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Research paper

Binary Effect of Palm Oil Fuel Ash and Eggshell Waste Powder on Heat of Hydration for Mortar

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Abstract

The effects of mortar containing palm oil fuel ash and eggshell waste powder on heat of hydration was investigated. This study covers the basic properties like the chemical composition of raw materials and the hydration temperature for binary mortar. Malaysia is one of the world's largest palm oil producers. Palm oil fuel ash (POFA) is a product of the combustion of palm oil waste which is not used and usually disposed of in landfills. The use of eggs in the food industry also generate waste egg shells that can be transform into powder namely eggshell waste powder (ESP). The development in construction technology has contributed to research in producing various methods and materials that provide advantages in the construction field. One of the technologies is to investigate the effectiveness of OPC replacement with appropriate waste materials. In this research, POFA and ESP was used as ingredients to replace a proportion of OPC in the mortar thereby reducing the use of OPC. POFA used in this study were in forms of ground POFA (GPOFA) and unground POFA (UPOFA). GPOFA and ESP are ground to achieve a similar size as OPC while UPOFA was used in its original size. The total percentages replacement of POFA and OPC was 20% by weight with the different level replacements of 4%, 8%, 12%, 16% and 20%. The design of mortar mix proportion made up of three groups, A, B and C. Group A is the control mortar that is OPC only. Group B is the mortar that contains OPC, POFA and ESP. Meanwhile, a third group C, consisting of a mixture of OPC, GPOFA and ESP. The mix proportion used for hydration temperature determination was chosen from the previous study which identified the strength of mortar compression. The optimum compressive strength of each group is chosen to obtain the mortar hydration temperature. For determination of mortar hydration temperature, plywood with size 300 mm x 300 mm x 450 mm cube was used as the exterior mold. It was packed with 76 mm thick polystyrene acting as the insulator. Polyvinyl chloride (PVC) pipe with diameter of 150 mm and a height of 300 mm is used to fill the mortar mix. A thermocouple (Type K) was inserted into the center of each box and was connected to a data logger system. Temperature rises due to heat of hydration in all mixes were recorded for 5 days. The results revealed that the replacement of OPC with binary materials is beneficial, particularly for mass mortar where thermal cracking due to excessive heat rise is of great concern.

Keywords*: Compressive strength; ESP; Heat of hydration; OPC replacement; POFA.*

1. Introduction

High demand of usage and benefits provided by the use of Ordinary Portland cement (OPC) have led to experimental studies and researches to improvise each and every aspect of cement. One example of it is to replace or lessen the use of it and thus determine the effect given by the material tested. Pozzolanic material that contains chemical properties similar to the OPC are commonly brought into field of study as partial cement replacement for concrete and mortar design [1], [2]. Concrete demand around the world has the most value of man-produced material compared to any other [2]. As there are no other materials that worked the same as cement in terms of its strength, durability and workability, we cannot completely replace its uses in mortar and concrete mixes with other materials [1]. But there are claims reported that it is possible to partially replace the cement content with other pozzolanic effect materials.

The reuse of pozzolanic waste materials is considered as the best environmental alternative to solving the problem for disposal [2]–[5]. Pozzolans are any materials that have siliceous and aluminous properties. Most of the increase in cement demand could be met by the use of supplementary cementing materials [6]–[10]. Palm oil fuel ash (POFA) and eggshell waste powder (ESP) are some example of pozzolan that can be use either as a binary or separately to replace cement content partially in concrete or mortar mixes [11].

Eggshells are agricultural waste generated from chick hatcheries, bakeries, fast food restaurants and others that can destroy the environment and cause environmental problems that require proper handling. The incorporation of ESP in OPC replacement will not only solve the problem of eggshell disposal, but also can make construction materials more economical. There are limited studies on the utilization of eggshell waste powder as an alternatives material to cement. Malaysians generally consume 20 million eggs daily [12]. Eggshell is known to contain calcium carbonate ($CaCO_3$). The findings from the study by Ujin et al. on its potential to partially replace cement had shown an increase in the setting times of the concrete mixes [13].

One of the potential recycled materials that have not been fully exploited is POFA. Silicate source at POFA is produced after combustion of palm oil fiber. According to Tangchirapat et al. the use of POFA as pozzolanic material for partially or wholly replacing OPC has not been investigated carefully when compared to other materials such as fly ash, especially in high strength mortar or concrete [14]. Research findings by Safiuddin et al. and Karim et al. has confirmed that the limit on the use of POFA for partial cement replacement is between 0 - 30 % of cement weight to obtain significant impact. [15], [16]. Indeed, partial replacement has a good effect on the general properties of concrete as well as reducing costs.

The hydration of cement compounds is exothermic in which heat is produced in the concrete matrix during hydration. When the cement is hydrated, the compound reacts with water to obtain stable low-energy states, and the process is accompanied by energy release in the form of heat [7]. Heat of hydration, is the amount of heat lost at a certain temperature when the hydration process is complete [17]. The importance of hydration heat in concrete technology is covered in various scopes. The amount of heat released and the rate of heat release from the hydration of individual compounds can be used as their reactivity index [18]. Furthermore, hydration heat can explain the setting and hardening of cement and predict temperature rise as well.

The mortar temperature due to hydration is largely controlled by the material and the mix of properties and by environmental factors [18]. In fact, heat hydration depends on the chemical behavior of the compound, and is almost equal to the amount of individual hydration of the individual compound when the ratio of each mixture by the mass is hydrated separately. Again, the main constituents in Portland cement are calcium; therefore, overall heat development will definitely be affected by the quantity of calcium in the mix. High cement content may be useful for obtaining higher initial strength in concrete. However, the greater heat as a result of chemical reactions can cause durability problems such as cracking and shrinkage on concrete.

Therefore, this study was aimed in the use of POFA and ESP in mortar. Although the eggshell is rich in calcium and analogous to limestone in the chemical composition, it is a waste material. There is a need to understand the physical and mechanical properties of blended mortar made of POFA and ESP. Therefore, the main objective of this study is to the development of hydration temperature of blended mortar.

2. Material and Method

2.1. Selection and Preparation of Palm Oil Fuel Ash and Eggshell Waste Powder

In this study, POFA was obtained from a palm oil mill in Johor, Malaysia. POFA was sieved after collection using 300 µm sieve size to remove larger particle materials and foreign material. Next, POFA that passes the sieve is oven dried at 105-110 °C for 24 hours. POFA is divided into two groups namely unground POFA (UPOFA) as in Fig. 1 and ground POFA (GPOFA) as illustrated in Fig. 2. UPOFA is the original POFA taken from the landfill and is used directly in its original form and size without any modification. Meanwhile, UPOFA is ground to improve the fineness to ensure that 1-3% retained on a sieve of 325 (45 µm) which complies with the requirements of ASTM C618. Eggshell used in this study was obtained from bakeries, restaurants and stalls. Collected eggshells are cleaned with tap water and then dried to remove eggs, egg yolks and others. The eggshells are then ground into powder by ensuring only 1-3% is retained on sieve 325 (45 µm) to comply with ASTM C618 requirements as shown in Fig. 3.

Fig. 1: Unground palm oil fuel ash (UPOFA)

Fig. 2: Ground palm oil fuel ash (UPOFA)

Fig. 3: Ground eggshell waste powder (ESP)

2.2.2. Concrete Materials and Mixes

The compositions used in the present investigation were selected from a previous study that have identified the optimum compressive strengths for three groups. Details of series of cement replacement to POFA and ESP can be referred to Jamellodin et al. [19]. The optimum mix design proportion of mortar are as shown in Table 1. Group A is the control mortar. Group B is blended mortar containing 80% OPC, 12% unground POFA and 8% ESP. Meanwhile, the third group, C is OPC which is replaced by 20% GPOFA and ESP.

Ordinary Portland cement (Type 1) was used in the study. Fine aggregates with dry conditions are used to ensure that they do not affect the water cement ratio during mixing. The water source used is regular treated water coming directly from the laboratory water supply.

Table 1: Mix design proportion selection for heat of hydration testing

Group	Mix Design	Selected Mix Design	Compressive Strength (MPa)
A	OPC100%	C100	20.0
B	OPC + UPOFA + ESP	C80UP12E8	16.9
C	OPC + GPOFA + ESP	C80GP16E4	21.3

2.3. Determination of Chemical Composition of OPC, POFA and ESP

The chemical composition of materials is determined by X-ray fluorescent (XRF) analysis, using Bruker S4 Pioneer machine as shown in Fig. 4. The ratio between OPC, POFA and ESP with alumina oxide are 8:2. This ratio was used due to the quantitative of samples that is in a powder condition. The mixture was then stirred and compacted with 15 times of pressure using the press machine to form a pellet as in Fig. 5. Next, the pellet was placed in the desiccator to prevent from air contamination while waiting for the XRF testing.

Fig. 4: Brukner S4 Pioneer machine for XRF testing

Fig. 5: Specimen pellets for X-ray fluorescent testing (a) OPC (b) POFA (c) ESP

2.4. Measurement of Heat of Hydration

The compositions used in the present investigation were selected from a previous study that have identified the optimum compressive strengths based on three groups [19]. In the present investigation, plywood with size 300 mm x 300 mm x 450 mm cube was used as the exterior mould. It was packed with 76 mm thick polystyrene acting as the insulator. Polyvinyl chloride (PVC) pipe with diameter of 150 mm and a height and 300 mm is used to fill the mortar mixed as in Fig. 6. A thermocouple (Type K) was inserted into the centre of each box and was connected to the data logger system. Temperature recording continued for 5 days for each composition of mortar. An insulated cubical box and test arrangement are illustrated in Fig. 7 and Fig. 8. The same method is used by other researchers to determine the hydration temperature [7], [9].

When the mortar was poured into a cylindrical mould, the heat is released by the hydration process and subsequently increased the temperature of the mortar mass. Increasing and decreasing of hydration temperatures are monitored more frequently in the first 24 hours and at lower intervals thereafter until the temperature is close to the initial reading. The hydration temperature measurements are continued for 5 days for all mix design proportion.

3. Results and Discussion

3.1. Chemical Composition of OPC, POFA and ESP

Chemical composition in POFA shows that silicon dioxide (SiO_2) has the highest content which is 53.3% followed by 9.2% of calcium oxide (CaO). Silica is an important ingredient needed in cement because it gives strength to the mortar. The setting time is prolonged with the presence of a large amount of silica but it can increase its strength. The chemical analysis in Table 2 shows that the percentage of CaO in ESP is 98%, which is highest than other elements. Similarly, Pliya et al. observed at 97.8% CaO in their brown eggshells [20]. Boro et al. also found CaO content in ESP was 98.2% [21].

Fig. 6: Mortar is filled in an insulated cylinder.

Fig. 7: Test equipment for measuring hydration temperature.

Fig. 8: Data logger system for collecting temperature data.

Table 2: Chemical composition of OPC, POFA and ESP

Chemical Composition	OPC (%)	POFA (%)	ESP (%)
Silica dioxide (SiO_2)	16.40	53.3	0.05
Magnesium Oxide (MgO)	1.22	4.1	1.12
Calcium Oxide (CaO)	69.60	9.2	98.0
Potassium Oxide (K_2O)	0.67	6.1	0.11
Iron Oxide (Fe_2O_3)	3.70	1.9	0.02
Zinc Oxide (ZnO)	-	-	-
Aluminium Oxide (Al_2O_3)	4.70	1.9	0.04
Phosphorus Pentoxide (P_2O_5)	-	2.4	0.09
Sulphur Trioxide (SO_3)	2.65	-	0.49

3.2. Heat of Hydration of Mortar

The histories of different mortar mixes due to the time-temperature relationship have been presented in Table 3. Recorded data is measured in mid-depth cylinder mortar. While, the development of temperature is due to heat liberation at the mid-mortar depth during the hydration process of all specimens shown in **Error! Reference source not found.**.

It has been observed that during the initial reading, the temperature rise for the GPOFA and UPOFA with ESP mortars is almost similar. The initial temperature rise rate for GPOFA + ESP mortars was slightly higher than others. However, these three specimens seem to have reached the maximum temperature at the same time. Despite the development of thermal temperature behavior approximately being the same, mortar made of 80% OPC with 16% GPOFA and 8% ESP was recorded at the highest peak temperature of 64°C at 12 hours after casting. The specimen made with 80% OPC with 12% UPOFA and 8% ESP mortar peaks at 58.3°C after 13 hours while control mortar made with 100% OPC, recorded peak temperature of 56.7°C after 12 hours of casting. High contents of CaO in ESP contributes to higher calcium hydroxide ($Ca(OH)_2$) production in the hydration process thus causing the mortar to increases in the hydration temperature. The fineness of replacement materials particulates also has been a major factor in boosting the reactivity between all materials and increasing the hydration acceleration of POFA+ESP mortars. The lowest peak temperature was achieved by specimen made of control mortar.

Table 3: Characteristics of heat of hydration of OPC with POFA and ESP replacement

Group	Selected mix design	Initial temperature (°C)	Peak temperature (°C)	Time since mixing to peak temperature (hours)
A	C100	34.6	56.7	12
B	C80UP12E8	35.5	58.3	13
C	C80GP16E4	36.0	64.0	12

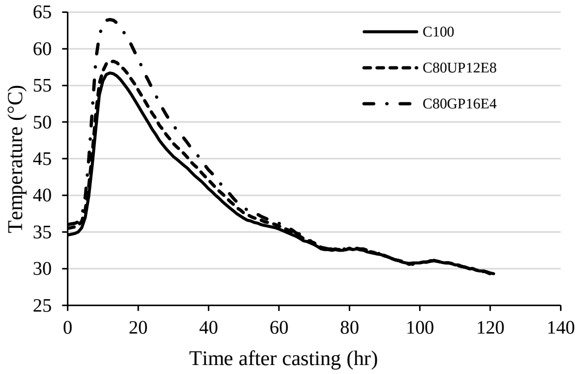

Fig. 9: The development of hydration temperature

After peak temperature reading was recorded, the heat produced was then observed to be decreasing gradually over time to a point where similar temperature reading achieved for all three specimens. Final temperature recorded at the end of the test for all three samples were in the range of 29-30°C.

The use of mixture of POFA and ESP in mortar whether in ground or unground were observed to be not effective in the purpose of reducing the heat of hydration produced during curing period and hardening paste. The hydration temperature of mortar depends on the amount of $Ca(OH)_2$ produced in the hydration process of cement and reactivity of materials used. As POFA contains a very small amount of CaO, the amount of $Ca(OH)_2$ would be less in the products of hydration. Despite that, ESP chemical contents is mostly taken part by CaO of over 50%. Huge composition of the chemical element had helped in replacing its absence in the POFA. The observation made above suggest that the partial replacement of OPC by POFA and ESP do not bring significant effect in reducing the heat of hydration produced during curing

4. Conclusion

POFA and ESP are relatively new varieties of pozzolanic materials and have been characterized to be a unique supplementary cementing material in mortar. The results obtained in this study demonstrated that partial replacement of cement by POFA and ESP not effective in controlling heat of hydration of mortar. POFA is known to have a low composition of CaO. However, the high CaO content in ESP makes the mixture of two pozzolanic materials not significant in terms of hydration temperature. It has resulted higher $Ca(OH)_2$ during the hydration process thus does not reducing the temperature of hydration.

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