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EFFECT OF WATER-TO-BINDER RATIO ON DENSITY, COMPRESSIVE STRENGTH AND MORPHOLOGY OF FLY ASH/LADLE FURNACE SLAG BLENDED ONE-PART GEOPOLYMER

Water-to-binder (W/B) ratio has a great influence on the bulk density, compressive strength and morphology of fly ash/ladle furnace slag (FA/LFS) blended one-part geopolymer. The objective of this work is to evaluate the effect of W/B ratio on the performance of the one-part geopolymer. The one-part geopolymer were prepared at W/B ratio of 0.20-0.30 and cured at room temperature for 28 days. The bulk density, water absorption, apparent porosity and compressive strength were determined, while the morphology was examined by scanning electron microscopy (SEM). The results showed that the one-part geopolymer with W/B ratio of 0.25 had highest compressive strength (39 MPa) with denser (2.1 g/cm^3) structure as well as low water absorption (3.97%) and low apparent porosity (8.33%). The micrograph showed the optimal one-part geopolymer has less agglomeration of FA and LFS particles.

Keywords: Fly ash; Ladle furnace slag; One-part geopolymer; W/B ratio

1. Introduction

Ordinary Portland cement (OPC) has been long-established in building technologies, even though its manufacturing process contributed to high energy consumption and carbon dioxide (CO_2) emission. Geopolymer, an inorganic polymer, found to be an greener option for OPC. The production of geopolymer not only enabling minimal CO_2 emission, but also industrial wastes recycling [1]. Geopolymer could be synthesized by two major constituents: alkali activators (alkali hydroxide and alkali silicate) and aluminosilicate precursors such as fly ash (FA) [2], metakaolin (MK) [3], ground granulated blast furnace slag (GGBFS) [4] and ladle furnace slag (LFS) [5]. Geopolymerization occurs when the aluminosilicate precursors dissolved in alkali activator solution, followed by the polycondensation, creating a stable three-dimensional Si-O-Al-O framework.

One-part technology in geopolymer formation mimics how OPC is handled in practical applications. The purpose of introducing this method is to eliminate the shortcoming of traditional geopolymer formation, which causes inconvenience of handling alkaline solution and the necessity of technical skill. One-part technology only involved the combination of water and dry mixture of solid aluminosilicate precursors and alkali activators. This could prevent the unexpected accidents and eventually ensure worker's safety. These benefits open up the possibility of widespread implementation of one-part geopolymer [6].

Several studies have used slag in the production of conventional geopolymer, implying that the incorporation of two or more aluminosilicate precursors is beneficial to the development of geopolymer. Based on our previous study [7], LFS have proven to be integrated into FA one-part geopolymer. Hui-Teng et al. [5] and Yong-Sing et al. [8] reported that the cementitious properties of LFS were favorable to the engineering properties of the geopolymer. Thus, LFS was chosen as the precursor in this study to evaluate the effect of water-to-binder (W/B) ratio on its performance.

Water is an essential component that participated in geopolymerization to produce reaction product, this subsequently enhanced the mechanical strength of one-part geopolymer. Sadeghian et al. [9] proposed that raising the W/B ratio (>0.50) resulted a porous structure which is detrimental to the compressive strength of GGBFS one-part geopolymer. Oderji et al. [10] came to same conclusion as the FA/GGBFS one-part geopolymer exhibited dramatic strength decrement when water content in-

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creased. However, it is discovered that the W/B ratio influenced by the type of source material employed in one-part geopolymer. For instance, Murri et al. [11] stated that higher water content is necessary to lower the alkalinity of LFS mixture which prompt to the formation of CASH gel and enhanced the mechanical properties of geopolymer. There is a difficulty of controlling the effective W/B ratio precisely, hence, the research on the ratio in FA/LFS blended one-part geopolymer is requisite.

This study's goal is to assess how the W/B ratio affects the density, compressive strength and microstructure of the one-part FA/LFS blended geopolymer. In order to fulfill the required mechanical strength for usage in building applications, such as walls and slabs, it is essential to determine the optimal W/B ratio.

2. Materials and methods

In this study, FA was obtained from Sultan Azlan Shah Power Station, TNB Janamanjung Sdn. Bhd., Perak and the LFS was sourced from Southern Steel Berhad, Penang. The chemical composition of these aluminosilicate precursors was established through X-ray Fluorescence (XRF), as listed in TABLE 1. Since the CaO content of the FA was less than 18% and the total amount of SiO_2, Al_2O_3 and Fe_2O_3 was over 70% and the loss of ignition (LOI) less than 5%, the FA used complies with the ASTM C618 requirements and classified as Class F FA. The alkali activators

TABLE 1

Chemical composition of FA and LFS

Component	FA (wt.%)	LFS (wt.%)
SiO_2	44.70	19.60
Al_2O_3	22.90	6.54
CaO	8.19	46.20
Fe_2O_3	10.70	8.12
MgO	3.24	5.51
SO_3	1.03	2.53
Others	9.24	11.5
LOI (%)	2.53	2.72

utilized were technical grade anhydrous sodium metasilicate (Na_2SiO_3) and sodium hydroxide (NaOH). The anhydrous Na_2SiO_3 granules had a mesh size of 18 with the composition of SiO_2 of 50-53%, whereby the NaOH was in flakes form with purity of 98%.

The FA/LFS blended one-part geopolymer was proportioned by FA/LFS ratio of 9.0, together with anhydrous Na_2SiO_3 and NaOH. The alkali activator-to-aluminosilicate (AA/AS) and anhydrous Na_2SiO_3-to-NaOH (SM/SH) ratios were set at a constant of 0.20 and 5.00, respectively. The range of water-to-binder (W/B) ratios was set between 0.20 to 0.30. The details of the mix designation of the FA/LFS blended one-part geopolymer are given in TABLE 2.

TABLE 2

Mix designation of FA/LFS blended one-part geopolymer

Mix	W/B	AA/AS	SM/SH	FA (g)	LFS (g)	Na_2SiO_3 (g)	NaOH (g)	Water (g)
OPG1	0.20			156.25	17.36	28.94	5.79	41.67
OPG2	0.25	0.20	5.0	150.00	16.67	27.78	5.56	50.00
OPG3	0.30			144.23	16.03	26.71	5.34	57.69

After the preparation, the FA, LFS, anhydrous Na_2SiO_3 and NaOH were mixed together by mechanical stirrer until a homogenous paste was obtained, followed by addition of water (Fig. 1). The one-part geopolymer paste was then cast in 50×50×50 mm^3 plastic mold and cured under ambient temperature for 24 hours. Thin plastic sheet was used to cover the one-part geopolymer to prevent the moisture loss. After demolding, the one-part geopolymer was kept at ambient temperature until the day of testing (28 days).

The bulk density was calculated by dividing the mass by the volume of the one-part geopolymer according to ASTM C138. The compression testing was performed by Shimadzu UH-100kNI Universal Testing Machine (UTM) according to ASTM C109 at a constant rate of 5mm/min. Three one-part geopolymers were tested for each mix designations and the average compressive strength was calculated. The microstructure of
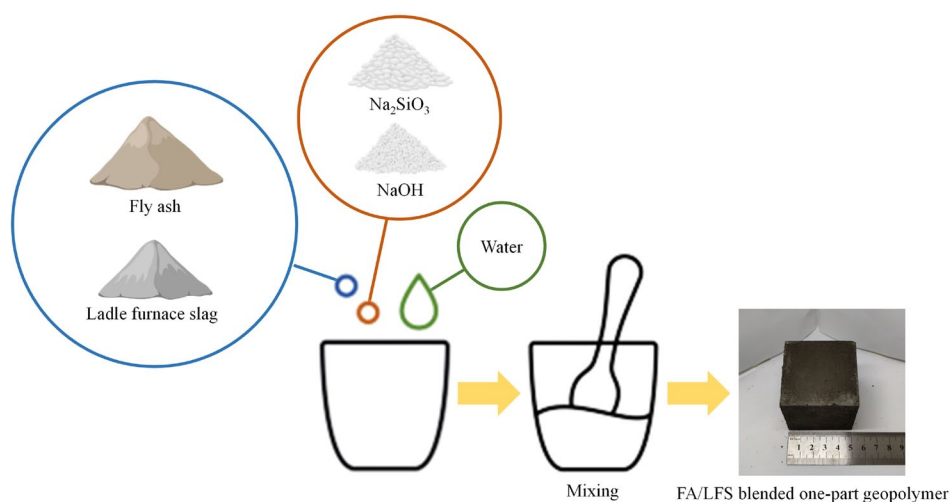

Fig. 1. The procedure of FA/LFS blended one-part geopolymer formation

the one-part geopolymer was revealed by TESCAN VEGA 14 Scanning Electron Microscopy (SEM). The pieces of the one-part geopolymer were coated with gold by using Sputter Coater NS-800 to prevent electrostatic charge while imaging.

3. Results and discussions

Fig. 2 shows the bulk density and compressive strength of the FA/LFS blended one-part geopolymer at different W/B ratios. When the amount of water increased, the bulk density of the one-part geopolymer rose (2.1 g/cm^3) and then fell (1.9 g/cm^3). This is because a matrix with large amount of water content has a tendency to lose its solid binder, leading to the formation of additional bound water. The bound water evaporates with time, creating pores within the matrix and a less dense of FA/LFS blended one-part geopolymer is obtained.

Similar trend between the compressive strength and bulk density can be observed, suggesting that a denser structure may be the reason for rise in compressive strength. The compressive strength of FA/LFS blended one-part geopolymer gradually increased from 38 MPa (OPG 1) to 39 MPa (OPG 2) before sharply decreasing to 12 MPa (OPG 3), indicating that the W/B ratio had a substantial impact on the compressive strength. In general, an adequate water content is necessary in order to dissolve the solid aluminosilicates and solid alkali activators, and then produce additional geopolymer products during the geopolymerization. Contrarily, too much water causes a too workable paste and redistricts the alkali activator's ability to excite, which leads to less geopolymer gel formation as well as pores [12,13]. Therefore, W/B ratio of 0.25 is the optimal formulation to achieve the denser structure and compressive strength of FA/LFS blended one-part geopolymer. Similar findings have found on FA one-part geopolymer synthesized by Mohammed et al. [14] whereas Ye et al. [15] and Shah et al. [16] advocated a higher W/B ratio (>0.25) to produce red mud and lithium slag based one-part geopolymer. 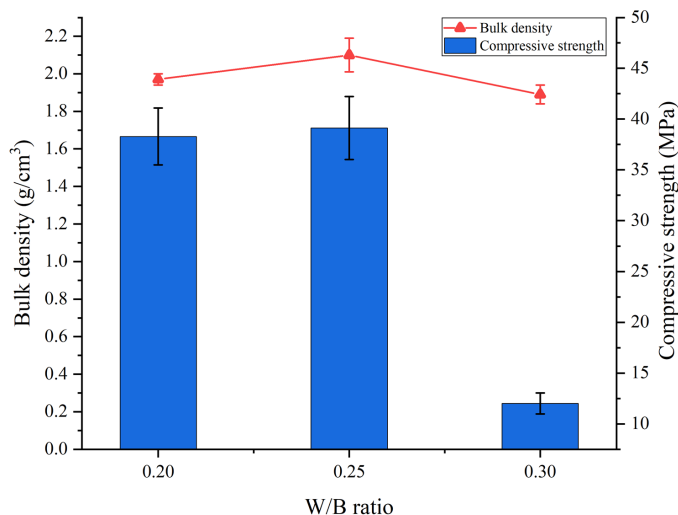That what to say, since the Al and Si concentration varies, the W/B ratio changes depending on the kind of aluminosilicates source.

Fig. 3 illustrates the water absorption and apparent porosity of FA/LFS blended one-part geopolymers. Water absorption and apparent porosity followed comparable trend, implying that the water absorption of FA/LFS blended one-part geopolymer can be correlated with its apparent porosity. The water absorption and apparent porosity decreased and increased with the increasing of W/B ratio. At W/B ratio of 0.20, regardless the high bulk density (Fig. 2), a low water content caused a recognizable rise in viscosity of the mixture, which permitted the introduction of residual air bubbles through being trapped within the FA/LFS blended one-part geopolymer during mold casting [17]. The residual air bubbles are unable to escape due to the yield force, resulting high amount of interconnection between pores [18]. When W/B ratio increased to 0.25, the minimum water absorption and apparent porosity achieved (3.97 and 8.33%, respectively). The results were in line with the bulk density and compressive strength (Fig. 2), indicating that the denser blended one-part geopolymer produced a structure with less porosity and excellent mechanical strength. When the W/B ratio reaches to 0.30, the excess water is easy to evaporate from the FA/LFS blended one-part geopolymer to cause extensive drying shrinkage [19].
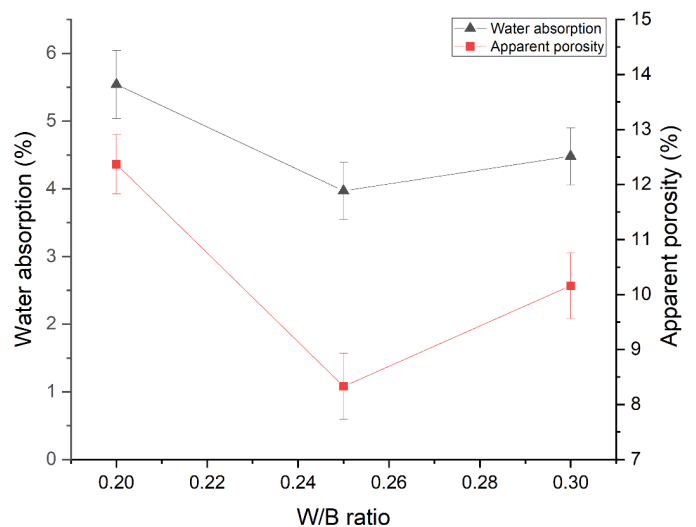

Fig. 3. Water absorption and apparent porosity of FA/LFS blended one-part geopolymer

Fig. 2. Bulk density and compressive strength of FA/LFS blended one-part geopolymer

Fig. 4 shows the SEM micrograph of FA/LFS blended one-part geopolymers, captured at 500× magnification. FA/LFS blended one-part geopolymer is shown to be heterogenous with aluminosilicate particles that unreacted or partially reacted, pores and cracks. OPG 1 has a lot of unreacted FA and LFS particles, suggesting that the lack of water caused the solid alkali activator and aluminosilicate sources to not dissolve completely. Besides, OPG 1 appeared to have tiny voids due to the high viscosity of the mixture are limits the bubbles emitted to atmosphere. Moreover, it also can be seen that a denser structure was obtained by OPG 2 with less FA and LFS particles aggregation. One-part geopolymers with denser structure may usually be identified as having
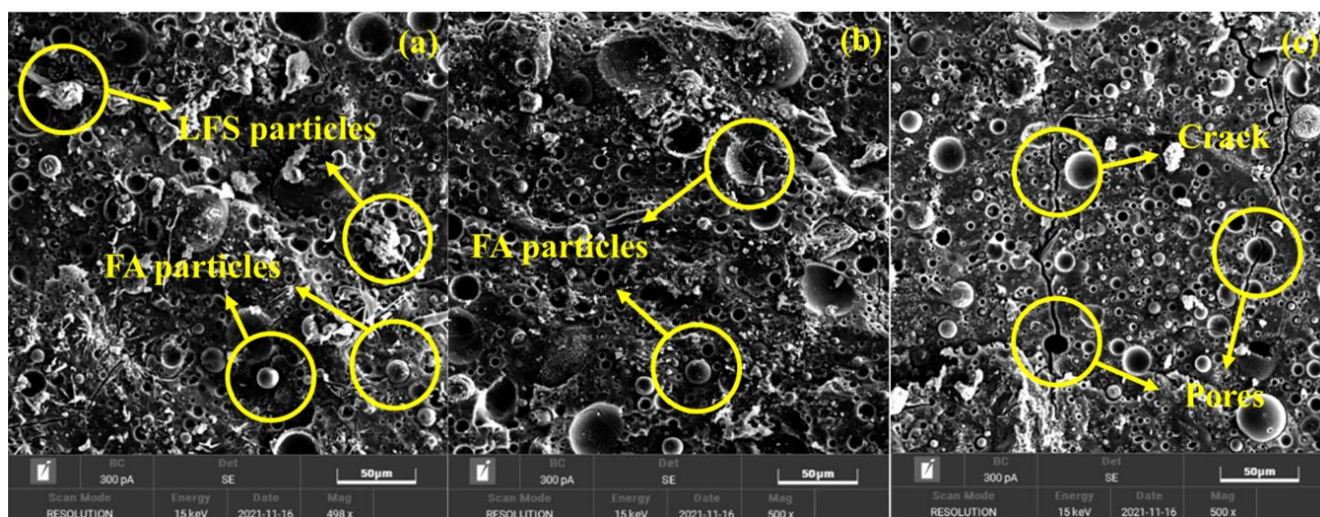
Fig. 4. SEM micrograph of FA/LFS blended one-part geopolymer at W/B ratio of (a) 0.20, (b) 0.25 and (c) 0.30

greater levels of geopolymerization, resulting in excellent compressive strength (39 MPa). This indicated that the ideal water content was capable of offering a sufficient and workable mixture to enable the geopolymerization process. In comparison, OPG 3 has a greater number of pores and cracks due to the significant shrinkage of the one-part geopolymer. Similar findings have been made by Oderji et al. [20] A porous structure increased the stress concentration points, resulting crack propagation and structural failure and then lower compressive strength achieved (12 MPa).

4. Conclusion

The results of the experimental investigation were reported in this work to assess how the W/B ratio affect the bulk density, compressive strength and morphology of FA/LFS blended one-part geopolymer. W/B ratio plays a crucial role in determining the performance of the one-part geopolymer. A denser structure with less aggregation of unreacted FA and LFS particles was obtained when the W/B ratio of 0.25 was employed. Furthermore, with the similar W/B ratio, the FA/LFS blended one-part geopolymer attained the maximum compressive strength of 39 MPa.

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