ENGINEERING PROPERTIES OF RUBBERISED CONCRETE INCORPORATING PALM OIL FUEL ASH

PARHAM FOROUZANI

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Civil Engineering)

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To my lovely parents

who gave me endless love, trust, constant encouragement over the years, their prayers and financial supports

And

To my lovely wife

for her love, patience, support, and for enduring the ups and downs during the completion of this thesis.

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ABSTRACT

The utilisation of waste materials and by-products is a partial solution to environmental and ecological problems. One important recent development, in the field of concrete technology, is the utilisation of waste materials and by-products in the construction industry, as aggregates in the production of various types of concrete. Agro-waste materials, such as palm oil fuel ash (POFA), show a great potential ability to be utilised as a pozzolanic material in concrete. The problem of the rising costs of construction materials, coupled with evident environmental degradation, and the need to improve concrete properties; especially in terms of acoustic properties, has stimulated the necessity to incorporate tyre-rubber aggregates (TRA) and POFA in concrete. Rubberised Concrete (RC) is produced by replacing a volume percentage of the traditional coarse and/or fine aggregate with tyre-rubber particles. TRA has been utilized in various gradations from used vehicle tyres and POFA has been replaced partially as cementitious material. This research investigates the wide range of physical, mechanical and acoustic properties of concrete containing recycled TRA and POFA to assess its suitability as a construction material. The influence of factors, such as rubber aggregate content, size, shape and type of rubber particle, was also considered. TRA is classified into three groups, namely fine fibre (R_1), fine granular (R_2) and coarse granular (R_3). The concrete mixture is designed based on ACI 211-91. The TRA component of the mixture is replaced in 5% to 30% by volume. The results of this study show that the best proportion of POFA is 20% with a water-binder ratio of 0.38; which improves the 28-day concrete strength. The results show that despite a great loss in strength with increasing TRA replacement, this type of concrete is acceptable for various structural applications requiring medium to low compressive strengths. It is found that for the same volume of rubber (coarse and fine TRA), coarse rubber particles increase air content, decrease compressive, indirect tensile, and flexural strengths, and improve the deformability of concrete, compared to concrete containing fine TRA. Furthermore, the modified rubberised concrete exhibits superior acoustic properties. The results of sound absorption coefficient and sound transmission loss show that the coarse aggregates have more influence on improving the sound-proofing properties by up to 42.5% with 30% TRA incorporation. These attributes make rubberised POFA concrete a potential candidate for application in a promising flooring system that is cost-effective and has increased sound-proof properties. The possible quantities of concrete produced worldwide for such applications would ensure the viability of this product. Therefore, this type of concrete shows promise in becoming an additional sustainable solution for tyre-rubber waste management.

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ABSTRAK

Penggunaan bahan-bahan buangan dan produk sampingan adalah penyelesaian separa kepada masalah alam sekitar dan ekologi. Satu perkembangan penting baru-baru ini dalam bidang teknologi konkrit adalah penggunaan bahan-bahan buangan dan produk sampingan dalam industri pembinaan sebagai agregat dalam pengeluaran pelbagai jenis konkrit. Bahan-bahan sisa agro, seperti abu bahan api kelapa sawit (POFA), menunjukkan potensi besar untuk digunakan sebagai bahan pozzolanic dalam konkrit. Masalah kenaikan kos bahan-bahan binaan, ditambah pula dengan pencemaran alam sekitar yang jelas, dan keperluan untuk meningkatkan sifat-sifat konkrit, terutama dari segi ciri-ciri akustik, telah merangsang keperluan untuk menggabungkan agregat tayar-getah (TRA) dan POFA dalam konkrit. Konkrit Getah (RC) dihasilkan dengan menggantikan peratusan isipadu agregat kasar tradisional dan/atau agregat halus dengan zarah-zarah tayar-getah. TRA telah digunakan dalam pelbagai penggredan daripada tayar terpakai kenderaan dan POFA telah digantikan sebahagiannya sebagai bahan bersimen. Penyelidikan ini menyiasat pelbagai sifat-sifat fizikal, mekanikal dan akustik pada konkrit yang mengandungi TRA yang dikitar semula dan POFA untuk menilai kesesuaiannya sebagai bahan pembinaan. Pengaruh faktor-faktor seperti kandungan agregat getah, dan saiz, bentuk dan jenis zarah getah juga dipertimbangkan. TRA diklasifikasikan kepada tiga kumpulan, iaitu serat halus (R_1), butiran halus (R_2) dan butiran kasar (R_3). Campuran konkrit direka bentuk ACI 211-91. Komponen TRA dalam campuran digantikan sebanyak 5% hingga 30% mengikut isipadu. Keputusan kajian ini menunjukkan bahawa bahagian terbaik POFA adalah 20% dengan nisbah air-pengikat sebanyak 0.38, yang meningkatkan kekuatan konkrit 28 hari tersebut. Keputusan menunjukkan bahawa walaupun sebahagian besar kekuatan kehilangan dengan peningkatan penggantian TRA, konkrit jenis ini boleh digunakan untuk pelbagai aplikasi struktur yang memerlukan kekuatan mampatan yang sederhana hingga rendah. Telah didapati bahawa untuk isipadu getah (TRA kasar dan halus) yang sama, zarah getah kasar meningkatkan kandungan udara, menurunkan kekuatan mampatan, tegangan tidak langsung dan lenturan, dan meningkatkan perubahan bentuk konkrit berbanding dengan konkrit yang mengandungi TRA halus. Tambahan pula, konkrit getah yang diubahsuai mempamerkan sifat-sifat akustik yang unggul. Keputusan pekali penyerapan bunyi dan kehilangan penghantaran bunyi menunjukkan bahawa agregat kasar mempunyai pengaruh yang lebih ke atas peningkatan sifat-sifat kalis bunyi sehingga 42.5% dengan penggabungan TRA sebanyak 30%. Ciri-ciri ini menjadikan konkrit getah POFA calon yang berpotensi untuk aplikasi sistem lantai yang berkesan dari segi kos dan mempunyai sifat-sifat kalis bunyi yang lebih baik. Kuantiti konkrit yang mungkin dihasilkan di seluruh dunia untuk aplikasi begini akan memastikan kebolehlaksanaan produk ini. Oleh itu, jenis konkrit ini berpotensi menjadi penyelesaian tambahan yang mampan bagi pengurusan sisa tayar-getah..

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LIST OF ABBREVIATIONS

ACI - American Concrete Institute

AEA - Air Entraining Admixture

ASCE - American Society Civil Engineers

ASHTTO - American Association of State Highway and Transportation Officials

ASR - Alkali Silica Reaction

ASTM - American Society for Testing and Materials

EDX - Energy Dispersive X-ray

FESEM - Field Emission Scanning Electron Micrograph

GGBS - Ground Granulated Blast Furnace Slag

LOI - Loss on Ignition

LVDT - Linear Variable Displacement Transducer

MOE - Modulus of Elasticity

NRC - Noise Reduction Coefficient

OPC - Ordinary Portland Cement

POFA - Palm Oil Fuel Ash

PRC - Plain Rubberized Concrete

RCPT - Rapid Chloride Penetration Test

RHA - Rise Husk Ash

RILEM - International Union of Testing and Research Laboratory for Materials and structures

SBR - Styrene Butadiene Rubber

SEM - Scanning Electron Micrograph

SP - Supper Plasticiser

SSD - Saturated Surface Dry

STC - Sound Transmission Loss

TRA - Tire Rubber Aggregate

UPV - Ultrasonic Pulse Velocity

VDC - Volts of Direct Current

XRD - X-ray Diffraction

LIST OF SYMBOLS

A_c - The cross section of specimen
A_c - Design air content
A_s - Air content of the sample tested
GS_R - Specific gravity of rubber aggregate
L_r - Distance between the lower roller
M_c - Mass of container filled with concrete
M_m - Mass of container
$V_{N.F}$ - Solid volume of fine aggregate
V_m - Volume of container
W_R - Weight of rubber aggregates in concrete mixture
f_c - The compressive strength in mega Pascal
f_c' - Compressive Strength
f_{ct} - Flexural strength in mega Pascal
g_1 - Bulk density, dry
g_2 - Apparent density
γ_w - Density of water
Al - Almina
Al_2O_3 - Aluminium oxide
c - Mass of surface
C - Carbon
C_2S - Calcium silicate
C_3Al - Tricalcium aluminate
$Ca(OH)_2$ - Calcium hydroxide
CaO - Calcium oxide
C-A-S-H - Calcium silicate hydrate
Cl - Chloride
CO_2 - Carbon dioxide

C-S-H - Calcium silicate hydrate

E - Dynamic modulus of elasticity

E_s - Modulus of Elasticity

Fe - Iron

Fe_2O_3 - Iron oxide

f_r - Flexural Strength

K_2O - Potassium oxide

MgO - Magnesium oxide or magnesia

P_2O_5 - Phosphorus oxide

R - Percentage of rubber aggregate replacement

SG_c - Specific gravity of cement

SG_{ca} - Specific gravity of coarse aggregate on saturated surface dry basis

SiO_2 - Silicon oxide

SO_3 - Sulphur trioxide

TiO_2 - Titanium oxide

W/B - Water to binder ratio (by weight)

D - Density of concrete

E - Modulus of elasticity

G - Aggregate correction factor

L - Distance between transducers (m)

T - Effective transit time

V - Pulse velocity

ε - Longitudinal strain

μ - Dynamic poison’s ratio

ρ - density of water

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CHAPTER 1

INTRODUCTION

1.1 Overview

Concrete has been the most commonly used manufactured material in the world since its invention. Concrete is a composite material comprising three major fractions, namely aggregate, cement, or binder (supplementary cement materials), and water, in suitable proportions, thus allowing the resulting mixture to set and harden over time. It is common knowledge that aggregates are the inert materials in concrete; however, being the major constituent, the proper selection of aggregates is very important to accomplish innovation in concrete production (de Brito and Saikia, 2013). In fact, the proper selection of aggregates and the manipulation of their size distribution are very important steps in the development of almost all types of special concrete. The aggregate fraction in concrete is about 60% to 80% of its total volume (Neville, 2011). Moreover, the preparation of some types of concrete, such as light and heavyweight concrete, as well as concrete resistant to sound or vibration, can only be achieved through the proper selection of aggregates.

Recently, the worldwide growth of the automobile industry and the increase in car use has tremendously boosted tyre production. For example, in the United States alone, around 233.3 million scrap tyres were generated in 2013; this is approximately equal to 3,824.3 thousand tonnes (U.S. Environmental Protection Agency, 2013). The European Union countries discarded 3.2 million tonnes of scrap tyres in 2009 (Bravo and de Brito, 2012). In Malaysia, the estimated number of waste tyres is 8.2 million annually (Thiruvangodan, 2006). Furthermore, the quantity of scrap tyres generated in Malaysia for various years is presented in Table 1.1. Therefore, large quantities of waste materials and by-products are generated from manufacturing processes, service industries, and municipal solid wastes. As a result, solid waste management has become one of the major environmental concerns in the world. The increase in public awareness about the environment, the scarcity of landfill space, and the ever-increasing cost of goods, the utilisation of waste materials and by-products has become an attractive alternative to disposal. The high consumption of natural sources, extreme quantities of industrial wastes produced, and environmental pollution require the delineation of new solutions for sustainable development.

Table 1.1: Number of scrap tyres generated in Malaysia (National Solid Waste Management Department, 2011)

Year	Quantity of Scrap Tyres (Tonne/Year)
2007	208.911
2008	211.209
2009	232.325
2010	245.087

Another important recent development in the field of concrete science is the utilisation of waste materials and by-products in the construction industry, as well as the use of these materials as aggregates in the production of various types of concrete. The utilisation of waste materials and by-products is a partial solution to environmental and ecological problems. The use of these materials helps not only in having them utilised in cement, concrete, and other construction materials but also in reducing the cost of cement and concrete manufacturing. It also has numerous indirect benefits, such as reduction in landfill costs, energy savings, and environmental protection from possible pollution effects. Furthermore, the utilisation of these materials may improve the microstructure, durability, and mechanical properties of mortar and concrete, which may be difficult to achieve using only ordinary Portland cement.

Meanwhile, palm oil fuel ash is known as an agricultural by-product, and such waste material is simply disposed in landfills without any commercial returns. However, this may have a mal-effect role in the environment and landfills areas. In fact, Malaysia is the second largest producer of palm oil in the world. According to a report on the Malaysian palm oil industry (2009), palm oil production reached 17.7 million tonnes. There are more than 200 palm oil mills operating in the country. On average, 43 tonnes or more of empty fruit bunches, husks, and shells are generated per 100 tonnes of fresh fruit bunches processed. The total solid waste generated by this industry has been estimated to amount to more than 8.1 million tonnes a year. These wastes are mostly used in boilers as fuel to generate power for the mill. After this process, the waste becomes ash. This ash is known as palm oil fuel ash (POFA) (Shafigh et al., 2014; Foo and Hameed, 2009)

Significant research on the use of by-products in cement-based materials has been on-going, and the results show that POFA has the great potential to serve as a partial replacement binder material in concrete mixtures.

1.2 Importance of the Study

The disposal of rubber tyre waste has become a serious problem because of the generation of huge amounts of tyres, which are non-biodegradable by nature. Over the past decades, millions of scrap tyres have been disposed into open land fields. These stockpiles seriously threaten both the environment and public health because of their potential to serve as suitable breeding fields for mosquitoes, particularly because scrap tyres oftentimes retain water, which provides enough humidity and a warm place for mosquito breeding. Mosquitoes are one of the major public health threats that increase the likelihood of spreading disease. Moreover, these stockpiles create a fire danger because tyre components contain flammable content. Some researchers reported that tyre fires had continued for several months. Moreover, under the high temperatures of tyre fires, the tyres melt and release hydrocarbons and other pollutants to the ground and, in some cases, even to the ground water. In addition, tyre fires have produced black smoke, which causes serious air pollution (Guneyisi et al., 2004; Eldin and Senouci 1994; Hernandez–

Oliveras et al., 2002; Li et al., 2004-b; Topcu 1995; Khaloo et al., 2008; Siddique and Naik, 2004; Khatib and Bayomy 1999; Ghaly and Cahill, 2005).

Although concrete is the most commonly used construction material, it does not always fulfil some requirements, especially in service. Portland cement concrete (PCC) is a composite material that is well-known for its mechanical properties, with including adequate compressive strength, acceptable tensile strength, and low toughness, which resulted in brittleness and low deformability (Guneyisi et al., 2004; Khaloo et al., 2008). An ideal PCC is expected to have such properties as high tensile strength and light weight. Moreover, the prompted demand for the modification of the brittle property of concrete resulted in the utilisation and application of alternative materials with deformable property, such rubber tyres, as coarse or fine aggregates or as a filler materials for the preparation of various types of concrete (Kumaran et al. 2012; Siddique and Naik 2004; Fattuhi and Clark, 1996; Chiu, 2008; Khaloo et al., 2008; Li et al., 2004-a). Elastic and deformable of tyre-rubber particles could improve concrete properties, especially in terms of brittleness and sound insulation properties. Therefore, the addition of proper materials to concrete is one of the most popular fields in the concrete modification research area, and a large number of studies have been conducted to identify and introduce new materials as additives or replacements to improve or modify concrete properties (Hall et al., 2012; Khaloo et. al 2008; Pelisser et al., 2011; Sunthonpagasit and Duffey, 2004).

1.3 Problem statement

At present, the rapid growth of the automobile industry increased not only automobile production, but also the amount of industrial waste materials, such as scrap tyres. Industrial waste materials, such as waste tyres, should be handled properly to reduce the mal-effect on the environment and the rate of wastage. Moreover, the economic situation in developing countries demands for cost reduction in construction projects. Therefore, cutting costs related to concrete has a major role in this goal, given that concrete is the most commonly used material in construction projects.

The utilisation of pozzolanic materials, polymers, fibres, and waste materials in concrete has been studied many years ago because shortcomings in the performance of concrete, either in the fresh or hardened state, motivated engineers to seek improvements. The inclusion of all these materials is a typical approach. Over the past decades, numerous research works have been conducted on the use of agro-waste ashes as supplementary cementing material in concrete construction. Among others, palm oil fuel ash (POFA) played a tremendous role in this regard.

In addition, in the application of concrete, desirable concrete properties include lighter weight, higher toughness, better sound absorption, and higher impact resistance. Although concrete is the most commonly used construction material, it does not always fulfil these requirements. New applications for recycling waste materials have recently been realised to improve the properties of concrete. One of these applications is the utilisation of scrap tyres to replace aggregates partially. The major weakness of using rubber in concrete is the low compression strength of rubberised concrete. It remains a problem in the use of rubberised concrete as a structural component. Thus, it is recommended for use as a non-loading member in construction. Utilising tyre-rubber aggregates in concrete has great potential to produce acoustic material. However, the low strength of rubberised concrete prevents engineers from fully benefiting from this attribute.

Therefore, this research endeavours to find a way to utilise rubberised POFA concrete in structural application, especially in the floor component for low-cost buildings, as concrete with high potential in terms of acoustic and soundproofing properties.

1.4 Aim and Research Objective

The aim of this research is to investigate the effect of incorporating palm oil fuel ash (POFA) for the partial substitution of cementitious material, with tyre-rubber aggregate replacement utilised as the aggregate in concrete to achieve green and sustainable concrete production.

i. The main objectives of this research are as follows:

i. To determine the optimum mix design for rubberised concrete with different types, sizes, and amounts of tyre-rubber particles incorporating POFA for application to structural concrete.

ii. To identify the engineering properties of concrete with different types, shapes, and sizes of tyre-rubber aggregate in terms of physical and mechanical qualities.

iii. To evaluate the durability of POFA-rubberised concrete, this study was based on such parameters as fire endurance, water absorption, chloride penetration, and carbonation of modified-rubberised concrete.

iv. To determine the property-improvement of POFA-rubberised concrete in terms of acoustic properties. The properties to be evaluated include: sound absorption and sound transmission properties of POFA-rubberised concrete in the corporation and different types, shapes, amounts, and sizes of tyre-rubber aggregates.

1.5 Scope and Limitation of the Research

In general, this research focused on the impact of tyre-rubber aggregate on the engineering properties of concrete. However, this research work was concerned with the development of the utilization palm oil fuel ash (POFA) concrete. Primarily, POFA replaced cement partially at a range from 15% to 30%. Then, the amount of replacement was optimised based on the compressive strength. Tyre-rubber aggregates were categorised in three groups, namely fine fibre crumb rubber (0.8 to 3.3 mm), fine granular crumb rubber (1 to 4 mm), and coarse granular crumb rubber (5 to 8 mm). The range of replacement level of natural aggregate with the tyre-rubber aggregate was from 5% to 30%.

The experimental study focused on the engineering properties of modified rubberised concrete, particularly, compressive strength, as well as the acoustic properties, durability, and fire safety performance of rubberised POFA concrete.

1.6 Significance of the Research

The disposal of rubber tyre waste has become a serious problem because of the generation of huge amounts of tyres, which are non-biodegradable by nature. The extensive references, including excellent reviews, are available on the use of tyre-rubber as coarse or fine aggregates or as a filler material for the preparation of various types of concrete (Kumaran et al. 2012; Kumaran et al. 2011; Siddique and Naik 2004). Meanwhile, studies are on-going to identify a balance between reutilising scrap tyres and the mechanical properties of rubberised concrete, especially in terms of compressive strength.

Furthermore, previous research found that POFA exhibited a satisfactory performance when introduced to the concrete as a pozzolanic material. Therefore, reusing of by-products from the agro-industry, such as POFA, may help decrease the threats of disposal hazard materials and save nature by reducing the CO_2 emissions associated with reduction in the demand manufacturing of Portland cement.

The outcome of this research can prepare supportive information for utilising POFA as a binder replacement and tyre-rubber particles as aggregates. Furthermore, this research work aim to provide a soundproof concrete with the used of the tyre aggregates with proper compressive strength, which is accepted as a property of structural concrete that may be deemed as strength of this research.

1.7 Thesis Organisation

The thesis is organised and presented in several chapters as follows:

Chapter One: This chapter presents a general appraisal and overview of the study. It includes the introduction, importance of the study, problem statement, aim of the study, objectives of the research, as well as the scope and significance of research in this field. Furthermore, the layout of the thesis is briefly described in this chapter.

Chapter Two: This chapter provides a comprehensive description of the properties of rubberised concrete and explains the recent research works on the use of POFA as pozzolanic material. An in-depth review of the effects of the application of POFA as pozzolanic material on the properties of concrete is discussed. The contribution of rubber aggregate utilisation to the concrete properties, specifically both fresh and hardened properties, is described.

Chapter Three: The use of the proper materials and the methodology for the use of the appropriate standard and modification are necessary when conducting the tests described in this chapter.

Chapter Four: The procedures for the modification of the mixture proportion of concrete in terms of POFA utilisation in concrete as pozzolanic material to enhance concrete strength and rubber aggregate to serve as a partial replacement for natural aggregates. This chapter reveals the results of POFA and its effect on concrete properties. It also presents the methods of substitution for rubber aggregates and why this method was chosen.

Chapter Five: This chapter reveals the properties of rubberised POFA concrete in the fresh and hardened states in long-term studies. The parameters studied in this chapter include workability in terms of the slump of concrete, fresh density, and air content. In addition, the relationship between some data is developed in order to establish a correlation. For the investigation on hardened properties, tests falling in this category include compressive, flexural, and tensile strength. It also presents the results obtained and discussion made on the evaluation of mechanical properties. The deformability and conductivity of modified rubberised concrete is discussed in this chapter. Tests conducted in this category include modulus of elasticity and ultrasonic wave transmit of concrete containing different amounts and sizes of rubber aggregates.

Chapter Six: The aspects of durability performance considered in this chapter are permeability (water absorption and total porosity), chloride content (rapid chloride penetration test), carbonation, and fire endurance.

Chapter Seven: The acoustic properties of rubberised concrete in the high- and low-frequency sound wave study are outlined in this chapter. Furthermore, the soundproofing properties of rubberised concrete with different types and amounts of rubber aggregates are discussed.

Chapter Eight: This chapter concludes this dissertation by stating the findings and achievements of the study and the contribution of the research to the existing knowledge. Recommendations are presented for further research in related areas as well.

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