EXPERIMENTAL AND MODELLING STUDIES OF MORTAR CONTAINING EGGSHELL POWDER AND SILICA FUME

BRONECA SIBIN

FACULTY OF ENGINEERING
UNIVERSITI MALAYSIA SABAH
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BRONECA SIBIN

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BRONECA SIBIN
MK1911035T

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(Ts. Dr. Ahmad Nurfaidhi Rizalman)
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MK1911035T

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NAME	:	**BRONECA SIBIN**
MATRIC NO.	:	**MK1911035T**
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SUPERVISOR
Ts. Dr. Ahmad Nurfaidhi Rizalman

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16 February 2022

ABSTRACT

There have been an increase of Ordinary Portland Cement (OPC) production since it is the primary binder in concrete and mortar. However, its production consumed a lot of energy and caused many environmental problems. Therefore, various efforts have been made to identify alternative materials to replace cement in concrete and mortar. This includes combining two (2) alternative materials to compensate the shortcomings of each them in the properties of concrete and mortar. This research aimed to study the engineering properties of the binary and ternary blended (TB) cement-mortar containing eggshell powder (ESP) and silica fume (SF). The first objective was to study the microstructural, chemical and physical properties of ESP and SF. The results indicated that both materials were suitable to be used as partial OPC replacement. For the second objective, the flowability, compressive strength, flexural strength and hardened density properties of cement-mortar containing ESP and SF were evaluated at 28 days of curing period. The replacement level for the binary blended mortar varies from 0% to 30%. Meanwhile, the combination for the TB mortar was (ESP%:SF%) 5:12, 10:20, 15:15, 20:10 and 25:5. The results showed that the ESP generally had negative effects on the engineering properties of mortar, while the SF significantly improved the engineering properties of mortar. Nevertheless, the combination of both materials in TB mortar provided better performances than the ESP mortar, but lower than SF mortar. Finally, the mix proportion of TB cement-mortar was optimized using Response Surface Methodology based Central Composite Design (RSM-CCD) model. The software used was Design Expert software. The regression analysis showed that both ESP and SF replacement had significant effects on the engineering properties of TB mortar. Meanwhile, the optimum mix design for the maximum strength and density of the TB mortar was as follows: eggshell powder of 5% and silica fume of 18.8%. As a conclusion, this study provides an insight on the engineering properties of ESP and SF as a potential OPC replacement in binary and ternary blended cement-mortar. This is not only reducing the downside effect of OPC usage and production, but also create more sustainable construction materials and help to protect the environment.

ABSTRAK

KAJIAN EKSPERIMEN DAN PEMODELAN MORTAR YANG MENGANDUNGI SERBUK KULIT TELUR DAN ASAP SILIKA SEBAGAI PENGGANTI SIMEN

Terdapat peningkatan pengeluaran simen portland (OPC) kerana ia merupakan pengikat utama dalam konkrit dan mortar. Walau bagaimanapun, proses pembuatan simen menggunakan banyak tenaga dan menyebabkan banyak masalah alam sekitar. Oleh itu, pelbagai usaha telah dilakukan untuk mengenal pasti bahan alternatif untuk menggantikan simen di dalam konkrit dan mortar. Ini termasuk menggabungkan dua (2) bahan alternative untuk mengimbangi kesan sampingan bahan-bahan tersebut kepada sifat konkrit dan mortar. Justeru itu, penyelidikan ini bertujuan untuk mengkaji sifat-sifat kejuruteraan mortar campuran binari dan ternari (TB) yang mengandungi serbuk kulit telur (ESP) dan asap silika (SF). Objektif pertama kajian ini adalah untuk mengkaji sifat mikro, kimia dan fizikal ESP dan SF. Hasil kajian menunjukkan bahawa kedua-dua bahan tersebut sesuai digunakan sebagai pengganti separa OPC. Untuk objektif kedua, sifat aliran, kekuatan mampatan, kekuatan lenturan dan sifat ketumpatan simen-mortar yang mengandungi ESP dan SF dinilai pada hari ke-28 tempoh rawatan mortar. Tahap pengganti untuk mortar campuran binary adalah dari 0% hingga 30%. Sementara itu, kombinasi untuk mortar TB adalah (ESP%:SF%) 5:12, 10:20, 15:15, 20:10 dan 25: 5. Hasil kajian menunjukkan bahawa ESP secara amnya mempunyai kesan negatif terhadap sifat kejuruteraan mortar, sementara SF menambah baik sifat kejuruteraan mortar. Walaupun begitu, gabungan kedua-dua bahan tersebut di dalam TB mortar memberikan kesan yang lebih baik berbanding mortar ESP, tetapi sedikit lemah berbanding mortar SF. Akhirnya, bahan-bahan campuran di dalam mortar TB telah dioptimumkan dengan menggunakan metodologi tindak-balas permukaan berasaskan pusat reka bentuk komposit (RSM-CCD). Perisian yang digunakan adalah perisian 'Design Expert'. Analisis regresi menunjukkan bahawa kedua-dua pengganti ESP dan SF mempunyai kesan ketara terhadap sifat kejuruteraan mortar TB. Sementara itu, reka bentuk optimum untuk campuran bahan-bahan mortar TB yang mempunyai kekuatan dan ketumpatan maksimum adalah seperti berikut: 5% untuk serbuk kulit telur dan 18.8% asap silika. Secara umumnya, kajian ini memberikan gambaran mengenai sifat-sifat kejuruteraan ESP dan SF yang berpotensi untuk digunakan sebagai pengganti OPC di dalam campuran binari dan ternari. Ini bukan hanya mampu mengurangkan kesan negatif penggunaan dan pembuatan OPC, tetapi juga menyediakan bahan binaan yang lebih lestari dan membantu melindungi alam sekitar.

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LIST OF SYMBOLS

A, B	-	Factor Variables
Al_2O_3	-	Aluminium Oxide
β_{12}	-	Regression Coefficient of Interaction Effect
β_{11}, β_{22}	-	Regression Coefficient of Quadratic Effect
β_1, β_2	-	Regression Coefficient of Linear Effect
β_0	-	Regression Coefficient of Intercept
$CaCO_3$	-	Calcium Carbonate
CaO	-	Calcium Oxide
$CH/\ Ca(OH)_2$	-	Calcium Hydroxide
CO_2	-	Carbon Dioxide
C_3S	-	Tricalcium Silicate
$C-S-H$	-	Calcium Silicate Hydrate
Fe_2O_3	-	Iron Oxide
SiO_2	-	Silicon Dioxide
Sf	-	Flexural Strength
fm	-	Compressive Strength
α	-	Alpha
Y	-	Response Variables

LIST OF ABBREVIATION

AASHTO	-	American Association of State Highway and Transportation Officials
ACI	-	American Concrete Institute
ANOVA	-	Analysis of Variance
AP	-	Adequate Precision
ARD	-	Absolute Relative Deviation
ASR	-	Alkali-Silica Reaction
ASTM	-	American Society for Testing and Materials
BBD	-	Box-Behnken Design
BS EN	-	British Standard European Norm
CCD	-	Central Composite Design
CSA	-	Coconut Shell Ash
CS	-	Compressive Strength
DoE	-	Design of Experiment
ESP	-	Eggshell Powder
FA	-	Fly Ash
FFD	-	Full Factorial Design
FS	-	Flexural Strength
GGBS	-	Ground Granulated Blast-Furnace Slag
HD	-	Hardened Density
ITZ	-	Interfacial Transition Zone
LOI	-	Loss of Ignition
MK	-	Metakaolin
OPC	-	Ordinary Portland Cement
OPT	-	Optimum Replacement Level
POFA	-	Palm Oil Fuel Ash
RSM	-	Response Surface Methodology
SCMs	-	Supplementary Cementing Materials
RHA	-	Rice Husk Ash
SAI	-	Strength Activity Index

SDA	-	Saw Dust Ash
SEM	-	Scanning Electron Microscope
SF	-	Silica Fume
TAESP	-	Treated Air-dried Eggshell Powder
TOESP	-	Treated Oven dried Eggshell Powder
TB	-	Ternary Blended
UAESP	-	Untreated Air-dried Eggshell Powder
UOESP	-	Untreated Oven dried Eggshell Powder
WPSA	-	Waste Paper Sludge Ash
XRF	-	X-Ray Fluorescence

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CHAPTER 1

INTRODUCTION

1.1 General

Nowadays, concrete and mortar have became essential building materials in the construction industries especially in developing countries. Moreover, the increase in the economic and worldwide population have pushed for more infrastructure development, thus boosted the concrete production. In fact, it was estimated that the concrete production may increase up to 18 billion tons by 2050 (Zareei et al., 2017). This increases demand in cement since it is the primary binder in concrete and mortar. According to statistics by previous researchers, the cement production around the globe has reached up to 4.1 billion tons in 2020 and expected to escalate up to 5.5 billion tons by 2050 (Cree & Pliya, 2019; Statistica, 2020). In Malaysia alone, more than 16.1 million metric tons of cement was produced in five (5) consecutive years from 2015 until 2020. Meanwhile, the cement market in Sabah is anticipated to grow due to the Pan Borneo Highway development (New Straits Times, 2018; Statistica, 2021).

The cement production not only consumed a lot of energy (fuel and electricity), but it also known to cause many environmental problems, such as depletion of limestone resources and raise greenhouse effect (Al-Safy, 2015; Liu et al., 2020; Pone et al., 2018). This is because about 1.65 tonnes of limestone resources is required to produced one (1) ton of cement (British Geological Survey, 2005). Furthermore, the production of one (1) ton of cement has released approximately one (1) ton of carbon dioxide (CO_2) into the atmosphere, which contributed around 5% to 8% of the global greenhouse gas emission (Lehne & Preston, 2018; Ryu et al., 2019). This makes the cement industries the second largest industrial emitter in the world, after the iron and steel industry (Díaz et al., 2017; Harvey, 2018). Therefore, identifying alternative materials to replace cement in concrete and mortar is considered as solutions to reduce the production of cement (Ahmed et al., 2009; Demirhan et al., 2019; Sankar et al., 2020). This reduces the carbon dioxide (CO_2) emission and prevents more raw resources like limestone to be extracted further.

1.1.1 Eggshell and Silica Fume Ternary Blended Cement

Eggshell is one of the solid industrial wastes from the poultry farm and food manufacturing industries. According to Waheed et al., (2020), the increase of eggs consumption for the past several years has led to the increase amount of eggshell waste disposal. In fact, the total eggs production in 2018 was 78 million metric tons, which put up around 8.58 million metric ton of eggshell waste was produced globally. In Malaysia, each person consumes an average of 370 eggs a year, making Malaysia among the largest eggs eater in the world (Lee, 2011; The Star, 2020). Some of the statistics on the eggs production around the world and in Malaysia are shown in Appendix A. Additionally, Chu, (2019) reported that around 16,973 tons of food waste such as eggshell wastes are deposited in the landfills everyday without proper treatment. This has caused many environmental problems including land degradation, contamination of water resources, risk to the public health, and more (Hamada et al., 2020; Shekhawat et al., 2019; Singh et al., 2018). On top of that, the disposal of eggshell waste requires high management cost due to the scarcity of the available landfill site (Faridi & Arabhosseini, 2018; Tiong et al., 2020). Thus, one of the approaches to tackle the eggshell waste management problem is by recycling and reusing the eggshell as an alternative material in the concrete industry.

Eggshell composed primarily of calcium carbonate ($CaCO_3$), magnesium carbonate, calcium phosphate and other organic matter (Kamkum et al., 2015). Since it has nearly similar chemical composition to limestone, eggshell can be used as a partial replacement of cement (Gabol et al., 2019; Cree & Pliya, 2019). Shekhawat et al., (2019) added that the high calcium oxide (CaO) content within the eggshell powder (ESP) is similar to the cement, thus allows the eggshell to be used as the partial cement substitution in concrete and mortar. Furthermore, it was proven that implementing the ESP as the cement replacement material enhanced the mechanical and durability properties of the concrete (Afolayan, 2017; Mohamad et al., 2016; Tan et al., 2018; Vivek & Sophia, 2019). This includes concrete workability, heat of hydration thermal shrinkage, permeability, sulphate resistance and ASR expansion. However, some disadvantages of the use of ESP in concrete, include lowering the rate of strength gain, increasing drying shrinkage, increase water requirement and lower the freeze-thaw resistance (Afolayan, 2017).

Silica fume (SF) is another type of industrial waste which is commonly used as an additives or a partial cement replacement in concrete and mortar (Nochaiya et al., 2010). Although a highly pozzolanic Supplementary Cementing Materials (SCMs) such as SF does not possess any cementing properties, it contains high amount of silica and alumina (also known as aluminusilicates) which is very reactive in the presence of moisture (Black, 2016; Moghadam & Izadifard, 2020; Mohamed, 2019). Previous researchers discovered that SF as partial cement replacement in concrete and mortar improved the mechanical strength, chemical and reinforcement corrosion resistance (Dai et al., 2018; Mehta & Ashish, 2019; Panesar, 2019; Pedro et al., 2017; Sankar et al., 2020; Zhang et al., 2016). This was due to the active pozzolanic reaction and filler effect of the material. Hence, SF as a partial cement replacement could be one of the possible solution to reduce the usage of cement in concrete, consequently limiting the quarrying of limestone resources.

Although the use of SCMs as binary blended cement in concrete and mortar have been proven beneficial, there are several drawbacks and limitations (Nehdi & Sumner, 2002; Sam et al., 2017). For instance, the use of ESP reduced the concrete workability Jhatial et al (2019), meanwhile the use of POFA slightly lowered the rate of strength development of the concrete (Sofri et al., 2015). Therefore, previous researchers introduced a ternary blended cement that combines two (2) other SCMs to compensate the shortcomings of the SCMs in the properties of concrete and mortar (Azman et al., 2017; Gruszczyński & Lenart, 2020; Rezaifar et al., 2016; Taylor, 2014).

For instance, although ESP has similar calcium oxide (CaO) content as the cement, it has low content of silica oxide (SiO) (Hamada et al., 2020; Kamaruddin et al., 2018). Therefore, it does not have pozzolanic properties to react with the