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Influence of porosity on the tensile strength of fine grained mortar containing fly ash, palm oil fuel ash and rice husk ash

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Abstract. The study is to identify the influence of porosity on the tensile strength of fine grained mortar containing fly ash (FA), palm oil fuel ash (POFA) and rice husk ash (RHA). The aim of this study is to reduce the consumption of cement due to its negative impact on the environment. The cement-to-sand ratio used in the mix design of fine grained mortar is 1: 2. The maximum size of fine grained sand used in this study is 0.6 mm. There are four (4) mix designs of fine grained mortar which include control mortar (100% OPC), 80% OPC + 20% FA, 90% OPC + 10% POFA and 80% OPC + 20% RHA. The selection of the mix design for each type of fine grained mortar was based on the mix designs of previous studies which produced the highest compressive strength. The tensile strength test and the porosity test were carried out in this study. The tensile strength test was performed on cylinder specimens measuring 100 mm diameter and 200 mm height according to ASTM C496. On the other hand, the porosity test was conducted on prism specimens measuring 40 x 40 x 160 mm. The results showed that fine grained mortar containing FA achieved the highest tensile strength of 5.9 N/mm^2 and a low porosity of 12.7%.

1. Introduction

The porosity structure in mortar greatly influences its performance. For example, porosity determines the rate at which aggressive ions can enter the mass and cause interference in the mortar. Porosity is related to cement, mineral mixtures and aggregate particles against water cement ratio as well as curing conditions. A reduction in the porosity of solid materials increases its strength in general, and the strength of cement-based materials in particular [1]–[3].

Fine grained mortar (FGM) is one of the cement-based materials which act as a binder for the repair and reinforcement of structural elements. FGM is unique as it contains fine grained sand with a maximum size of 0.6 mm. Due to its small grain size, it is possible to produce very thin concrete elements using FGM. On the other hand, the substitution of pozzolan material with cement can

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improve the strength and durability of mortar.

Nowadays, pozzolans from industrial and agricultural by-products such as fly ash, palm oil fuel ash and rice husk ash are commonly used as cement replacement. Calcium silicate hydrate is formed during the hydration between pozzolanic material and calcium hydroxide. This formation can reduce the pore size of crystalline hydration products, making the mortar microstructure more uniform besides improving its impermeability and durability. In addition, it can also increase the service life of a structure.

The substitution of pozzolanic material can reduce construction costs and reduce the negative impact towards the environment. Fly ash (FA) is a by-product of coal combustion in electric power generation plants whereas palm oil fuel ash (POFA) and rice husk ash (RHA) are agricultural by-products. The substitution of FA in FGM has been studied by previous researchers but research studies on the use of POFA and RHA in FGM are still lacking [4]–[6]. Thus, this study incorporated FA, POFA and RHA with 10% to 20% replacement of cement to examine its effects on the tensile strength and porosity of fine grained mortar. The objective of this paper is to determine the relationship between tensile strength and the porosity of FGM incorporated with FA, POFA and RHA.

2. Fine grained mortar

FGM can be presented as one of the new innovative technology binder systems in which fine sand with a grain size of 0.6 mm or less is used to produce high strength mortar [7]–[10]. The FGM mix shows that FGM has a high flow consistency that offers technical penetration to textiles. It is possible to obtain very thin concrete elements using FGM due to its fine grain size. It also has a high binder content when it is added with different pozzolanic additives and plasticizers [11]. The workability of cementitious material has been obtained by some compatible water reducing admixtures such as superplasticizers.

The use of a mixture of pozzolans has been shown to be advantageous owing to its synergic effects [12]. In this work, ordinary Portland cement, fly ash, palm oil fuel ash and rice husk ash are used as cement replacement materials in blended cement. Tensile strength and porosity tests are conducted to understand the mechanisms and uses of these types of waste in concrete.

The addition of fine pozzolanic particles cause large pore segmentation and increases the number of nucleation sites for hydration product precipitation in cement paste. This results in pore production and reduced calcium hydroxide content in the cement paste. The FGM containing FA results in lower porosity than FGM containing RHA [2].

At present, pozzolans have been widely used to replace cement in the construction industry in order to reduce costs and protect the environment [13], [14]. In addition, the use of pozzolans can help reduce waste disposal problems, improve mortar and concrete properties and lower the cost of cement production. The use of pozzolans is also associated with the current situation that demand for sustainable concrete and mortar performance [14].

Fly ash is the most common and widely used cement substitute for cement and mortar in the construction industry. FA is one of the by-products of coal combustion in electric power generating plants which is then collected from exhaust gases using electrostatic precipitators or bag filters [10]. Fly ash can be tan to dark grey, depending on its chemical and mineral constituents. The tan and light colours are colour usually associated with high lime content. Brownish colours are usually associated with iron content. Dark grey to black colour is usually caused by unburned carbon content. Fly ash colour is usually very consistent for each power plant and coal source [15], [16].

Palm oil fuel ash is a solid waste product by the palm oil industry. It is obtained in the form of ash from the combustion of oil palm bunches. POFA is produced from the combustion of palm oil biomass at 800 °C to 1000 °C after the palm oil extraction process. Palm oil biomass is used as fuel to facilitate power generation at palm oil mills. POFA contains a high amount of silica and silica oxide that meet the criteria of pozzolanic materials [7], [17], [18]. It has a high potential to be used as a substitute for cement or as a filler to produce strong mortar and concrete [19].

10th Asia Pacific Structural Engineering and Construction Conference 2018

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RHA is one of the agricultural by-products which is also widely used by the construction industry [20]. Well-burned RHAs can contribute significantly to mortar and concrete properties through pozzolanic reactions. The slow burning of rice husks under temperatures between 500°C to 700°C produces RHA with porous and cellular microstructure. RHA contains a high content of non-crystalline or amorphous silica with a high specific surface area and high pozzolanic reactivity [2], [21], [22]. Therefore, it is one of the pozzolanic materials that can be used as a substitute for cement because RHA particles have complex shapes which can break porous structures [9].

3. Experiment details

3.1. Materials

Fly ash was obtained from the thermal power plant called Kapar Energy Ventures in Kapar, Selangor. FA was oven dried at 105° C to 110° C for 24 hours and then ground by the grinder with 1-3% retained on sieve number 325. This process complies with the ASTM C618 requirements. POFA was obtained from a palm oil mill in Kluang, Johor. POFA was ground using a grinder for 15 minutes at a speed of 350 rpm to ensure 1-3% was retained on sieve number 325 (45μ m) which complied with ASTM C618 requirements. Rice husks were collected from Muar, Johor. The rice husks were burnt at a temperature of 600°C for six hours. Before that, the rice husks were washed 5 times to clean them of all impurities. Then, the rice husks were oven dried at $105-110^{\circ}$ C for 24 hours. Later, RHA was ground using a grinder with 1-3% retained on sieve number 325 which complied with ASTM C618 requirements.

3.2. Mix proportions

The mixture of the sample was designed to determine the suitability of mixed FGM ratios for obtaining the FGM with the highest strength. The mix design involved 4 samples with each pozzolan in the ratio of 1:2. All the samples were mixed uniformly according to the water-cement ratio obtained from the standard consistency test of cement and were cured for 28 days.

Four (4) series of mixed design proportions were adopted from previous studies by Z Jamellodin [10], and Yuslinda, [7]. The FGM specimens were prepared for the tensile strength test and the porosity test. OPCs were replaced with three pozzolans namely, FA, POFA and RHA at percentages of 20%, 10% and 20%, respectively by the weight of cement. The sand-to-binder ratio of 2 by weight and the water-to-binder ratio of 0.45 were used. The FGM mixed proportions with FA, POFA and RHA are shown in Table 1.

Mix No	Mix design proportion	Cement (%)	FA (%)	POFA (%)	RHA (%)	Fine grained sand	Water/binder
M1	OPC	100	-	-	-	2	0.45
M2	FA20	80	20	-	-	2	0.45
M3	POFA10	90	-	10	-	2	0.45
M4	RHA20	80	-	-	20	2	0.45

Table 1. The mix proportion by weight of FGM used in tensile strength and porosity test.

3.3. Determination of tensile strength

The tensile strength test was carried out according to ASTM C496 [23]. Cylinder specimens measuring 100 mm diameter and 200 mm height were prepared. After 1 day of casting, the specimens were demoulded and cured in water until the day of the test. The tensile strength of mortar specimens was determined at the age of 28 days. Three specimens were duplicated for each FGM mixed design proportion. The reported results were the average tensile strength for the three specimens.

3.4. Determination of porosity

Prisms specimens with dimensions of 40 x 40 x 160 mm were prepared for the porosity test accordance to ASTM D7063/D7063M-11. The porosity of mortar specimens were determined at the age of 28 days. After that, the prisms were dried at $100 \pm 5^{\circ}$ C until constant weight was achieved. The porosity can be calculated using equation 1 as follows:

$$P = [(W_a - W_d)/(W_a - W_w)] \ge 100$$
(1)

P refers to vacuum saturated porosity (%),

 W_a refers to the specimen weight in air of saturated sample (gm),

 W_d refers to the dry weight of the specimen after 24 h in the oven at 100 ± 5 °C (gm) and W_w refers to the specimen weight in water (gm).

4. Results and discussions

4.1. Tensile strength test

The tensile strength and porosity results of FGM containing FA, POFA and RHA according to their percentage by weight which are 20%, 10% and 20% respectively are shown in Table 2. According to the results, the tensile strength of FGM containing FA was the highest at 5.9 N/mm². Meanwhile, FGM containing POFA achieved the lowest tensile strength among all pozzolan materials which is of 5.5 N/mm². However, the tensile strength of FGM containing POFA was still higher compared to the tensile strength of control mortar which was only 5.4 N/mm². All three pozzolans were found to have increased the tensile strength of FGM.

This also indicates that with the replacement of cement with raw materials contribute to the strength of FGM. This is due to the fineness of the pozzolans which were combined with OPC and cured for 28 days to strengthen the bond between the particles. The high tensile strength could also be due to the increase in mortar microstructure that only happens through a pozzolanic reaction [7], [24]. The pozzolanic reaction occurred between silica or lime and calcium hydroxide during the hydration of OPC. This produced calcium silica hydrate (C-S-H) and calcium alumina hydrate which can cover cracks and pores [7].

4.2. Porosity test

Also can be seen the results of porosity in Table 2, FGM containing 20% FA has a lower porosity value of 12.7% compared with to the control FGM which has a porosity of 13.5%. Among all FGMs containing pozzolans, FGM containing POFA had the highest porosity value of 13.1%, followed by RHA with a porosity value of 12.9%. From the results, it can be concluded that FGM containing 20% of FA, 10% of POFA and 20% of RHA achieved a better performance than the control mortar in terms of porosity. This is because pozzolans such as FA, POFA and RHA are more effective in modifying pores and reducing the porosity of FGM [2].

Specimen no.	Symbol	Tensile strength (N/mm ²)	Porosity (%)
1	Control	5.4	13.5
2	FA20	5.9	12.7
3	POFA10	5.5	13.1
4	RHA20	5.6	12.9

Table 2. Tensile strength and porosity of FGM at 28 days.

10th Asia Pacific Structural Engineering and Construction Conference 2018IOP PublishingIOP Conf. Series: Materials Science and Engineering 513 (2019) 012027doi:10.1088/1757-899X/513/1/012027

4.3. Relationship between tensile strength and porosity

The relationship between tensile strength and porosity at the age 28 days was shown in Figure 1. It can be observed that the higher the tensile strength, the lower the porosity. It can be seen that cement replaced with 20% of FA, 10% of POFA and 20% of RHA achieved the highest tensile strength and the lowest porosity. This is because FA, POFA and RHA tend to modify pores more effectively than control mortar [2]. Meanwhile, the value of tensile strength for the control mortar was the lowest while its porosity was the highest among all the other specimens. The incorporation of pozzolans reduces the average pore size and modifies pores in FGM.



Figure 1. Relationship between porosity and tensile strength.

Based on the results, the pozzolans used in this research were found to be suitable for use in FGM. This may help create a green and sustainable construction industry. Besides that, incorporating FA, POFA and RHA into FGM slightly increases its strength. The relationship between tensile strength and porosity can also be shown using the R^2 value which was 0.8231 after a curing period of 28 days. Hence, this relationship was used in determining the tensile strength and porosity of FGM incorporated with FA, POFA and RHA as cement replacement.

5. Conclusions

This research was carried out to determine the tensile strength and porosity of FGM containing FA, POFA and RHA as cement replacement. From the results obtained, it can be concluded that the objectives of this study have been achieved.

The tensile strength of FGM containing FA, POFA and RHA as cement replacement was shown to be better than the tensile strength of the control mortar. The addition of 20% of FA, 10% of POFA and 20% of RHA is able to improve the tensile strength of FGM. FGM containing 20% of FA achieved the highest tensile strength of 5.9 N/mm², followed by FGM containing POFA and RHA with tensile strength values of 5.5 N/mm² and 5.6 N/mm², respectively. Meanwhile, the tensile strength of the control mortar was found to be the lowest.

The percentage of porosity for FGM containing FA, POFA and RHA as cement replacement was lower than that of the control mortar. FGM containing FA obtained the lowest percentage of porosity which is 12.7%, followed by RHA and POFA with percentages of porosity of 12.9% and 13.1%, respectively. This indicates that FGM containing FA, POFA and RHA were slightly effective in reducing the porosity of FGM.

10th Asia Pacific Structural Engineering and Construction Conference 2018

IOP Conf. Series: Materials Science and Engineering **513** (2019) 012027 doi:10.1088/1757-899X/513/1/012027

When the value of R is close to 1, this means that there is a good relationship between tensile strength and porosity in FGM. Hence, it is verified that the addition of pozzolans is capable of improving tensile strength and reducing porosity in FGM.

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