Construction and Building Materials 144 (2017) 608–623

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Influence of source materials and the role of oxide composition on the performance of ternary blended sustainable geopolymer mortar

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HIGHLIGHTS

- High rate of geopolymerization resulted in achievement of 3 day strength.
- Lower difference in strength between mixes with 14 M and 12 M with high percentages of GGBS.
- Ternary combination of RHA, GGBS and MK achieved higher strength than binary combination.
- Unreactive particles of RHA reduced strength of mortar with high volume of RHA.
- Amorphorsity of mortar increased with the increase in percentage of MK as binder.

ARTICLE INFO

Article history:
Received 30 October 2016
Received in revised form 19 March 2017
Accepted 22 March 2017

Keywords:
Geopolymer
Rice husk ash
Blast furnace slag
Metakaolin
Ternary binder
Compressive strength
Chemical composition
X-ray diffraction
SEM
EDS

ABSTRACT

This research article reports the contribution of different oxides present in rice husk ash (RHA), ground granulated blast furnace slag (GGBS) and metakaolin (MK) on the performance of geopolymer mortars. Twenty-six mixes were designed with combined base materials and varied $NaOH_{aq}$ concentration, that was used as one of the activators. RHA, GGBS and MK contents were varied between 15% and 70%, 0% and 75%, and 0% and 40%, respectively. The binder/fine aggregate, water/binder and alkaline activator/binder ratios were kept constant while all the specimens were cured at 65 °C for 24 h. The mixture (ternary) that contained 25% RHA, 25% MK and 50% GGBS ($M_{25}R_{25}G_{50}$) produced the highest compressive strength of 48 MPa; in addition, it produced better flow rate and lower density than any binary combinations. The findings through microstructural and characterization tools show that regardless of the source, SiO_2 and CaO present in the base materials contributed to the strength, while Al_2O_3 influenced the amorphorsity of the products.

1. Introduction

The cement industry is one of the major sources of pollution as it contributes 5% of the total carbon dioxide (CO_2) worldwide; 50% of the emissions are from the chemical process and 40% from burning fuel [1]. The production of one ton of concrete creates about 410 kg CO_2. This could be reduced to 290 kg with 30% fly ash as a cement replacement [2]. Among the solution adopted in minimizing greenhouse gas emissions is the utilization of industrial by-products, such as fly ash (FA), silica fume (SF), ground granulated blast furnace slag (GGBS), palm oil fuel ash (POFA), metakaolin (MK) and rice husk ash (RHA) as the cement replacement materials. In recent years, increase in the awareness on the reduction of environmental solid wastes and its impact on human health has encouraged many researchers to consider their usage in the production of construction materials. One of the significant achievements is the development of geopolymer concrete using waste materials, such as FA, GGBS, RHA, MK and POFA, as source materials. RHA, MK, POFA and GGBS contain a large amount of alumina and silica – though of varied percentage - which make them to be potentially useful in the synthesis of geopolymer concrete.

The annual world rice production amounts to approximately 400 million metric tons of which more than 10% is husk [3]. To

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http://dx.doi.org/10.1016/j.conbuildmat.2017.03.178
0950-0618/

solve the problem with huge cost spent for transportation and removal of RHA and environmental pollutions caused by it, it is necessary to make proper use of this pozzolanic waste material. RHA is rich in silica with about 85–90% [4]. The uniqueness of rice husk ash is its pozzolanic reaction and filling effect [5]. RHA mainly consists of amorphous silica with a very little quantity of crystalline phase which is responsible for the pozzolanic activity [6].

MK has been used as a pozzolan since the mid-1990s. Kaolin, after suitable treatment, is the main source of MK. MK has attracted a lot of attention due to its having both pozzolanic and micro-filling features [7]. Although MK is an inorganic material, it is similar to organic materials because it reacts with solid polymers to form a strong alumina-silicate network by polycondensation [8]. When MK mixes with slag under alkaline activation condition, both the calcium silicate hydrate system and geopolymer system interact at their contact surfaces and produce good strength performance [8].

GGBS has been widely used in Europe, and increasingly in the United States and in Asia (particularly in Japan and Singapore) for its dominance in concrete stability [9]. GGBS has been activated successfully by an alkaline medium for more than 40 years [10]. The use of GGBS with Ordinary Portland cement and other pozzolanic materials has enhanced the durability of concrete structures [11]. Both glassy and crystalline phases are found in slag. In GGBS, glass content is between 85 and 90% and this glassy nature promotes cementitious properties to the GGBS.

Malaysia consumed 2.76 billion metric tonnes of natural aggregate (gravel and sand) worth USD14.4 billion in 2010 [12]. Moreover, sand with a proper proportion of fine particles will have fewer voids and the quantity of cement required will be less. Such sand will be more cost-effective. That is why natural sand should be replaced by manufactured sand (M-sand), which is a derivative of QD attained by centrifuging it using equipment known as the Vertical Shaft Impact (VSI). Donza et al. [13] stated that the shape and texture of M-sand provides improved strength due to the good interlocking between particles.

The polymerisation process involves a substantially fast chemical reaction under alkaline condition on Si-Al minerals, that results in a three dimensional polymeric chain and ring structure consisting of Si-O-Al-O bonds [14]. The alkalis used in this study were sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH). Hardjito et al. [15] stated that alkali concentration plays a noteworthy role for geopolymerization, and that a higher concentration of NaOH produces greater compressive strength. There are lot of advantages of using higher concentration of activator, among them improving slag hydration capability [16] and prevention of faster setting are very significant [17]. The temperature also increases the energy of reactant particles so that they can overcome the difficulty of transportation for ion species in the aqueous phase due to acceleration of the activator concentration [17].

According to Isaia et al. [18,19] studies, when one less reactive pozzolan is added to make a ternary mixture with another one more reactive pozzolan such as RHA, silica fume, a synergistic environment is created among ternary pozzolans for which the strength result becomes higher than any binary combination [20]. The strength of blended concrete is improved due to synergistic or high reaction effect when the blend of fine pozzolans are incorporated [21]. As the speciality of geopolymer mortar is the use of non-cement binder, compressive strength development of geopolymer mortar greatly depends on the combined effect of binary or ternary binders. Karim, Zain, Jamil and Lai [22] reported that geopolymer mortar with ternary combination of RHA, GGBS and POFA produced higher compressive strength than the mortar with binary combination of GGBS and POFA due to having more silica. Ng et al. reported that compressive strength of geopolymer mortar is greatly influenced by the strength of the geopolymer binder materials [23]. SM Kabir et al. produced 28-day compressive strength of 47 MPa with the addition of GGBS up to 35%, POFA up to 45% with 20% MK [24].

The main objective of this research was to investigate the development of the compressive strength of geopolymer mortar using four locally available waste materials –RHA, MK and GGBS as binders, and M-sand as fine aggregate. The effects of varying the oxide composition through the variation in the quantity of these three binders percentagewise on the compressive strength were investigated. Besides, the optimum percentage of the binders in the development of geopolymer mortar was also obtained. The flowability, density, and optimum compressive strength of cube specimens were determined with various binder dosages. Microstructural investigation has been done to determine the roles of oxide compositions on the performance of ternary blended geopolymer mortars.

2. Experimental programme

2.1. Materials

2.1.1. Source materials

Tables 1and 2 show the chemical composition (wt%) and physical properties of all three source materials, respectively. The highest silica, alumina and CaO contents of 94%, 40% and 46% were found in RHA, MK and GGBS, respectively. MK contains about 50% SiO_2 and 40% Al_2O_3. Other oxides present in small amounts include Fe_2O_3, TiO_2, CaO and MgO, as shown in Table 1. The carbon content was estimated as the percent loss on ignition. The LOI value of RHA is 7.76 and it is of grey black colour. Its specific gravity is 2.3 and the specific surface area is 2981.2 m^2/kg. Metakaolin is an off-white powder. Its specific gravity is 2.5 and its specific surface area is 4315.8 m^2/kg. GGBS was obtained from YTL Cement Marketing Sdn. Bhd., Malaysia. GGBS is a glassy, granular material essentially consisting of oxides, such as SiO_2, CaO, Al_2O_3, and MgO. GGBS is an off-white powder. Its relative density is 2.85–2.95 and its surface area 400–500 m^2/kg. The specific gravity is 2.89. The particle size distributions of GGBS, MK and RHA are shown in Fig. 1. RHA possesses higher surface area, yet coarser particle size than GGBS that would have contributed to the porous structure of RHA [6]. GGBS contains almost 75% CaO and SiO_2 together whereas Portland cement possesses about 85% CaO and SiO_2 together. GGBS contains more Al_2O_3 than OPC. The total binder content is 766 kg/m^3.

2.1.2. Manufactured sand

Manufactured sand (M-sand) is more angular and has a rougher surface texture than naturally weathered sand particles. Its specific gravity is 2.78 and Fineness modulus (FM) is 3.19. Fig. 2 represents the particle size distribution of M-sand. From the particle-size distribution curve, it can be seen that Cu (uniformity co-efficient) is greater than 6 and the Cc (co-efficient of gradation) is between 1 and 3. Hence, the M-sand is well graded and falls under zone-C [BS 882:1992]. With a well-designed screening system, the required grading (Zone II) and fineness modulus (2.4–3.1) can also be achieved consistently in the case of M-sand.

2.2. Specimen preparation, curing and testing

2.2.1. Alkali activation of mortar

Alkali activation is one of the profitable means of activation [25] and the alkalis that are normally used are sodium silicate (Na_2SiO_3), sodium carbonate (Na_2CO_3) and sodium hydroxide (NaOH). In this investigation, NaOH in pellet form and Na_2SiO_3 solution were used as alkali activators; the specific gravity of NaOH was