RDU 170339

MECHANICAL PROPERTIES OF HIGH VOLUME PALM OIL WASTE LIGHTWEIGHT AGGREGATE CONCRETE CONTAINING PALM OIL FUEL ASH

(SIFAT MEKANIKAL KONKRIT AGGREGAT RINGAN YANG MENGANDUNGI ABU TERBANG KELAPA SAWIT)

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RESEARCH VOTE NO:

RDU170339

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Universiti Malaysia Pahang

2018

ACKNOWLEDGEMENTS

Alhamdulillah, All praises to Allah S.W.T on the completion of this research Thanks to my research members and also postgraduate students especially Nur Azzimah Zamri in completing this research. My sincere appreciation goes to the management of Kilang Sawit Lepar Hilir for providing the palm oil wastes. Thanks to the technical staff at Heavy Structure Laboratory, Faculty of Civil Engineering and Earth Resources of Universiti Malaysia Pahang.

Thank you

ABSTRACT

In Malaysia, the abundance of palm oil waste namely palm oil clinker (POC) and palm oil fuel ash (POFA) keep on generated due to high palm oil demand. These two types of waste are usually dumped at the nearby landfill which causes environmental pollution. It is seen that the use of these two types of palm oil waste materials would release some of the total amount of waste landed in the landfill. This research was conducted to investigate the mechanical and durability performance of palm oil clinker lightweight aggregate concrete containing palm oil fuel ash as partial cement replacement. Five types of POC mixes were prepared consisting of 0%, 10%, 20%, 30% and 40% POFA as partial cement replacement. Two types of curing were employed that is water curing and air curing. The finding shows that selection of suitable type of curing and amount of POFA used would contribute towards concrete strength enhancement. Application of water curing with 10% of POFA as partial cement replacement resulted in the highest strength and higher than plain OPS LWAC due to pozzolanic reaction. Continuous presence of water during curing period has facilitate the on better reaction for production of C-S-H gel which important for better strength of concrete. On the other hand, air cured specimen exhibit lower strength value at all curing age. The water absorption test result water cured specimen exhibit lower percentage of water absorbed. When exposed to acid resistance test and sulphate resistance test, water cured POC LWAC with POFA shows higher durability than control specimen. Inclusion of suitable amount 10% POFA as partial cement replacement reduces the vulnerable calcium hydroxide owing to pozzolanic reaction that consume it during the production of secondary C-S-H gel. Conclusively, integration of 10% POFA as partial cement replacement enhances both mechanical and durability properties of POW LWAC.

ABSTRAK

Di Malaysia, sisa buangan industri sawit iaitu klinker dan abu terbang kelapa sawit semakin banyak dijana kerana peningkatan permintaan terhdapa minyak sawit. Kedua-dua sisa buangan ini lazimnya dibuang di tapak pembuangan sampah berhampiran yang menyebabkan pencemaran alam sekitar. Justeru itu, kajian ini dijalankan untuk mengkaji sifat-sifat mekanikal dan ketahanlasakan konkrit ringan klinker kelapa sawit yang mengandungi abu terbang kelapa sawit sebagai bahan pengganti separa simen. Sebanyak lima bancuhan yang terdiri dari 0%, 10%, 20%, 30% and 40% abu terbang kelapa sawit sebagai bahan pengganti separa simen telah digunakan di dalam kajian ini. Dua jenis kaedah awetan telah digunakan iaitu awetan air dan awetan udara. Kajian mendapati kaedah awetan dan kuantiti abu terbang kelapa sawit yang digunakan membantu dalam peningkatan kekuaatan konkrit aggregate ringan. Aplikasi kaedah awetan air dan penggunaan 10% abu terbang kelapa sawit menghasilkan konkrit dengan kekuatan lebih tinggi dari konkrit kawalan. Aplikasi awetan air yang berterusan membantu tindakbalas balas bagi penjanaan C-S-H gel yang lebih baik. Walaubagaimanapun, konkrit yang diawet dengan menggunakan awetan udara mempamerkan kekuatan yang lebih rendah sepanjang tempoh eksperimen. Konkrit ringan klinker kelapa sawit dengan abu terbang yang diawet dengan kaedah awetan air juga menunjukkan keputusan yang memberangsangkan apabila ujian penyerapan air menunjukkan nilai yang lebih rendah daripada konkrit kawalan. Apabila diletakkan di dalam medium berasid dan sulfat, specimen yang sama menunjukkan rintangan yang lebih tinggi berbanding konkrit kawalan. Penggunaan abu terbang kelapa sawit yang bersesuaian berjaya mengurangkan kalsium hidroksida kerana telah digunapakai ketika tindakbalas pozzolan untuk penghasilan C-S-H gel sekunder. Kesimpulannya, penggunaan 10% abu terbang kelapa sawit sebagai bahan separa pengganti simen mampu meningkatkan kekuatan dan ketahanlasakan konkrit aggregate ringan.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

%	Percentage
MPa	Megapascal
℃	Celcius
mm	Milimeter
m	Meter

LIST OF ABBREVIATIONS

POFA	Palm Oil Fuel Ash
POC	Palm Oil Clinker
LWAC	Lightweight Aggregate Concrete
LWC	Lightweight Concrete
$Ca(OH)_2$	Calcium hydroxide
CSH	Calcium Silicate Hydrate gel
OPC	Ordinary Portland Cement

CHAPTER 1

INTRODUCTION

1.1 Introduction

Concrete is one of the most important and widely used construction materials in the world (Naik, 2008). Concrete is the ideal material for construction because it is strong enough to meet the needs for various application according to type of concrete developed. At present, lightweight aggregate concrete has gain an insight in construction industry interest due to the benefits offered by this lightweight concrete such as excellent thermal properties, reduction of weight of members and smaller section. Most of the benefit of this type of concrete is due to the lightweight aggregate concrete mixture is made with a lightweight coarse aggregate and in some cases the entire fine aggregates may be a lightweight product. The lightweight aggregate used contribute towards reduction of weight members in which resulted to smaller foundation needed that will reduce the total cost of construction. According to Kenneth and Harmon (2015), structural lightweight concrete has many varied applications including multistory building frames and floors, bridges, offshore oil platforms, and prestressed or precast elements of all types. Other than that, in order to remain competitive especially in the era of globalization, the Malaysian government has formulated a roadmap called IBS roadmap 2003-2010 to promote the usage of IBS in the local construction industry (Shaari, 2006). Thus, the development of lightweight concrete is in line with our Government's overall initiative in promoting usage of IBS in Malaysia construction sector.

Oil palm cultivation in Malaysia was introduced by the government to eradicate poverty among Malaysian people in rural areas. In 1960, the Federal Land Development Authority (FELDA) began exploring new land used for palm oil cultivation (Hai, 2002). Nowadays, oil palm plantations cover about 5.4 million hectares in Malaysia (MPIC, 2015). In 2014, a total of 19.22 million tons of crude palm oil was produced, which is 2.34 % higher compared to the year 2013. As a result, enormous amount of waste produced from the palm oil industry creates a significant economic and disposal problem (Rupani et al., 2013). Examples of solid waste from palm oil industry are empty fruit bunches (EFB), palm oil clinker (POC), oil palm shell (OPS), and palm oil fuel ash (POFA), as well as liquid waste, normally referred to as POME (Palm Oil Mill Effluent). The increasing production of palm oil waste at an alarming rate has recently attracted much attention for an alternative sustainable application. As a solution, various study has been conducted by researchers in order to turn these by-products into value-added products.

At the same time, Malaysia is heading towards being a developed country. This is in line with Vision 2020 which introduced by the former Prime Minister of Malaysia, Tun Dr Mahathir bin Mohamad during the tabling of the Sixth Malaysia Plan in 1991 (Koh and Balasingamchow, 2015). Therefore, in order to reach this goal, natural resources need to be extracted to produce construction materials. The result of continuous cycle of deforestation would eventually lead to the depletion of these non-renewable materials resulting in ecological imbalance as well as a shortage of locally produced building materials. This not only will cause the cost of construction products rise, but so will the residential properties in Malaysia (Abd Razak et al., 2013). Moreover, the expensive price of homes nowadays is a major financial burden to Malaysian people (Osmadi et al., 2015). Thus, the concerns over materials scarcity that need to be extracted from natural resources have led researchers to identify alternative sustainable materials that could replace existing material in concrete production.

1.2 Problem Statement

The production of lightweight aggregate concrete would help to reduce the consumption of natural granite aggregate which is the most preferred choice as a coarse aggregate in construction. Large quantities of coarse aggregate are produced from quarries around and has disastrous environmental consequences. According to Minerals and Geoscience Department Malaysia, the total aggregates production for 2010 was 101,809 million tonnes an increase of about 17 per cent compared with 86.5 million tonnes produced in 2009. Due to this activity, natural resources is becoming a scarce commodity and hence exploring alternatives to it has become imminent. Nevertheless, the production of this kind of concrete requires utilization of binder in higher amount as compared to normal concrete. To produce cement for concrete, mountains had to be 'slaughtered' in which intensifies erosion problem. Other than that, the cement industry is also one of the primary producers of carbon dioxide that causes major greenhouse gas. In 2013, the cement plants accounts for 5.5% of global carbon dioxide emission, the main cause of global warming (Global Carbon Budget, 2014).

At the same time, billions of tons of waste are generated from palm oil industry. This industry produces a wide variety of waste in large quantities (Sridhar and AdeOluwa, 2009). Among the waste that is produced is palm oil fuel ash, palm oil clinker, palm oil shell, and palm oil kernel shell. Annually, over 4 million tonnes of palm oil fuel ash (POFA) (Mohamed at al., 2005) and huge amount of palm oil clinker (POC) were generated (Kanadasan and Abdul Razak, 2015). The quantity of waste from this industry not only creates difficulty to dispose at landfill, but also causes contamination of air, soil and water. For example, palm oil fuel ash and palm oil clinker are dumped at the nearby landfill causing environmental problems and health hazards. Therefore, researcher has initiating the research in order to overcome this problem by converting this material to become more profitable value especially in the construction industry. For example, utilization of palm oil clinker as lightweight aggregate to replace granite and limestone in concrete can help to reduce natural aggregate. Other than that, replacing cement with palm oil ashes can reduce the heat of hydration of concrete thus opens up a new avenue to reducing CO_2 emissions from the production of cement. Furthermore, CIDB Malaysia are now promoting lightweight concrete product that assures valuable advantages such as the reduction of unskilled workers, less wastage, less volume of building materials, increased environmental and construction site cleanliness and better quality control, among others. These advantages also promote a safer and more organised construction site, and reduces the completion time of construction.

1.3 Objective of Research

The objectives of this research are listed below:

a) To examine the effect of palm oil fuel ash content as mineral admixture on the compressive strength of palm oil waste lightweight aggregate concrete.
b) To investigate the effect of different curing regimes on physical and mechanical properties of palm oil waste lightweight aggregate concrete containing palm oil fuel ash as mineral admixture
c) To investigate the durability performance of palm oil waste lightweight aggregate concrete containing palm oil fuel ash

1.4 Scope of Research

The experimental research is aimed at investigating the best design mix in order to produce palm oil clinker (POC) lightweight aggregate concrete containing palm oil fuel ash (POFA). After obtaining the best control mix design, the mix were used to determine the mechanical and durability performance of this novel lightweight aggregate concrete with variety content of palm oil fuel ash (POFA) as partial cement replacement. The percentage of cement content utilised as partial cement replacement in this research are 0%, 10%, 20%, 30% and 40%. The mechanical properties testing involves in this research are compressive strength, flexural strength, splitting tensile strength and modulus of elasticity. Durability properties investigated are acid attack, sulphate attack, carbonation, and water absorption. The effect of curing regimes namely water curing and air curing on the mechanical and durability properties of the concrete specimen were investigated at 7, 28, 60, 180, 270 and 365 days.

1.5 Research Significance

Discovery from this research would provide information on the effectiveness of palm oil fuel ash (POFA) content as partial cement replacement towards the mechanical and durability properties performance of palm oil clinker (POC) lightweight aggregate concrete (POC LWAC). The result from this research would also provide more information on the strength and durability performance of palm oil clinker (POC) when subjected to different curing regimes. Thus, integrating palm oil fuel ash (POFA) and palm oil clinker (POC) would produce environmentally-friendly lightweight concrete and significantly reduce palm oil waste dumped at the landfill by incorporating high volume waste from palm oil industry.

1.6 Layout of Report

This thesis is typically divided into eight chapters, namely introduction, literature review, methodology, results of mechanical properties and durability properties and lastly the conclusion. This thesis begins the research design that includes the literature review related with this research at present. In the first chapter, it highlights the objective of this research, research scope as well as the significance and lastly the layout of the thesis.

Chapter two briefly review literature related to the present study of lightweight aggregate concrete and also the improvements made to the concrete. The literature review consists of the properties regarding the new materials for construction utilized in this study, production and also benefits to the construction industry. Palm oil clinker (POC) and palm oil fuel ash (POFA) used in this concrete research were examined in terms of its properties. The chapter also included the discussion of the mechanical and durability properties of concrete.

Chapter three present the details on how to conduct this research. This chapter covers the research design and methodology, including material preparation, design mix used, standards and methods followed in carrying out the research. Chapter four discussed the influence of curing regime towards compressive strength, flexural strength, splitting tensile strength and modulus of elasticity performance of palm oil clinker lightweight aggregate concrete with different percentage of POFA. Chapter five covers the data presentation, results and analysis of palm oil clinker lightweight aggregate concrete with POFA in terms of durability with respect to its acid resistance, sulphate resistance, carbonation and water absorption. Chapter seven concludes this thesis with a number of conclusions and several recommendations for improving this study.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

For nearly centuries, lightweight concrete has been used in the construction industry and continues to expand with more innovative and reliable material that is more sustainable. In 1981, a review of the international use of lightweight concrete in highway bridges concluded that outside the United Kingdom, lightweight aggregate concrete (LWAC) have been used widely and successfully in bridge construction for over 50 years. It further concluded that decisions to use lightweight concrete were generally because of the economic advantage, with savings in reinforcement and prestressing steel, reduced construction costs and simple piers and foundations. In 1991, it is reported that there were more than 300 major lightweight concrete bridges in North America, at least 100 in the Soviet Union (then), a significant number in Europe and incredibly, more than 2000 short span precast lightweight concrete bridges in the province of Alberta, Canada.

The review also referred to 30 years of experience of using lightweight aggregate concrete (LWAC) in bridge construction in Canada with no difference in maintenance costs compared with normal weight concrete and 20 years in Japan, where lightweight aggregate concrete performed at least as normal weight concrete. A United Kingdom survey, also published in 1991, investigated the performance of 40 lightweight aggregate concrete structures up to 30 years old, of which seven were bridges, and reported 'no evidence that lightweight aggregate concrete is any durable than normal weight concrete'. Clearly, the use of lightweight concrete in construction generally, and bridge construction in particular, is not new and its cost effectiveness and long-term performance has been well demonstrated and documented. The properties of lightweight aggregate concrete and its application in structures is covered by both British and European Standards.

2.2 Classification of Lightweight Concretes

In general, lightweight concrete is more expensive than ordinary concrete and mixing, handling and placing also require considerably more care and attention than ordinary concrete. However, for many purposes the advantages of lightweight concrete outweigh its disadvantage. Lightweight concrete is classified according to the purpose for which it is to be used. Lightweight concrete can be categorized by density into three broad types: low density, low strength concrete, which has useful insulative properties; moderate density, moderate strength concrete, which, among other applications, is used for making concrete blocks; structural lightweight concrete, which has a density slightly lower than normal concrete and is used for supporting sections and foundations (Short and Kinniburgh, 1978 and Bhatty and Reid, 1989).

Moderate strength lightweight concrete requires a fair degree of compressive strength, and thus they fall about midway between the structural and low-density concretes. These are sometimes designed as “fill” concretes. Compressive strengths are approximately 7.0 MPa to 17.0 MPa (Neville, 2011) with density of between 800 to 1400 kg/m^3 (ACI 213R, 2003). The insulation characteristics are intermediate which is between structural and low density lightweight concrete. Moderate-strength lightweight concrete used for concrete block and other applications where some useful strength is desirable. Low density concrete is employing chiefly for insulation purposes due to its low coefficient of thermal conductivity. With low unit weight, seldom exceeding 800 kg/m^3, heat insulation value is high. This concrete strength are low, ranging from about 0.69 to 6.89 N/mm^2.

Structural lightweight concrete is a versatile building material typically with unit weights from 40 to 57 kg/m^3 and compressive strengths from 17 MPa to more than 55 MPa. Since it is generally 20% to 40% lighter than normal weight concrete, a structure's dead load can be reduced, its foundation costs lowered, and it's concrete and rebar lessened. Structural lightweight concrete also resists fire better than normal weight concrete because of its lower thermal conductivity and its lower coefficient of thermal expansion. The secret to high quality lightweight structural concrete lies in the aggregate used to produce the mix. Structural lightweight concrete has been used for bridge decks, piers and beams, slabs and wall elements.

2.3 Structural High Strength Lightweight Aggregate Concrete

Structural lightweight aggregate concrete with a minimized density at a definite strength level is called high strength lightweight aggregate concrete. Thus the term "high strength" in case of lightweight aggregate concrete is not related to the strength, but to the relation of strength to density. The production of high strength lightweight aggregate concretes are usually by using special artificial aggregates together with mineral or chemical admixtures. These investigations have demonstrated the possibilities of producing high strength lightweight aggregate concrete using selected artificial lightweight aggregates (Zhang and Gjorv, 1991 and Swamy and Lambert, 1983). However, by using pozzolanic and superplasticizer for improving binder strength and natural lightweight aggregates instead of processed artificial aggregates, the cost of structural concretes can be reduced. Lightweight aggregate concrete with increased strength and decreased unit weight can also be produced based on system of Portland cement, pozzolan and superplasticizer. Recent developments in high-strength concrete are based on the use of very effective combinations of high range water reducers and silica fume (Bache, 1988). There were no sufficient data available concerning mixture proportioning and behavior of this new type of concrete that can be useful for structure design and application. For all high strength lightweight aggregate concrete, high strength mortar matrix are used as in general the concrete strength will be limited by the efficiency of the aggregates. This fact is due to the brittle behavior of lightweight aggregate, in which affect the strength of the concrete. Consequently, the validity of the design and calculation have to be proven with regard to the use of high strength lightweight aggregate concrete in order to determine the possible limits of application.

2.3.1 Definition

High strength structural lightweight aggregate concrete is an important and versatile material in modern construction. These type of lightweight concrete can be made from variety of lightweight aggregates either from natural or manufactured aggregates. Examples of natural aggregates such as shales, pumice, diatomite, volcanic cinders and slates while manufactured aggregate can be from iron blast furnace slag, clay, sintered fly ash, and shale. According to RILEM (1978), the density of high strength lightweight aggregate concrete is often not more than 2000 kg/m^3. High strength structural lightweight aggregate concrete solves weight and durability problems in buildings and exposed structures. High strength lightweight aggregate concrete has strengths comparable to normal high strength concrete, yet is typically 25% to 35% lighter. It has many and varied applications including multistory building frames and floors, bridges, offshore oil platforms, and prestressed or precast elements of all types. Many architects, engineers, and contractors recognize the inherent economies and advantages offered by this material, as evidenced by the many impressive lightweight concrete structures found today throughout the world.

2.3.2 Mixing Ingredients

High strength lightweight aggregate concrete were made of ordinary Portland cement, lightweight aggregate, fine aggregate, water and superplasticizer.

2.3.2.1 Ordinary Portland Cement

The strength of lightweight aggregate concrete (LWAC) was often limited by the efficiency of the aggregates. Thus, in order to produce LWAC with higher strength, higher amount of cement content are required. According to Neville (2011), 260 to 630 kg/m^3 of cement are needed to produce lightweight aggregate concrete. Higher amount of cement needed for these type of concrete which 50% higher than the quantity of cement needed to produce ordinary concrete is due to the weak bond between the lightweight aggregate particles. Thus, more cement are required to bind the aggregates together. However, cement consumption in concrete contributes towards deforestation apart from increasing the global warming. The rise in world cement production, as shown in Figure 2.1 is due to its widespread use in construction activities and geographic abundance of its main raw materials. The growing cement industry is also due to factors like growing demand of housing, rising construction demand, rapid urbanization and GDP growth. In 2014, the world cement production is around 4.3 billion tonnes and China produces the most cement globally by a large margin at estimated 2.35 billion metric tons (Figure 2.2). Currently, half of the world's cement production was produced by China. Owing to the growing environmental concerns of the cement industry, alternative cementitious material such as palm oil fuel ash (POFA) that replace or supplement the use of Portland cement have become an area of increasing interest amongst researchers.

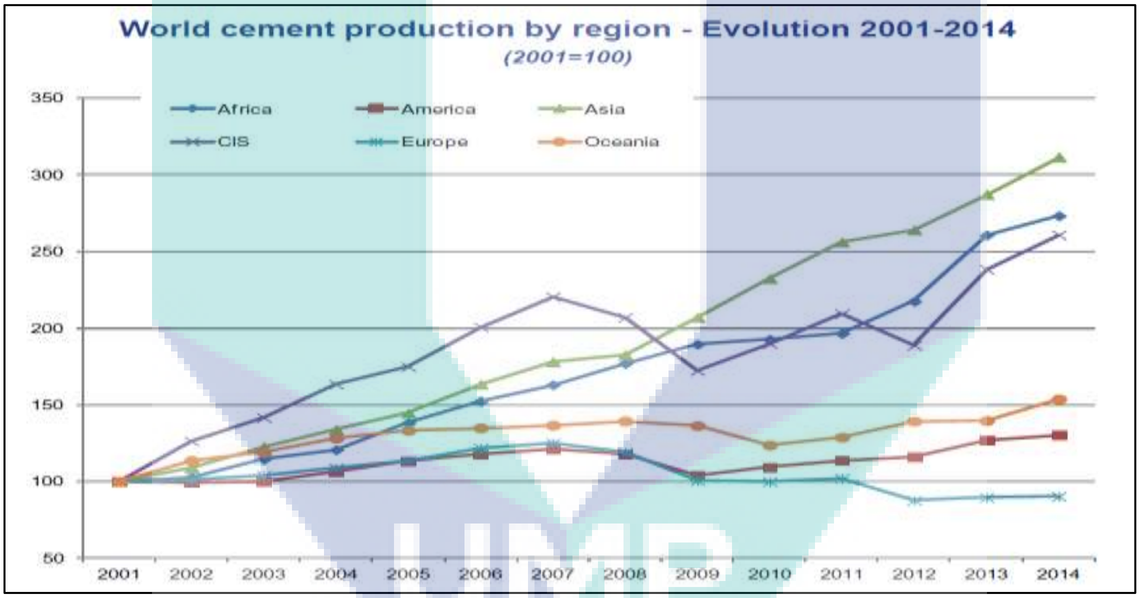


Figure 2.1. World cement production (2001-2014) (million tons)

Source: Cembureau (2014)

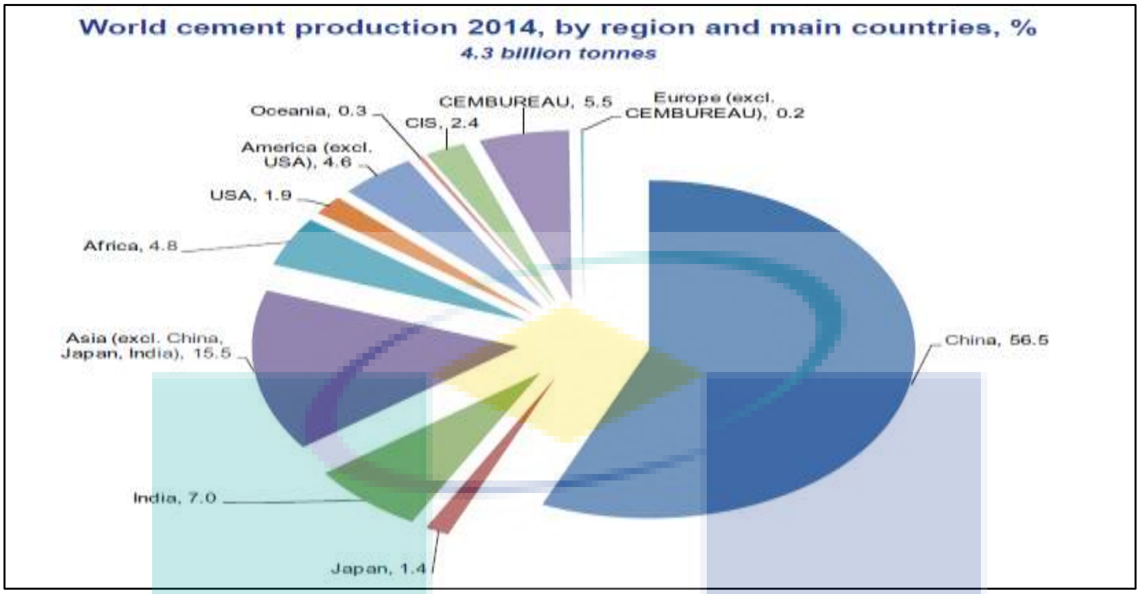


Figure 2.2. World cement production (2014)

Source: The IMF (2015).

2.3.2.2 Lightweight Aggregate

Lightweight aggregates are minerals, natural rock materials, rock-like products, and byproducts of manufacturing processes that are used as bulk fillers in lightweight structural concrete, concrete building blocks, precast structural units, road surfacing materials, plaster aggregates, and insulating fill. Other than that, lightweight aggregates are also used as soil conditioners and cover for architectural wall. The bulk density of coarse lightweight aggregates is usually around 960 kg/m^3. Lightweight aggregates may be classified into four groups that are natural lightweight aggregate materials, manufactured structural lightweight aggregate, manufactured insulating ultra-lightweight aggregate and byproduct lightweight aggregates.

Natural lightweight aggregate materials are prepared by crushing and sizing natural rock materials, such as pumice, scoria, tuff, breccia, and volcanic cinders. Manufactured structural lightweight aggregates such as shale, clay, or slate are prepared by pyro processing in rotary kilns or on traveling grate sintering machines. For manufactured insulating ultralightweight aggregates, these lightweight aggregate are prepared by pyro processing ground vermiculite, perlite, and diatomite. Byproduct lightweight aggregates which are prepared by crushing and sizing foamed and granulated slag, cinders, and coke breeze. Lightweight aggregate materials are produced mainly by two methods. The first method of lightweight aggregate production is from naturally occurring raw materials. The second method is byproduct production from iron and steel production.

Apart from natural and manufactured lightweight aggregate, agricultural waste which has properties like lightweight aggregate can also be used in lightweight aggregate concrete production. Examples of by-products used in lightweight aggregate concrete production are palm oil clinker (Rasel Ahmmad, 2014), oil palm shell (Shafigh et al., 2016) and coconut shell (Gunasekaran et al., 2017). The abundant agricultural wastes produced promotes its potential to be utilized as alternative lightweight aggregate in concrete. Apart from contribute towards reducing waste that is abundantly produced, the used of agricultural waste as lightweight aggregate in concrete is seen to promote green construction building, and at the same time preserves natural resources. In general, most lightweight aggregates have higher water absorption values compared to that of conventional aggregate. It has been reported that lightweight concretes with porous aggregates (high water absorption) are less sensitive to poor curing as compared to normal weight concrete especially in the early ages due to the internal water supply stored by the porous lightweight aggregate (Al-Khaiat and Haque 1998).

2.3.2.3 Fine Aggregate

Lightweight concrete can be manufactured with a combination of fine and coarse lightweight aggregate or coarse lightweight aggregate and normal fine aggregate. In some cases a portion or the entire fine aggregates may be a lightweight product. Fine aggregate used in lightweight aggregate concrete are usually originated from natural river sand or lightweight aggregate sand. Lightweight aggregate sand which is lighter and lower in density than conventional fine aggregate would produce lighter concrete which in turn reduces the overall weight of the structure. Complete placement of normal weight fine aggregate with a lightweight aggregate will decrease the concrete density by approximately 160 kg/m^3. However, the use of lightweight fine aggregate would reduce the concrete strength as the concrete density becomes lower (Chandra & Berntsson, 2002). Thus, proper selection of lightweight fine aggregate with suitable design mix is essential in order to obtain concrete with desirable strength.

2.3.2.4 Water

The water demand of lightweight aggregate concrete is strongly affected by the surface texture and shape of the aggregate particles. One important consequence of the large variation in the water demand of concretes made with different lightweight aggregate is that, to achieve a given required strength, there has to be a corresponding variation in the cement content: this way the water/cement ratio is maintained but, as already mentioned, the value of the actual water/cement ratio is not normally known. A lower w/c ratio of 0.4 is generally specified if a higher quality concrete is desired. Using a low w/c ratio is the usual way to achieve a high strength and high quality concrete, but it does not guarantee that the resulting concrete is always appropriate for countertops. Unless the aggregate gradation and proportion are balanced with the correct amount of cement paste, excessive shrinkage, cracking and curling can result.

Good concrete results from good mix design, and a low w/c ratio is just one part of a good mix design. The more the w/c ratio is increased (that is, the more water that is added for a fixed amount of cement), the more the strength of the resulting concrete is reduced. The simplest way to think about the w/c ratio is to think that the greater the amount of water in a concrete mix, the more dilute the cement paste will be. This not only affects the compressive strength, it also affects the tensile and flexural strengths, the porosity, the shrinkage and the color. This is mostly because adding more water creates a diluted paste that is weaker and more susceptible to cracking and shrinkage. Shrinkage leads to micro-cracks, which are zones of weakness. Once the fresh concrete is placed, excess water is squeezed out of the paste by the weight of the aggregate and the cement paste itself. When there is a large excess of water, that water bleeds out onto the surface. The micro channels and passages that were created inside the concrete to allow that water to flow become weak zones and micro-cracks.

Other than that, the impurity in water samples used in mixing concrete can impair the strength of concrete especially the compressive strength of concrete (Abram, 1924). In a similar way, water used for curing concrete can impair the strength of the concrete (Smith, 1976). Impurities and deleterious substances which are largely introduced from water used in mixing concrete are likely to interfere with the process of hydration, preventing effective bond between the aggregates and matrix. The impurities sometimes reduce the durability of the aggregate (Neville, 2011).

2.3.2.5 Superplasticizer

It has been recognized that the use of superplasticizer is very effective to improve the workability of concrete. Generally, lightweight aggregate has high water absorption due to the porous aggregate and the reduction of water-cement ratio in fresh concrete is usually regarded as a negative phenomenon as it can lead to loss of the mixture workability (Domagala, 2015). Superplasticizing admixture able to improve the lightweight concrete workability at very low water-cement ratio, avoiding the segregation problems, has been developed. The general chemical admixtures used to reduce the water demand for a given workability is Type F water reducers (ASTM C 494). A number of researchers (Yeginobali, 1996; Rasel Ahmmad, 2014 and Shafigh et al., 2014) used Type F superplasticizer to increase workability during the production of lightweight aggregate concrete.

Therefore, the addition of superplasticizer is vital to achieve the required flowability in the fresh state of lightweight aggregate concrete mixture containing low water content. Adding superplasticizer in the concrete mix will cause dispersion of cement particles. The dispersion of cement particles caused as a result of negative charge left on the admixture adsorbed cement particle, which will repel the other cement particles. This phenomenon is called electrostatic repulsion. Due to the deflocculating action, more uniform dispersion of cement particles were produced. In other words, superplasticizer enhance the workability of the concrete mix allowing reduction of water-cement ratio. Reduction in water-cement ratio would increase the concrete strength (Alsadey, 2012). Yamakawa et al. (1990) highlighted that the concrete strength increase when superplasticizer was added due to the effectiveness of compaction producing denser concrete. The improvement of concrete mechanical properties is the result from the reduction of the total porosity and the improvement of the workability of the fresh concrete state (El-Gamal et al., 2012). Conclusively, superplasticizer play a vital role in lightweight aggregate concrete in improving the workability and strength of concrete.

2.3.3 Density of Lightweight Aggregate Concrete

The equilibrium density of lightweight concrete is a standardized value that approximates the density of in-place concrete in service. The ACI 318 Building Code for Structural Concrete defines lightweight concrete as concrete containing lightweight aggregate meeting the requirements of ASTM C330 with an equilibrium density of the lightweight concrete between 1440 kg/m^3 and 1850 kg/m^3. Lower concrete density may be specified for non-structural applications. ASTM C567 use the standard test method for determining the density of structural lightweight concrete in various conditions and the relationship between them. ASTM C567 provides procedures for determining the equilibrium density and oven dry-density of lightweight concrete. However, because it takes a long time to obtain the measured equilibrium density, ASTM C567 provides a method of calculating the approximate equilibrium density from the oven-dry density. Oven dry density can be reached by structural lightweight concrete after placing in an oven at 110 ± 5 °C for a period of time sufficient to react constant weight. The British Standard, BS 81110: Part 2: 1985 classified lightweight concrete as concrete having densities of 2000 kg/m^3 or lower while the Draft International Standard Model Code for Concrete Construction classifies lightweight concrete as having densities between 1200 and 2000 kg/m^3. However, according to Neville (2011), the practical range of densities of lightweight concrete is between about 300 and 1850 kg/m^3.

The density of structural lightweight aggregate concrete will decrease as it dries and will eventually reach equilibrium with its environment. The absorption and moisture content of the lightweight aggregate are principal factors that impact the difference between the fresh bulk density of lightweight concrete and its equilibrium density. In service conditions, the decrease in density is a function of aggregate moisture content, ambient conditions, and the ratio of the surface area to the volume of the concrete member. There are different types of lightweight aggregate depending on the source of the materials and the method of manufacture. Absorption of lightweight aggregate sources can range typically from 6 to 20% or more. Lightweight concrete made with aggregates with higher porosity (absorption) may take longer time to reach equilibrium density. In ASTM C567, it is indicated that based on extensive tests the equilibrium density will be approximately 50 kg/m^3 greater than its oven-dry density. Equilibrium density is used in specifications and for structural design of structures.

2.3.4 Compressive Strength of Lightweight Aggregate Concrete

The use of high strength lightweight concrete in buildings and bridges has construction related benefits such as providing longer spans. High strength concrete relies more heavily on the quality of the aggregate than does low or even medium strength concrete. In production of high strength and durability of lightweight aggregate concrete, low absorption lightweight aggregates are more preferable (ACI 357-97). According to ASTM C 330, lightweight concrete has a compressive strength in excess of 17.25 MPa at 28 days of age when tested in accordance with methods stated in ASTM C 330. Lightweight concrete has strengths comparable to normal weight concrete, yet is typically 25% to 35% lighter. According to Neville (2011) lightweight aggregate concrete strength can be increased up to 70 MPa. Lightweight concrete with compressive strengths of up to 34.5 MPa has been used in commercial construction routinely since the early 1930’s. However, during the last two decades, much higher lightweight concrete strength has been specified. Such wide range of compressive strength is due to different type, texture and density of coarse aggregate used (Mehta and Monteiro, 1993).

The strength of lightweight aggregate concrete is influenced by different source, type, shape and texture of lightweight aggregate used (ACI 213R, 2009). Rougher surface aggregates creates stronger bond between the aggregate and paste producing higher concrete strength. Due to the different properties of lightweight aggregate from different source, lightweight aggregate concrete strength mix design were determined using trial mixes unlike normal weight concrete that can be determine based on general parameters such as water-cement ratio. According to Adámek et al. (2007), the grains of porous lightweight aggregates is the source of weaker element of the lightweight aggregate concrete structure. The porous aggregate contribute towards lower lightweight aggregate concrete strength than normal conventional concrete. The strength of lightweight aggregate concrete is also influenced by water cement ratio and cement content

(Neville, 2011). The effect of water cement ratio to lightweight aggregate concrete is the same as ordinary concrete (Clark, 1983). The higher the water absorption of lightweight aggregate, the higher the water requirement will be, resulting in concrete with higher porosity and lower strength. The higher the cement content in lightweight aggregate mix, the greater the strength of the concrete. Increasing in cement content will increase the production of C-S-H gel around the cement particles

2.3.5 Flexural Strength of Lightweight Aggregate Concrete

Flexural strength is a measure of concrete tensile strength in bending. Numerous studies on lightweight aggregate concrete have been performed focusing on determining the mechanical properties such as flexural strength. It was reported that the flexural strength of plain lightweight aggregate concrete is lower than normal weight concrete of the same compressive strength (Domagala, 2011). Previous studies shows that flexural strengths for lightweight aggregate concrete values with density within 1200 to 1600 kg/m^3 were generally rather low that is below 3 MPa (Bogas et al., 2013). Holm and Bremner (2000) reported that the flexural strength of high strength lightweight aggregate concrete was generally 9-11% of compressive strength. According to Hassanpour et al., (2012), lightweight aggregate concretes without fibers perform poorly compared to normal concrete in terms of flexural strength. On the other hand, the increase in flexural strength due to the addition of fiber in lightweight aggregate concrete is higher than in normal weight concrete (Balendran, 2002). Similar to conventional aggregate, the failure in tension for lightweight aggregate concrete occurs due to the breaking of bond between the aggregate and cement matrix or by fracture of the concrete matrix itself (Gunasekaran et al., 2011). Smaller size aggregate produces higher compressive strengths in concrete compared to concretes containing larger aggregate due to its higher packing density. However, by using fibers, mixes with flexural strengths of up to 7 MPa can be obtained at 28 days.

2.3.6 Modulus of Elasticity of Lightweight Aggregate Concrete

Knowledge of the elastic modulus of concrete is essential in the determination of the deflection of reinforced and prestressed concrete structures. Estimating the modulus of elasticity of concrete is generally based on compressive strength, which is not a satisfactory practice as the value of the elastic modulus of concrete not only depends on compressive strength but is also affected by the type of aggregate used in the concrete. The problem may become more acute if the conventional aggregates are to be substituted with artificial or natural aggregates suitable to the local conditions. Teychenne et al. (1978) stated that the elastic modulus of concrete depends on the aggregates used. Different type of lightweight aggregate used produces different modulus of elasticity value. High loads are required to deform lightweight aggregate concrete using stiffer lightweight aggregate due to its higher value of elastic modulus (Hull and Clyne, 1996). On the other hand, lower lightweight aggregate stiffness will result in larger deformation of lightweight aggregate concrete.

The modulus of elasticity of lightweight aggregate concrete also depends on the aggregate surface texture (Neville, 2011). Lightweight aggregate with rough surface texture provides mechanical interlocking between the aggregates and cement paste. The modulus of elasticity increased with the increase in the crushing strength of lightweight aggregate. The modulus of elasticity of lightweight aggregate concrete is about 60-70 per cent of that of normal weight concrete. Yang and Huang (1998) suggested that the modulus of elasticity of lightweight aggregate concrete is mainly affected by the volume content and properties of lightweight aggregate. It can therefore be concluded that the volume content of lightweight aggregate is one of the primary parameters that must be considered in the development of models for lightweight aggregate concrete. This also confirmed that the shape of lightweight aggregate concrete has some influence on the modulus of elasticity of lightweight aggregate concrete.

2.3.7 Splitting Tensile Strength of Lightweight Aggregate Concrete

Shear, torsion, bond strength, development length and crack resistance are related to tensile strength of the coarse aggregate and mortar phases and the degree in which the two phases are securely bonded. Traditionally, tensile strength has been defined as a function of compressive strength, but this is known to be only a first approximation that does not reflect aggregate particle strength, surface characteristic or moisture’s content and distribution. The splitting tensile strength of lightweight concrete is used in structural design criteria. The tensile strength of lightweight aggregate concrete was about 0.8-0.85 of that of normal weight concrete (NWC) of equal strength. Contrary to compressive strength, the LWAC with less porous aggregates has lower tensile structural efficiency than NWC. The elastic modulus of LWAC is affected by the volume content, particle density and shape index of LWA (Cui et al., 2012).

Tensile strength tests on lightweight concrete specimens that undergo some drying correlate well with the behavior of concrete in actual structures. Moisture loss progressing slowly into the interior of concrete members will result in the development of outer envelope tensile stresses that balance the compressive stresses in the still-moist interior zones. ASTM C 496 requires a 7-day moist curing and 21-day laboratory air drying at 23°C at 50% relative humidity before conducting splitting tests. Lightweight concrete splitting tensile strengths vary from approximately 75 to 100% of normal weight concrete of equal compressive strength. Replacing lightweight fine aggregate with normal weight fine aggregate will normally increase tensile strength. Further, natural drying will increase splitting tensile strength.

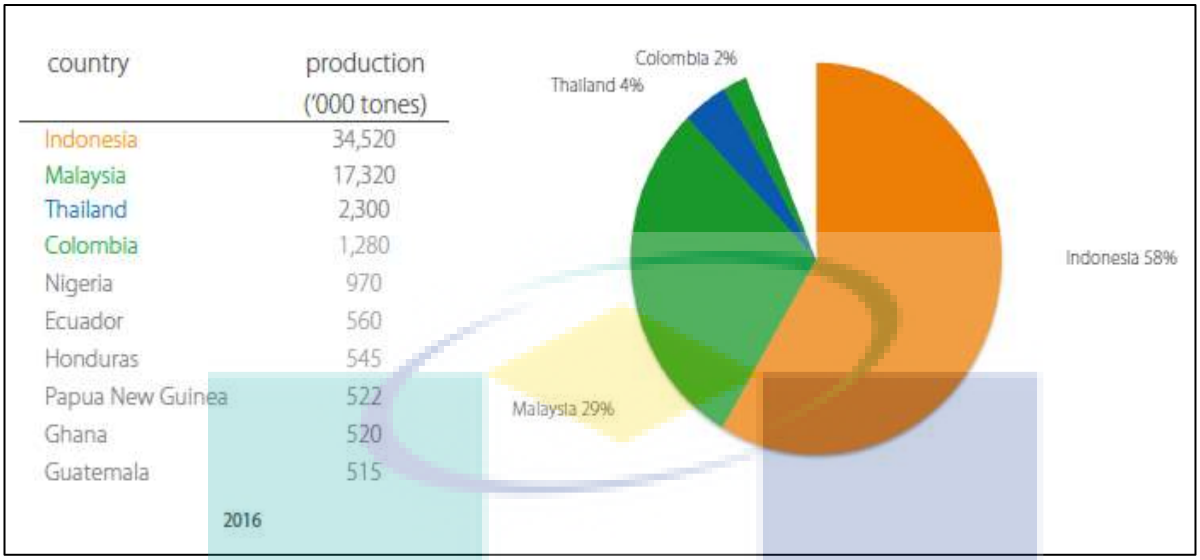
2.3.8 Water Absorption of Lightweight Aggregate Concrete

The estimation of water absorption by aggregates is still one of the major challenges related to the production of structural lightweight aggregate concrete. This makes it harder to control the effective water content in concrete, which affects the mixing, workability, transportation, placement and compaction of structural lightweight aggregate concrete and, consequently, its mechanical properties and durability. In terms of durability, many LWAC can perform equivalent to or better than normal weight concretes. The durability of LWAC depends mainly on the types of lightweight aggregate used apart from the composition of cement paste. Water absorption is particularly important in concrete, as well as being important for durability. It can be used to predict concrete durability to resist corrosion. However, because of the cellular nature of lightweight aggregates, the absorption is higher than most normal weight aggregates. In other words, the porous nature of lightweight aggregates makes them absorbs more water. Generally, the absorption capacity of lightweight aggregate concrete is high due to the porous nature of aggregate used (Bozkurt and Yazicioglu, 2010). The variation in absorption capacity of LWAC depends on the lightweight aggregate porosity that differs from one type to another.

2.4 Oil Palm Industry in Malaysia

Palm oil production is vital for the economy of Malaysia, which is the world's second-largest producer of the commodity after Indonesia. Almost half of all palm oil consumed globally is grown in Indonesia, with Malaysia contributing another 29 percent (Figure 2.4). The growing trend of Malaysian palm oil production is illustrated in Figure 2.5. In 2018, crude palm oil (CPO) production climbed by 2.44% to 21.0 million tonnes against 20.50 million tonnes in the previous year. According to the Plantation Industries and Commodities Minister Datuk Seri Douglas Uggah Embas, the government is intensifying its efforts to realize the Gross National Income Contribution for the palm oil industry of RM 178 billion by 2020 (Malaysian Palm Oil Board, 2015). As a result, Malaysian palm oil industry continues to increase productivity thus contributing to greater income to the country.

This industry significantly contributes towards job arising jobs at various levels, higher yield for the government from the sale of products and services, tax collection and improve the welfare of Malaysian resident. However, due to the vast amount of wastes produce from this industry, it has created severe disposal problem (Awaluddin et al., 2015). Almost 70% of the volume from the processing of fresh fruit bunch is removed as wastes. The by-product generated from the oil palm industries includes empty fruit bunches (EFB), oil palm shell (OPS), palm oil fuel ash (POFA), oil palm trunks (OPT) and palm oil mill effluent (POME). However, by looking at the high economic potential from this industry, it is necessary to ensure that the palm oil industry remain for the long term by adopting sustainable palm oil waste management practices.



country	production ('000 tones)
Indonesia	34,520
Malaysia	17,320
Thailand	2,300
Colombia	1,280
Nigeria	970
Ecuador	560
Honduras	545
Papua New Guinea	522
Ghana	520
Guatemala	515

2016

Figure 2.3 World Palm Oil Production in 2016

Source: Varqa, (2017)

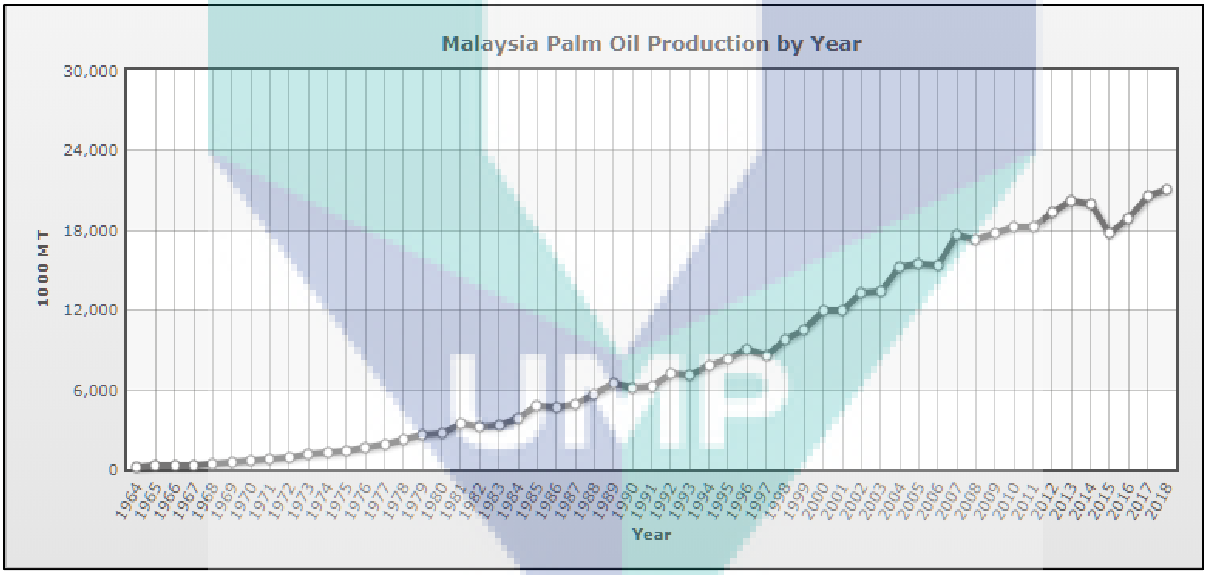


Figure **Error! No text of specified style in document.**.4 Production of palm oil in Malaysia

Source: United States Department of Agriculture (2018)

2.5 By-Product of Oil Palm Industry

Oil palm is the most important product from Malaysia that has helped to change the scenario of it's agriculture and economy. By looking at the trend of Malaysian palm oil production which increases over the years (Figure 2.4), it is foreseen that a larger amount of by-product would be generated. Wastes which is produced from the oil palm industries include oil palm trunks (OPT), palm oil fuel ash (POFA), palm oil clinker (POC), oil palm shells (OPS) and palm oil mill effluent palm (POME). However, the presence of these oil palm wastes has created a major disposal problem. Due to this problem, Malaysian Palm Oil Board was challenged to convert the agricultural waste to high value products.

According to Hosseini & Abdul Wahid (2015) this waste if not properly treated or controlled, it can lead to the effects of environmental pollution. The stench emitted from palm oil landfills also causes air pollution apart from liquid waste discharged into waterways and causes water pollution. On the other word, the issue surrounding palm oil waste disposal is expected to be more crucial and would create considerable negative impact to the environment if, not resolved. However, we can simply no longer afford to dispose the residues when there is an economically useful alternative. Researchers has long consider the current issues regarding the disposal of palm oil mill residues thus continuously working to transform these abundantly available by-products into useful products. In a scientific breakthrough, researchers have discovered how to turn palm oil waste into wellness.

2.6 Properties of Palm Oil Clinker

Clinkers are one of the wastes produced from burning of palm oil solid wastes in the boiler combustion process. Fresh fruit bunches, fibers and shells, as solid wastes, were used as fuel to generate steam at the palm oil mills. After burning, porous lumped clinker is formed. It is like a porous stone, grey in colour, flaky and irregular in shape (Mohammed et al., 2011). Palm oil clinker is abundantly available and is normally treated as a waste with no economic value. This by-product is collected from inside the boiler. The clinkers were flaky and irregular shaped while the edges were rough and spiky as shown in Figure 2.5. The physical properties such as water adsorption, moisture content and bulk density are shown in Table 2.1.

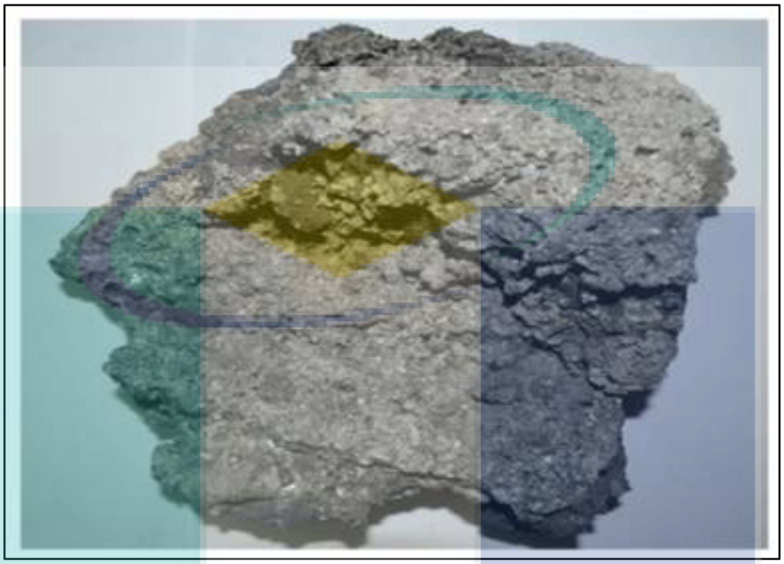


Figure 2.5. Palm oil clinker

Source Kanadasan et al. (2015)

Table 2.1

Physical Properties of Fine Palm Oil Clinker

Properties	**Results**
Aggregate size (mm)	5–14
Bulk density (kg/m^3)	781.08
Specific gravity (SSD)	1.82
Moisture content	0.07
Water absorption (24 h)	4.35
Fineness modulus	6.75
Los Angeles abrasion value (%)	27.09
Aggregate impact value (AIV) (%)	25.36
Aggregate crushing value (ACV) (%)	18.08

Source: Mohammedet al. (2014)

2.7 Utilization of Palm Oil Clinker In Concrete

Previous studies (Omar and Mohamed, 2002) have shown that palm oil clinker can be used as coarse aggregate in concrete and that the density and the 28-day compressive strength of concrete containing this aggregate fulfil the requirements of structural lightweight aggregate concrete. Contemporary studies have shown that palm oil clinker can be used as lightweight aggregate for producing structural lightweight concrete with compressive strength in the range of 17 - 53.6 MPa which is a range of normal strength to high strength ranges of lightweight concrete. Although previous researches have shown separately that palm oil concrete can be successfully used as structural lightweight concrete (Mohammed et al., 2011) the lightweight concrete is still not a common construction material in the construction industry and there has been some reticence concerning its use in concrete structures. In terms of structural properties, Mohammed et al. (2013) found that palm oil clinker concrete (POCC) beam satisfies the deflection criteria of BS8110 code up to 0.54% of reinforcement.

2.8 Properties of Palm Oil Fuel Ash

Palm oil fuel ash was produced from palm oil fibers, nut shells, palm kernel and empty fruit bunches which are incinerated in boilers. These palm oil ashes possesses pozzolanic characteristic that can improve concrete performance in terms of mechanical and durability properties when properly treated. Studied by Awal and Hussin (1997), Jaturapitakkul (2007), and Tangchirapat (2009), proved that POFA has a good pozzolanic reactivity. The fineness of pozzolanic ash also tends to affect both the fresh and hardened state properties of concrete (Awal, 1998). According to Chang et al. (2012), the colour of treated ground palm oil fuel ash was light brown to grayish red due to unburned residual has been removed. Generally, the ash used as pozzolanic material needs to produce in a finer size so that can function effectively in increasing the strength of concrete. According), the increased fineness of POFA will reduce the expansion and loss in the compressive strength of concrete. In finely divided form and in the presence of moisture, it will chemically react with calcium hydroxide (lime) at ordinary temperatures to form compounds having cementitious properties. Table 2.2 presents the chemical composition of POFA used after it has been treated using high temperature and grinding method.

Table 2.2
Chemical Composition of Unground and Ground Palm Oil Fuel Ash

Composition	Ground POFA	Ultrafine POFA
Silicon dioxide (SiO_2)	51.18	65.01
Aluminium Oxide (AL_2O_3)	4.61	5.72
Ferric Oxide (Fe_2O_3)	3.42	4.41
Calcium Oxide (CaO)	6.93	8.19
Magnesium Oxide(MgO)	4.02	4.58
Sulphur Oxide (SO_3)	0.36	0.33
Pottasium Oxide (K_2O)	5.52	6.48
Sodium Oxide (Na_2O)	0.06	0.07
Carbon (C)	19.05	0.09
Loss of Ignition (LOI)	21.6	2.53
SiO_2+ AL_2O_3+ Fe_2O_3	59.21	75.14

Source: Megat Johari et al. (2011)

2.9 Utilization of Palm Oil Fuel Ash in Concrete

Palm oil fuel ash (POFA) has been known to possess a pozzolanic property that can partially replace ordinary Portland cement (OPC) in concrete. POFA used in conventional concrete was first initiated in Malaysia as a complementary cementing material in year 1990. However, the highest amount of POFA that can be added in concrete is only 10% with result comparable with the control specimen (Tay, 1990). However, researchers managed to produce concrete with enhance strength by utilizing smaller POFA size after grinding the pozzolanic material into finer sizes (Awal and Hussin, 1997). This is due to the ground POFA with higher fineness is a reactive pozzolanic material that speeds up the pozzolanic reaction enabling the high strength concrete to gain strength faster.

2.10 Durability of Concrete

Acid can damage the lightweight aggregate concrete from different aspects. The resistance of lightweight aggregate concrete against acid attack mainly depends on the type of lightweight aggregate, amount of cement used as well as concrete composition. Normal weight concrete comparing with lightweight aggregate concrete is seen to be more vulnerable to acid damage. Compared to normal weight concrete, lightweight aggregate concrete requires more cement for its production thus more $Ca(OH)_2$ will be produced. $Ca(OH)_2$ which is vulnerable towards acid attack would reacts with HCl to produce $CaCl_2$ lowering the degree of alkalinity. $CaCl_2$ which is water-soluble calcium compounds are then leached away by aqueous solution. This resulted in broken down cement compound and the concrete to lose its strength. Apart from that, acid attacks increase the concrete porosity thus the acid penetration to the concrete will become easier.

Sulphate attack is one of the common degradation mechanisms for concrete in severe environments. This mechanism is also one of the important factors influencing the durability of concrete. Sulphate can react with hydrated calcium aluminate and produce expansive products, such as ettringite and gypsum. As a result, the concrete becomes more compact and its strength is slightly increased in the initial stage of the reaction process. However, with the gradual formation of an expansive stress on concrete through continuous accumulation of expansive products, tensile stress is developed in the concrete. Once the stress exceeds the tensile strength of the concrete, cracks are formed that finally result in the reduction of the bearing capacity (Santhanam et al., 2003; Schmidt, 2009 and El-Hachem, 2012). This causes the concrete to crack, further damaging the concrete.

Carbonation varied with density, strength and exposure conditions and was mostly less than 10 mm. Laboratory studies by Grimer (1967) and Schulze and Gunzler (1968) have also shown that the carbonation rates were low in high density and strength LWC. Swenson and Sereda (1968) found that too high or too low moisture content of LWC was not conducive to rapid carbonation. Swamy and Jiang (1996) found that carbonation was higher for concrete with higher total porosity at a given water to cement ratio. Roy et al. (1996) and Atis (2003) found that the carbonation was inversely proportional to compressive strength. Haque et al. (2004) reported an improvement in carbonation performance of LWC when fine LWA ‘lytag’ in LWC was replaced with normal weight sand and the carbonation depth in sanded LWC was comparable to that of equal grade NWC. Gu¨ndu¨z and Ug˘ur (2005) investigated the carbonation of pumice aggregate LWC and found that carbonation lowered as the aggregate to cement ratio was lowered. Carbonation depth also varied with the type of LWA used. However, a good quality matrix (high-strength concrete with low water to cement ratio) was necessary to have better carbonation performance.

2.11 Summary of Research Gap

During the past decades, many experimental studies involving palm oil waste in concrete have been conducted. Most palm oil waste in concrete studies mainly focused on utilizing single palm oil waste material in concrete such as palm oil fuel ash (Tangchirapat et al. 2009), oil palm shell (Mannan and Ganapathy, 2001) and palm oil clinker (Mohammed et al., 2011). However, studies study on integration of palm oil fuel ash (POFA) and palm oil clinker (OPC) in production of lightweight aggregate concrete are scarce in the technical literature. Moreover, there is no publication neither on the mechanical properties and durability performance are available for this research.

Therefore, in this research, the performance of palm oil fuel ash as partial cement replacement in palm oil clinker lightweight aggregate concrete towards mechanical and durability properties have been investigated. The mechanical testing involved are compressive strength, flexural strength, modulus of elasticity and splitting tensile strength. The durability of palm oil clinker lightweight aggregate concrete containing palm oil fuel ash as partial cement replacement when exposed to acidic and sulphate will also be examined to evaluate this concrete performance towards aggressive environment. Apart from that, the test towards carbonation and water absorption will also conducted which explain the internal structure in terms of capillary pore of this concrete.

CHAPTER 3

METHODOLOGY

3.1 Introduction

The methodology chapter tackles the detail on the experimental work in scientific method and also all types of testing deployed in this research. The beginning part of this chapter present the details of the mixing ingredients used for the specimens preparation. This chapter followed by section presenting brief explanation on trial mix method that been used to produce POC LWAC mix. Then, steps to produce POC lightweight aggregate concrete with 0%, 10%, 20%, 30% and 40% POFA was also explained. After that, details on types of test conducted for this experimental work was also presented. To determine the mechanical properties, the primary tests included compressive strength, flexural strength, modulus of elasticity and splitting tensile strength. For durability properties, the tests involved are acid attack, sulphate attack, carbonation and water absorption.

3.2 Mixing Ingredients

Six main ingredients namely ordinary Portland cement (OPC), sand, palm oil clinker (POC), palm oil fuel ash (POFA), water and superplasticizer were used to produce the POC lightweight aggregate concrete with POFA samples in this experimental work.

3.2.1 Cement

For binding purpose, Orang Kuat Portland Cement brand from YTL Corporation was used throughout this experimental programme . Ordinary Portland Cement (OPC) was classified as Type I cement as according to MS EN 197 Part 1 (2014). Portland cement is known as common or general-purpose cement. It is commonly used for general construction especially when making precast and precast-prestressed concrete that is not to be in contact with soils or ground water. All the cement used were stored away from damp floors and stacked close together in a well-aired, clean and dry place.

3.2.2 Sand

Local river sand was used throughout this study. Testing of fine aggregates is done as per relevant BS or ASTM. The sand was air-dried until saturated surface dry (SSD) condition before kept in container to protect it from getting wet due to excessive moisture condition or rain.

3.2.3 Palm Oil Clinker

In this study, palm oil clinker (POC) was used as lightweight coarse aggregate. POC were collected from a palm oil mill located in the state of Pahang, Malaysia. The POC was obtained in large chunks during the oil palm shell and fiber incineration process. Before using, the POC were crushed using stone crusher and sieved using 10 mm and 5 mm sieve. The particles below 10 mm and above 5 mm was taken and used as coarse aggregate.

3.2.4 Palm Oil Fuel Ash (POFA)

Palm oil fuel ash as is a by-product obtained from burning palm oil shell and husk from a palm oil mill owned by Boustead Plantations Berhad which is located in Paloh Hinai, Pahang. The unprocessed POFA was sieved using 300 µm sieve in order to remove impurities that will affect the overall concrete strength. The collected palm oil ashes were dried in the oven at the temperature of 110 °C ± 5 for 24 h to remove moisture in it before sieved using 300 µm sieve to remove larger size of POFA particle. Then, it was ground for 30 000 cycles using modified Los Angeles abrasion machine to obtain finer particles that fulfill the fineness requirement of ASTM C618 (2017) for pozzolanic material. The chemical composition of POFA used in experimental work is presented in Table 3.1.

Table 3.1
Chemical Constituent of Palm Oil Fuel Ash

Chemical Constituent	**Percentage (%)**
Silicon dioxide (SiO_2)	41.8
Aluminium oxide (Al_2O_3)	31.0
Ferric oxide (Fe_2O_3)	9.0
Calcium oxide (CaO)	15.1
Magnesium oxide(MgO)	< 0.1
Pottasium oxide (K_2O)	2.6
Sulphur trioxide (SO_3)	< 0.1
Loss of ignition (LOI)	10.0

3.2.5 Water

In this research, tap water that is clean and free from impurities was used for mixing and curing purposes. For research involving durability purposes, distilled water was used during the preparation of chemical solutions.

3.2.6 Superplasticizer

In this research, SIKA Visco-Crete®-2199 superplasticizer purchased from Sika Kimia Sdn Bhd, Negeri Sembilan that meets the requirements of Type A water-reducing admixtures as stated in ASTM C494-05 (2005) was used. This type of admixture is chloride free according to BS 5075 and is compatible with all types of Portland Cement including Sulfate Resistant Cement

(SRC). The main function of this brownish liquid superplasticizer was used to reduce water in concrete production while maintaining the workability.

3.3 POC Lightweight Concrete Production

The mix proportion used in preparing the control specimens is presented in Table 3.2. The rest of the mixes were prepared by varying the percentage of POFA from 10%, 20%, 30% and 40%. Several steps have been followed in order to produce the concrete specimens. First of all, the mixer use for concrete mixing must be inspected to ensure that they are clean and free from dirt and debris. Then, the moulds to be used to pour fresh concrete were ensured clean and dirt free. Before concrete was placed in it, the mould was lightly oiled or greased in order to prevent concrete from sticking to it. Then, the weighted ingredients namely, palm oil clinker, sand, cement, palm oil fuel ash, water and superplasticizer were weighed to the desired amount accurately. After that, the weighted materials were poured into the rotating mixer and mixed for three to five minutes a lump-free pourable consistency is achieved. After a uniform, workable consistency mix was achieved, the mix were immediately taken out and poured inside the oiled mould. After compaction, the moulds were covered with gunny sack and left overnight before demoulded. The concrete specimens were demoulded one day (24 hours) after casting and cured.

Table 3.2. Mix proportion of POC LWAC control mix

Mix Proportions (kg/m^3)				
Cement	**Sand**	**POC**	**w/c**	**Sp (%)**
480	750	565	0.45	1

3.4 Experimental Program

The mechanical properties of the specimens namely compressive strength, flexural strength, modulus of elasticity and splitting tensile strength were investigated using cubes (100 mm x 100 mm x 100 mm), prisms (100 mm x 100 mm x 500 mm) and cylinders (100 mm diameter with 200 mm height) respectively. All the concrete specimens were subjected to two different types of curing namely water curing and air curing.. The durability testing involved in this research was acid attack, sulphate attack, carbonation and water absorption of concrete specimens.

3.5 Properties Measurement

3.5.1 Slump Test

The slump test is a means of assessing the consistency of fresh concrete. This test was conducted according to BS EN 12350-1 (2009) . Before commencing the test, the internal surface of the mould was thoroughly cleaned and freed from superfluous moisture and adherence of any old set. The mould is then placed on a smooth, horizontally leveled rigid and non-absorbent surface such as a rigid plate. During the filling process, the mould is held firmly in place by standing on the two foot pieces provided in the slump cone. The mould was filled in three layers, each approximately one-third of the height of the mould when tamped. Each layer is tamped 25 times of the tamping rod with the strokes being distributed uniformly over the cross-section of the layer. After the top layer is rodded, the concrete is struck off the level with a sawing and rolling motion of the tamping rod. The mould is removed from the concrete immediately, in 5 s to 10 s by raising it slowly in the vertical direction. The difference in level between the height of the mould and that of the highest point of the subsided concrete is measured. The difference in height in mm is the slump of the concrete.

3.5.2 Compressive Strength Test

Out of many test applied to the concrete, compressive strength is the utmost important test which gives an idea about all the characteristics of concrete. This mechanical test was conducted to measure the maximum amount of compressive load a concrete can bear before fracturing. The compressive strength of all concrete cubes of (100 x 100 x 100 mm) were measured following the procedures stated in MS EN 12390 Part 3 (2012). A total of 420 specimens with approximately 84 control specimens and 336 POC LWAC containing 0%, 10%, 20%, 30% and 40% POFA as partial cement replacement were tested. All the specimens were subjected to twor different types of curing regimes namely water curing and air curing The specimens were tested at the age of 7, 28, 60, 120, 180, 270 and 365 days of curing. Before the sample was placed inside the compressive strength test machine, the sample was weighed and recorded. Before placing the cube sample inside the compressive strength test machine, the testing machine bearing-surfaces was wiped to ensure it was clean. The sample was placed at the center of the lower plate and the load was applied. The maximum concrete strength was directly taken from the machine or calculated using Eq. 3.1 (MS EN 12390 Part 3, 2012).

$$\text{Compressive strength, } f_c = \frac{P}{A_c} \tag{3.1}$$

Where,

P = maximum load applied to the specimen (N)

A_c = cross sectional area of the specimen (mm^2)

3.5.3 Flexural Strength Test

Flexural strength, also known as modulus of rupture, bend strength, or fracture strength. This test was important in concrete to measure the concrete flexibility and also the bending properties of the material. The flexural strength of POC LWAC for control and concretes consisting various percentage of POFA was measured in accordance with MS EN 12390 Part 5 (2012) by using specimen with size of 100 x 100 x 500 mm. The flexural strength test was carried out at the age of 7, 28, 60, 120, 180, 270 and 365 days. This test was performed by using flexural testing machine with two point loading. The flexural machine consists of two supporting rollers and two load applying rollers that need to be wipe clean in order to remove grit. The maximum load read that was also known as the breaking load was recorded. The value of flexural strength f_{cf} was calculated by using Eq. 3.2 (MS EN 12390 Part 5, 2012).

$$f_{cf} = \frac{F \times l}{d_1 \times d_2^2} \qquad (3.2)$$

Where,

F = the breaking load (N)

d_1 and d_2 = the lateral dimensions of the cross sections (mm)

l = distance between the supporting rollers (mm)

3.5.4 Modulus of Elasticity

The modulus of elasticity of concrete is a function of the modulus of elasticity of the aggregates and the cement matrix and their relative proportions. This test was performed in order to determine the concrete ability to maintain its original form when stretched. A cylinder of 100 mm diameter and 200 mm length was used to determine the modulus of elasticity and will be tested according to BS 1881-121: 1983 as in (Figure 3.20). In this research, POC lightweight aggregate concrete cylinders containing 0% POFA and also other mixes of POC lightweight aggregate concrete cylinders containing 10%, 20%, 30% and 40% POFA were prepared and tested. After casting, these specimens were covered with wet gunny and demoulded after 24 hours. These specimens were then cured using different types of curing regimes namely water curing and air curing until the testing date. The specimens were tested at the age of 7, 28, 60, 120, 180, 270 and 365 days of curing. After the curing age, the rough surface of the concrete was smoothed using sandpaper. After that, the surface of the specimens were attached with two strain gauges at the center of the specimen with the distance of not less than 1/4 of the length of specimen from the end. After the specimen was ready, it was placed axially at the center of the machine. The static modulus of elasticity in compression, Ec was calculated using Eq. 3.3.

$$\frac{\Delta\sigma}{\Delta\epsilon} = \frac{\sigma_a - \sigma_b}{\epsilon_a - \epsilon_b} \tag{3.3}$$

Where

σ_a = upper loading stress (in N/mm^2)
σ_b = basic stress (0.5 N/mm^2)
ϵ_a = mean strain under the upper loading stress
ϵ_b = mean strain under the basic stress

3.5.5 Splitting Tensile Strength

The tensile strength is one of the basic and important properties of the concrete. However, the determination of tensile strength of concrete is necessary to determine the load at which the concrete members may crack. The test was done according to ASTM C496-11. This testing requires of three moulded cylinder specimens of Ø100 mm x 200 mm. Five types of concrete mixes containing various percentage of POFA (0%, 10%, 20%, 30%, 40%) were tested. The specimens were cured using different types of curing regimes namely water curing and air curing until the testing date. The specimens were tested at the age of 7, 28, 60, 120, 180, 270 and 365 days of curing. After the curing age, diametrical lines were draw on two ends of the specimen so that they are in the same axial plane. The diameter of the specimen was determined to the nearest 0.2 mm by averaging the diameters of the specimen lying in the plane of premarked lines measured near the ends and the middle of the specimen. The length of specimen was taken be nearest 0.2 mm by averaging the two lengths measured in the plane containing pre marked lines. One of the plywood strips was centered along the centre of the lower platen. The specimen was placed on the plywood strip and align it so that the lines marked on the end of the specimen are vertical and centered over the plywood strip. The second plywood strip was placed length wise on the cylinder centred on the lines marked on the ends of the cylinder. The assembly was positioned to ensure that lines marked on the end of specimen are vertical and the projection of the plane passing through these two lines interest the centre of the platen. The load was applied without shock and it was increased continuously at the rate to produce a split tensile stress of approximately 1.4 to 2.1 N/mm^2/min, until no greater load can be sustained. The maximum load applied to specimen was recorded. The appearance of concrete and any unusual feature in the type of failure was noted. The split tensile strength of the specimen was computed to the nearest 0.25 N/mm^2. The static splitting tensile strength, T was calculated using Eq. 3.4.

$$\mathrm{T} = \frac{2P}{\pi l d} \tag{3.4}$$

Where

T = splitting tensile strength (MPa)
P = maximum applied load indicated by the testing machine (N)
l = length, mm
d = diameter, mm

3.5.6 Response to Acid Attack

Acid resistance test was conducted to determine the effect of POFA as partial cement replacement towards acid resistance of POC lightweight aggregate concrete as cement replacement. During this test, three parameters were determined that were measurement of mass loss, visual assessment and strength deterioration has been done by (Vaishnavi and Kanta Rao, 2015). This test was conducted by preparing concrete cubes of 100 x 100 x 100 mm. All the concrete cubes were cured for 28 days using two types of curing regime namely water curing and air curing before immersing it in acid solution. After 28 days, the mass of all concretes were measured. Then, six specimens from each mixes were immersed in 5% (HCl) solutions for 1800 hours. At every 100 hour, the weight of the specimen was measured and any changes in terms of specimen shape and deterioration was observed until the period of 1800 hours. The pH of the hydrochloric acid solution was regularly monitored and adjusted to keep it constant that was of about 2 similar to experimental method adopted by Allahverdi and Škvára (2006). The mass loss was determined by using Eq. 3.5 (Janfeshan Araghi et al., 2015).

$$M_{Lt} = \frac{M_t - M_i}{M_i} \times 100 \tag{3.5}$$

Where

M_{Lt} = cumulative weight reduction
M_t = weight at time, t (kg)
M_i = initial weight before exposure to sulfuric acid (kg)

At the end of testing period, at 1800 hour, all the concretes were tested for strength loss using compressive strength machine. The average value of six specimens was taken and reported. Strength deterioration was determined using Eq. 3.6 (Olusuola and Joshua, 2012).

$$\text{Strength deterioration} = \frac{f_{cw}-f_{ca}}{f_{cw}} \times 100 \tag{3.6}$$

Where

f_{cw} = average strength of concrete cubes cured in water
f_{ca} = average compressive strength of cubes immersed in acid solutions

3.5.7 Sulphate Resistance Test

This test method provides a means of assessing the sulphate resistance that determine the durability performance of POC lightweight aggregate concrete cubes containing POFA as cement replacement. The sulphate solution was prepared according to ASTM C1012 (2004). The degree of sulphate attack was evaluated by measuring mass change similar to the experimental approach applied by Murthy et al., (2007). Five mixes of POC lightweight aggregate cubes containing 10%, 20%, 30% and 40% POFA were prepared and cured for 28 days using two types of curing regime namely water curing and air curing. Six specimens from each mix were immersed in 5% sodium sulphate (Na_2SO_4) solution for 12 months. Mass measurement and visual assessment of the concretes were conducted every week until the age of 12 months. The mass loss was determined by using Eq. 3.7 (Murthy et al., 2007).

$$\text{Mass loss (\%)} = \frac{m_1 - m_2}{m_1} \times 100 \tag{3.7}$$

m_1 = mass of specimens before immersion

m_2 = mass of specimens after immersion

3.5.8 Carbonation

Carbonation test was conducted to determine the carbonation depth of concrete and was covered by BS EN 14630 (2006). This test was carried out by spraying out an indicator solution called phenolphthalein on freshly exposed concrete surfaces. Five POC lightweight aggregate concrete prisms containing 0%, 10%, 20%, 30% and 40% POFA were prepared. All the specimens were cured using four types of curing regime namely water curing and air curing. The carbonation test was conducted at 28, 60, 120, 180, 270 and 365 days. On the testing day, the samples were split up, cleaned and brushed. Then, the indicator was sprayed on the concrete surface in order to determine its carbonated area and thickness. The indicator would remain colourless when sprayed on carbonated area which shows that the concrete had lost its alkalinity with pH below 8.6. The depth of colourless region were measured using Vernier calliper which indicated the degree of carbon dioxide induced. On the other hand, the indicator would change to pink colour when contact with non-carbonated area with pH was above 8.6.

3.5.9 Water Absorption Test

The water absorption test is done in accordance with BS 1881: Part 122 (2011). POC lightweight aggregate concrete cubes containing 0%, 10%, 20%, 30% and 40% POFA were prepared. All specimens were subjected to different types of curing namely water curing and air curing for 28 days. After 28 days curing, the concrete was dried inside oven for 72 h ±2 h. After the drying process, the specimens were cooled in sealed container for 24 h ±0.5. Immediately after the cooling process, the specimens were weighed and the mass was recorded. The specimens were then fully immersed in water at a depth at which there was 25 mm ± 5 mm of water above top of the specimens for 30 ± 0.5 minutes. After the immersion process, the specimens were shaken to remove water from the concrete surface. The concrete was then dried up using cloth as rapidly as possible until all water on the concrete surface was completely removed. The specimens were weighed and the mass was recorded. All the data were recorded and the degree of absorption was calculated using Eq. 3.10 (BS 1881: Part 122 (2011).

$$\text{Degree of absorption} = \frac{m_1 - m_2}{m_2} \times 100 \tag{3.10}$$

Where

m_1 = weight of specimen after immersed in water
m_2 = weight of specimen after dried up

CHAPTER 4

MECHANICAL PROPERTIES

4.1 Introduction

This chapter discussed the effect of POFA content towards dry density and mechanical properties of POC lightweight aggregate concrete. The beginning of these chapter discuss the dry density of these type of concrete when subjected to different types of curing for 28 days. The mechanical properties testing namely compressive strength, flexural strength, splitting tensile strength and modulus of elasticity were discussed throughout this chapter. All samples were subjected to different types of curing regimes namely water curing and air curing.

4.2 Compressive Strength

Figure 4.1 to 4.2 presents the compressive strengths data for 7, 28, 60, 90, 180, 270 and 365 days of age of POC LWAC made with different percentage of POFA and subjected towards different curing regimes namely water curing and air curing. The graph trend shows that the strength of all samples increases when the curing age increased. All water cured specimens exhibit better strength than air cured specimens. The results of compressive strength for all concrete percentages and for all curing regimes can be regarded as strength for structural lightweight concrete. It was reported by (Holm, 1994) and (Omar & Mohamed, 2002) that the 28-day compressive strength of high strength lightweight concrete must comply with minimum strength of 35 MPa. The compressive strength for all mixes were in the range of 43 to 64 MPa at the age of 28 days. The strength shows that these type of concrete is suitable to be used as high strength structural lightweight concrete. According to ACI 213R (2003), the minimum compressive strength for high-strength structural lightweight concrete is 40 MPa.

The need for adequate curing of concrete must be emphasized. Curing has a strong influence on the properties of hardened concrete as proper curing will increase the concrete strength. Evidently, curing method influences the strength development of POC LWAC containing different percentage of POFA. From the graph, water curing produces compressive strength higher than other types of curing for all POFA percentages. The reason behind its better strength is continuously chemical reaction called hydration of the ingredients in the cement, activated by water and mixing. Concrete requires water to react within its composition which in turn forms C-S-H gel that fills the voids of concrete and imparts strength to concrete. Continuously submerging the concrete inside water helps to reduce evaporation, so that continuous hydration can take place in the cement particles in concrete (Nahata et al., 2014). The graph trend also shows that the strength of all samples increases when the curing age increased.

According to Neville (2011), at least 80% of relative humidity is required for hydration to proceed. In case for air curing, as cement hydrates the internal relative humidity decreases causing the concrete to self-desiccate as no external water is provided. The concrete self-desiccated to a level where hydration stops. This may influence desired concrete properties, especially if the internal relative humidity drops below 80% within the first seven days. Thus, since hydration was not completed due to low humidity, air-curing caused a decrease in compressive strength for all specimens due to the evaporation of the water in concrete samples. The graph also shows that the hydration process stopped at 180 days of curing age due to missing of moisture inside concrete. Research done by Atis (2005) revealed that concrete with pozzolanic material is more sensitive to dry curing conditions. If the concrete is not cured and is allowed to dry in air, it will gain only 50% of the strength of continuously cured concrete (Mamlouk and Zaniewski, 2011).

POC LWAC samples with 10% POFA shows better compressive strength results than other specimens including control specimen. This is due to pozzolanic materials that are able to combine with portlandite in the presence of water to produce new reaction products called C-S-H gel that exhibits a binding character (Martinez-Ramirez et al., 2006 and Martens et al., 2009). Hydration process results in the formation of portlandite $Ca(OH)_2$, largely amorphous calcium silicate hydrates (C-S-H) and minor crystalline phases containing aluminium, iron, and sulphate. In the presence of POFA, it consumes Portlandite which is harmful that produced during the cement hydration will be reduced relatively during hydration process. This reaction is called pozzolanic reaction which produces more C-S-H gel. C-S-H gel particles fill spaces between aggregate grains, thereby resulting in a denser concrete matrix and interfacial transition zone between cement matrix and aggregates (Moon et al., 2016). This resulted in lower the permeability and increases the compressive strength of concrete.

Replacement of cement with 20% POFA resulted in strength comparable to control specimen. Replacement of POFA of more than these amount resulted in drier concrete mix thus produces voids upon hardened. 40% POFA replacement resulted in the lowest concrete strength due to higher voids. Concrete with high voids loses moisture to evaporation quickly, and this can lower internal moisture levels and stop hydration. If the concrete dries out, it stops gaining strength. When more than 30% is replacing, the compressive strength goes below than targeted strength of 60 MPa when cured under water curing. Thus it shows that higher amount of POFA cannot be used to replace cement in concrete. The maximum amount of POFA that work efficiently was determined at 10% replacement. Researchers figure out that it is not recommended to replace Portland cement Type I by POFA at rates higher than 20% (Hussin et al, 2009; Sooraj, 2013 and Muthusamy et al., 2015).

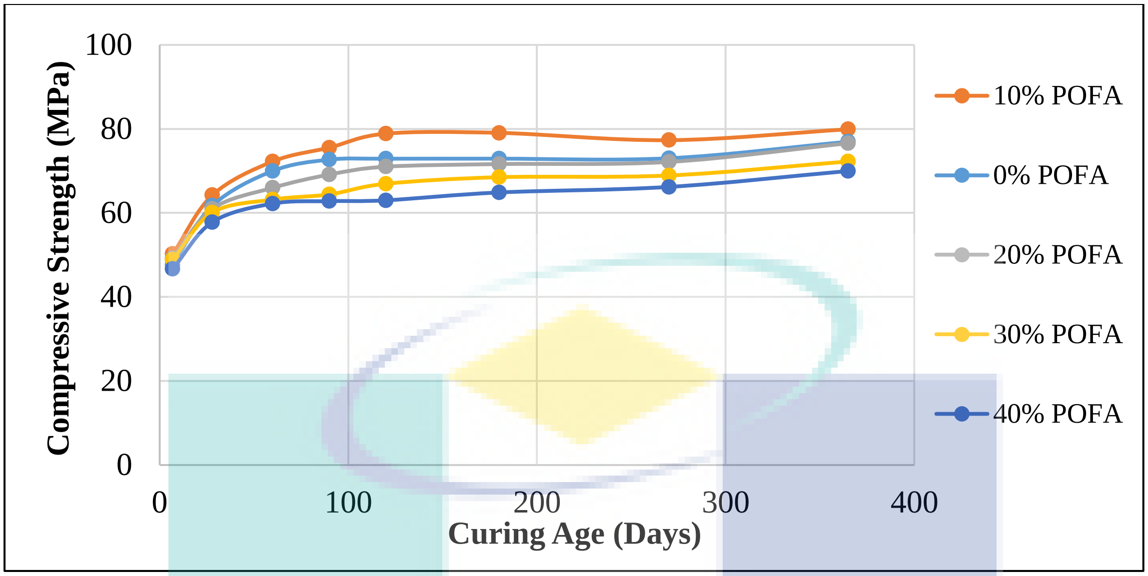


Figure 4.1 : Compressive strength of POC LWAC with POFA specimens subjected to water curing for 365 days

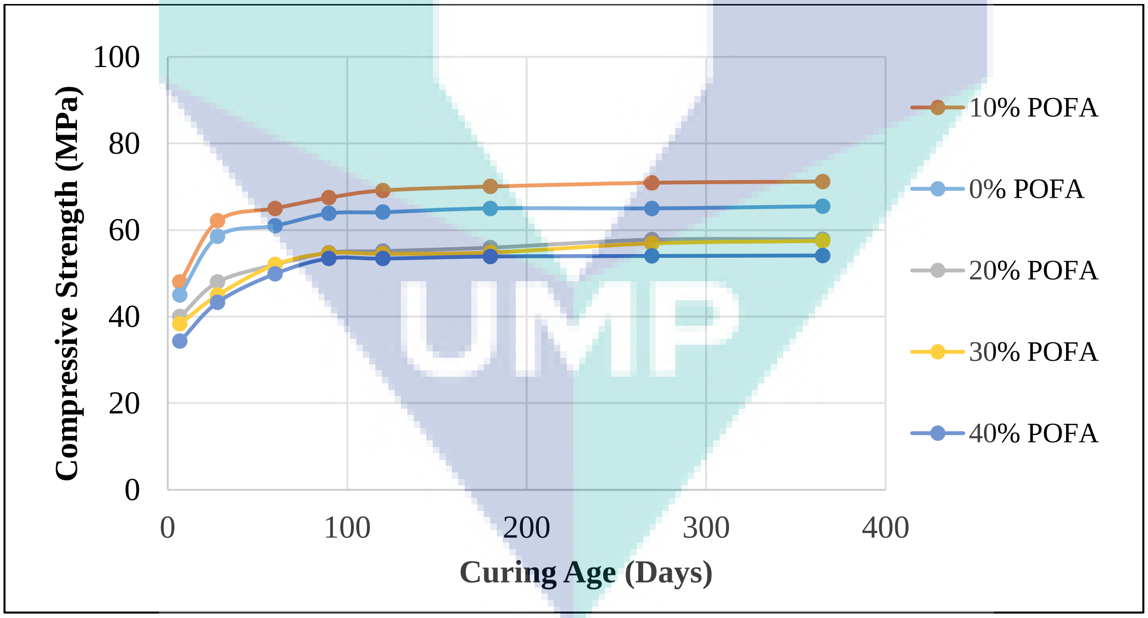


Figure 4.2 : Compressive strength of POC LWAC with POFA specimens subjected to air curing for 365 days

4.3 Flexural Strength

. The flexural strength developments of POC LWAC with variation percentage of POFA are presented in Figure 4.3 and 4.4. The results indicate that the flexural strength is growing at curing period of 7, 28, 60, 90, 120, 270 and 365 days of age. It was observed that the flexural strength for all mixes were in the range of 7.7 to 14.76 MPa at 28 days of curing age. According to Neville (2011), a 60 MPa lightweight aggregate concrete have flexural strength around 5.5 to 10 MPa. In case for POC LWAC with POFA, the flexural strength is higher by 30% than predicted flexural strength. This finding is not surprising as flexural strength as high as 8 MPa has been obtained by Ahmad and Mohd Noor (2007) when producing plain POC LWAC with strength of 50 MPa. The flexure strength of lightweight aggregate concrete depends on the type of coarse aggregate used especially its shape, surface and texture. A rougher aggregates surface generates a stronger bond between the paste and the aggregate creating a higher flexural strength. The behavior was confirmed by Popovics (1998) in experimental concrete, entirely rough coarse aggregate surface led to high flexural strength. The reason for this is the strong bond between the matrix and the aggregate.

There are several factors causing variability of flexural strength of concrete including the curing condition (NRMCA, 2016). Water curing provides better curing that improves concrete strength at the same age. Since water is necessary for hydration process, air curing is indeed resulted towards the least flexural strength than other types of curing. Research done by Légeron and Paultre (2000) cured under standard testing conditions and cured using air curing shows significance difference. They found significant differences between the modulus of rupture of concrete specimens and this difference is varied from 35% to 100% for high performance concrete. However, in this cases, the flexural strength difference between water curing and air curing varies between 10 to 12%.

Same as compressive strength, flexural strength of POC LWAC is substantially improved by incorporating POFA. The maximum 28 days flexural strength can be found for POC LWAC with 10% POFA under water curing. This may be because of better packing of concrete ingredients due to lubricating effect of POFA. The effect of pozzolanic materials of the concrete on flexural tensile strength was also studied by Siddiqui (2011) and Amudhavalli and Mathew

(2012). They concluded that optimum amount of pozzolan is about 10 to 15% for maximum flexural strength. Pozzolanic materials contribute towards pozzolanic reaction that increases substantially the quantity of strengthening gel (Nazari, 2011). However, the strength was found optimum at 10%. The result is in line with research done by Yasar et al. (2004) in his research by utilizing 10% pozzolanic material in scoria lightweight aggregate concrete.

Replacement of cement by 20% POFA is still acceptable as the flexural result produces not much difference than control specimen. The difference in value is only around 2.5 to 5.2%. However, utilization of POFA of more than 30% is not encouraged as it shows noticeable reduction in strength. It may be due to the poor interlocking between the aggregates. When cement replacement with POFA is more than optimum amount, there will be insufficient $Ca(OH)_2$ that will be consumed by POFA to produce C-S-H gel. As a result, the concrete strength is lower. In 40% POFA replacement, the crack propagated around the POC aggregate particles, leaving a tortuous fracture surface. However, for 10% POFA replacement, the cracks propagated through POC aggregates particles, resulting in a relatively smooth fracture surface.

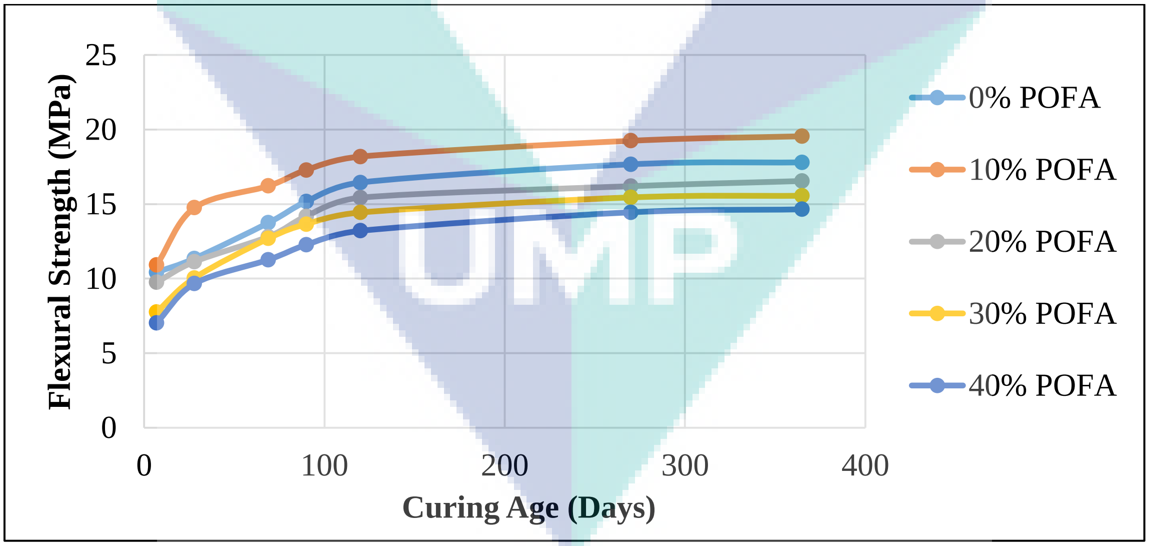


Figure 4.3: Flexural strength of POC LWAC with POFA specimens subjected to water curing up to 1 year

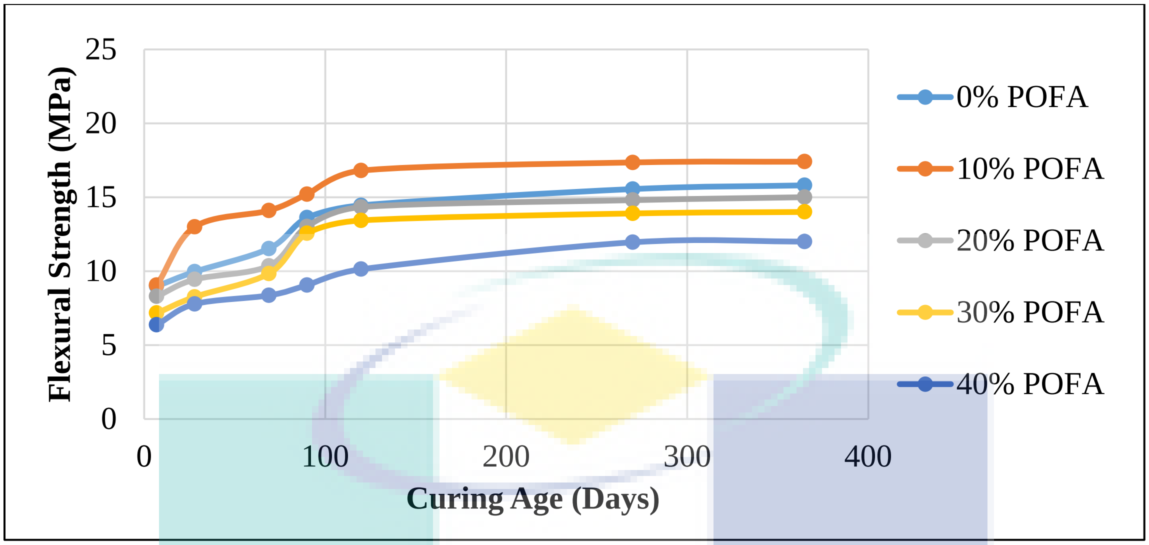


Figure 4.4: Flexural strength of POC LWAC with POFA specimens subjected to air curing up to 1 year.

4.4 Splitting Tensile Strength

The result of splitting tensile test carried out on POC LWAC made with 0%, 10%, 20%, 30% and 40% of POFA cylindrical specimen are presented in Figure 4.5 to 4.6. The splitting tensile strengths for all concrete percentages increased with increasing compressive strength in similar trend. This was in line with the findings of Akinpelu et al. (2017) where they also concluded that splitting tensile strength of concrete is directly proportional to compressive strength. ASTM C496 (2004) reported that 28 days splitting tensile strength requirement for structural lightweight concrete member must be at least 2.0 MPa. Thus, according to this criteria, POC LWAC with POFA for all types of curing can be used for making structural concrete elements since the splitting tensile strength is more than 2.0 MPa at all ages.

According to Neville (2011), the splitting tensile strength for high strength lightweight aggregate concrete is differ by 1 MPa than normal weight concrete of similar strength. The splitting tensile results show higher strength for 0% and 10% POFA replacement when cured under water curing. The strength is around 4.7 to 5.6 MPa at 28 days of curing age. Apart from its higher strength, the samples increasing brittleness behavior as it produces explode failure during the testing. This type of failure was also found by other researchers when producing high strength lightweight aggregate concrete (Zhou, Barr, & Lydon, 1995). In high strength concrete, the explosive behavior is usually due to its higher amount of cement consumption. However, in this case, the porous palm oil clinker aggregates were filled by hydration products making it stronger and denser. When the concrete failed, it split into two flat surface. The smooth surface is due to the crack through the coarse aggregate. According to Mayfield (1990), splitting tensile test that usually show failure through the coarse aggregate particles conforming good bond of the aggregate and cement paste.

As splitting tensile strength is associated with bonding between aggregates and hydrated compound (Holm and Bremner, 2000) curing method affects largely towards its performance. Water curing provides continuously moisture for hydration and pozzolanic reaction that in turns increase the concrete bonding. Same as compressive and flexural strength, water curing was also regarded as the best curing that produces the highest strength for splitting tensile strength. At 28 days, the splitting tensile strength of POC LWAC in water curing increases by 19% than control specimens. According to Omar and Mohamed (2002), this splitting tensile strength ratio for high strength lightweight concrete under constantly moist cured is around 6 to 7% of its compressive strength which is in line with results acquired in these research. Conroy-Jones and Barr (2004) and Edson & Amudhan (2014) figure out that water curing performs the best when high strength lightweight concrete was measured for splitting tensile strength.

In the technical term of curing, the samples that were stored in the open air in the laboratory would be considered as uncured specimens. Thus, air curing produced the lowest strength among all curing regimes due to lack of reaction for hydration process. Air curing produces splitting tensile strength around 2 to 4 MPa compared to water curing which is around 2.5 to 5.6 MPa at 28 days. Hydration depends on the availability of internal water and the curing environment. If there is not enough water, cement particles remain unhydrated and will not crystallize to form the strong bonds between the aggregates and cement paste. Research conducted by Bogas & Noguiera (2014) and Abalaka & Okoli (2013) also shows reduction in the splitting strength of air-cured lightweight aggregate concrete.

In all cases maximum splitting tensile strength is achieved with 10% cement replacement with POFA. POFA which has pozzolanic properties contribute towards pozzolanic reaction thus produces higher strength. Through pozzolanic reaction in the concrete structure, a secondary C-S-H gel were produced and improving the aggregate-cement interface thus becoming stronger concrete. However, utilization of POFA in POC LWAC of more than 20% would decrease the concrete strength significantly. Due to larger amount of POFA inclusion, it leads to less cement that resulted in aggregate could not bind perfectly with cement paste. The poorest tensile result was attributed by 40% POFA, which is the largest amount of cement replacement in POC LWAC mixes. However, the result is still in the range for structural lightweight aggregate concrete application.

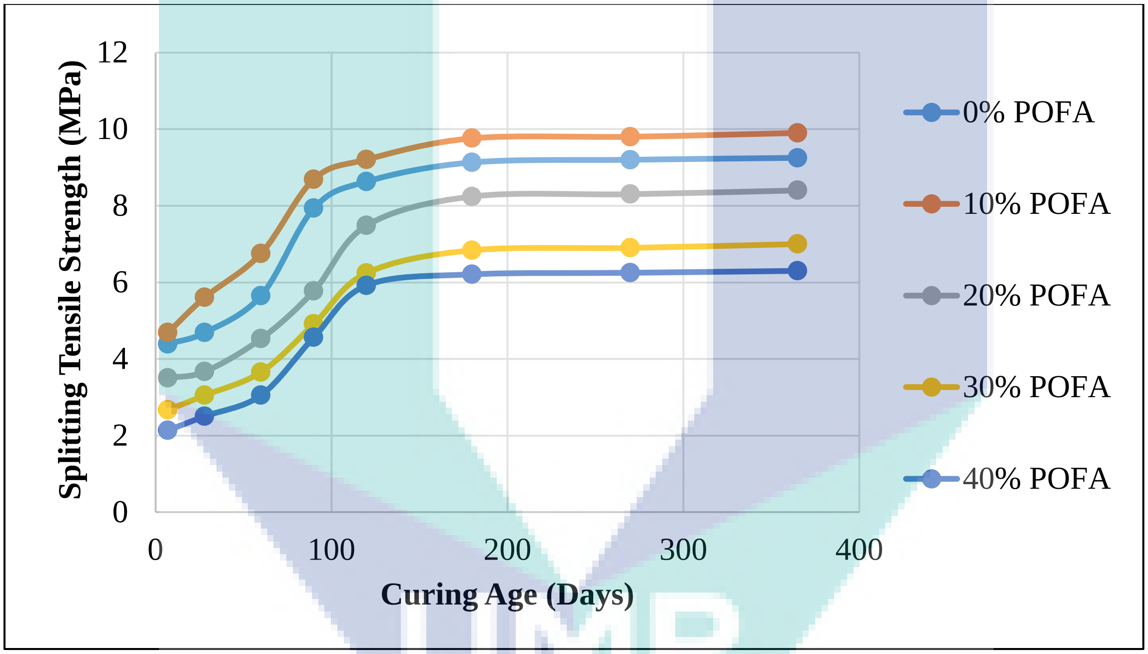


Figure 4.5 :Splitting tensile strength of POC LWAC with POFA specimens subjected to water curing for 365 days

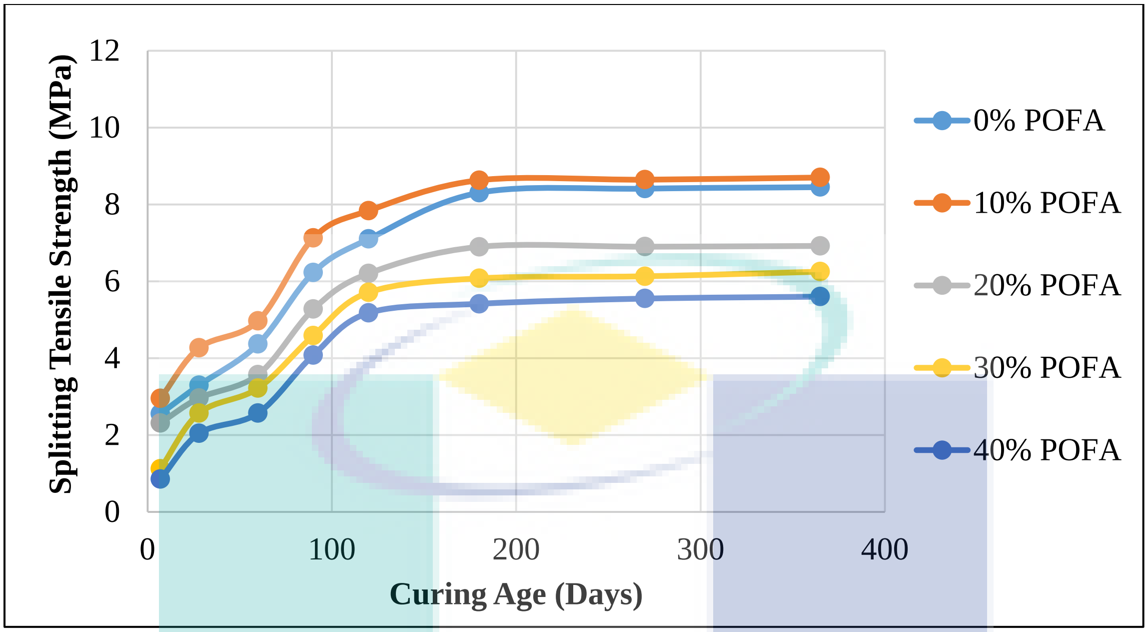


Figure 4.6:Splitting tensile strength of POC LWAC with POFA specimens subjected to air curing for 365 days

4.5 Modulus of Elasticity

The modulus of elasticity of concrete is a function of the modulus of elasticity of the aggregates and the cement matrix and their relative proportions (Ashraf, 2017). The relationship between POFA percentages and elasticity modulus of POC LWAC subjected to water curing and air curing depicted in Figure 4.7 to 4.8 at ages from 7 to 365 days. The values obtained for the modulus of elasticity of LWAC ranged from 10 to 20 GPa, and were on average of one third of the values obtained for NWC, which is compatible with results found by other authors (Moravia et al., 2010). The result is in line with result obtained by Cui, Lo, Memon, Xing, & Shi (2012) when producing lightweight aggregate concrete for structural purposes. The high result might due to the bond between the aggregate and the hardened cement paste which is particularly good in lightweight aggregate concrete. Another reason for this is the rough surface texture of palm oil clinker so that there is mechanical interlocking between the two materials.

The value of modulus of elasticity for water cured specimen is higher than air cured ones. The positive influence of water curing was already apparent at the age of 7 days. The modulus of elasticity of water curing specimens increased more steeply than other samples. According to

Wu, Wei, Liu, & Xing (2016), the factors that affected the concrete modulus of elasticity is the cement matrix. The void spaces and the microcracks in the transition play a major role in affecting the stress-strain behavior of concrete. Thus, proper curing is important to assist towards producing denser concrete microstructure. In these experimental programme, water curing provides the best curing medium for POC LAWAC containing POFA as it continuously provides moisture for hydration process thus strengthen the cement bonding with aggregates in concrete.

The lowest strength development of the modulus of elasticity of the uncured concrete can be explained by a lack of water necessary for the cement to fully hydrate with modulus of elasticity values between 9 to 15 GPa. If the concrete surface is not protected from water evaporation, there can be a massive risk of microcracks forming not only on the surface but inside the concrete member as well. When these microscopic defects occurred, the development of the concrete's elasticity properties will be irreversibly affected throughout the whole time of its aging. A rapid loss of water from the concrete, especially during the first few hours, has a critical influence on cement hydration. This can result in microcracks that form in the internal structure of the concrete (Maslehuddin et al., 2013). The stagnation in the development of the material properties of uncured concrete in terms of elasticity modulus has already been published by Kocab, Kucharczykova, Misak, Zitt, & Kralikova (2017).

As the bond stress between the aggregates and hardened cement paste is highly influence the stress-strain relation (Neville, 2011), additional of mineral admixture such as pozzolan that would help to increase the concrete bonding matrix is significant. The properties of concrete can be improved by physical or chemical processes that take place in the transition zone between the lightweight aggregate and the cement matrix. The chemical processes are associated with the pozzolanic activity of this aggregate and with the deposition of C-S-H in voids in the transition zone, while the physical interactions are associated with the mechanical interlocking of these aggregates with the cement paste (Wasserman and Bentur, 1996). In this cases, 10% POFA contributes towards the highest modulus of elasticity due to pozzolanic activity. Although all curing shows that 10% cement replacement by POFA produces the highest strength, 28 days water curing produces modulus of elasticity higher by 17%.

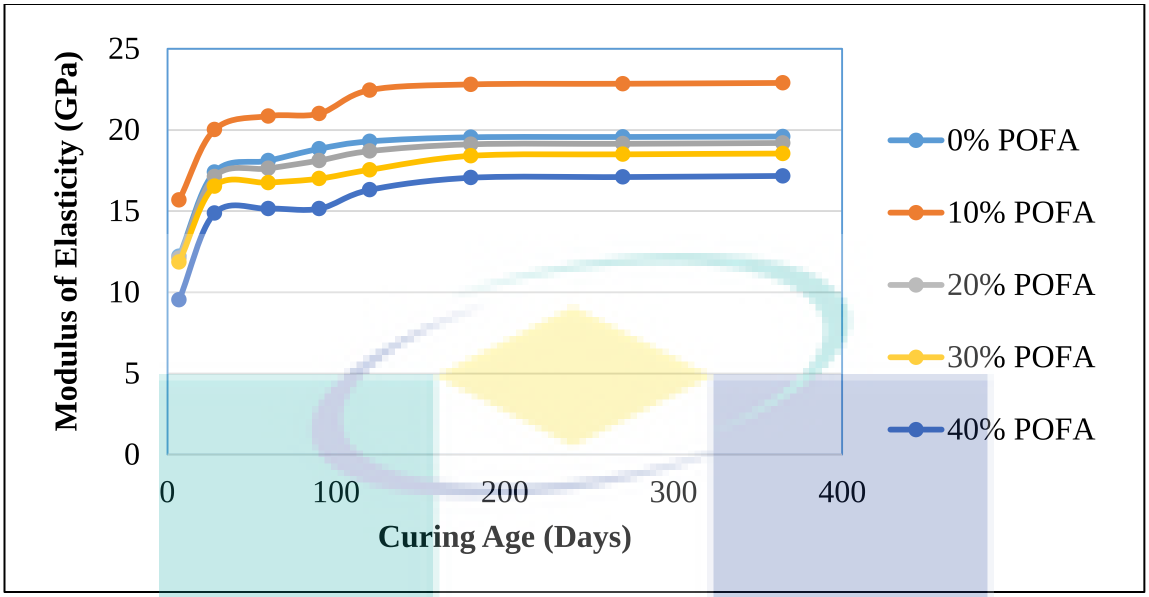


Figure 4.7:Modulus of elasticity of POC LWAC with POFA specimens subjected to water curing for 365 days

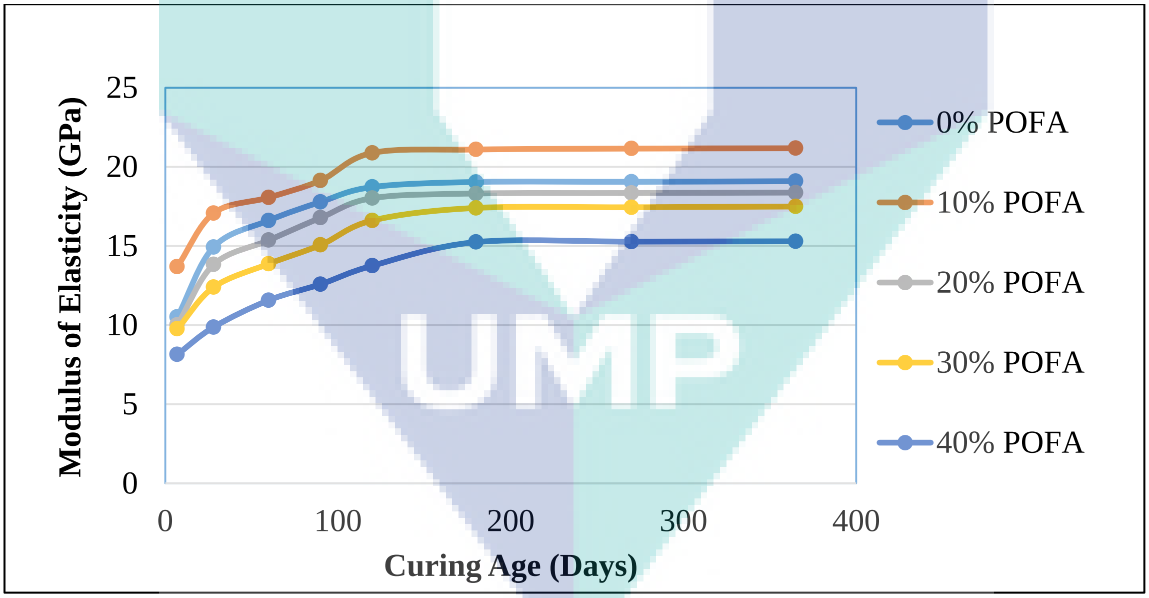


Figure 4.8: Modulus of elasticity of POC LWAC with POFA specimens subjected to air curing for 365 days

4.6 Summary

Conclusively POC LWAC with POFA is best cured using water curing as it promotes hydration process that greatly influenced the densification of these type of lightweight aggregate concrete. The optimum POFA replacement was denoted by 10% POFA as it performs the best in terms of mechanical strength namely compressive, flexural, splitting tensile and modulus of elasticity. Calcium silicate hydrate (C-S-H) gel developed during pozzolanic reaction occupies significantly micro-pores inside the concrete thus increase its strength.

CHAPTER 5

DURABILITY PROPERTIES

5.1 Introduction

This chapter presents and discusses the durability performance of palm oil clinker lightweight aggregate concrete containing various percentage of palm oil fuel ash as partial cement replacement. This chapter consists of six durability testing namely acid resistance, sulphate resistance, fire resistance, carbonation, water absorption and porosity test.

5.2 Durability Properties

5.2.1 Water Absorption

The effect of POFA content on the water absorption of POC LWAC subjected to different curing method are illustrated in Figure 5.1. From the graph, it clearly shows that different percentage of POFA and curing regimes resulted in different rate of water absorption. The observation is in agreement with research done by Wang, Bao, & Baojuan (2017) and Bozkurt & Yazicioglu (2010) who stated that water absorption of high strength lightweight aggregate concrete is influenced by curing method. According to Neville (2011), the concrete water absorption of not more than 10 % is classified as high-quality concrete. Interestingly, the water absorption for all specimens were in the range of 0.2 to 1.2 % respectively as shown in

Figure 6.5 which is within the range for high-quality concrete that is lower than 10% as reported by Neville (2011). According to Wilmshurst (2017), extremely good concrete water absorption is between 4 or 5% by mass while very good concrete is between 5 or 6%.

According to Castro, Bentz and Weiss (2011), water absorption is influenced by the volume of the pores and pore size distribution, as well as the size of the partially empty capillary pores. Ramamurthy et al. (2009) opined that the water absorption is mainly influenced by paste phase. In this research, the incorporation of 10 % POFA as partial cement replacement material has notable effect on high strength POC LWAC water absorption. The effect of incorporation of optimum amount of POFA has decreased the rate of water absorption. This improved volumetric water absorption is due to refined pore structure and the conversion of the calcium hydroxide, which tends to form into calcium silicate hydrate (C-S-H) due to the presence of reactive silica, which makes concrete less porous and more compact. This finding is in confirmation of the results of the study by Walid, Oudjit, Bouzid and Belagraa (2015) and Jensen & Lura (2006). Water absorption of POC LWAC with 40% POFA shows the highest water absorption as too much POFA produces drier mix. The dry mixture made the compaction harder thus produces more voids for absorption to occur.

From the graph, it obviously shows that water curing is the best curing medium for POC LWAC with POFA as it provides the lowest percentage of water absorption amongst all. Water curing results in the increment of total amount of C-S-H gel that contributing towards formation of a more compact concrete microstructure. On the contrary, rate of water absorption of POC LWAC is significantly high upon air curing. Higher specimens' temperature due to the absence of water emptying a wide range of pores that in turn results in a higher rate of absorption. The observation was in agreement with Castro et al. (2011) and (Zhang & Zhong, 2014) who claim that drier samples show much higher water absorption. Additionally, lower humidity will empty smaller pores, creating a stronger suction force in the materials and resulting in a greater sorption rate, as well as a larger overall total absorption. Furthermore, the results were also due to the reduction of hydration products resulted from inadequate water supply caused by excessive evaporation.

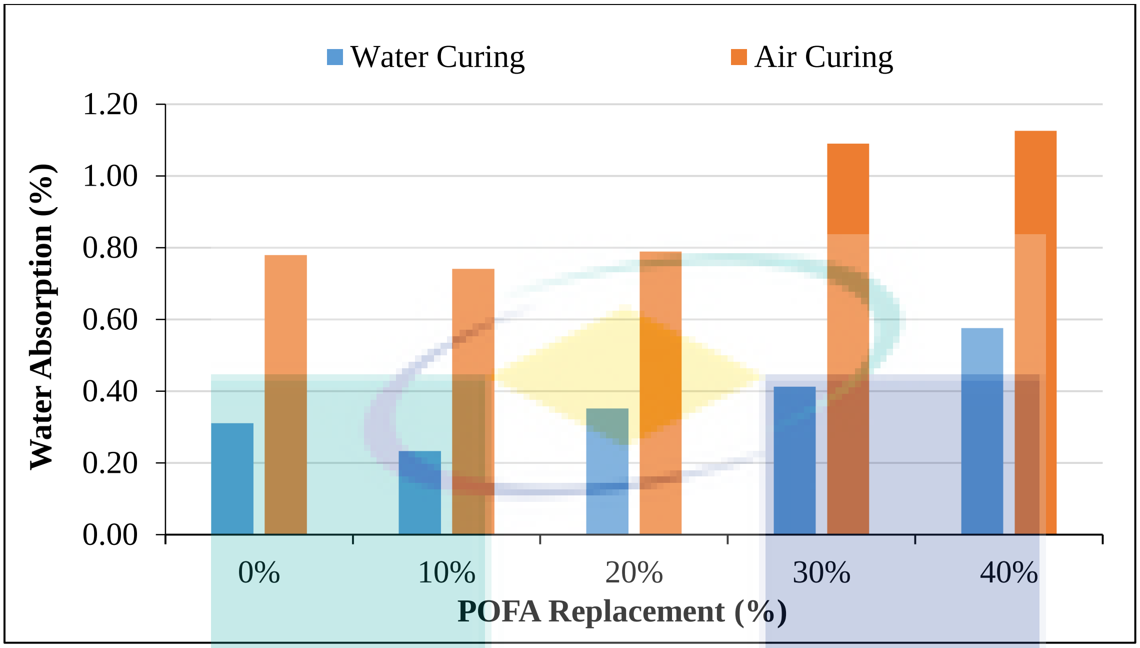


Figure 5.1 Water absorption of POC LWAC with different percentage of POFA

5.2.2 Acid Resistance

This section discusses the effect of different percentage of POFA as partial cement replacement towards acid resistance of POC LWAC subjected to different curing method. Generally, water curing and the presence of POFA in suitable amount was found to lower the detrimental effect of POC LWAC when subjected towards acid attack as can be observed in Figure 5.2, 5.3 and 5.4. Water curing shows the best performance with the lowest mass loss value and lower strength deterioration as compared to air cured specimen. This is caused by continuously water curing that actively participates in the hydration of cement and pozzolanic reaction thus improving the internal structure making it harder to be penetrated by acid. Termkhajornkit et al. (2006) highlighted that water curing enhances the concrete internal structure quality. Goyal et. al (2009) proves that concrete with denser microstructure would exhibit more resistance against mass loss as well.

Only optimum amount of POFA is able to provide resistance towards acid attack. Replacement of cement by optimum amount of pozzolanic materials such as POFA would reduce significantly amount of calcium $Ca(OH)_2$ that is vulnerable towards acid attack. In addition, Ca(OH)$_2$ produced during hydration process would be consume by silica in POFA converting it into C-S-H gel making the concrete denser which contributes towards increasing durability. Researchers are working towards improvement of concrete durability towards acid attack by adding pozzolans (Roy et al., 2001; Kawai et al., 2005 and Kim et al., 2007). Excessive POFA replacement in POC LWAC causes dryness to the concrete fresh state in which will affect when it hardens. Concrete mixes that are too dry will cause them to be difficult to compact thus produces undesirable pores. These pores ease the acid intrusion into the concrete. Researchers (Elyamany et al. 2014 and Chemrouk, 2015) claims that well concrete compaction is very crucial to prevent concrete pores.

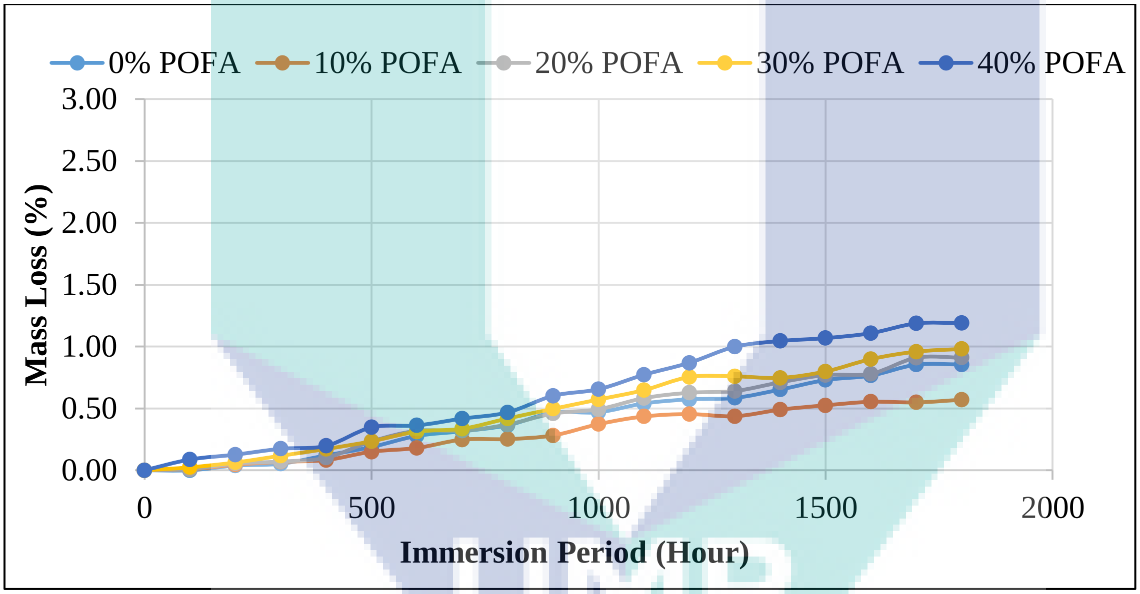


Figure 5.2 Mass loss percentage of water cured POC LWAC with POFA specimens immersed in HCl solution for 1800 hours

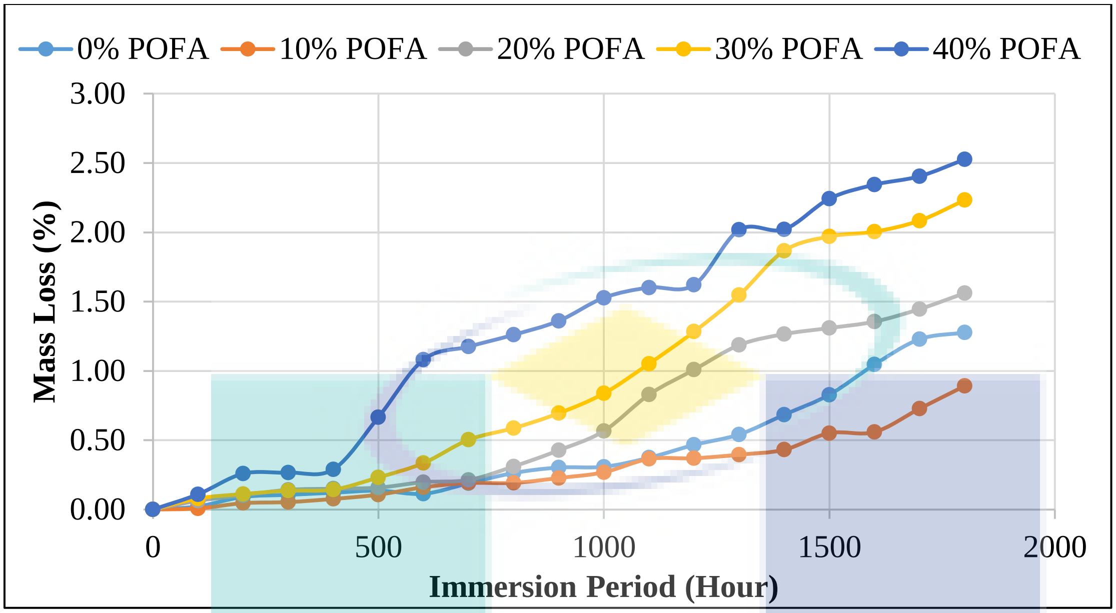


Figure 5.3 Mass loss percentage of air cured POC LWAC with POFA specimens immersed in HCl solution for 1800 hours

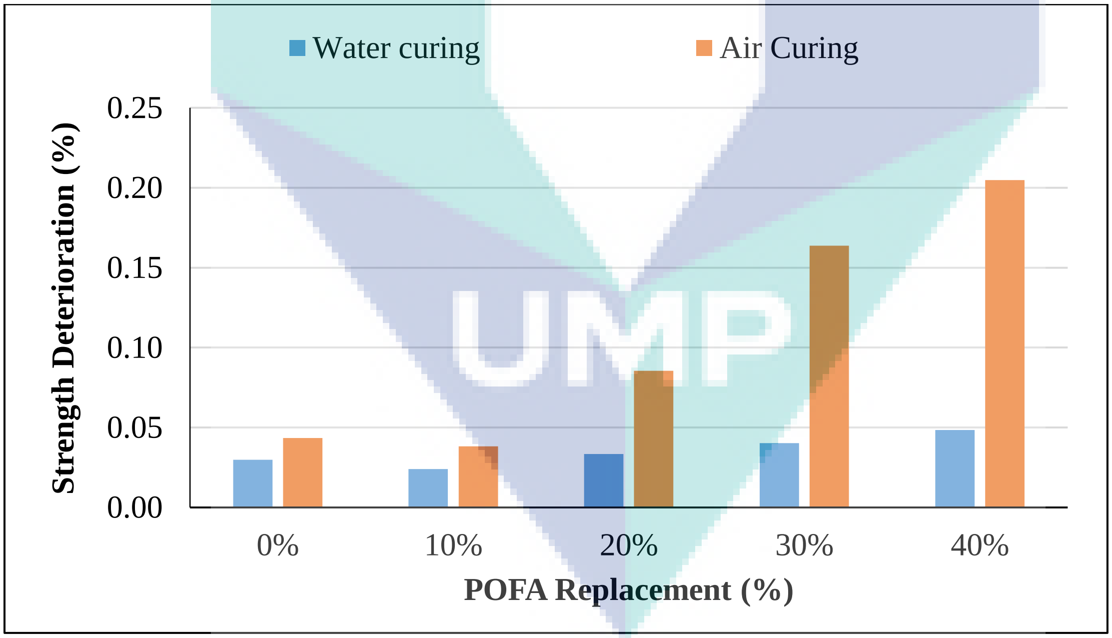


Figure 5.4 Strength deterioration of POC LWAC and POC LWAC with POFA immersed in water and HCl solution for 1800 hours

5.2.3 Carbonation

Figure 5.5 and 5.6 depicts the carbonation depth of POC LWAC containing 0%, 10%, 20%, 30% and 40% POFA when subjected to various curing condition namely water curing and air curing. In this research, the depth of carbonation was reduced considerably when 10% POFA was utilized in POC LWAC. In other words, replacement of optimum amount of POFA was found to be effective in reducing the intensity of carbonation. The use of pozzolan materials increases amount of C-S-H gel produced from the pozzolanic reaction which covers the fine pores inside the concrete internal structure thus reducing the carbonation intrusion. However, replacement of POFA beyond optimum amount significantly increase the carbonation rate. Previous studies also revealed the fact that beyond 10% replacement of pozzolan will show its effect on carbonation and is also responsible for corrosion (Grimaldi, Carpio, & Raharinaivo, 1989). Park (1995) found that the greater the amount of pozzolanic materials the deeper the carbonation depth becomes. This researcher stated that this phenomenon is primarily due to the reduction in the alkali content in the cementitious materials and the calcium silicate hydrate formed from the pozzolanic reaction absorbs more alkali ions, hence lowering the pH level in concrete (Mindess, Young, & Darwin, 2002). Compaction of concrete seem to have a very important effect on the carbonation depth as maximum carbonation was observed on low compacted specimens. POC LWAC with 40% produces concrete which is hard to compact. Contrarily, the minimum carbonation was obtained on POC LWAC with 10% POFA specimens which shows maximum compaction. These observation is in agreeable with Gonen and Yazicioglu (2007) who observed that the maximum carbonation were observed on low-compacted specimens.

Curing methods also influence the resistance of POC LWAC with POFA towards carbonation. As expected, all concrete samples cured continuously under water showed no traces of carbonation until the age of one year. The presence of water at all-time promotes the generation of larger amount of C-S-H gel which contributes to densification of concrete internal structure, making it more durable. Bai et al. (2002) suggests that water-curing reduces sorptivity, which reflects a finer pore structure that will inhibit ingress of aggressive elements into the pore system reducing carbonation. Moreover, the slow solubility of CO_2 in water (Taylor, 2014) assisted the water cured specimen to be free from carbonation effect during the period of this study. Specimens exposed to air curing demonstrates the larger carbonation depth as compared to other samples. This observation was also observed by Fattuhi (1988). They found out that the carbonation rate reaches the highest when the specimens was uncured. Without cured, specimen exposed to open space would accelerate the carbonation process. Improper curing method disrupts the promotion of larger amount of C-S-H gel in POC LWAC containing POFA causing it to be more affected by carbonation. Conclusively, the application of proper curing that promotes larger production of C-S-H gel increase carbonation resistance of POFA concrete.

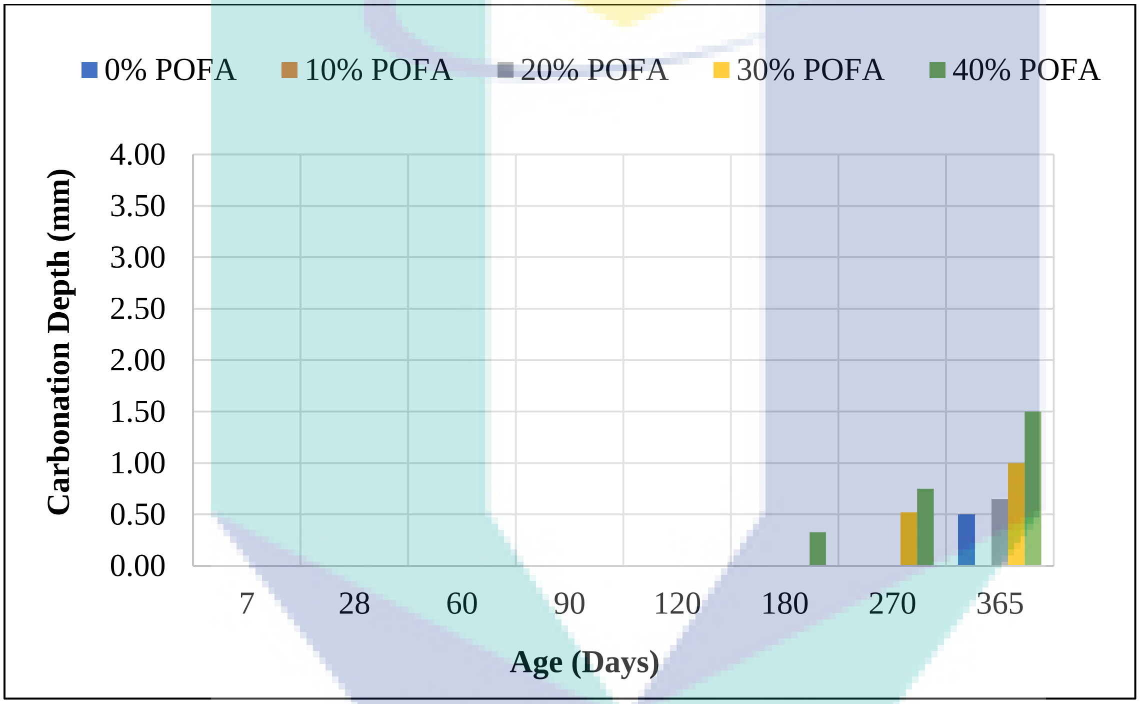


Figure 5.5 Carbonation depth of POC LWAC with POFA specimens after subjected to water curing up to 365 days

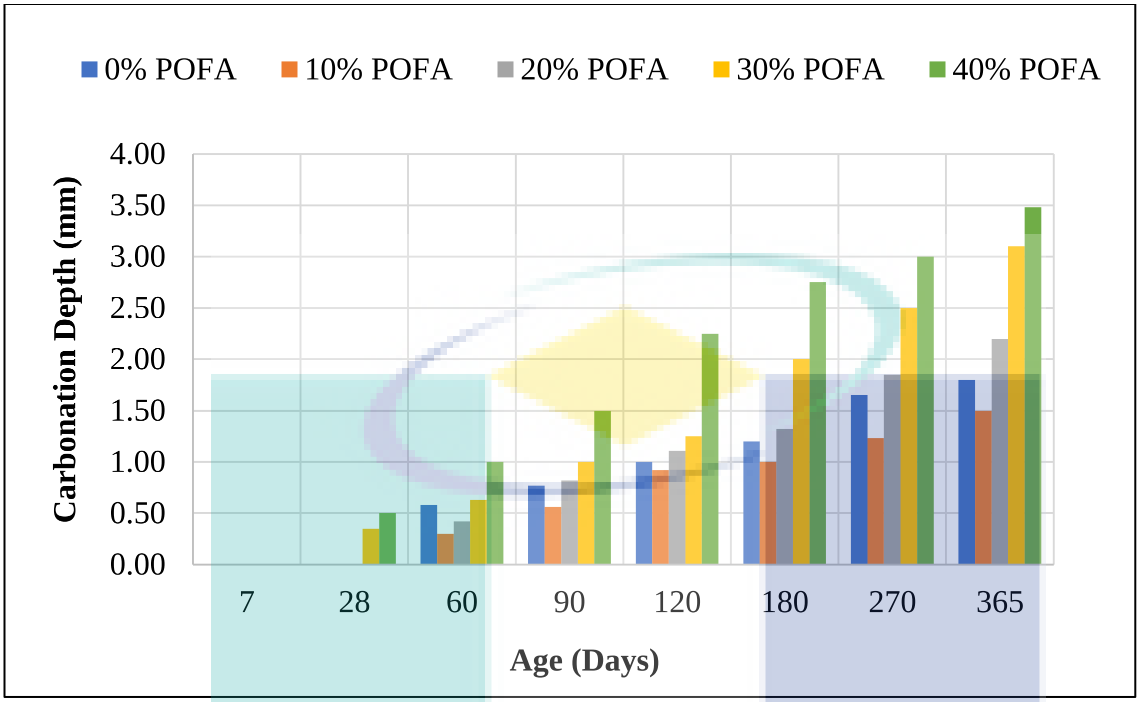


Figure 5.6 Carbonation depth of POC LWAC with POFA specimens after subjected to air curing up to 365 days

5.2.4 Sulphate Resistance

The mass change results of concrete specimens that were measured for 48 weeks of immersion in sodium sulphate solution is presented in Figure 5.7 to 5.8. The weight loss of POC LWAC with POFA specimens exposed to sulphate solution exhibits three distinct stages. On overall, in Stage I, the specimen's weight keeps steady from week 1 until week 5. In Stage II, from week 5 to week 30, the specimen's weight loss increases gradually. In Stage III, the weight loss decreases at a steady rate after 30 days. The rate of the increase was seen to be higher for POC LWAC with 40% POFA under air curing. In addition, there is no obvious distinction between control and POC LWAC with 10% POFA replacement.

Investigators found that adding mineral additives such as pozzolanic materials during concrete mixing could significantly improve the durability of concrete. The use of pozzolanic material has been reported as a highly effective treatment for reducing sulphate-induced damage or enhancing the sulphate resistance of concrete (Torii et al., 1995; Lee et al., 2005; Ghrici, Kenai, & Said-Mansour, 2007; Sezer et al., 2008 and Bonakdar & Mobasher, 2010). The concrete resistance against sulphate attack is attributed to the pore refinement process and further densification of the transition zone occurring due to the c 6.8 tonversion of lime forming from the hydration of cement into additional binding material through pozzolanic reaction. Apart from pore refinement, the use of pozzolans will also controlled the amount of calcium aluminate C_3A and calcium hydroxide in the hydrated cement paste of Portland cements. Hence, the production of ettringite and gypsum can be reduced. This decreases the internal expansive stress and reduces damage (Mullauer, Beddoe, & Heinz, 2013).

However, Figure 6.8 to 6.9 shows that higher POFA content of more than optimum amount correspond to higher mass change for POC LWAC containing POFA. Although replacing a part of cement by pozzolanic material would reduce the sulphate attack, it produces low-workability concrete which dries too quickly. This produces non-homogeneity concrete thus larger pores were produced upon hardening. These pores resulted in ease of sulphate ions penetration into the concrete internal structure. In other word, the higher amount of POFA, the larger the concrete pores thus higher the sulphate ion penetration rate. According to Newman and Choo (2003), poor compaction increased sulphate ingress. POC LWAC with 40% POFA resulted in the highest mass change compared to other specimens. These finding is in line with research carried out by Vaishnavi and Kanta Rao (2014) when utilizing high volume of pozzolanic materials in concrete. Conclusively, dense, fully compacted concrete of low permeability is essential to minimize the aggressive effects of sulphate attack.

In terms of curing method, it is perceived that water curing contribute towards the least mass change of all specimens. Well cured concrete can minimize pores and cracks, making concrete more water tight, thus preventing moisture and water borne chemicals from entering into the concrete and thereby increasing its durability (Kulkarni & Pereira, 2011). Contrarily, the highest mass change was denoted by air curing. If adequate moisture is not maintained in the curing environment, the concrete cannot reach its full design strength, and cracking may occur. Durability of the concrete may also be reduced due to inadequate hydration of the cementitious material (Naderi, Sheibani, & Shayanfar, 2009).

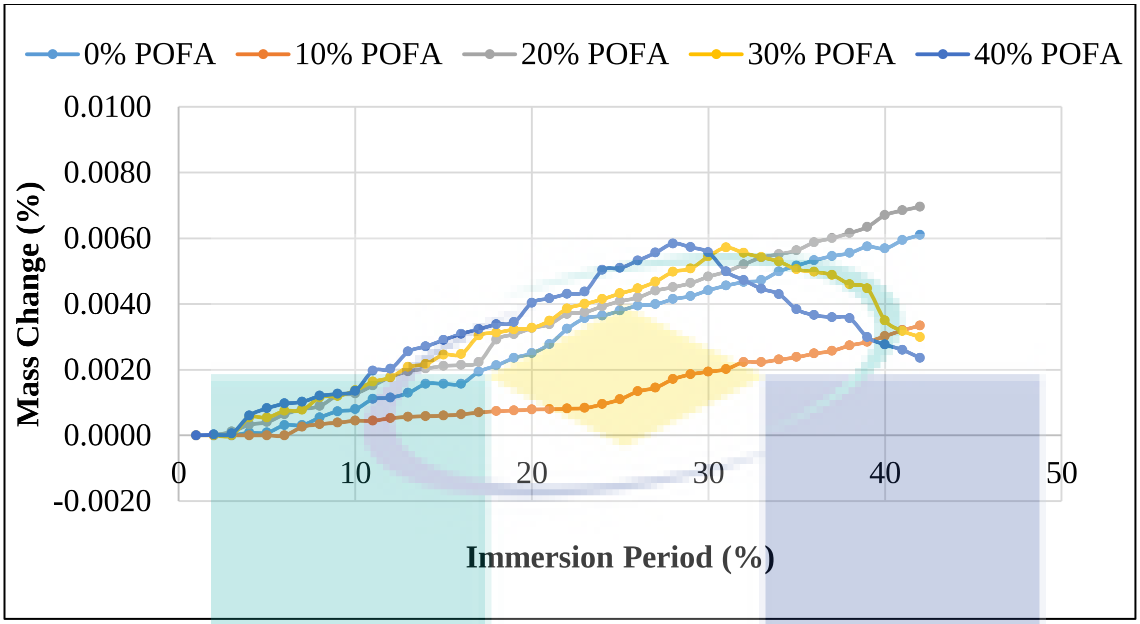


Figure 5.7 Mass change of POC LWAC with POFA specimens immersed in sodium sulphate solution for 48 weeks under water curing

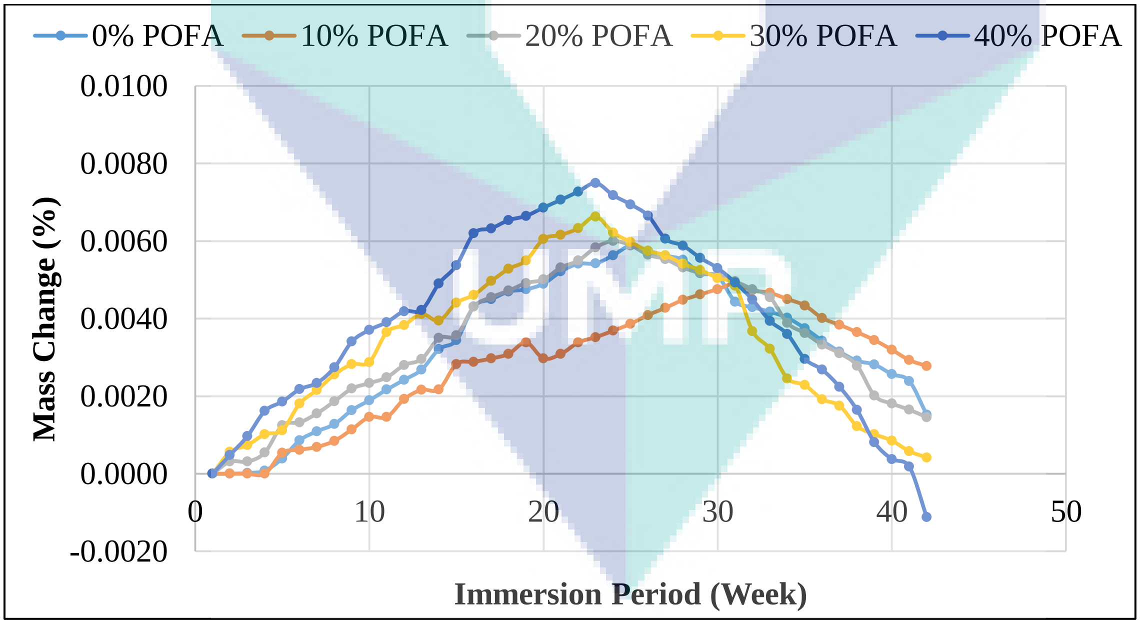


Figure 5.8 Mass change of POC LWAC with POFA specimens immersed in sodium sulphate solution for 48 weeks under air curing

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Introduction

In this chapter, it concludes the overall experimental research findings derived from every chapter based on the objectives in Chapter one. This section guided for better understanding on the effect of palm oil fuel ash as partial cement replacement in palm oil clinker lightweight aggregate concrete towards mechanical and durability performance. Apart from conclusion, several recommendations for further investigation have also been included on this section.

6.2 Brief Conclusion

6.2.1 Effect of POFA Content as Partial Cement Replacement on Compressive Strength of POC Lightweight Aggregate Concrete

The test results in Chapter four provides information needed to fulfill the first objectives of this study that been focused on investigating the effect of palm oil fuel ash (POFA) content as partial cement replacement on compressive strength of palm oil clinker lightweight aggregate concrete. The highest compressive strength was noted in the 10% cement replacement by POFA Incorporation of suitable content of POFA produces largest amount of C-S-H gel from hydration process and pozzolanic reaction which densify the concrete structure making it higher compressive strength. On the other hand, the inclusion 30% and 4% of POFA in the concrete result in strength reduction.

6.2.2 To investigate the effect of different curing regimes on physical and mechanical properties of palm oil waste lightweight aggregate concrete containing palm oil fuel ash as mineral admixture

For the second objective, the mechanical properties of POC LWAC containing POFA those are compressive strength and flexural strength elasticity under different types of curing regimes namely water curing and air curing is discussed in Chapter four. Generally all water cured specimens exhibit higher value in terms of compressive strength, flexural strength, splitting tensile strength and modulus of elasticity. Application of water curing with 10% of POFA as partial cement replacement resulted in the highest strength and higher than plain OPS LWAC due to pozzolanic reaction. Continuous presence of water during curing period has facilitate the on better reaction for production of C-S-H gel which important for better strength of concrete. On the other hand, air cured specimen exhibit lower strength value at all curing age.

6.2.3 To investigate the durability performance of palm oil waste lightweight aggregate concrete containing palm oil fuel ash

Chapter five presents results and analysis assuring the last objective that is to investigate the durability performance of palm oil clinker (POC) lightweight aggregate concrete containing palm oil fuel ash (POFA) as partial cement replacement in terms of acid attack, sulphate attack, carbonation and water absorption. POC LWAC with POFA exhibits lower water absorption than plain POC LWAC for all types of curing. Water curing appears to be the better type of curing for POC LWAC with POFA as it shows lower amount of water absorption than air cured ones. When exposed to acid resistance test and sulphate resistance test, water cured POC LWAC with POFA shows higher durability than control specimen. Inclusion of suitable amount 10% POFA as partial cement replacement reduces the vulnerable calcium hydroxide owing to pozzolanic reaction that consume it during the production of secondary C-S-H gel. Looking at the carbonation effect, application water curing and utilization suitable amount of POFA to produce palm oil clinker (POC) lightweight aggregate concrete enhances the resistance of concrete to carbonation.

6.3 Recommendation for Further Research

There are several recommendations to expand the research of POC LWAC containing POFA as partial cement replacement:

1. The effect of POFA content towards corrosion resistance of POC LWAC is one of the area that can be looked into.
2. The effect of POFA content on fire resistance properties of POC LWAC is also another area that is interesting to be ventured.
3. Investigation on the properties of POC LWAC with POFA containing crushed clinker as partial sand replacement is also an area that can be investigated.

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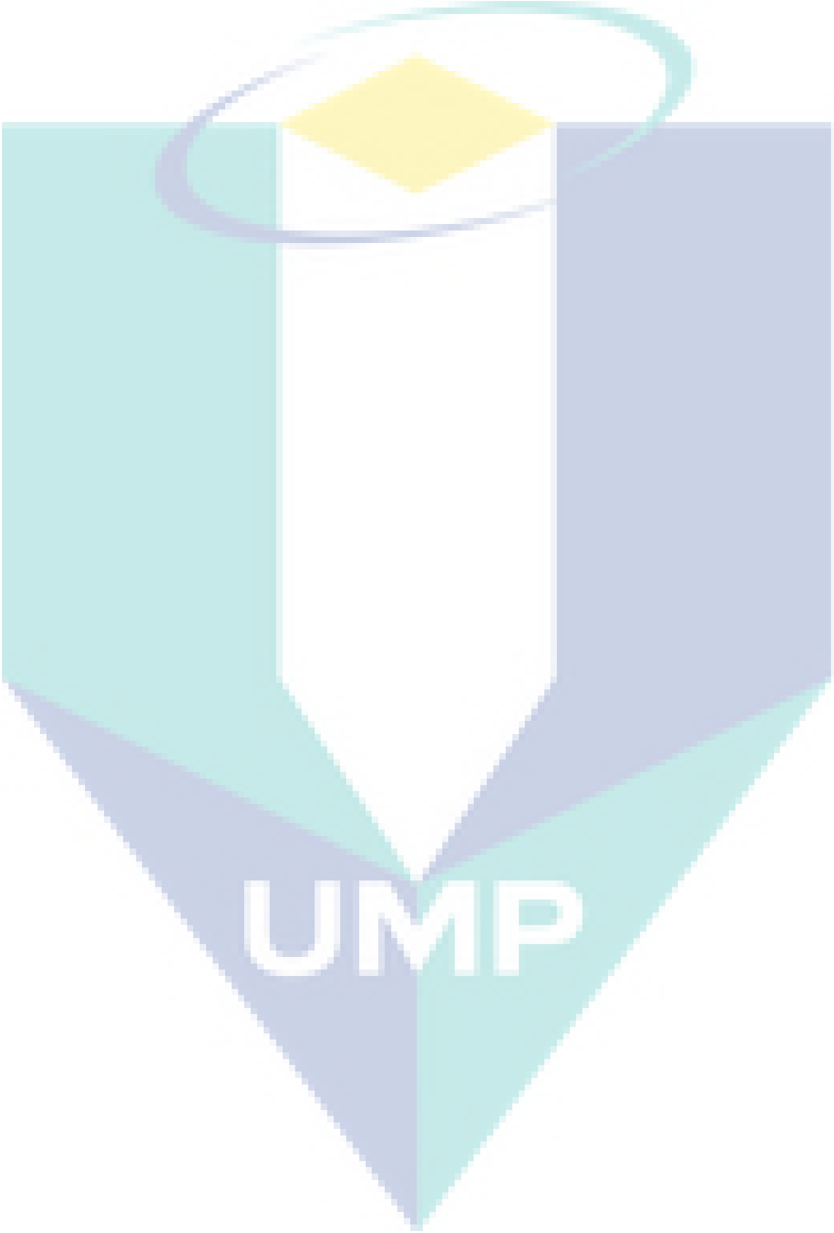
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