ALHAMDULILLAH

All Praise For Allah, Creator Of This Universe

Thanks For The Precious Iman & Islam You Blessed On Me

Thanks For All The Strength And Knowledge You Granted On Me

And Also Peace Be Upon The Holy Prophet Muhammad

All This Hardship I Dedicate To Some Special People In My Life

My Sweethearts, Ever Loving Pa, Muthusamy & Ma, Jayar

Endless Appreciation On All Sacrifices You Did For Me

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I love all of you dearly

Thanks

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ABSTRACT

Utilization of palm oil fuel ash (POFA) which is an abundantly generated waste by Malaysian palm oil industry in producing a new construction material is seen as one of the ways to reduce the quantity of this by-product disposed at landfill. This thesis presents an experimental study on the engineering properties and durability of aerated concrete consisting of POFA as partial cement replacement, known as POFA cement based aerated concrete. Two types of mixes are prepared. One consists of a control mix whereas another one consists of 20 percent of POFA. The latter has been found to give the highest strength as compared to any other replacements. More than one thousand specimens comprising cubes (70.6 x 70.6 x 70.6 mm), panels (540 x 250 x 25 mm), mortar bars (25 x 25 x 250 mm) and prisms (40 x 40 x 160 mm), (40 x 40 x 50 mm) and (225 x 225 x 25 mm), plates (650 x 100 x 25 mm) and (885 x 270 x 25 mm) have been tested in this study. The influences of POFA with numerous replacement level and mixing constituents on compressive strength of aerated concrete have been investigated. The effects of curing methods on the compressive and flexural strengths of the specimens up to one year are also studied. Studies on the durability aspect of the mix are conducted to investigate its acid resistance, sulphate resistance, performance in sea water, carbonation, dimensional stability, as well as fire resistance. POFA aerated concrete is then used to produce panels for the investigation of their compressive strength. The experiments reveal that continuous water curing is the best method in assisting POFA aerated concrete for a higher strength than the ordinary Portland cement (OPC). A constant presence of moisture is significant for the strength development of POFA aerated concrete since pozzolanic reaction can only take place at the later age, after calcium hydroxide is available from the hydration. Utilization of POFA in aerated concrete improves the durability of the lightweight concrete when exposed to aggressive environment, such as acid, sulphate and sea water. The weight loss for OPC specimen is 3.94% from its original weight as compared to POFA aerated concrete which lost only 0.9% when immersed in hydrochloric acid solution for 1800 hours. Upon exposure to 10% sodium sulphate solution, OPC mortar bar exhibit map cracks and expand as much as 14 times higher than POFA specimen. Besides that, POFA specimens also demonstrate higher durability to sea water when it exhibits lower strength reduction compared to plain aerated concrete after an exposure to marine environment for one year. The non combustible characteristic of this product and a very low influence on fire growth fulfills the requirement of the highest Class 0 under Clause 204A in Building By-Law (1984). Finally, the study shows that POFA aerated concrete mix can be used to produce panels with adequate strength as non load-bearing element in construction.

ABSTRAK

Penggunaan abu terbang kelapa sawit yang dijana dalam kuantiti yang banyak oleh industri minyak sawit di Malaysia dalam penghasilan bahan pembinaan yang baru dilihat sebagai satu cara untuk mengurangkan kuantiti sisa yang dilupuskan di tapak buangan. Tesis ini membentangkan suatu kajian eksperimen terhadap sifat kejuruteraan dan ketahanlasakan konkrit berudara berasaskan POFA sebagai bahan separa pengganti simen. Dua bancuhan telah disediakan. Satu bancuhan terdiri daripada konkrit kawalan manakala yang satu lagi ditambah dengan 20% POFA sebagai bahan separa pengganti simen di mana ianya telah dikenalpasti mempunyai kekuatan tertinggi berbanding gantian lain dalam kajian ini. Lebih daripada seribu sampel berbagai jenis terdiri dari kiub (70.6 x 70.6 x 70.6 mm), panel (540 x 250 x 25 mm), bar mortar (25 x 25 x 250 mm) dan prisma pelbagai saiz (40 x 40 x 160 mm), (40 x 40 x 50 mm) dan (225 x 225 x 25 mm) serta plat (650 x 100 x 25mm) dan (885 x 270 x 25 mm) telah diuji dalam kajian ini. Pengaruh gantian POFA dalam pelbagai kadar dan bahan-bahan campuran terhadap kekuatan konkrit berudara telah dikaji. Kesan kaedah awetan terhadap kekuatan mampatan dan lenturan sampel sehingga umur setahun turut diselidiki. Kajian terhadap ketahanlasakan sampel ini dari segi rintangan terhadap asid, sulfat, air laut, pengkarbonatan, kestabilan dimensi dan rintangan terhadap api turut dijalankan. Konkrit berudara POFA digunakan kemudian untuk menghasilkan panel dan diuji kekuatan mampatannya. Hasil ujikaji menunjukkan awetan air yang berterusan adalah kaedah terbaik untuk membantu konkrit berudara POFA mencapai kekuatan lebih tinggi daripada sampel simen Portland (OPC). Kehadiran air yang berterusan sangat penting untuk peningkatan kekuatan konkrit berudara POFA kerana tindakbalas pozzolana berlaku agak lewat iaitu setelah kalsium hidroksida yang terhasil daripada proses penghidratan wujud. Penggunaan POFA di dalam konkrit berudara meningkatkan ketahanlasakan konkrit ringan apabila didedahkan di persekitaran yang agresif iaitu asid, sulfat dan air laut. Kehilangan berat sampel OPC adalah sebanyak 3.94% daripada berat asalnya berbanding konkrit berudara POFA yang cuma kehilangan 0.9% setelah direndam dalam larutan asid hidroklorik selama 1800 jam. Apabila direndam dalam larutan yang mengandungi 10% sodium sulfat, bar mortar OPC retak dan mengalami pengembangan sebanyak 14 kali lebih tinggi daripada sampel POFA. Setelah diletakkan di dalam air laut selama setahun, sampel POFA turut menunjukkan ketahanlasakan yang lebih tinggi terhadap air laut apabila pengurangan kekuatannya adalah kurang berbanding konkrit berudara kawalan. Sifat bahan ini yang tidak mudah terbakar dan berkeupayaan rendah dalam membantu pembakaran memenuhi syarat kelas tertinggi iaitu *Class 0* di bawah *Clause 204A* dalam *Building By-Law* (1984). Kajian ini membuktikan bancuhan konkrit berudara POFA boleh menghasilkan panel yang memiliki kekuatan sesuai untuk digunakan sebagai struktur tidak menanggung beban dalam pembinaan.

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LIST OF ABBREVIATIONS

AAC	Autoclaved Aerated Concrete
AC	Aerated Concrete
ACI	American Concrete Institute
Al_2O_3	Aluminium Oxide
ASCE	American Society of Civil Engineers
ASTM	American Society of Testing of Materials
BS	British Standard
C	Carbon
C_2S	Dicalcium Silicate
C_3A	Tricalcium Aluminate
C-A-H	Calcium Aluminate Hydrate
C-S-H	Calcium Silicate Hydrate
CaO	Calcium Oxide
$Ca(OH)_2$	Calcium Hydroxide
CO_2	Carbon dioxide
Fe_2CO_3	Ferric Oxide
HCL	Hydrochloric Acid
K_2O	Potassium Oxide
LOI	Loss On Ignition
LVDT	Linear Variable Differential Transformer
Na_2O	Sodium Oxide

NAAC	Non-Autoclaved Aerated Concrete
OPC	Ordinary Portland Cement
P_2O_5	Phosporus oxide
PFA	Pulverised Fuel Ash
POFA	Palm Oil Fuel Ash
RHA	Rice Husk Ash
RH	Relative Humidity
RILEM	International Union of Testing And Research Laboratories For Materials And Structures
SEM	Scanning Electron Microscope
SiO_2	Silicon dioxide
SO_3	Sulphur Oxide
SMF	Sulfonated Melamine-Formaldehyde Polycondensate
SNFC	Sulfonated Naphthalene-Formaldehyde Condense
SP	Superplasticizer
UTM	Universiti Teknologi Malaysia
XRD	X-ray diffraction

LIST OF SYMBOLS

A	=	Cross-sectional area
b	=	Width
d	=	Depth
E	=	Modulus of elasticity
f	=	Compressive strength
F	=	Load
i	=	sub-index
I	=	Fire propagation index
L	=	Length
R	=	Modulus of rupture
S	=	Drying shrinkage
T	=	Thickness
W	=	Weight
ε_a	=	Strain
θ	=	Angle
°C	=	Temperature
%	=	Percentage

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Research towards producing a new concrete material stems out from two factors presented by two different industries in Malaysia that is by-product of palm oil industry and the growing need of construction trade. Firstly, the steadily growing palm oil industry has led to generation of the palm oil mill by-product known as palm oil fuel ash (POFA) in higher volume being dumped in the landfill. Malaysia being the largest producer and exporter of palm oil in the world, accounting for 52% of the total world oils and fats exports in year 2006 (Sumathi *et al*, 2008) is predicted to maintain its lead position over the next one and a half decade (Basiron and Simeh, 2005). Therefore, it is anticipated that bigger quantity of POFA will be discarded as environmental polluting waste in future unless this material is processed for other applications. Innovation of a new product through integration of this freely available waste would be one of the solutions to convert this environmentally polluting by-product into beneficial material for the development of human civilization.

Secondly, the popularly utilized lightweight concrete material known as aerated concrete in European countries construction industry owing to its lightness and versatility, offers application of new alternative building material for the

improvement of Malaysian building technology. This lightweight material which is capable of contributing towards the reduction of building dead load and resulting in more economic structural design (Short and Kinniburgh, 1978; Narayanan and Ramamurthy, 2000b) would benefit the local contractor. Success in producing modified aerated concrete integrating palm oil fuel ash not only could reduce the amount of ashes ending up as waste but also able to introduce new agro based cement aerated concrete suitable for the use in tropical countries.

The incorporation of palm oil fuel ash (POFA) as partial cement replacement material in the lightweight concrete mix would decrease the amount of cement used as compared to ordinary aerated concrete hence reduce the high dependency on cement. This approach has been suggested by previous researchers Zakaria (1997) and Abdul Awal (1998) who highlighted that the usage of new cement substitutes from industrial or agricultural waste as the solution towards high dependency of building towards cement supply. This is because the shortage of cement supply which occurred during last century not only caused hardship in obtaining cement but has shot the prices of cement up causing the cost of all building materials made of cement increase as well (Zakaria and Hussin, 1996a). Therefore, the creation of a new material is not only expected to offer an extra incoming profit for palm oil industry and reducing ash ending at landfill but also able to contribute towards improvement of Malaysian construction technology.

1.2 Problem Statement

Aerated concrete that has been introduced in the Malaysian construction market is the product that has been produced and used in the countries with different climate. In this case, the imported product would be expensive due to the cost of production and transportation. Therefore, the current research concentrates mainly on the problem of producing and studying the performance of aerated concrete

consisting POFA as partial cement replacement. The availability of this agro based cement material in Malaysia is expected to be an alternative for the contractors in this country to buy locally made lightweight concrete easily rather than purchasing it from oversea. This approach would assist the contractors to cut down cost of construction project that usually increase due to the higher price paid for the imported lightweight products and transportation cost of the material as well. Furthermore, the last part of the study also ventured into the possibility of using the POFA cement based aerated concrete mix in producing the aerated concrete panel. Production of a new lightweight panel is expected to be an alternative building material for sustainable construction.

1.3 Aim and Objectives

The main aim of this research is to study the engineering properties of the POFA cement based aerated concrete. The related objectives of the present research are as follows:

i. To study the effect of POFA content as partial cement replacement on the compressive strength of aerated concrete
ii. To study the effect of different curing regimes on compressive strength and flexural strength of POFA cement based aerated concrete
iii. To study the performance of POFA cement based aerated concrete towards drying shrinkage and carbonation after subjected to different curing regime
iv. To examine the durability of POFA cement based aerated concrete when exposed to aggressive condition namely acid, sulphate, and sea water environment.
v. To investigate the engineering properties of POFA cement based aerated concrete panel as well as the fire resistance properties.

1.4 Research Hypothesis

Palm oil fuel ash (POFA) can be integrated as a partial cement replacement in aerated concrete to enhance the strength and durability properties of this lightweight concrete. The strength of aerated concrete with POFA is comparable with plain aerated concrete and it also can be used for non load-bearing application.

1.5 Scope of Study

This research is a continuation of the studies on POFA usage in concrete production that have been conducted by other researchers in Faculty of Civil Engineering, Universiti Teknologi Malaysia. The present research is an attempt to incorporate POFA in the production of lightweight concrete specifically known as aerated concrete. On overall, this study is fully experimental in nature whereby the investigation is focused on the development of a new concrete material called as POFA cement based aerated concrete. Basically, the research is aimed to investigate the engineering properties and durability aspect of this agro based cement aerated concrete material. Not only that, the same mix is also used to produce non load-bearing panel for the purpose of studying its engineering properties besides subjecting it to fire resistance test.

In the first stage of the laboratory work, a mix proportion for POFA cement based aerated concrete was developed as well as producing a normal aerated concrete that was used as control subject. Two sets of trial mix each for OPC aerated concrete and POFA cement based aerated concrete was carried out with various level combinations of raw materials. Based on the results obtained, a mix was chosen based on the density as well as the compressive strength for each type of concrete.

Then, the selected mix was used throughout this research including when producing the non load-bearing panels.

In the second stage, the performance of POFA cement based aerated concrete mix developed were investigated mainly focusing on its engineering properties and durability aspects. Factors affecting the compressive strength of this material such as ash content and different curing regimes were looked into prior to studying the flexural strength and modulus of elasticity of this lightweight concrete. Then, the durability of the mix was also experimented in terms of moisture absorption properties, carbonation, drying shrinkage as well as the performance of this material in aggressive environment namely sulphate, acid and sea water.

At the final stage, the suitability of POFA cement based aerated concrete mix developed to be used as a non load-bearing wall panel was also examined. The strength performance of this material has been investigated through the compressive test conducted on the panels prepared. Other than that, properties such as bending strength and fire resistance of this material have also been looked in this study. On overall, the test conducted in this experimental study is in accordance to the existing standards.

1.6 Significance of Research

Findings from the research would contribute towards the advancement of knowledge on the use of POFA as a partial cement replacement material for producing aerated concrete possessing enhanced strength and durability in comparison to the plain aerated concrete. Furthermore, outcome of the study would also provide more information on the performance of POFA cement based aerated

concrete panel in terms of engineering properties when subjected to different curing regimes.

1.7 Layout of Thesis

Chapter one outlines the introduction that gives overall view of this research. It starts with the general introduction followed by explanation on the research problem before moving further to the objectives and scope of this research. Then, significant of the study is highlighted briefly before thesis layout is presented at the end of the section.

Chapter two discusses on the literature review that begins with introducing aerated concrete and then elaborating on its properties before presenting the latest update of research involving collaboration of aerated concrete and pozzolanic material. Followingly, the second part of this section details out general particulars on palm oil fuel ash origin including the chemical and physical characteristic of this by-product. Explanation is then focused on the merit incorporating POFA as partial cement replacement in normal concrete in terms of strength and durability. Then, the final part of this chapter presented reviews of the materials used to produce aerated concrete together with their function in the mixture as well as some details regarding non load-bearing wall.

Chapter three discusses details on the experimental program comprising of material used, specimen preparation and also testing methods adopted. After touching a bit on the preparation of the raw materials and making of the specimens, the rest of discussion has been focused on elaboration of the testing methods employed in this study which is in accordance to the available standards.

Chapter four illustrates the results comprising of trial mixes that have been conducted in order to select the optimum design mix of POFA cement based aerated concrete mix. At the beginning, discussion is focused on the physical and chemical composition of POFA that will be used as partial cement replacement in this study. Then, the result of trial mixes presented in this section is discussed mainly focusing on the effect of mixing ingredients towards strength and density of this lightweight concrete. Finally, the selected optimum design mix is displayed at the end of this chapter.

Chapter five generally reports on the analysis of engineering properties of this newly modified aerated concrete in comparison to control specimen. Influence of different curing regimes and curing age towards compressive strength and flexural strength of POFA cement based aerated concrete is also explained based on the presented data. Discussion on the microstructure study has also been included in this section in order to explain the strength performance of aerated concrete consisting POFA. The section comes to an end with the presentation of the result on modulus of elasticity of POFA aerated concrete that been compared with the performance of control specimen.

The results displayed in chapter six focused on the behaviour of POFA cement based aerated concrete in terms of durability aspect. The early part of the section, demonstrate the results on moisture absorption properties, carbonation and dimensional stability of this material which have been presented in the forms of graphs and discussed. Later, the discussion is centered to the performance of aerated concrete exposed against different types of aggressive conditions namely acid, sulphate and marine environment which are explained in detail.

Chapter seven is the final part of the study involving the analysis on engineering properties of panel as well as plate produced using POFA cement based aerated concrete and the fire resistance of this material. Results on the effect of curing regimes towards performance of panel and plate have also been included and

discussed. The section is ended with presentation on the result of fire resistance tests that have been conducted on this agro based cement aerated concrete specimen.

Finally, chapter eight concludes the results of the study together with few recommendations which have also been outlined for future research.