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Assessing the effect of biomass ashes with different finenesses on the compressive strength of blended cement paste

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ABSTRACT

This study assesses the effect of biomass ashes with different finenesses on the compressive strength of blended cement paste. rice husk ash (RHA), palm oil fuel ash (POFA) and river sand (RS) were ground to obtain two finenesses: one was the same size as the cement, and the other was smaller than the cement. Type I Portland cement was replaced by RHA, POFA and RS at 0%, 10%, 20%, 30% and 40% by weight of binder. A water to binder ratio (W/B) of 0.35 was used for all blended cement paste mixes. The percentages of amorphous materials and the compressive strength of the pastes due to the hydration reaction, filler effect and pozzolanic reaction were investigated. The results showed that ground rice husk ash and ground palm oil fuel ash were composed of amorphous silica material. The compressive strength of the pastes due to the hydration reaction decreased with decreasing cement content. The compressive strength of the pastes due to the filler effect increased with increasing cement replacement. The compressive strengths of the pastes due to the pozzolanic reaction were nonlinear and were fit with nonlinear isotherms that increased with increasing fineness of RHA and POFA, cement replacement rate and age of the paste. In addition, the model that was proposed to predict the percentage compressive strength of the blended cement pastes on the basis of the age of the paste and the percentage replacement with biomass ash was in good agreement with the experimental results. The optimum replacement level of rice husk ash and palm oil fuel ash in pastes was 30% by weight of binder; this replacement percentage resulted in good compressive strengths.

1. Introduction

In the manufacture of cement, the clinker production process requires a great amount of energy and emits a large amount of carbon dioxide (CO_2) into the atmosphere. According to the Intergovernmental Panel on Climate Change (IPCC), the production of cement in 2005 accounted for approximately 7% of the CO_2 emissions worldwide [1]. Global cement production will increase by an average of 2.1% every year between 2005 and 2030, reaching a level that is 1.7 times greater than that in 2005 because of the growth of countries [2]. The increase in CO_2 emissions has led to the greenhouse effect and an increase in the earth's temperature. The environmental impact of cement production must be reduced by reducing the production of ordinary Portland cement. To reduce the environmental problems, pozzolanic materials, such as fly ash, silica fume and agro-waste ashes, are used as mineral admixtures to reduce the production of cement, thus reducing the emission of CO_2 and the use of energy. This solution has been reported to be environmentally friendly. In addition, the incorporation of mineral admixtures in concrete can also improve the mechanical properties and durability of the concrete [3–5].

Rice husk ash (RHA) is a by-product of electricity generation biomass power plants. In Thailand, the annual production of RHA has been approximated at 1.6 million tons [6]. Several researchers have shown that the main chemical composition of rice husk is silicon dioxide (SiO_2), and the highest amount of amorphous silica was achieved when rice husk ash was burned between 500 and 700 °C [7,8]. Thus, RHA is a pozzolanic material and can be used as a supplementary cementitious material to replace Type I Portland cement by up to 30% [9,10]. Rukzon et al. [11] found that rice hush ash with high fineness can improve the compressive strength and produce a mortar with low porosity. For durability, the results showed that the use of RHA to partially replace Type I Portland cement improves the concrete water permeability [12], chloride penetration [10,13], and resistance to deterioration due to sulfate [3,4].

Palm oil fuel ash (POFA) is a by-product of palm oil factories, where palm shells, empty fruit bunches and palm fiber are burnt as fuel at temperatures of 800–900 °C. It has been estimated that more than 100,000 tons of palm oil fuel ash are produced in

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Thailand every year [14]. Palm oil fuel ash is rarely utilized, and the amount produced is increasing annually. Previous researchers have found that POFA is a pozzolanic material, and ground POFA with high fineness can be used to replace Type I Portland cement at a rate of up to 30% by weight of binder. Chindaprasirt et al. [13] indicated that POFA improves the compressive strength and provides good resistance to chloride penetration. Tangchirapat and Jaturapitakkul [15] showed that POFA with high fineness can reduce the drying shrinkage and water permeability of concrete.

Cyr et al. [16] reported that the effect of mineral admixtures on the compressive strength involved three factors. First, the dilution effect is the strength proportional to the amount of cement in the mixture. Second, the physical effect is the strength that depends on the fineness and the amount of powder, which lead to the nucleation effect and filler effect. The nucleation effect accelerates the hydration production and leads to a more homogeneous paste. The filler effect is due to a suitable arrangement of small particles that fill the voids of the paste and increase its compressive strength. Third, the pozzolanic reaction occurs between $Ca(OH)_2$ and the SiO_2 and Al_2O_3 from pozzolanic materials, which produces an increase in calcium silicate hydrate C–S–H [17–19]. However, many researchers have studied the pozzolanic reaction, using, for example, ASTM C618, strength activity index ASTM C311, X-ray diffraction (XRD), thermogravimetric analysis (TGA) and chemical titration. Moreover, Tangpagasit et al. [20] studied the use of river sand as an inert material to replace Type I Portland cement to evaluate the packing effect and pozzolanic reaction of fly ash in mortar. They found that river sand is an inert material and that the packing effect is not dependent on the age of the mortar but rather on the particle size while the pozzolanic reaction depends on the fineness and age of the mortar.

Previous studies have already reported the influence of the finenesses of RHA and POFA on the compressive strength and observed that ashes with a median particle size larger than OPC ($\sim$15 μm) can be used to replace OPC at 10% [10] while smaller sizes than OPC can be used at 20% to 30% by weight of binder [15]. However, the separation of the influences of the hydration reaction, the filler effect and the pozzolanic reaction on compressive strength of blended cement pastes has not been well defined. If a by-product material from biomass plants can be used as a cement replacement in concrete, it will help reduce energy use by reducing the production of cement clinker and reducing the volume of waste disposed to landfills. Thus, the objective of this study is to quantify the effect of the hydration reaction, the filler effect and the pozzolanic reaction on compressive strength of paste. In addition, equation derived from results determine from experimental testing was derived to predict the compressive strength of a paste due to the hydration reaction, filler effect, and pozzolanic reaction. The chemical properties and percentages of amorphous materials were investigated. The effects of ground rice husk ash and ground palm oil fuel ash with two different finenesses, which influences the hydration reaction, filler effect, and pozzolanic reaction, on the compressive strength of blended cement pastes were determined.

2. Experimental details

2.1. Materials

The materials used in this study were Type I Ordinary Portland cement (OPC), rice husk ash (RHA), palm oil fuel ash (POFA), and river sand. RHA and POFA were collected from thermal power plants in Thailand, and the inert material used was ground river sand (RS). The original RHA and POFA had large particles with low pozzolanic properties [11,21]. Thus, the original RHA and POFA were sieved through a sieve No. 16 to remove the large particles and any incompletely combusted material. The difference in compressive strength between the pozzolan paste and inert material paste can be determined as the compressive strength due to the pozzolanic reaction [20]. Then, the RHA, POFA and RS were ground to two different sizes. To eliminate the filler effect, RHA, POFA and RS were ground to have the same particle size as OPC for the first fineness of materials (CRHA, CPOFA and CRS). For the second fineness from the filler effect of materials (FRHA, FPOFA and FRS), the materials were ground to have particles that could act as fillers between the particles of cement by an attrition mill for 60 min at 1000 rpm using 2 mm diameter steel balls.

As shown in Fig. 1a, if the median particle size of a material is the same as that of OPC ($\sim$15 μm), the filler should have the save particle size as OPC.

$$d = D = 15\mu m \quad (1)$$

If the median particle size of the material is smaller than that of cement and acts as filler between the particles of cement, as shown in Fig. 1(b), the median size of the material can be calculated with Eq. (3) [22]:

$$d = cos30^{\circ} \frac{D/2}{D/2 + d/2} \quad (2)$$

$$d = 0.15D = 0.15(15) = 2.25\mu m \quad (3)$$

The SEM photographs of the materials are shown in Fig. 2. It was found that the ground RHA and POFA consisted of irregular, crushed particles. A similar conclusion was also reported by other researchers [13]. The physical properties of the materials are presented in Table 1. The first group of materials (CRHA, CPOFA and CRS) had particle sizes equal to that of cement. The specific gravity of CRHA, CPOFA and CRS was 2.29, 2.36 and 2.59, respectively. The Blaine fineness values of CRHA, CPOFA and CRS were 7600, 6700 and 3900 cm^2/g, respectively. For the small particle group (FRHA, FPOFA and FRS), the specific gravity and Blaine fineness of FRHA, FPOFA and FRS were 2.31, 2.48, 2.61 and 18,000, 14,900 and 6300 cm^2/g, respectively. The particle size distributions of the materials are shown in Fig. 3. The median particle sizes of CRHA, CFOFA and CRS were close to the particle size of the cement, while those of FRHA, FPOFA and FRS were smaller than that of cement.

2.2. Mix proportion

Ground RHA, POFA and RS were used to partially replace Type I Portland cement at the rates of 0%, 10%, 20%, 30% and 40% by weight of binder. A water to binder (W/B) ratio of 0.35 was used for all mixtures and is shown in Table 2. To ensure homogeneity, the OPC, RHA, POFA and RS were first mixed together for 3 min in the mixer, and then the water was added. Afterwards, the mixture was mixed for another 2 min. After mixing, the cement pastes were immediately cast into cube specimens of $50 \times 50 \times 50$ mm. The cast specimens were covered with plastic to prevent water loss. After casting for 24 h, the specimens were removed from the molds and cured in saturated lime water at a temperature of 23 ± 2 °C.

2.3. Compressive strength

The cube specimens of $50 \times 50 \times 50$ mm were prepared in accordance with ASTM C109 [23]. They were tested to determine the compressive strength at the ages of 7, 28, 60 and 90 days. Each compressive strength value reported is the average of five samples.