen. This is mainly due to the POFA proportions which having a content of high reactive silica which can reacted as pozzolans with calcium hydroxide from cement in the presence of moisture to form compounds with cementitious properties. The pozzolanic reaction had generated additional C-S-H gel which contribute more strength to the concrete and subsequently produce more strong and dense concrete.

Generally, compressive strength and performance index are directly proportional to curing age. For LFC-CM, the highest 28-day compressive strength and performance index were achieved by 0.56 w/c mix proportion, which are 6.34 MPa and 4.64 MPa per 1000 kg/m^3 respectively. For LFC-PF25, the highest 28-day compressive strength and performance index were achieved in 0.56 w/c mix proportion, which are 7.09 MPa and 5.19 MPa per 1000 kg/m^3 respectively. Besides, for LFC-PF50, the highest 28-day compressive strength and performance index were achieved in 0.56 w/c mix proportion, which are 6.48 MPa and 4.80 MPa per 1000 kg/m^3 respectively.

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Introduction

This chapter discusses about the results of lightweight foamed concrete incorporated with POFA in term of compressive, splitting tensile and flexural strength and Poisson’s ratio. The specimens were cured in water for 7, 28, 58 and 90 days for testing.

5.2 Compressive Strength

The compressive strength for LFC-CM, LFC-PF25 and LFC-PF50 are illustrated in Figure 5.1.

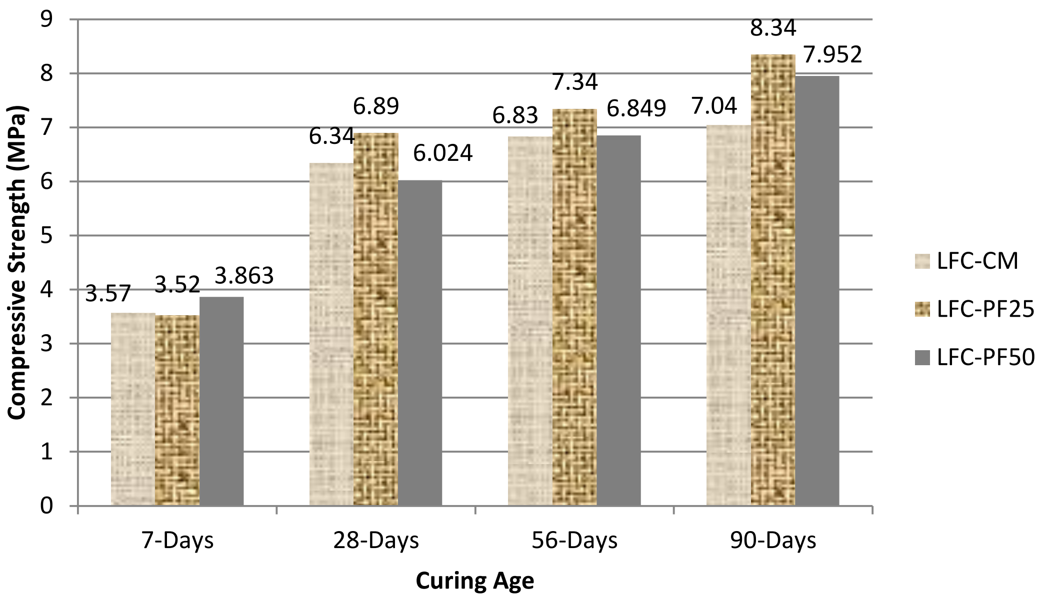

Figure 5.1: Compressive Strength Development up To 90 Days of Age for LFC-CM, LFC-PF25 and LFC-PF50

Figure 5.1 shows that the compressive strength is directly proportional to the curing age for every mix proportion. For LFC-PF25, it possesses a low compressive strength of 3.52MPa in the early stage. However, its compressive strength is gained the highest in the later stage with 6.89MPa, 7.34MPa and 8.34MPa for 28, 56 and 90 days respectively. For LFC- PF50, the development of compressive strength is relatively low in the later stage compared to LFC-CM and LFC-PF25. However, the compressive strength of LFC-PF50 is gained and higher than LFC-CM in 90days with 7.952MPa.

In 90 days of curing age, the specimens incorporated with POFA is higher than control mix because it is due to the pozzolanic reaction occurred in the later stage. The pozzolanic properties of POFA tend to react with calcium hydroxide (Ca(OH)) from the hydration process which is deteriorated to concrete in order to produce extra calcium silicate hydrate (C-S-H) which is a gel compound that contributes to the strength of the concrete by filling the capillary pores with C-S-H and improves the interfacial bonding between the aggregates and pastes at later ages (Karim, 2011). Subsequently, a stronger and denser concrete is produced as well as enhance the durability of the concrete.

Table 5.1: 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 curing age
90 days	LFC-CM	100
	LFC-PF25	118
	LFC-PF50	113

Table 5.1 shows that the development of compressive strength of LFC-PF25 and LFC-PF50 are 18% and 13% higher than LFC-CM at 90 days respectively.

5.3 Splitting Tensile Strength

The splitting tensile strength for LFC-CM, LFC-PF25 and LFC-PF50 are illustrated in Figure 5.2.

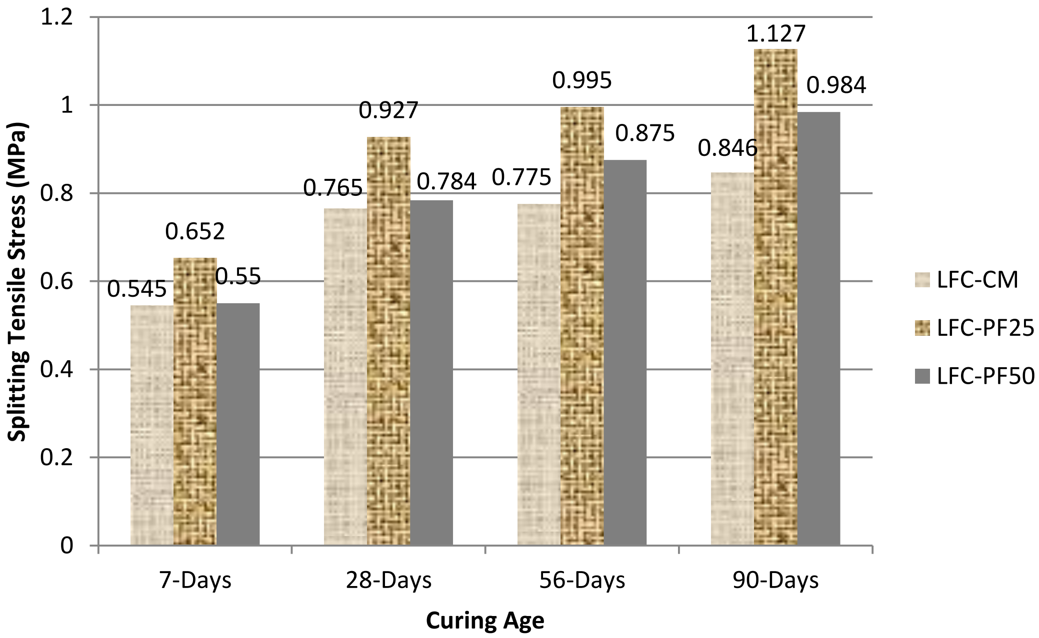

Figure 5.2: Splitting Tensile Strength Development Up To 90 Days of Age for LFC-CM, LFC-PF25 and LFC-PF50

Figure 5.2 shows that the splitting tensile strength is directly proportional to the curing age for every mix proportion. Based on the bar chart, incorporation of POFA in lightweight foamed concrete has enhanced the splitting tensile strength as compared with the control mix. In every curing stage, LFC-PF25 possesses highest splitting tensile strength compared to LFC-CM and LFC-PF50. It possesses 0.652MPa, 0.927MPa, 0.995MPa and 1.127MPa for 7, 28, 56, and 90 days respectively.

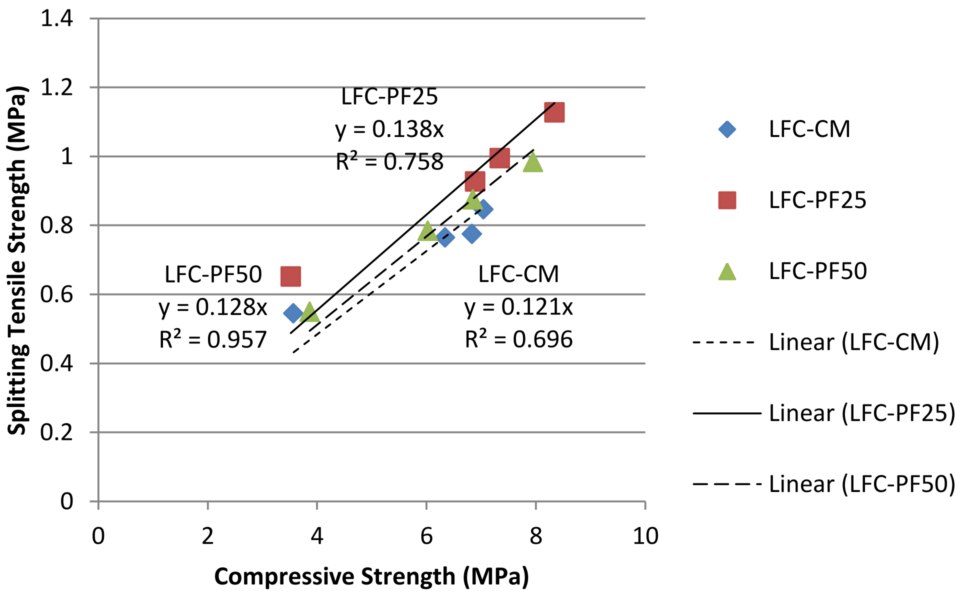

Figure 5.3: Relationship of Splitting Tensile Strength-Compressive Strength for LFC-CM, LFC-PF25 and LFC-PF50 Up to 90 Days of Age

Figure 5.3 shows the relationship between splitting tensile and compressive strength for LFC-CM, LFC-PF25 and LFC-PF50. It is clearly show that the splitting tensile strength is directly proportional to compressive strength. Therefore, LFC-PF25 has higher splitting tensile strength compared to other mix proportion as it possesses a higher compressive strength compared to LFC-CM and LFC-PF50 as well. In addition, Figure 5.3 shows the splitting tensile strength was in the range of 12 to 15% corresponding to the compressive strength. On the other hand, although the splitting tensile and compressive strength are directly proportional to each other but its relationship can be affect by aggregate type, particle size distribution, age of concrete, curing process and air content (Parra, 2011).

Table 5.2: 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-PF25	133
	LFC-PF50	116

Table 5.2 shows that the development of splitting tensile strength of LFC-PF25 and LFC-PF50 are 33% and 16% higher than LFC-CM at 90 days respectively. It is clearly shows that the splitting tensile strength of lightweight foamed concrete incorporated with POFA is achieved higher flexural strength than control mix which is use 100% as sand as filler.

5.4 Flexural Strength

Figure 5.4 illustrates the development of flexural strength for LFC-CM, LFC-PF25 and LFC-PF50 respectively.

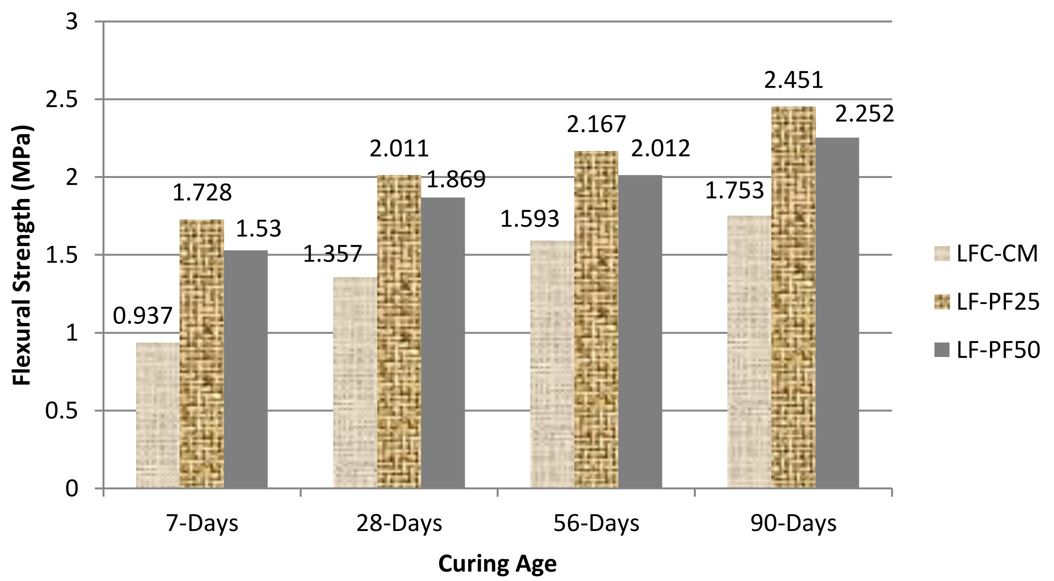

Figure 5.4: Flexural Strength Development up To 90 Days of Age for LFC-CM, LFC-PF25 and LFC-PF50

Figure 5.4 shows that the flexural strength is directly proportional to the curing age for every mix proportion. For LFC-PF25, it possesses a flexural strength of 1.728MPa in the early stage. However, its flexural strength is gained the highest in the later stage with 2.011MPa, 2.167MPa and 2.451MPa for 28, 56 and 90 days respectively. For LFC- PF50, the development of flexural strength is relatively low compared to LFC-PF25. The flexural strength of LFC-PF50 is gained as 2.252MPa and higher than 1.753MPa for LFC-CM at 90days of age. Figure 5.4 is clearly shows that the flexural strength of lightweight foamed concrete incorporated with POFA is achieved higher flexural strength than control mix which is use 100% as sand as filler.

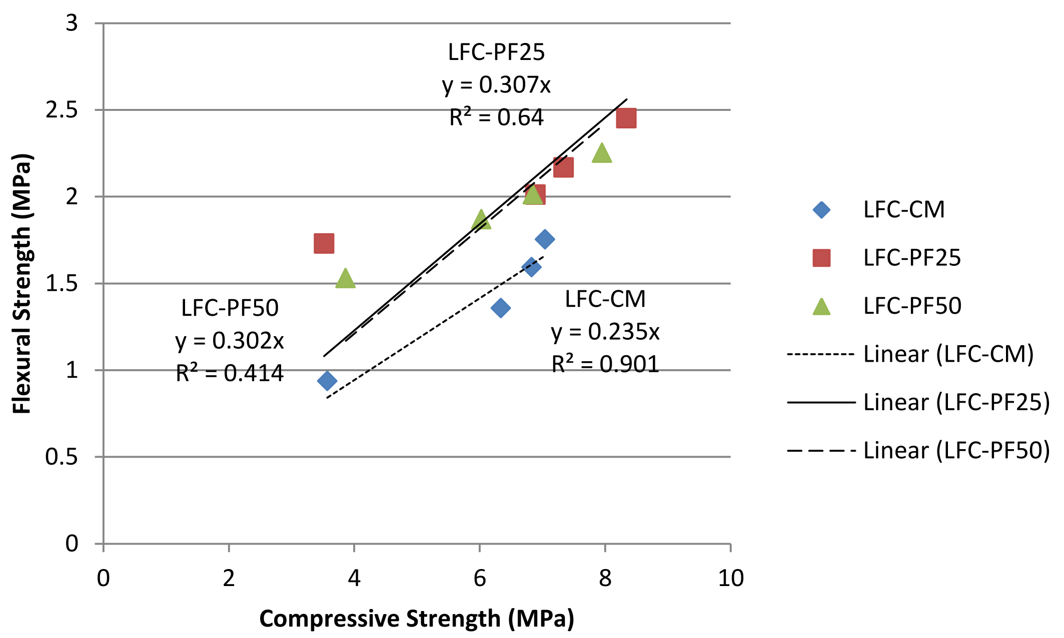

Figure 5.5: Relationship of Flexural Strength-Compressive Strength of LFC-CM, LFC-PF25 and LFC-PF50 Up to 90 Days of Age

Figure 5.5 shows the relationship between flexural and compressive strength for LFC-CM, LFC-PF25 and LFC-PF50. Basically, the development of flexural strength has same trend with compressive strength development and the figure is clearly show that the flexural strength is directly proportional to compressive strength. In addition, Figure 5.5 shows the splitting tensile strength was in the range of 23 to 31% corresponding to the compressive strength.

Table 5.3: 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-PF25	140
	LFC-PF50	128

Table 5.3 shows that the development of flexural strength of LFC-PF25 and LFC-PF50 are 40% and 28% higher than LFC-CM in 90 days respectively. It is clearly shows that the flexural strength of lightweight foamed concrete incorporated with POFA is achieved higher flexural strength than control mix which is use 100% as sand as filler.

5.5 Poisson's Ratio

The Poisson's ratios for LFC-CM, LFC-PF25 and LFC-PF50 are calculated and recorded in Table 5.4.

Table 5.4: 28 Days Poisson's ratio for LFC-CM, LFC-PF25 and LFC-PF50

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	1.88	0.000641	0.0000181	0.00196	0.327
LFC-PF25	2.60	0.001235	0.0000113	0.00428	0.289
LFC-PF50	2.09	0.001498	0.0008946	0.00380	0.161

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 5.4 shows that the Poisson's ratio for LFC-CM is 0.327 under 40% of maximum compressive strength. Besides that, the Poisson's ratio for LFC-PF25 and LFC-PF50 are 0.289 and 0.161. The Poisson's ratio represents the compressibility of a material. Therefore, the material is more compressible when the lower the Poisson's ratio for the material is. The results show that lightweight foamed concrete incorporated with POFA is more compressible than the control mix due to the low Poisson's ratio for LFC-PF25 and LFC-PF50.

5.6 Compressive Toughness

Figures 5.6, 5.7 and 5.8 illustrate the Poisson's ratio stress-strain relationship for LFC-CM, LFC-PF25 and LFC-PF50 for 28 days of age.

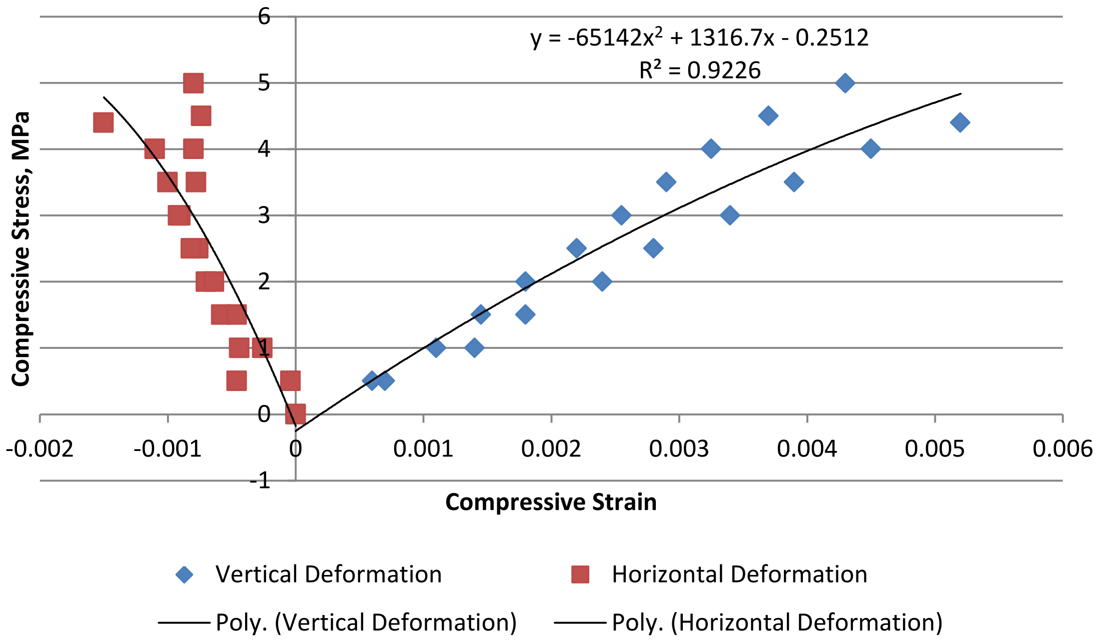

Figure 5.6: 28 Days Stress-Strain Relationship of LFC-CM

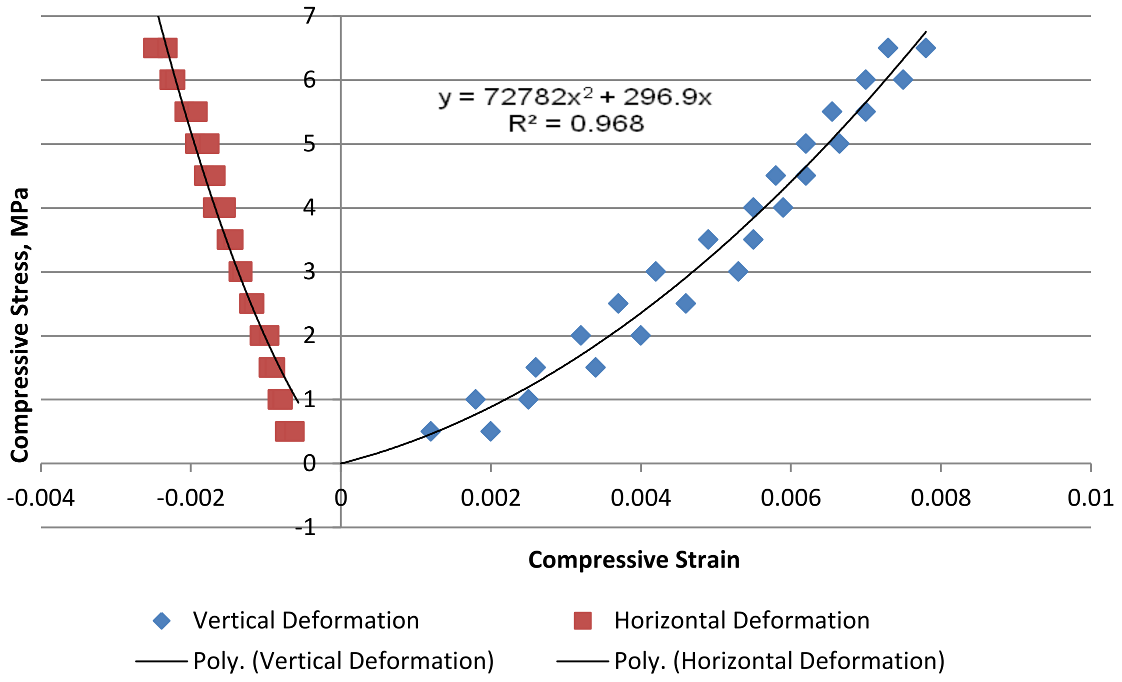

Figure 5.7: 28 Days Stress-Strain Relationship of LFC-PF25

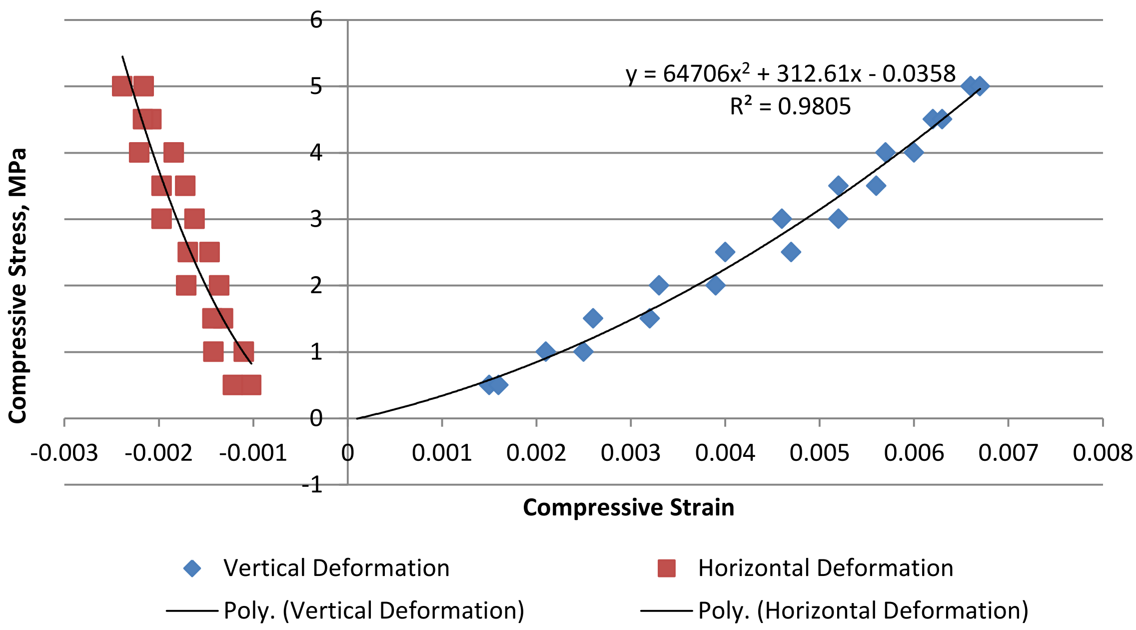

Figure 5.8: 28 Days Stress-Strain Relationship of LFC-PF50

Table 5.5: Compressive Toughness of LFC-CM, LFC-PF25 and LFC-PF50 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	$\sigma = 65142\varepsilon^2 + 1317\varepsilon - 0.251$	0.9226	4.70	4750	2.33×10^{15}
LFC-PF25	$\sigma = 72782\varepsilon^2 + 296.9\varepsilon$	0.9680	6.50	7628	10.77×10^{15}
LFC-PF50	$\sigma = 64706\varepsilon^2 + 312.61\varepsilon - 0.035$	0.9805	5.23	6900	7.09×10^{15}

Table 5.5 shows the compressive toughness for LFC-CM, LFC-PF25 and LFC-PF50. Compressive toughness is the amount of energy per volume that a material can absorb before fracturing. The compressive toughness is calculated by integrating the stress-strain curve for vertical deformation of cylinder. The compressive toughness for LFC-CM, LFC-PF25 and LFC-PF50 are 2.33×10^{15} J/m^3, 10.77×10^{15} J/m^3 and 7.09×10^{15} J/m^3 respectively. The results show that lightweight foamed concrete incorporated with POFA possesses higher compressive toughness than the control mix. Therefore, LFC-PF25 and LFC-PF50 are more ductile than the LFC-CM as specimen incorporated with POFA can absorb more energy per volume before fracturing.

5.7 Performance Index

Table 5.6 presents the performance index for LFC-CM, LFC-PF25 and LFC-PF50 in 7, 28, 56 and 90days respectively. The highest performance index was achieved by LFC-PF25 and followed by LFC-PF50 at 90 days of age.

Table 5.6: Compressive Performance Index of Lightweight Foamed Concrete

Age	Mix	Compressive Strength (MPa)	Hardened Density (kg/m^3)	Performance Index ($MPa/1000kg/m^3$)
7 days	LFC-CM	3.570	1312	2.72
	LFC-PF25	3.520	1310	2.69
	LFC-PF50	3.863	1256	3.08
28 days	LFC-CM	5.204	1285	4..93
	LFC-PF25	6.890	1302	5.29
	LFC-PF50	4.024	1295	4.65
56 days	LFC-CM	5.614	1312	5.21
	LFC-PF25	7.340	1310	5.60
	LFC-PF50	4.849	1315	5.21
90 days	LFC-CM	7.040	1321	5.33
	LFC-PF25	8.340	1285	6.49
	LFC-PF50	7.952	1340	5.93

5.8 Summary

The effect of incorporated with POFA in lightweight foamed concrete had been studied and discussed in terms of compressive, splitting tensile and flexural strengths, Poisson’s ratio and compressive toughness and strength activity index with Portland cement.

Based on compressive strength test, LFC-PF25 possesses a low compressive strength of 3.52MPa in the early stage. However, its compressive strength was gained the highest in the later stage with 6.89MPa, 7.34MPa and 8.34MPa for 28, 56 and 90 days respectively. For LFC- PF50, its compressive strength development was gained in later strength and achieved 7.952MPa in 90 days which is higher than LFC-CM with 7.04MPa.

For splitting tensile strength properties, it is directly proportional to the curing age for every mix proportion. LFC-PF25 possesses highest of splitting tensile strength compared to LFC-CM and LFC-PF50. It possesses 0.652MPa, 0.927MPa, 0.995MPa and 1.127MPa for 7, 28, 56, and 90 days respectively. Besides that, splitting tensile strength is also directly proportional to the compressive strength as well. Besides that, splitting tensile strength of lightweight foamed concrete incorporated with POFA achieved higher flexural strength compared to that of control mix.

Next, flexural strength is directly proportional to the curing age for every mix proportion. For LFC-PF25, it possesses a flexural strength of 1.728MPa in the early stage and it gained the highest in the later stage with 2.011MPa, 2.167MPa and 2.451MPa for 28, 56 and 90 days respectively. The development of flexural strength for LFC- PF50 is relatively low compared with LFC-PF25. It gained 1.53MPa of flexural strength in early age and it achieved 1.869MPa, 2.012 and 2.252MPa in 28, 56 and 90 days of curing age, respectively. Besides that, flexural strength of lightweight foamed concrete incorporated with POFA is achieved higher flexural strength compared to that of control mix.

Incorporation of POFA in LFC has reduced its Poisson’s ratio. However, the Poisson’s ratio toughness of specimens with POFA has increased. The compressive toughness for LFC-CM, LFC-PF25 and LFC-PF50 are 2.33×10^{15} J/m^3, 10.77×10^{15} J/m^3 and 7.09×10^{15} J/m^3 respectively. The results show that lightweight foamed concrete incorporated with POFA possesses higher compressive toughness than that of control mix.

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±50 kg/m^3. This was achieved as three types of foamed concrete were prepared, which included LFC-CM, LFC-PF25 and LFC-PF50. The results are shown in Appendix A (Tables A1 to A3).

The second objective is to obtain optimum w/c ratios for LFC-CM, LFC-PF25 and LFC-PF50. This was achieved through trial mixes, where the optimum w/c ratios for LFC-CM, LFC-PF25 and LFC-PF50 are 0.56, 0.56 and 0.56, respectively.

The third objective is to study the effect of POFA on fresh properties in terms of fresh density and workability of concrete. It had been studied in accordance with ASTM C1437 and C1611 respectively. Incorporation of POFA as part of filler replacement in lightweight foamed concrete has reduced the workability compared to that of lightweight foamed concrete with 100% sand as filler.

The last objective is to study the effects of Palm Oil Fuel Ash (POFA) on engineering properties of lightweight foamed concrete in terms of compressive, flexural and splitting tensile strengths, Poisson’s ratio and compressive toughness. Except Poisson’s ratio, incorporation of POFA into lightweight foamed concrete has increased its compressive strength, flexural strength, splitting tensile strength and compressive toughness than those of mix with 100 % sand as filler.

6.2 Recommendations

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, Poisson’s ratio, compressive toughness and strength activity index with Portland cement.
3. The effect of other curing methods on engineering properties of LFC in term of compressive strength, splitting tensile strength, flexural strengths, Poisson’s ratio, compressive toughness and strength activity index with Portland cement.

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APPENDICES

APPENDIX A: Compressive Strength, Consistency, Stability and Performance Index for Various Types of LFC Specimens (Trial mixes)

Table A1: Compressive Strength of Various Types of LFC Specimens (Trial Mixes)

Age (days)	Mix	Dry Bulk Density (kg/m^3)	Compressive Strength (MPa)	Performance Index ($MPa/1000kg/m^3$)	Consistency
7	LFC-CM	1310	3.57	2.73	0.990
	LFC-PF25	1351	3.32	2.46	0.940
	LFC-PF50	1319	4.45	3.22	0.980
14	LFC-CM	1293	4.32	3.34	1.000
	LFC-PF25	1358	4.95	3.65	0.930
	LFC-PF50	1289	5.45	3.95	0.992
28	LFC-CM	1366	6.34	4.64	0.950
	LFC-PF25	1367	7.09	5.19	0.930
	LFC-PF50	1318	6.48	4.80	0.940

Table A2: The Consistency and Stability of LFC-CM

Mix Details	Fresh Density (kg/m^3)	Hardened Density (kg/m^3)			Consistency	Stability		
		7 days	14 days	28 days		7 days	14 days	28 days
LFC-CM-0.52-1	1269	1333	1300	1402	0.98	0.96	0.95	0.97
LFC-CM-0.52-2		1320	1295	1305				
LFC-CM-0.52-3		1290	1298	1295				
LFC-CM-0.52-4		1357	1439	1346				
LFC-CM-0.52-AVG		1325	1333	1312				
LFC-CM-0.54-1	1302	1300	1320	1332	1	0.99	0.98	0.96
LFC-CM-0.54-2		1340	1321	1341				
LFC-CM-0.54-3		1302	1340	1350				
LFC-CM-0.54-4		1306	1343	1381				
LFC-CM-0.54-AVG		1312	1331	1351				
LFC-CM-0.56-1	1295	1302	1295	1322	1	0.99	1	0.95
LFC-CM-0.56-2		1325	1305	1349				
LFC-CM-0.56-3		1323	1320	1391				
LFC-CM-0.56-4		1290	1252	1401				
LFC-CM-0.56-AVG		1310	1293	1366				
LFC-CM-0.58-1	1276	1301	1340	1299	0.98	0.96	0.96	0.96
LFC-CM-0.58-2		1334	1324	1301				
LFC-CM-0.58-3		1305	1322	1351				
LFC-CM-0.58-4		1360	1342	1353				
LFC-CM-0.58-AVG		1325	1332	1326				
LFC-CM-0.60-1	1289	1300	1300	1315	0.99	0.98	0.99	0.98
LFC-CM-0.60-2		1305	1325	1300				
LFC-CM-0.60-3		1350	1275	1340				
LFC-CM-0.60-4		1289	1300	1309				
LFC-CM-0.60-AVG		1311	1300	1316				

Table A3: The Consistency and Stability of LFC-PF25

Mix Details	Fresh Density (kg/m^3)	Hardened Density (kg/ m^3)			Consistency	Stability		
		7 days	14 days	28 days		7 days	14 days	28 days
LFC-PF25-0.52-1		1327.5	1245.5	1315.5				
LFC-PF25-0.52-2		1368.5	1337	1350				
LFC-PF25-0.52-3	1257	1396	1349.5	1384	0.97	0.91	0.94	0.92
LFC-PF25-0.52-4		1408	1422	1427.5				
LFC-PF25-0.52-AVG		1375	1339	1369				
LFC-PF25-0.54-1		1250	1264	1240				
LFC-PF25-0.54-2		1304	1187	1247				
LFC-PF25-0.54-3	1298	1274	1240	1280	1	1.03	1.05	1.02
LFC-PF25-0.54-4		1204	1244	1318				
LFC-PF25-0.54-AVG		1258	1234	1271				
LFC-PF25-0.56-1		1281.5	1285	1317.5				
LFC-PF25-0.56-2		1290	1331.5	1322.5				
LFC-PF25-0.56-3	1265	1388.5	1361	1375.5	0.97	0.94	0.93	0.93
LFC-PF25-0.56-4		1445.5	1455.5	1451				
LFC-PF25-0.56-AVG		1351	1358	1367				
LFC-PF25-0.58-1		1287.5	1355.5	1316				
LFC-PF25-0.58-2		1322	1374	1355.5				
LFC-PF25-0.58-3	1283	1384	1412.5	1383	0.99	0.95	0.92	0.93
LFC-PF25-0.58-4		1434.5	1432	1451.5				
LFC-PF25-0.58-AVG		1357	1394	1377				
LFC-PF25-0.60-1		1269.5	1302	1288				
LFC-PF25-0.60-2		1325.5	1372	1294				
LFC-PF25-0.60-3	1289	1342.5	1375	1337	0.99	0.97	0.95	0.97
LFC-PF25-0.60-4		1379	1385	1385.5				
LFC-PF25-0.60-AVG		1329	1359	1326				

Table A4: Compressive Strength and Performance Index of LFC-CM

Mix Details	Compressive Strength @ 7d (MPa)	Performance Index @ 7d (MPa/1000kg/m^3)	Compressive Strength @ 14d (MPa)	Performance Index @ 14d (MPa/1000kg/m^3)	Compressive Strength @ 28d (MPa)	Performance Index @ 28d (MPa/1000kg/m^3)
LFC-CM[1]-0.52-1	3.33		3.95		5.55	
LFC-CM-0.52-2	3.21		3.60		6.12	
LFC-CM-0.52-3	2.90	2.45	5.12	3.14	6.57	4.43
LFC-CM-0.52-4	3.52		4.05		5.00	
LFC-CM-0.52-AVG	3.24		4.18		5.81	
LFC-CM-0.54-1	3.06		3.97		4.53	
LFC-CM-0.54-2	3.33		4.60		6.62	
LFC-CM-0.54-3	3.59	2.50	4.17	3.16	6.53	4.32
LFC-CM-0.54-4	3.14		4.10		5.62	
LFC-CM-0.54-AVG	3.28		4.21		5.83	
LFC-CM-0.56-1	3.56		4.22		6.72	
LFC-CM-0.56-2	3.70		5.28		6.93	
LFC-CM-0.56-3	3.77	2.73	3.22	3.34	5.48	4.64
LFC-CM-0.56-4	3.25		4.56		6.23	
LFC-CM-0.56-AVG	3.57		4.32		6.34	
LFC-CM-0.58-1	4.08		5.23		5.78	
LFC-CM-0.58-2	3.65		5.06		4.68	
LFC-CM-0.58-3	3.24	2.74	4.57	3.74	6.11	4.17
LFC-CM-0.58-4	3.55		5.06		5.55	
LFC-CM-0.58-AVG	3.63		4.98		5.53	
LFC-CM-0.60-1	4.07		4.20		5.55	
LFC-CM-0.60-2	3.56		4.10		5.78	
LFC-CM-0.60-3	3.99	2.93	3.98	3.27	6.10	4.11
LFC-CM-0.60-4	3.74		4.72		4.21	
LFC-CM-0.60-AVG	3.84		4.25		5.41	

Table A5: Compressive Strength and Performance Index of LFC-PF25

Mix Details	Compressive Strength @ 7d (MPa)	Performance Index @ 7d (MPa/1000kg/m^3)	Compresive Strength @ 14d (MPa)	Performance Index @ 14d (MPa/1000kg/m^3)	Compressive Strength @ 28d (MPa)	Performance Index @ 28d (MPa/1000kg/m^3)
LFC-PF25-0.52-1	2.42		3.39		6.09	
LFC-PF25-0.52-2	2.97		4.12		7.10	
LFC-PF25-0.52-3	3.29	2.22	3.23	2.68	4.56	4.35
LFC-PF25-0.52-4	3.52		3.61		6.05	
LFC-PF25-0.52-AVG	3.05		3.59		5.95	
LFC-PF25-0.54-1	3.06		6.35		6.51	
LFC-PF25-0.54-2	3.67		3.60		2.82	
LFC-PF25-0.54-3	2.99	2.46	4.71	4.11	7.13	4.82
LFC-PF25-0.54-4	2.68		5.62		8.04	
LFC-PF25-0.54-AVG	3.10		5.07		6.13	
LFC-PF25-0.56-1	3.09		4.65		5.99	
LFC-PF25-0.56-2	3.11		4.74		7.12	
LFC-PF25-0.56-3	2.95	2.46	4.85	3.65	6.43	5.19
LFC-PF25-0.56-4	4.13		5.56		8.83	
LFC-PF25-0.56-AVG	3.32		4.95		7.09	
LFC-PF25-0.58-1	3.95		5.07		6.66	
LFC-PF25-0.58-2	3.87		5.76		6.20	
LFC-PF25-0.58-3	2.96	2.62	4.57	3.62	6.34	4.60
LFC-PF25-0.58-4	3.42		4.80		6.14	
LFC-PF25-0.58-AVG	3.55		5.05		6.34	
LFC-PF25-0.60-1	3.87		4.86		6.05	
LFC-PF25-0.60-2	3.89		4.44		5.44	
LFC-PF25-0.60-3	2.96	2.81	3.67	3.19	5.01	4.49
LFC-PF25-0.60-4	4.24		4.35		7.34	
LFC-PF25-0.60-AVG	3.74		4.33		5.96	

APPENDIX B:

Table B1: Compressive, Splitting Tensile and Flexural Strength of Various Types of LFC Specimens at 0.56 of w/c

Age (days)	Mix	Compressive Strength (MPa)	Splitting Tensile Strength (MPa)	Flexural Strength (MPa)
7	LFC-CM	3.570	0.545	1.807
	LFC-PF25	3.520	0.652	2.103
	LFC-PF50	3.863	0.550	2.442
28	LFC-CM	5.204	0.765	2.412
	LFC-PF25	6.890	0.927	3.059
	LFC-PF50	4.024	0.568	2.743
56	LFC-CM	5.614	0.775	2.833
	LFC-PF25	7.340	1.121	3.223
	LFC-PF50	4.849	0.581	2.843
90	LFC-CM	7.040	0.846	2.984
	LFC-PF25	8.340	1.206	3.869
	LFC-PF50	7.952	0.751	3.786

APPENDIX C: Microstructural Analysis for LFC-PF50 at 90 Days of age (SEM)

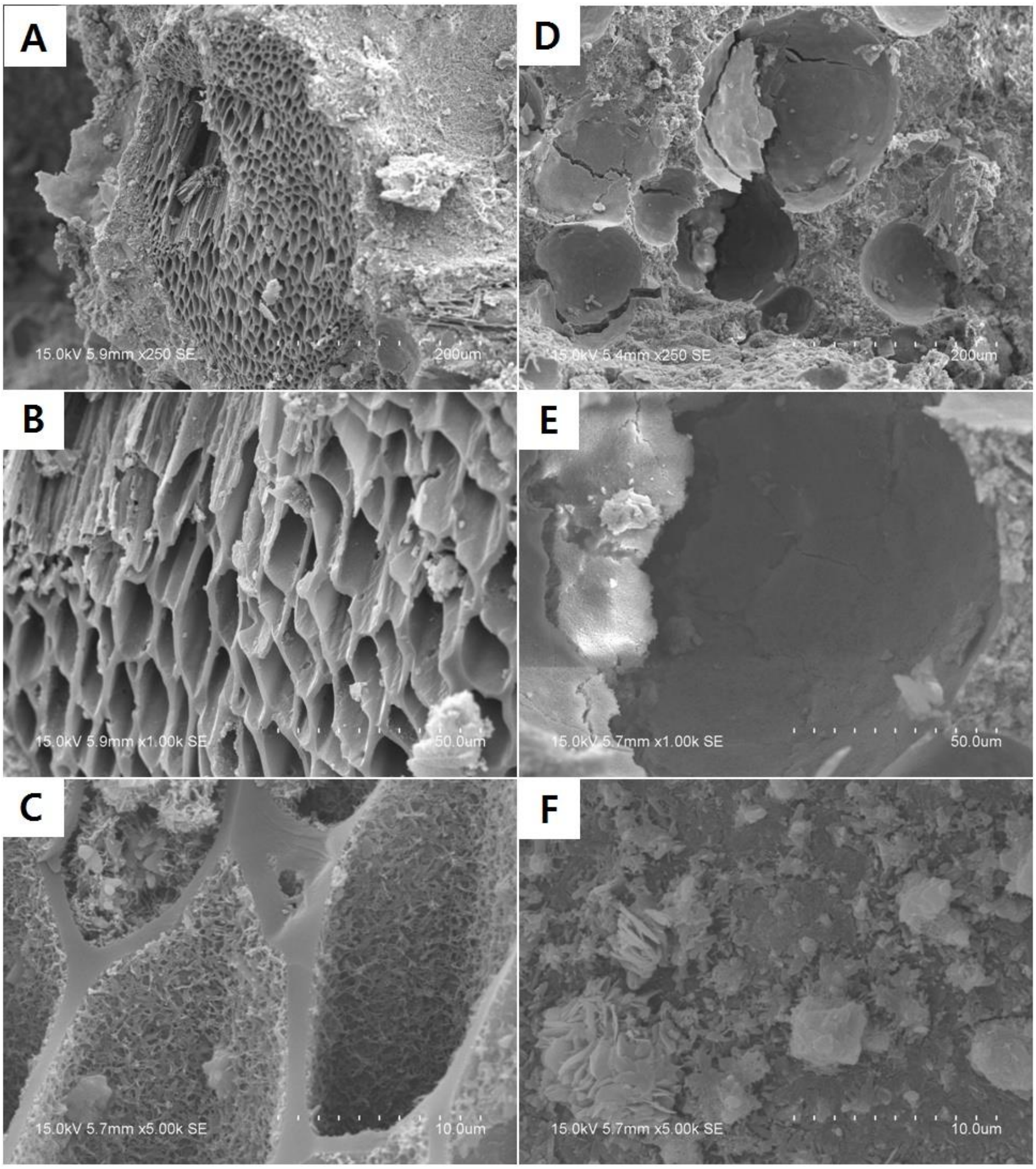


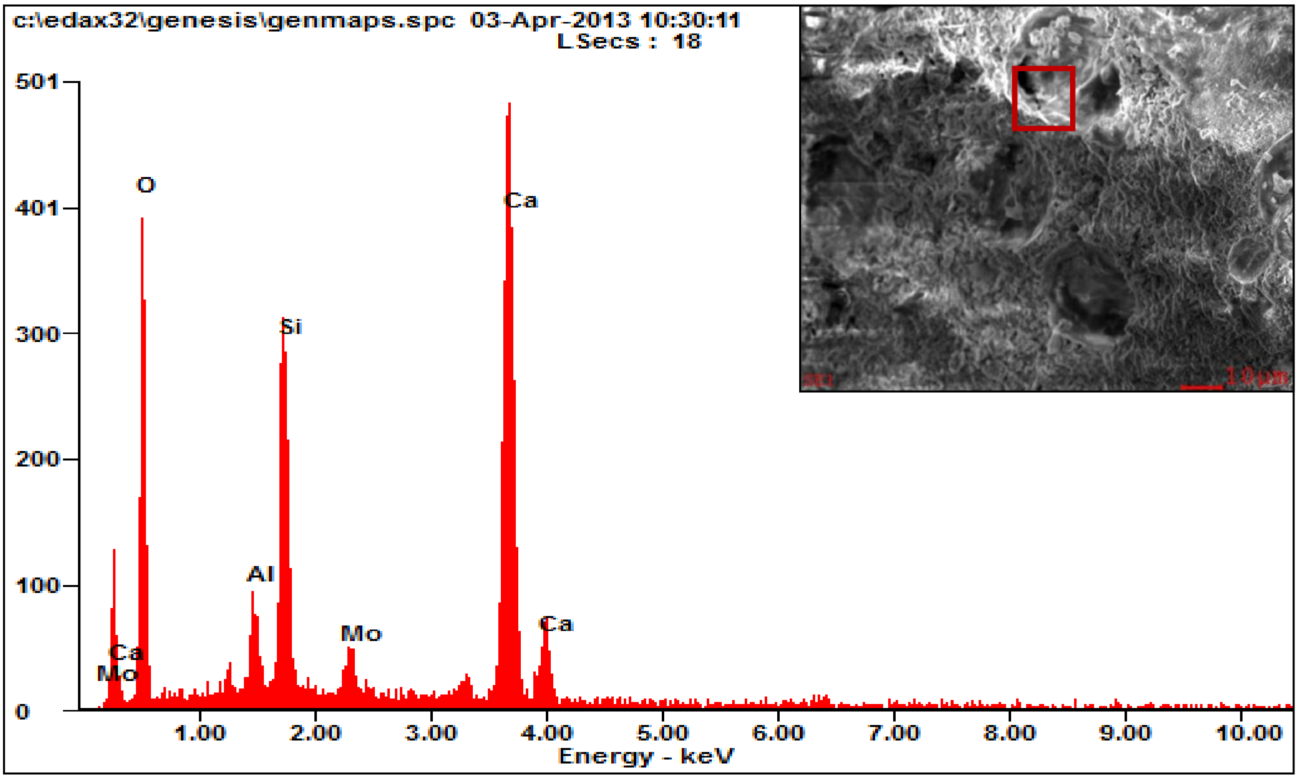
Figure C1: Microstructural Images of LFC-PF50 at 90 days of age of:

(a) & (d) 250x of magnification

(b) & (e) 1000x of magnification

(c) & (f) 5000x of magnification

APPENDIX D: Electron Dispersive Spectrometry of LFC-PF50 at 90 days of age



Element	*Wt%*	*At%*
OK	22.56	40.64
AlK	03.32	03.54
SiK	17.18	17.63
MoL	06.59	01.98
CaK	50.36	36.21
Matrix	Correction	MThin

D1: Percentage of Element Contained in Specimen LFC-PF50