Properties of Crumb Rubber Loading on Fly Ash Based Geopolymer Mortar for Sandwich Wall Panel

by

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A thesis submitted in fulfillment of the requirements for the degree of
Doctor of Philosophy

Faculty of Chemical Engineering Technology
UNIVERSITI MALAYSIA PERLIS

2022

ACKNOWLEDGEMENT

بِسْــــــــــــمِ اللهِ الرَّحْمَنِ الرَّحِيم

In the name of Allah, the Most Beneficent, the Most Merciful, praises be to Allah who gave me the power, the undying strength and the patience bestowed upon me during this study; and blessings and peace be upon our prophet Muhammad.

First of all, I would like to acknowledge the support of Universiti Malaysia Perlis and the Faculty of Chemical Engineering Technology, especially for providing the opportunity to undertake this study. My special acknowledgement goes to my main supervisor, Prof. Ts. Dr. Mohd Mustafa AlBakri Bin Abdullah for his constant encouragement, guidance and assistance during my period of study. The constant guidance and assistance offered by my co-supervisors, Prof. Ts. Dr. Che Mohd Ruzaidi Bin Ghazali and Dr. Romisuhani Binti Ahmad are gratefully acknowledged. I extend my appreciation to all Faculty of Chemical Engineering Technology staff and members of the Center of Excellence Geopolymer and Green Technology (CEGeoGTech), especially all the numerous friends whose names have not been mentioned. It was nice knowing you all.

Special thanks go to my mother, brother, sister, wife, and daughters for their encouragement, prayers, and endless love. Lastly, it is a pleasure to thank those who made this thesis possible. I offer my regards and blessing to all of those who supported me in any aspect during the completion of the thesis.

Ahmad Azrem Azmi

2022

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LIST OF ABBREVIATIONS

Al	Aluminium
Al_2O_3	Aluminium Oxide
Al-Si	Alumino-silicate
ASTM	American Society for Testing and Materials
CaO	Calcium Oxide
$Ca(OH)_2$	Calcium Hydroxide
CO_2	Carbon Dioxide
CRGM	Crumb Rubber Geopoymer Mortar
CRGSWP	Crumb Rubber Geopolymer Sandwich Wall Panel
CRM	Crumb Rubber Modifier
Fe_2O_3	Iron Oxide
KOH	Potassium Hydroxide
Na_2SiO_3	Sodium Silicate
NaOH	Sodium Hydroxide
OPC	Ordinary Portland Cement
SEM	Scanning Electron Microscope
Si	Silicon
SiO_2	Silicon Dioxide
SO_3	Sulfur Trioxide
XRF	X-Ray Fluorescence Spectroscopy

LIST OF SYMBOLS

%	Percentage
μm	Micrometer
g/cm^3	Gram per centimeter cube
M	The concentration of NaOH (M)
MPa	Megapascal
nm	Nanometer
mm	Millimeter
kg/m^3	Kilogram per meter cube
°C	Degree Celsius
W/mK	Thermal conductivity
m/s	Meter per second
dB	Decibels

Sifat-Sifat Pembebanan Serbuk Getah Pada Mortar Geopolimer Berasaskan Abu Terbang untuk Panel Dinding Apit

ABSTRAK

Penggabungan serbuk getah ke dalam mortar geopolimer berasaskan abu terbang mengurangkan pelepasan CO_2 kerana pengecualian simen Portland biasa (OPC), jumlah sisa tayar yang memasuki tapak pelupusan sampah dan jumlah agregat mineral semula jadi yang digunakan dalam mortar. Abu terbang (kelas F) bertindak balas dengan larutan alkali seperti natrium hidroksida (NaOH) dan natrium silikat (Na_2SiO_3) untuk menghasilkan gel aluminosilikat yang mengikat serbuk getah untuk menghasilkan mortar geopolimer serbuk getah (CRGM). Nisbah larutan NaOH (12M) dan nisbah larutan Na_2SiO_3 adalah tetap pada 2.5 dan nisbah pepejal kepada cecair adalah tetap pada 2 untuk semua campuran geopolimer abu terbang. Penambahan serbuk getah dalam campuran berat pepejal masing-masing bervariasi pada 0%, 5%, 10%, 15% dan 20%. Lapisan luar yang digunakan untuk panel dinding apit geopolimer serbuk getah (CRGSWP) adalah prima*flex* dengan ketebalan 9 mm. Kesan peratusan serbuk getah yang berbeza terhadap kekuatan mampatan mortar geopolimer berasaskan abu terbang ditentukan. Hasil kajian menunjukkan bahawa kekuatan mampatan CRGM menurun seiring dengan peningkatan pembebanan serbuk getah. Kekuatan mampatan CRGM-0, CRGM-5, CRGM-10, CRGM-15 dan CRGM-20 pada hari ke 28 masing-masing adalah 40.48 MPa, 36.13 MPa, 29.69 MPa, 23.13 MPa dan 20.13 MPa. Penurunan ini disebabkan oleh lekatan antara muka antara serbuk getah dan komponen simen yang lemah, sehingga kekuatannya menurun. Untuk kesan pendedahan suhu tinggi terhadap prestasi CRGM, mortar pada hari ke 28 masa pengawetan didedahkan pada suhu 200 °C, 400 °C, 600 °C dan 800 °C. Hasil menunjukkan penurunan kekuatan mampatan dan ketumpatan sementara peratusan kehilangan berat meningkat dengan peningkatan pembebanan serbuk getah pada semua suhu yang didedahkan. Prestasi CRGM dan CRGSWP bagi sifat-sifat mekanikal, penyerapan bunyi dan kekonduksian terma diuji dan dibandingkan. CRGSWP menunjukkan penurunan kekuatan mampatan dan lenturan ketika pembebanan serbuk getah meningkat. Peratusan penyerapan bunyi bagi CRGSWP adalah lebih tinggi berbanding CRGM, ini bermaksud penyerapan bunyi bagi CRGSWP adalah lebih baik daripada CRGM. CRGSWP-20 menunjukkan peratusan penyerapan bunyi tertinggi sebanyak 57.32% bagi frekuensi rendah dan 70.01% bagi frekuensi tinggi. Ujian kekonduksian terma bagi CRGSWP-20 (0.074 W/mK) menunjukkan nilai *k* lebih baik daripada CRGM-20 (0.298 W/mK). Tesis ini memperluas sumbangan penemuan peratusan pembebanan serbuk getah yang berbeza kepada sifat CRGM pada suhu bilik dan pendedahan pada suhu tinggi dan sifat-sifat mekanikal dan terma terhadap CRGSWP sebagai aplikasi panel dinding apit.

Properties of Crumb Rubber Loading on Fly Ash Based Geopolymer Mortar for Sandwich Wall Panel

ABSTRACT

The incorporation of crumb rubber into fly ash-based geopolymer mortar reduces the CO_2 emissions due to the exclusion of ordinary Portland cement (OPC), the number of waste tires entering the landfills and the amount of natural mineral aggregate being used in mortar. The fly ash (class F) reacts with an alkaline solution such as sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) to produce aluminosilicate gel that binds the crumb rubber to produce a crumb rubber geopolymer mortar (CRGM). NaOH solution (12M) and Na_2SiO_3 solution ratio were fixed constantly at 2.5, and the solid to liquid ratio was fixed at 2 for all fly ash geopolymer mixture. The additions of crumb rubber in the mixture by weight of solid were varied at 0%, 5%, 10%, 15% and 20%, respectively. The outer layer used for the crumb rubber geopolymer sandwich wall panel (CRGSWP) was prima*flex* with 9 mm thickness. The effect of different percentage crumb rubber loading on the compressive strength of fly ash-based geopolymer mortar was determined. Results show that the compressive strength of the CRGM decreased with the increase of crumb rubber loading. The compressive strength of CRGM-0, CRGM-5, CRGM-10, CRGM-15 and CRGM-20 at 28 days were 40.48 MPa, 36.13 MPa, 29.69 MPa, 23.13 MPa and 20.13 MPa, respectively. This reduction is due to poor interfacial adhesion between crumb rubber and cement components; thus, the strength is reduced. For the effect of elevated temperature exposure on the performance of CRGM, the mortars, at 28 days of curing time, were exposed to an elevated temperature at 200 °C, 400 °C, 600 °C and 800 °C. Results of the CRGM show a reduction in compressive strength and density while the percentage of weight loss increased with increasing crumb rubber loading at all elevated temperature exposure. The performance of CRGM and CRGSWP were tested and compared for their mechanical properties, sound absorption and thermal conductivity. CRGSWP and CRGM show a reduction in compressive and flexural strength as the crumb rubber loading increases. The sound absorption percentage of CRGSWP was higher compared to CRGM, which means that the sound absorption of CRGSWP is better than CRGM. CRGSWP-20 shows the highest percentage of sound absorption by 57.32% for the low frequency and 70.01% for the high frequency. Thermal conductivity test of the CRGSWP-20 (0.074 W/mK) shows better *k*-value than CRGM-20 (0.298 W/mK). This thesis expands the contribution of the findings of different percentage crumb rubber loading on the properties of CRGM at room temperature and elevated temperature exposure and the mechanical and thermal properties of CRGSWP as sandwich wall panel application.

CHAPTER 1 : INTRODUCTION

1.1 Research Background

The rapid growth in vehicle usage has led to a large number of tire production in Malaysia, leading to an increasing amount of waste tire rubber. Waste tires require a large area of the landfill for disposal and are not biodegradable. The accumulation of waste tires has become one of the most severe environmental issues. An urgent need to get rid of waste tires beneficially and in an eco-friendly way is needed (Boudaoud & Beddar, 2012; Si et al., 2017). New green materials are being developed using recycled tire rubber, such as rubberized mortar, to ease this problem. Crumb rubber replaces some of the aggregates in a mortar (Wongsa et al., 2018).

Geopolymer is a cementitious composite material that uses alumina and silica oxides from aluminosilicate source materials (such as fly ash, blast furnace slag, and metakaolin) and alkali activators such as sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) solution (Wongsa et al., 2020). Fly ash (containing silica and alumina) reacts with an alkaline liquid (Na_2SiO_3 and NaOH solutions) in a polymerization reaction to form a geopolymer paste that binds the non-reacted materials (crumb rubber). These efforts yielded two advantages: one addresses the environmental concern about carbon dioxide (CO_2) emissions from OPC production, and the other offers a solution for efficiently using fly ash in the process (Yahya et al., 2017).

Nowadays, utilizing recycled rubber in construction has received considerable attention from researchers. Utilizing recycled rubber derived from scrap tires in civil engineering applications such as mortar production represents an effective technique for safely using vast volumes of waste materials. This reuse promotes the development of eco-friendly buildings and encourages the concept of sustainable production. Furthermore, rubber aggregate has a lower density compared to conventional aggregate. Hence, it can significantly contribute to the development of semi-lightweight and lightweight mortar, which helps reach a more economical design (Ismail & Hassan, 2016). Therefore, this study is conducted to produce a geopolymer mortar incorporating different loading of crumb rubber, nevertheless offer good mechanical and thermal properties that can be applied for a non-structural concrete application.

Exposure to high temperatures will significantly affect the mortar structure. Many researchers (Uysal et al., 2012; Nadeem et al., 2014; Gupta et al., 2017; Saberian et al., 2019) have reported a decrease in compressive strength and quality loss due to temperature increase. Guelmine et al. (2016) observed that the addition of recycled rubber has little effect on the residual properties of the mortar exposed to 300 °C, and it has a significant effect when the temperature reaches 400 °C. Guo et al. (2014) studied that a large amount of crushed rubber would cause a substantial decrease in the compressive strength at high temperatures. Mousa (2017) investigated the effect of recycled rubber aggregates on concrete properties exposed to high temperatures of 300 °C, 400 °C, 600 °C and 800 °C for 120 minutes. They observed many visible cracks on the surface of concrete samples containing 5% recycled rubber aggregate. The compressive strength loss of samples containing rubber aggregate is more significant. Extreme circumstances that any structure may face during its service life include fires and high temperatures. Regular fires are the only thing that conventional OPC concrete can endure. As a result, fire resistance became a crucial characteristic in the reinforced construction methods commonly employed in high-rise structures.

Wall materials have become one of the focuses on the development of green buildings. Lightweight panels are currently used as materials of a wall to reduce energy consumption on the construction of the building in the aspect of material transportation and size reduction of the building structure compared with that of typical walls, particularly brick and concrete ones. Additionally, using materials developed from renewable sources would provide a more environmentally friendly and sustained construction (Phohchuay & Khongtong, 2018). To construct a building, the wall is considered an essential component. The desirable properties of a board or panel suitable for wall application are high durability, dimensional stability, toughness, fire resistance, good acoustic and thermal insulation properties, good biological resistance, rapid production and low production costs (Zakiah et al., 2018). Sandwich panel is a layered structural system composed of low-density core material, which acts integrally with the high strength facing material. Structures made of sandwich panels can be remarkably strong and lighter in weight. The trend for "stronger-lighter" products became increasingly important in the construction industry.

1.2 Problem Statement

It has been estimated that the manufacture of geopolymeric cement emits about 80% less carbon dioxide (CO_2) than the manufacture of ordinary Portland cement (OPC) (Duxson et al., 2007; McLellan et al., 2011). Fly ash is commonly utilized in the production of geopolymer mortar because of its potential to reduce CO_2 emissions and high energy consumption (Abbas et al., 2020). Meanwhile, the number of waste tires generated annually in Malaysia was estimated to be 8.2 million or approximately 57,391 tonnes. About 60% of the waste tires are disposed via unknown routes and becoming an environmental waste problem (Kotresh et al., 2014). Waste tires continue to cause severe environmental, health, and aesthetic issues since they are bulky, non-biodegradable, mosquito and rat breeding grounds and combustible materials (Parveen et al., 2013; Yung et al., 2013; Serdar et al., 2013; Rao et al., 2013; Ocholi et al., 2014; Ganiron Jr, 2014; Mohammed et al., 2017). Due to limitations in scrap tire recycling, one of the most practical solutions is to use waste tire crumb rubber as a replacement for fine aggregate in the mortar or concrete industry (Lintz et al., 2010; Antil et al., 2014; Assas, 2014). The incorporation of waste tire rubber into fly ash-based geopolymer mortar reduces the CO_2 emissions due to the exclusion of Portland cement, the number of waste tires entering the landfills and the amount of natural mineral aggregate used in mortar and concrete (Wongsa et al., 2018).

There are many researchers producing mortar incorporating crumb rubber in Portland cement (Jeong et al., 2016; Xue and Cao, 2017; Faizah et al., 2019; Yu & Zhu, 2019; Adibi et al., 2020; Moreno et al., 2020) and a few researchers investigating crumb rubber loading on geopolymer concrete (Park et al., 2016; Zaetang et al., 2019; Aly et al., 2019; Luhar et al., 2019). Park et al. (2016), Zaetang et al. (2019) and Luhar et al. (2019) studied the effect of crumb rubber loading in fly ash (Class C) geopolymer concrete, while Aly et al. (2019) investigated the effects of different percentages of crumb rubber on the compressive strength of slag-based geopolymer concrete. Based on the above-mentioned studies, it can be concluded that replacing natural sand with crumb rubber decreased the compressive strength of Portland cement mortar and geopolymer concrete.

However, there is still limited data on the use of crumb rubber in fly ash (class F) based geopolymer mortar. Therefore, this research focuses on producing crumb rubber in fly ash (class F) based geopolymer mortar with the highest compressive strength compared to the past research.

As mortar is a different in-kind material, increasing temperature influences both the aggregate and cement paste. Further, the behaviour of mortar at high temperatures depends on the composition and properties of its individual components (Luhar, 2017). Limited research can be found in the literature on the effects of elevated temperature on the normal and high strength of mortars. It is well established that mortar exposed to high temperatures loses its compressive strength more than 60% when heated to 800 ℃. Portland cement concrete experiences a rapid deterioration in compressive strength at 300 °C, while geopolymer concretes are stable at a high temperature of 600 °C (Hernández-Olivares & Barluenga, 2004). Joseph and Mathew (2015) also stated that geopolymer concrete shows better resistance to surface cracking when exposed to elevated temperatures compared to OPC concrete. While OPC concrete started developing cracks at 400 °C, geopolymer concrete did not show any visible cracks up to 600 °C and developed only minor cracks at an exposure temperature of 800 °C. However, there is a great need to investigate crumb rubber geopolymer mortar exposed to various elevated temperatures, as there is insufficient research in this regard in the literature.

The demand for lightweight concrete may be used for a sandwich wall panel in many applications (Mohamad et al., 2012; Fernando, 2015; Chen et al., 2015). However, it is only suitable for non-structural purposes such as lightweight concrete walls, building facades, and architectural units (Ahmad et al., 2012). The total panel mass, mechanical properties, sound absorption and thermal conductivity performance, are essential criteria to measure the design of lightweight sandwich wall panels (Xu et al., 2016). The sound and thermal performance of the insulation layer can be enhanced by providing a thicker layer of insulation; however, this solution will not always be workable due to the added cost of the materials and reduced utilized area of the building (Elkady, 2013). Sodupe-Ortega et al. (2016) and Fraile-Garcia et al. (2016) studied the use of crumb rubber aggregates in building bricks; this brick showed superior properties in terms of thermal and acoustic insulation when compared to conventional units. Although extensive work has been done on the mechanical properties, thermal conductivity and acoustic insulation of crumb rubber concrete, no work has been reported on the mechanical properties, thermal conductivity and sound absorption of the crumb rubber geopolymer sandwich wall panel.

1.3 Research Objectives

The purpose of this study was to investigate the effects of varying the loading of crumb rubber in fly ash-based geopolymer mortar on its performance and the properties of crumb rubber geopolymer sandwich wall panel as an application. The objectives of this study are:

i. To determine and characterize the effect of different percentage crumb rubber loading on the compressive strength of fly ash (class F) based geopolymer mortar.

ii. To investigate the effect of elevated temperature exposure on the performance of crumb rubber geopolymer mortar.

iii. To validate crumb rubber geopolymer mortar's mechanical and thermal properties in sandwich wall panel application.

1.4 Scope of Study

This research was conducted in three main phases, which are (1) the incorporation of different percentage crumb rubber loading on the compressive strength of fly ash (class F) based geopolymer mortar, (2) the effect of elevated temperature exposure on the performance of crumb rubber geopolymer mortar and (3) the mechanical and thermal properties of crumb rubber geopolymer mortar in sandwich wall panel application. The first phase of this study is the preparation of the fly ash-based geopolymer mortar with the addition of different loading of crumb rubber (0, 5, 10, 15, and 20%) and curing time by mixing the alkaline activator solution with fly ash to produce crumb rubber geopolymer mortar (CRGM). The ratio of solid to liquid is fixed at 2.0, and the ratio of alkaline activator (NaOH (12M) and Na_2SiO_3) is fixed at 2.5. CRGM underwent the compressive strength test, density test, water absorption test and the scanning electron microscope (SEM).

The second phase is the effect of CRGM on elevated temperature exposure (200 °C, 400 °C, 600 °C, and 800 °C). The visual surface was observed after the samples were cool naturally to room temperature inside the furnace; compressive strength test, density test and weight loss were conducted on the hardened mortar. The microstructural changes in specimens after exposure were also examined using SEM analysis. In the third phase, there are two types of panels: crumb rubber geopolymer mortar (CRGM) and crumb rubber geopolymer sandwich wall panel (CRGSWP). CRGM is the panel without an outer layer, while CRGSWP is the panel with a core (CRGM) in both sides' middle and outer layer. The outer layer used in this study is prima*flex* with 9 mm in thickness. The properties of CRGM and CRGSWP as an application were investigated. There are several testings such as compressive and flexural strength tests, thermal conductivity tests and sound absorption tests.

1.5 Thesis Outline

This thesis is divided into five chapters, including this introductory chapter. This first chapter describes the background, problem statement, research objectives, and thesis study scope. Chapter 2 summarizes the existing literature on geopolymer materials and properties as well as reviews the application of crumb rubber mortar as a core in a sandwich wall panel in the construction field. Chapter 3 describes in detail the experimental works and procedures to produce CRGM, including the material proportions, mix designs and processes. This chapter also describes the detail on producing the CRGSWP and the related testing.

Chapter 4 presents the test result and discussion of the findings from the experimental works. The characterization, physical and mechanical testing and morphological properties of the CRGM are highlighted in this chapter. This chapter also discusses the CRGM at elevated temperature exposure and CRGSWP as a sandwich wall panel for a non-structural concrete application. Chapter 5 covers the important conclusions drawn from the present study and offers suggestions for future research considering the current study's findings.

CHAPTER 2 : LITERATURE REVIEW

2.1 Geopolymer

Geopolymer term refers to the type of cementitious material formed by activating aluminosilicates in an alkaline activator solution (Al Bakri et al., 2012a). Geopolymer is a type of amorphous aluminosilicate product that exhibits the ideal properties of rock-forming elements, i.e., hardness, chemical stability, and longevity (Raijiwala et al., 2013). The geopolymer material's chemical composition is similar to that of natural zeolitic materials, which are well-known for their exceptional ability to absorb and solidify toxic chemical wastes such as heavy metal ions. However, the microstructure of the geopolymer material is amorphous rather than crystalline (Li et al., 2013; Joshi & Kadu, 2012). In 1978, Davidovits proposed that an alumino-silicate (Al-Si) compound could polymerise with an alkaline solution (Davidovits, 2020). Davidovits (2002) discovered the concrete used in ancient structures is alkali-activated aluminosilicate binders and named it geopolymer concrete because of the polymerisation reaction. This led to the idea of cement replacement and the subsequent creation of 'Geopolymer Concrete' (Singh et al., 2013).

Geopolymers have been synthesized by alkali activation of mineral compounds rich in silicon dioxide (SiO_2) and aluminium oxide (Al_2O_3) such as metakaolin, fly ash, and bottom ash (Yan & Sagoe-Crentsil, 2012). Geopolymer or alkali-activated binders behave similarly to Portland cement. They can set and harden at room temperature and can gain reasonable strength in a short period. Some proportions of geopolymer binders have been tested and proved successful in yielding synthetic mineral products with high