Effect of Binder to Fine Aggregate Content on Performance of Sustainable Alkali Activated Mortars Incorporating Solid Waste Materials

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This article investigated the effects of binder to aggregate ratio on the properties of granulated blast furnace slag (GBFS) alkali activated mortar incorporated with fly ash (FA), waste ceramic (CP) and bottle glass wastes (GP). Five types of alkali-activated mortars were prepared with a different binder to fine aggregate ratio (B:A) 0.30, 1.0, 1.5, 2.0 and 2.5. Sodium hydroxide (NH) with 6 molar concentrations added to sodium silicate (NS) and used as alkali activator solution, alkaline liquid to binder ratio (S:B) was kept 0.25 for all mixtures. Alkali-activated samples cured at ambient temperature (27 °C) and relative humidity (75 %). The results indicated that 1.0 (B:A) ratio was achieved the optimum results flow and bending stress, increasing binder to fine aggregate content effect negatively on workability and strength properties of alkali-activated mortars. The results also presented the porosity of alkali-activated samples has been influenced by increase binder content to fine aggregate from 1.0 to 2.5.

1. Introduction

Over the years, Ordinary Portland Cement (OPC) has diversely been utilized as binder in concrete and other construction materials worldwide (Huseien et al., 2015a). The mass production of OPC as led to serious environmental pollution regarding the considerable amount of greenhouse gases emission (Ogunbode et al., 2017). The OPC production alone is responsible for 6–7% of total CO_2 emissions as estimated by International Energy Agency (Huseien et al., 2015b), this was also confirmed by Palomo et al. (2011). In fact, among all the greenhouse gases, CO_2 gas emission is attributed to about 65% of the global warming. The scientific community asserted that the global average temperature could increase by approximately 1.4–5.8 °C over the next 100 years (Huseien et al., 2017). The term ''geopolymers'' was coined by Joseph Davidovits in 1972, geopolymers are a novel class of materials that are formed by the polymerization of silicon, aluminium, and oxygen species to form an amorphous three-dimensional framework structure (Davidovits, 2008). Geopolymeric reactants could range from kaolinite or metakaolin to a group of materials containing rich SiO_2 and Al_2O_3 oxides, e.g., fly ash, slag, construction waste and natural minerals (Huseien et al., 2016a). As we know, chemical bonds of Si–O and Al–O are among the most stable covalent bonds in nature.

The polycondensation degree of geopolymer is much higher than cement-based materials (Yusuf et al., 2014). Therefore, geopolymer materials possess many advanced properties such as the ease with which it can be recycled, excellent compressive and bond strength (Hussin et al., 2015), long-term durability and better acid resistance (Huseien et al., 2016b). Besides, it is also a ''Green Material'' for its low manufacturing energy consumption and low waste gas emission (Ismail et al., 2013). Because of these prominent characteristics, alkali-activated was considered as one of the potential candidates to solve the conflict between social development and environmental pollution from binder (Hussein et al., 2017). However, little work has been

reported about alkali activated repair materials. Repeated studies hinted that GBFS based activators are useful for improving the mechanical properties of alkali-activated (Huseien et al., 2016c). The alkali activation of GBFS is C-S-H and C-A-S-H gels which are the major reaction products identical to those of OPC whereas the alkali activation of FA, CP and GP is N-A-S-H gel. The glassy nature of GBFS phase allows it for easy activation of alkali than FA, CP and GP. In recent years, the term of alkali-activated was used for all mortars activated with materials containing calcium oxide such as GBFS to replace the geopolymer term (Bernal and Provis, 2014). The effect of binder to fine aggregate content on fresh and hardened properties of alkali-activated mortars cured at ambient temperature was evaluated in this study.

2. Methodology

2.1 Materials

Multi-blend binders were used to prepare mixtures. They included granulated blast furnace slag (GBFS), low calcium fly ash (FA), ceramic powder (CP) and glass powder (GP). Table 1 shows the chemical composition of materials by using XRF test. Their XRD and SEM are shown in Figures 1 and 2. FA comprised of mainly amorphous phase as exhibited by the broad hump around 18–62° with crystalline phases of mullite ($Al_6Si_2O_{13}$), quartz (Si), (Mg_2Si), ($CaSiO_2$) and (Al_4Ca). CP consisted largely of amorphous phase as verified by the presence of a hunch around 26–51° with some crystalline phases of quartz (Si), ($Al_{13}Fe_4$) and (Mg_2Si). GBFS and GP mainly composed of amorphous phase as displayed by a halo around 29–40° with a smaller amount of magnetite. Sand passing 100% of 2.36 mm sieve was used as fine aggregate for the tests conducted. Locally available river sand having a specific gravity of 2.74 was used as fine aggregate for alkali-activated mortar mixes. The most common alkaline liquid used in depolymerisation is a combination of sodium hydroxide or potassium hydroxide and sodium silicate or potassium silicate. In this study, sodium hydroxide prepare before 24 h with 6 M then mixed with sodium silicate and used as alkali activator solution.

Table 1: Waste materials chemical compositions

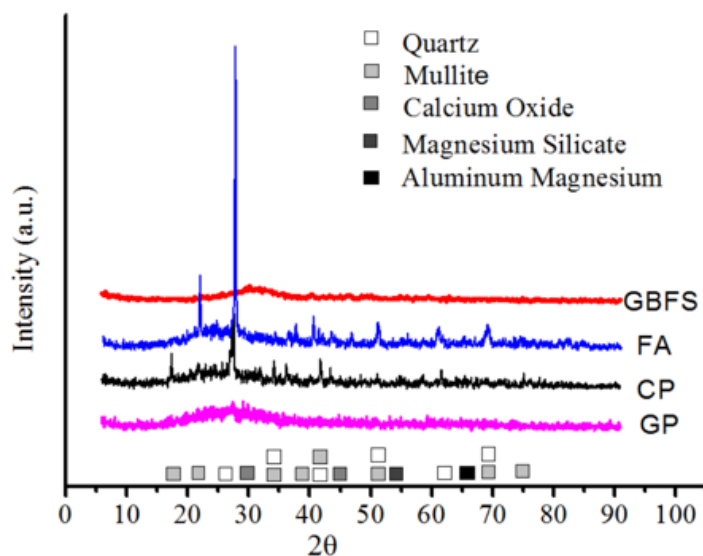| Materials	SiO2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3	LOI
OPC	20.80	4.70	3.40	65.30	1.50	0.40	0.12	2.70	0.90
GBFS	30.80	10.9	0.64	51.80	4.57	0.36	0.45	0.06	0.22
FA	57.20	28.80	3.67	5.16	1.48	0.94	0.08	0.10	0.12
CP	72.80	12.20	0.56	0.01	1.00	-	13.5	-	-
GP	69.14	13.86	0.24	3.16	0.68	0.01	0.01	4.08	-

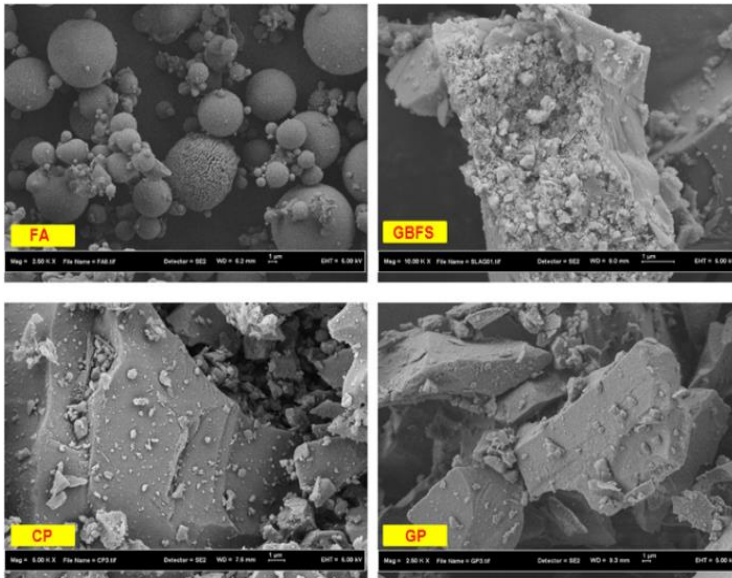*Figure 1: X-Ray Diffraction (XRD) of FA, GBFS, CP and GP waste materials*

Figure 2: Scanning Electron Microscopy (SEM)

2.2 Mix proportion and experimental program

Five alkali activated mortar mixtures were prepared with a different binder to fine aggregate (B:A) ratios, 0.30, 1.0, 1.5, 2.0 and 2.5. Sodium hydroxide molarity was kept constant for all mixtures, sodium silicate to sodium hydroxide (NS:NH) and solution to binder (S:B) ratios also kept constant for all mixtures in this study as shown in (Table 2). Mixing was performed in accordance with ASTM C109. 50 mm cube specimens were cast in steel moulds in this study. The Binder was mixed with fine aggregate till it became homogenous followed by solution addition to different factors and mixed for 3 min. The mortar was placed in moulds with two layers. Each layer was vibrated by using vibration table for 15 s. Moulds were left in the laboratory atmosphere for 24 h before de-moulding. They were then taken out and left at ambient temperature till test date 1, 3, 7 and 28 d.

Table 2: Alkali-activated mortars mix design

Binder						Factors		
GBFS	FA	CP	GP	M		S:B	NS:NH	B:A
55	15	15	15	6		0.25	3	0.30-2.5

3. Results and discussion

3.1 Workability

The workability of fresh alkali activated mortar mixtures were tested by flow test. The flow of fresh alkali activated mortars was measured in accordance with ASTM C1437-07. The flow test was conducted immediately after mixing. The binder content effect on the workability of alkali-activated mortars was investigated. The results presented the diameter flow of mortar decreased with more binder added to the mixture. The results of flow test recorded 17.75, 24.25, 21.5, 19 and 15 cm with 0, 30, 1.0, 1.5, 2.0 and 2.5 binders to aggregate ratio respectively. The mortar was prepared with 1.0 (B:A) display the optimum ratio. It becomes clear that an increase in binder content decreases the workability of alkali-activated due to the high water adsorption of the binder with a porous structure and high specific area compared to fine aggregate.

3.2 Setting Time

Setting time of alkali-activated mortars was tested by ASTM C191-08. The test was conducted at a temperature of 27°C. The mortar was prepared by mixing the binders and the alkaline solutions manual in a bowl and tested for setting time using Vicat apparatus. The setting time tests were carried out at a controlled temperature of 27°C. In such a situation, alkali-activated mortars low binder content takes a significantly longer time to set due to the slow rate of chemical reaction at low ambient temperature. In this study, alkali-activated mortar prepared with 0.30 (B:A) was used as a control sample. The results showed as the content of binder was increased from 0.30 to 1.0, 1.5, 2.0 and 2.5 in the mixture the setting time of mortar was a trend to decrease from 40 to 34, 19,

18 and 10 s respectively. The difference between initial and final setting time also decreased with increase binder content in the mixture. It also supports the fact that the higher the silicate content in the mortar, the slower the rate of setting. The results established that slag as part of the binary blended binder is effective to decelerate setting time of the mortars.

3.3 Compressive strength

The compressive strength test was performed by taking three cubes from each set of binder to aggregate 0.30, 1.0, 1.5, 2.0 and 2.5 respectively after 1, 3, 7 and 28 d. Figure 3 presents the compressive strength values at different periods. The results showed that compressive strength with high (2.5) and low (0.30) binder content display the low strength 37.6 and 32.4 MPa respectively compared to others alkali activated samples were prepared with 1.0, 1.5 and 2.0 of (B:A). The mortar was prepared with 1.5 (B:A) shown the high early strength 34.8 MPa after 24 h; the results also showed the mortar prepared with 1.0 (B:A) display the highest compressive strength after 28 d. It has known the low ratio of (B:A) affect bond strength between the fine aggregate particles and show low strength. The produce of C-S-H and C-A-S-H gels was reduced with increasing content of binder to 2.5 (B:A), with increase binder content the specific surface area was increased and led to increasing the alkali-activated solution absorption which effects directly on the dissolution of silicate and aluminium and shows low strength.
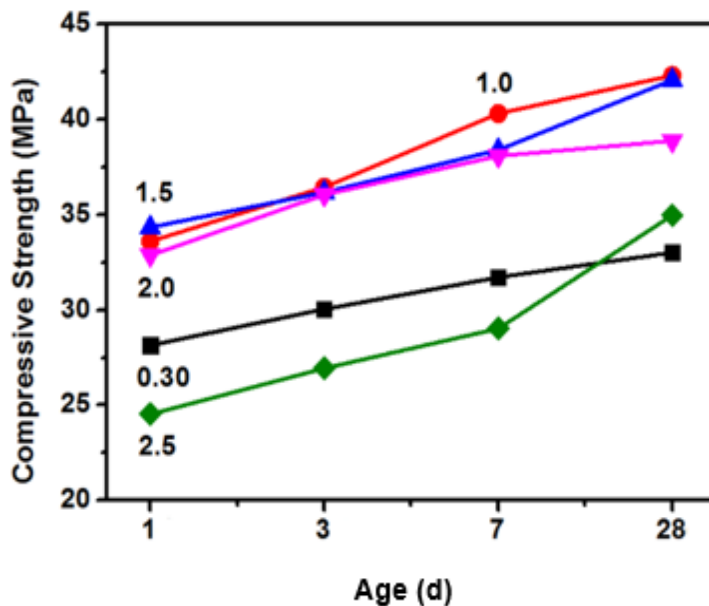

Figure 3: Effect of B:A on compressive strength of alkali activated mortar

3.4 Bending stress

The bending stresses of OPC notched beam filled with alkali activated mortars shown in Figure 4. The bending stress of OPC notched beam without filled materials (base line) was 0.67 MPa, while those with filled materials were increased as expected. For the mortars prepared with 1:1 binder to aggregate ratio, samples cured at ambient temperature and tested after 7 d were recorded 6.42 MPa bending stresses, the average improvement of 800% from the baseline. Mortar prepared with increased binder content to 1.5, 2.0 and 2.5 show lower bending stress than 1.0 binder to aggregate ratio, the bending stresses were 6.12, 5.78 and 4.98 MPa respectively as shows in Figure 5. The loss in the bending stress was increased with the increase in binder content replaced fine aggregate. Generally, all the beams notched with alkali activated mortars presented excellent bending stress compared to base line and OPC control sample. The results show the bending stress values are related to compressive strength results.
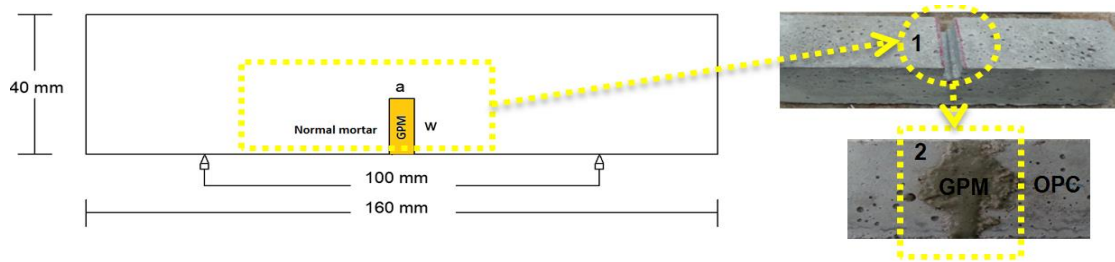
Figure 4: Test set up of bending stress of OPC notched beam with filled GPM specimens, At: W= 0.40 depth of prism, a=0.40 w
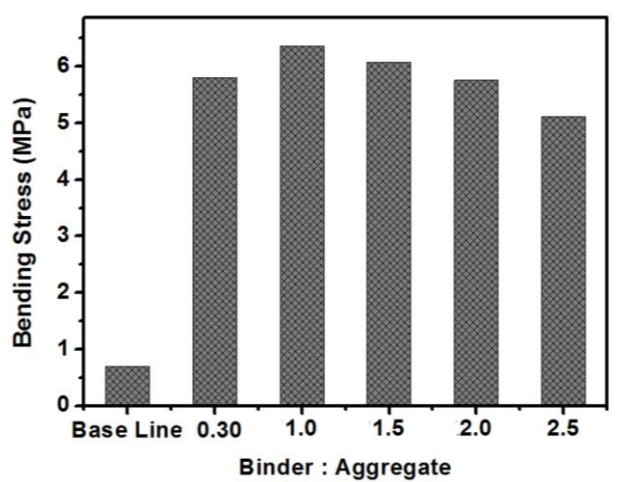

Figure 5: bending stress of OPC notched beam with filled Geopolymer mortar specimens with different binder to aggregate ratio

3.5 Water absorption

Figure 6 displays the effect binder to aggregate (B:A) ratio on water absorption of alkali activated mortar. Five mixtures were prepared with different ratios. Sodium hydroxide concentration, S:B and NS:NH ratios were fixed at 6 M, 0.25 and 3.0 respectively. The results indicated that an increase in binder ratio contributed to increase water absorption of samples. In fact the increase content of binder in the mixture led to reduction in the chemical reaction and low produce of C-S-H and C-A-S-H gels, which have influenced on microstructure of alkali-activated samples and increased pore as the binder increase.
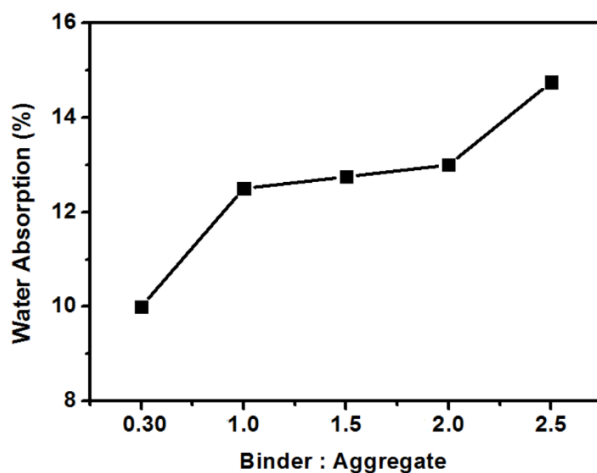

Figure 6: Effect of B:A on water absorption of alkali-activated mortar

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4. Conclusions

The current study evaluated the effect of binder to fine aggregate in workability, setting time (initial and final), compressive strength, water absorption and bending stress properties of alkali activated mortars. The results shown the alkali activated mortar is environmental friendly product and has the potential to replace OPC mortar in many applications in construction field, including repair materials. The workability of alkali activated mortars was found to reduce with increasing amount of binder to fine aggregate content. The highest workability of alkali activated mortar was observed for the mixture with 1:1 of binder to aggregate. Also the results showed that the increasing binder content led to reduce the workability, setting time and density of alkali activated mortars. For compressive strength properties, the optimum ratio of binder to aggregate (B:A) was 1:1, increasing binder content more than this ratio effected to reduce the strength of mortars. Similar trend of results was observed with bending stress values, and results trend to drop with increasing content of binder. Durability of alkali activated mortars influenced by binder content and the results show the water absorption increased with increase binder content and effect negatively on alkali activated mortar durability.

Reference

Bernal S. A., Provis J. L., 2014, Durability of Alkali-Activated Materials: Progress and Perspectives, Journal of the American Ceramic Society, 97 (4), 997-1008.

Davidovits J., 2008, Geopolymer Chemistry and Applications, Geopolymer Institute, Saint-Quentin, France:

Huseien G.F., Al-Fasih M.Y., Hamzah H.K., 2015a, Performance of self-compacting concrete with different sizes of recycled ceramic aggregates, International Journal of Innovative Research and Creative Technology, 1 (3), 264-269.

Huseien G.F., Mirza J., Ariffin N.F., Hussin M.W., 2015b, Synthesis and characterization of self-healing mortar with modified strength, Jurnal Teknologi, 76 (1), 195-200.

Huseien G.F., Mirza J., Ismail M., Ghoshal S., Ariffin M.A.M, 2016a, Effect of metakaolin replaced granulated blast furnace slag on fresh and early strength properties of geopolymer mortar, Ain Shams Engineering Journal, 8 (4), 512-520.

Huseien G.F., Mirza J., Ismail M., Hussin M.W., 2016b, Influence of different curing temperatures and alkali activators on properties of GBFS geopolymer mortars containing fly ash and palm-oil fuel ash, Construction and Building Materials, 125, 1229-1240.

Huseien G.F., Mirza J., Ismail M., Hussin M.W., Arrifin M., Hussein A., 2016c, The Effect of sodium hydroxide molarity and other parameters on water absorption of geopolymer mortars, Indian Journal of Science and Technology, 9 (48), 1-7.

Huseien G.F., Mirza J., Ismail M., Ghoshal S., Hussein A.A., 2017, Geopolymer mortars as sustainable repair material: A comprehensive review, Renewable and Sustainable Energy Reviews, 80, 54-74.

Hussein A.A., Jaya R.P., Hassan N.A., Yaacob H., Huseien G.F., Ibrahim M.H.W., 2017, Performance of nanoceramic powder on the chemical and physical properties of bitumen, Construction and Building Materials, 156, 496-505.

Hussin M., Bhutta M., Azreen M., Ramadhansyah P., Mirza J., 2015, Performance of blended ash geopolymer concrete at elevated temperatures, Materials and Structures, 48 (3), 709-720.

Ismail M., Yusuf T.O., Noruzman A.H., Hassan I., 2013, Early strength characteristics of palm oil fuel ash and metakaolin blended geopolymer mortar, Advanced Materials Research, 54, 1045-1048.

Ogunbode E.B., Egba E.I., Olaiju O.A., Elnafaty A.S., Kawuwa S.A., 2017, Microstructure and mechanical properties of green concrete composites containing coir fibre, Chemical Engineering Transactions, 61, 1879-1884.

Palomo Á., Fernández-Jiménez A., López-Hombrados C., Lleyda J.L., 2011, Railway sleepers made of alkali activated fly ash concrete, Revista Ingeniería de Construcción, 22 (2), 75-80.

Yusuf T.O., Ismail M., Usman J., Noruzman A.H., 2014, Impact of blending on strength distribution of ambient cured metakaolin and palm oil fuel ash based geopolymer mortar, Advances in Civil Engineering, 14 (1), 1-8.