CHEMICAL ENGINEERING TRANSACTIONS
VOL. 63, 2018

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Jeng Shiun Lim, Wai Shin Ho, Jiří J. Klemeš

ISBN 978-88-95608-61-7; **ISSN** 2283-9216

DOI: 10.3303/CET1863113

Performance of Sustainable Alkali Activated Mortars Containing Solid Waste Ceramic Powder

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As the cement industry contributed to increasing the global carbon dioxide emissions, researchers looked for other sustainable alternatives. Among them, one of the alternatives is alkali activated mortar containing no cement at all. Alkali-activated mortar is manufactured using industrial and agricultural wastes like ceramics, palm-oil fuel ash (POFA), granulated blast furnace slag (GBFS), fly ash (FA), metakaolin (MK), etc. Compared with Ordinary Portland Cement (OPC), alkali-activated is considered as a highly environmental product based mortar. The alkali activated mortar feasibility production using ceramic waste binder was evaluated in this study. The effect of replacing GBFS binder by ceramic powder (by varying percentage) upon its fresh-state properties, like workability, setting time, density and hardened properties such as compressive, tensile and flexural strengths of alkali-activated mortar was concurrently examined. The impact of curing regime on strength development of ceramic-GBFS based alkali activated was evaluated as well. Results revealed that with increased ceramic to GBFS content, the workability and setting time of mortar improved whereas the density decreased. On the other hand, when ceramic was replaced by up to 50 % of GBFS, it showed higher strengths as compared to OPC mortar. It is concluded that alkali activated mortar incorporating 100 percent wastes could be used in the construction industry with the almost negligible amount of environmental problems.

1. Introduction

To manufacture 1 t of Ordinary Portland Cement (OPC), about 1 t of carbon dioxide (CO_2) is emitted to the atmosphere (Ogunbode et al., 2017). The world produces more than 3.5 billion t of cement. This means about the same quantity of CO2 has emitted alone from cement industry (Huseien et al., 2015). Alkali-activated technology is one of the latest technologies attempting to decrease the usage of OPC. Alkali-activated is emerging new cement-less binder to make concrete as an alternative to OPC (Huseien et al., 2017). It has environmentally sustainable characteristics (Ariffin et al., 2013). Using industrial waste products like GBFS, POFA, MK and FA to produce alkali activated mortar binder show excellent results to be alternative to (OPC) mortar (Davidovits, 1999). The amorphous to semi-crystalline three-dimensional silico-aluminate structures of the Poly(sialate) type (-Si-O-Al-O-) or of the Poly(sialate-siloxo) type (-Si-O-Al-O-Si-O-) were named "geopolymers" by Davidovits (Mehta, 1999). Al-Si materials which are used as source materials undergo dissolutions, gel formation, setting and hardening stages to form geopolymers (Xu and Van Deventer, 2000).
Many factors influence the final fresh and hardened properties of alkali-activated mortars such as sodium hydroxide concentration, sodium silicate content, curing regime, silicate, aluminate and calcium ratio and others (Kabir et al., 2015). The durability of alkali-activated has improved using FA as researchers reported (Bhutta et al., 2013). Waste materials content high calcium oxide such as GBFS can be used to produce alkali activated cured at ambient temperature (Phoo-ngernkham et al., 2015). Kumar et al. (2010) reported the alkali

Please cite this article as: Ghasan Fahim Huseien, Mohammad Ismail, Mahmood Tahir, Jahangir Mirza, Ahmed Hussein, Nur Hafiza Khalid, Noor Nabilah Sarbini, 2018, Performance of sustainable alkali activated mortars containing solid waste ceramic powder, Chemical Engineering Transactions, 63, 673-678 DOI:10.3303/CET1863113

activation of GBFS results in precipitation of Calcium-Silicate-Hydrate (C-S-H) and calcium-alumino–silicate–hydrate (C-A-S-H) gels for alkali-activated concrete and mortar cured at 27 °C.
A substantial number of researchers have developed a variety of raw materials such as metakaolin, fly ash, and POFA incorporated with GBFS to synthesise alkali activated matrixes with excellent performance characteristics (Li et al., 2010). All these materials could supply the polymerisation reaction with sufficient silica and aluminium (Huseien et al., 2016). On the other hand, waste ceramic is a kind of typical silicon rich material (Ariffin et al., 2015); using it as source material to manufacture alkali activated could be an efficient and environment-friendly use. However, no dedicated study has been reported about the systematic characterisation of the material and ambient-temperature properties of alkali-activated mortar using waste ceramic as source material.
The aim of this experiment to evaluate fresh and hardened properties of alkali-activated mortar using a combination of waste ceramic powder (WC) and GBFS. Tests conducted on the alkali-activated mortar were workability, setting time, density, compressive, tensile and flexural strengths. Results obtained were expected to enrich the knowledge of alkali-activated and provide a promising alternative to reutilise waste ceramic economically and sustainably.

2. Methodology

2.1 Materials

Ceramic waste materials were collected from industrial construction wastes in Johor Bahru. Ceramic was crushed and sieved with 600 μm then grinding in Los Angeles machine for 6 h to get a ceramic powder with particle size less than 20 μm (From using particle size analysis test PSA). Commercially available GBFS was used as an additive. The chemical compositions of WC and GBFS showed in Table 1.
Sodium hydroxide was prepared with 6 M, 24 h ahead of time and then mixed with sodium silicate to be used as alkali activator solution to activate aluminium-silicate. River sand sieved with 2.36 mm was used as fine aggregate.

Table 1. WC and GBFS chemical compositions (XRF) by weight (%)

Materials	SiO2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3	LOI
GBFS	30.80	10.9	0.64	51.80	4.57	0.36	0.45	-	0.22
WC	72.80	12.20	0.56	0.01	1.00	-	13.5	-	-

2.2 Mix proportion and experimental program

Table 2 displays of various WC replaced GBFS in alkali-activated mixtures. The ratio of binder to fine aggregate (B:A), solution to binder (S:B) and sodium silicate (NS) to sodium hydroxide (NH) fixed with 0.5, 0.35 and 1.5 respectively. The Si:Al and Ca:Si ratio of each mix is shown in Table 2.
A total of five alkali activated mixes were considered along with standard OPC mortar. WC and GBFS based alkali activated mortar mixes were manufactured separately. Additionally mixes were prepared by replacing WC with GBFS in 0 %, 25 %, 50 %, 75 % and 100 % replacement levels (by weight). OPC control sample (Grade 25) based mortar mix was designed as per ASTM C109. WC-GBFS based alkali activated was mixed first for 2 min then added to fine aggregate and mixed for another 3 min. Waste ceramic (WC) and GBFS were activated by alkali activator sodium hydroxide and sodium silicate solutions to synthesize alkali activated-type material in this study. Moulds 50×50×50 mm (cube), 75×150 mm (cylinder) and 40×40×160 mm (prism) were used to prepare the specimens of each alkali activated mortar mix. The alkali activated mortar specimens were cured at ambient (27 °C) and elevated temperature (60 °C and 90 °C) for 24 h. The compressive, tensile and flexural strength were then evaluated at ages of 1, 7 and 28 d.

Table 2: Alkali-activated mortars mix design by weight (%).

Mix	Binder		Alkali solution				Chemical composition				
	WC	GBFS	B:A	S:B	NS:NH	Molarity	SiO_2	Al2O3	CaO	Si:Al	Ca:Si
1	0	100	0.5	0.35	1.5	6	30.0	10.90	51.80	2.83	1.68
2	25	75	0.5	0.35	1.5	6	41.30	11.22	38.85	3.68	0.94
3	50	50	0.5	0.35	1.5	6	51.80	11.55	25.90	4.48	0.50
4	75	25	0.5	0.35	1.5	6	62.30	11.87	12.95	5.25	0.21
5	100	0	0.5	0.35	1.5	6	72.80	12.20	0	5.97	0

3. Results and discussion

Five mixtures of alkali-activated mortar were designed to study the effect of ceramic replaced GBFS on the workability, setting time and strengths of mortars. The results were compared for the variation of WC: GBFS ratio at a time while other parameters remained constant.

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. A flow test was conducted immediately after mixing. The effect of ceramic on the workability of alkali-activated mortars was investigated. Results showed that the workability of mortar increased with more ceramic added to GBFS ratio. The results of flow test recorded 13, 15.25, 17, 20 and 24 cm with 0, 25, 50, 75 and 100 % WC: GBFS ratio respectively. Figure 1a shows the effect ceramic percentage has on the workability of alkali-activated mortars. The increased content of ceramic led to increasing content of silicate and reduced the content of calcium and affect positively on enhance the workability of mortar.

3.2 Setting Time

Setting time of alkali-activated mortar was tested in accordance with ASTM C191-08. The mortar was prepared by mixing the binders and the alkaline solutions manually in a bowl and tested for setting time using Vicat apparatus. Figure 1b depicts the influence of ceramic content on setting time. The setting time tests were carried out at a controlled temperature of 27 °C. In such a situation, alkali-activated mortar containing ceramic only as the binder takes significantly longer time to set due to the slow rate of chemical reaction at low ambient temperature. In this study, the alkali-activated mortar mixture without WC depended as control specimen, which was designed with GBFS only as the binder, showed speedy setting time. When ceramic was incorporated into the mixture, alkali-activated mortars setting time improved significantly. Both initial and final setting time increased with the increase of ceramic content. The mixture (2) containing 25 % ceramic in the binder achieved an initial setting time of 20 min, which increased to 24 and 64 min with 50 % inclusion and 75 % ceramic in the mixture (3) and (4) respectively. The rate of setting increased significantly as indicated by the substantial difference in the initial setting time. The difference between initial and final setting time also increased with addition of ceramic content in the mortar. It also supports the fact that the higher the silicate content in the mortar, the slower the rate of setting. The results established that GBFS as part of the binary blended binder is effective to decelerate setting time of alkali-activated mortar in ambient condition.

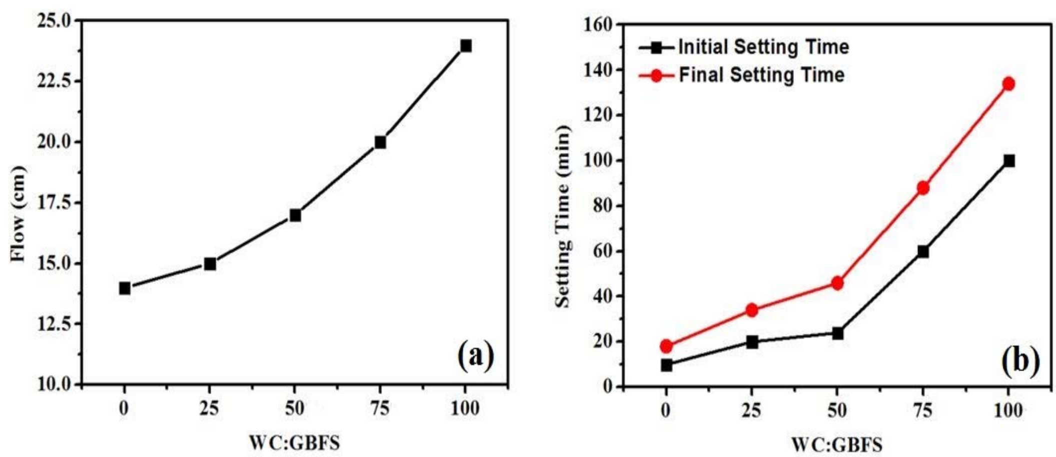

Figure 1: Effect of different ratios of WC: GBFS on (a) flow (b) setting time of alkali-activated mortars

3.3 Density

Waste ceramic powder replaced GBFS based alkali activated mortar effect on density was also investigated. Figure 2 shows the effect of increased ceramic ratio on binder alkali activated mortar, curing temperature effect was also studied at the same time. Samples were cured at three different temperatures 27 °C, 60 °C and 90 °C. The results indicated the density of alkali-activated mortar reduced with increased ceramic content as the specific gravity of waste ceramic powder lower than GBFS. The results of curing regime showed that alkali activated mortar cured at elevated temperature were lightweight than samples cured at ambient temperature.

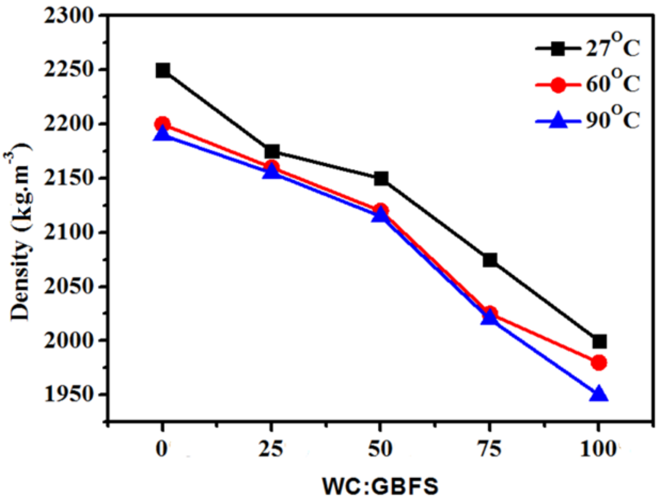

Figure 2: Effect of ceramic binder percentage on the density of alkali-activated.

3.4 Compressive strength

Compressive strength test was conducted at the age of 1, 7 and 28 d. Cube specimens of mortar were tested at a loading rate of 2.5 kN/s. Results of compressive strength tests for the mortar specimens are given in Figure 3. It is possible to conclude that compressive strength of alkali activated mortar decreases when ceramic waste content in the composition is increased. The final compressive strength of alkali activated mortar specimens with 75 % and 100 % ceramic waste was 18.6 and 4.6 MPa. Increased ceramic content created a weak contact zone between the composition binders of mortar. The results of WC replaced GBFS with 75 % and 100 % showed compressive strength lower than OPC (Figure 3a). Ceramic powder (WC) replaced GBFS at 25 % and 50 % showed higher compressive strength compared with OPC. Ceramic replaced GBFS with 25 % showed higher early strength than at 50 % after 24 h curing at ambient temperature 18.5 and 16.2 MPa respectively. After 28 d curing at ambient temperature specimen with 25 % addition still showed higher strength than replaced with 50 %, 54.4 and 50.4 MPa respectively. Ceramic mortar cured at elevated temperature showed lower strength than samples cured at an ambient temperature as a display in Figure 3b. Ceramic replaced GBFS with 25 % depicted high early and late strength compared with 50 % WC replaced GBFS. Results of compressive strength for samples cured at 60 °C displayed higher than samples cured at 90 °C.

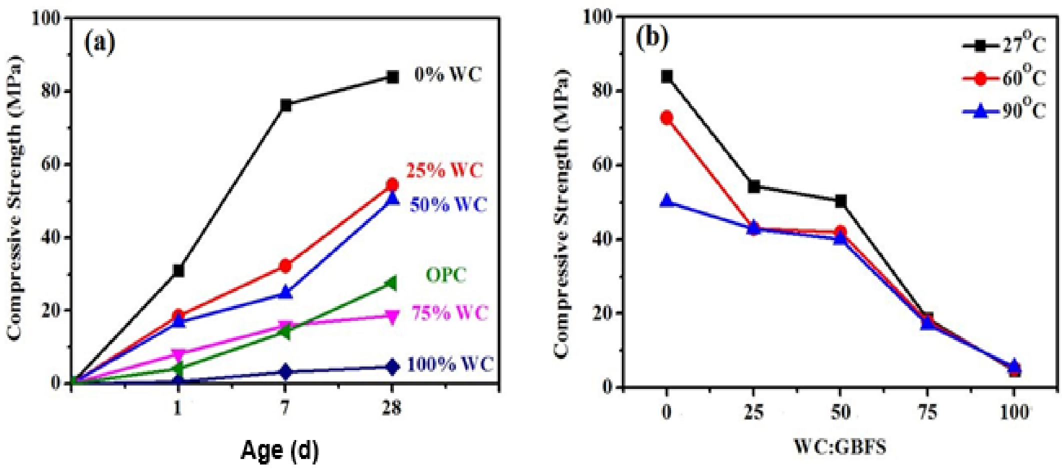

Figure 3: Development of compressive strength with various WC:GBFS (a) with age (b) with curing regime

3.5 Splitting tensile strength

The cylindrical test is required to determine the indirect tensile strength of alkali-activated mortar. The cylindrical test is based on ASTMD 3039. The splitting tensile strengths of all specimens are provided in Figure 4. At the age of 1, 3, 7 and 28 d the tensile strength was investigated for ceramic mixes replaced GBFS at 0, 25, 50 and 75 %. All samples were cured at ambient temperature. The tensile strength of alkali-activated mortar samples was decreased with increased ceramic content. The results of all alkali activated mortar mixtures tested showed higher strength compare to control sample (OPC) tested after 28 d age. The minimum tensile strength was recorded with ceramic replaced GBFS with 75 %, 3.2 MPa after 28 d. This strength was still higher than OPC test after 28 d with 2.4 MPa.

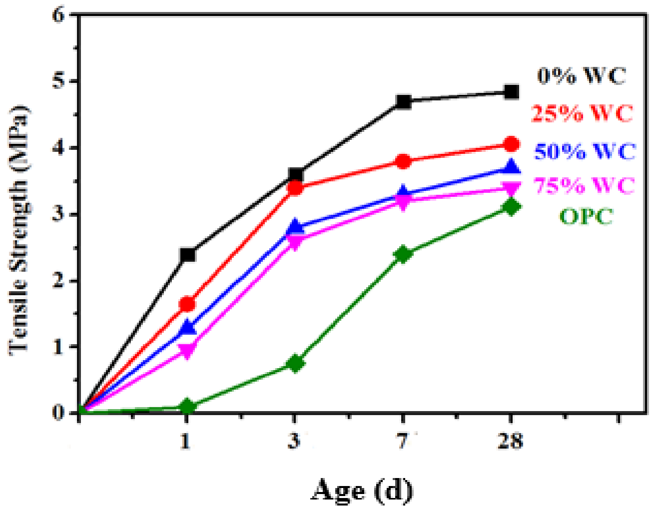

Figure 4: Tensile strength of mortar with various WC: GBFS

3.6 Flexural strength

The flexural test was conducted on prism size of 40 x 40 x 160 mm. The flexural test was conducted based on ASTM C348. Three-point bending test was conducted until failure occurred. The samples cured at ambient temperature and tested after 1, 3, 7 and 28 d, were compared with OPC control samples findings. The results of three mixtures of alkali-activated mortar with 0 %, 25 % and 50 % of WC: GBFS were investigated. Most of the alkali-activated mortar flexural strengths showed higher strength than OPC test after 28 d. The flexural strength at 28 d age of alkali-activated mortar achieved 5.34, 6.1, 6.8 and 7.9 MPa with 75, 50, 25 and 0 % WC replaced GBFS respectively, compared with OPC flexural strength achieved after 28 d as presented in Figure 4.

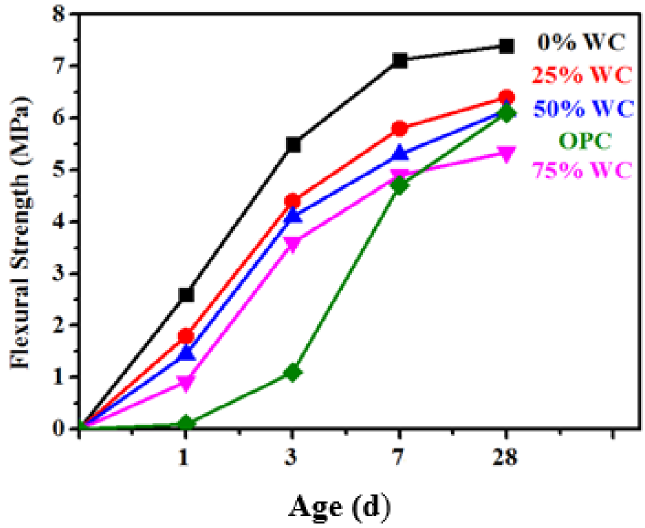

Figure 5: Flexural strength of mortar with various WC:GBFS

4. Conclusions

Nowadays, the reduction of pollution and recycle the wastes are the main concern of world. Alkali activated mortars introduced as new sustainable construction materials to alternative to ordinary Portland cement. This work has presented an experimental study in effect of curing temperatures on strength performance of alkali-activated mortar containing ceramic and slag as a binder. The results presented the replacing ceramic with GBFS led to enhance the workability of alkali activated mortars; it also decelerated alkali activated mortar setting time mortars at ambient temperatures. Waste ceramic powder replaced GBFS mortars showed that density of alkali activated mortar decreased when ceramic ratio was increased. Also the results showed the waste ceramic powder replaced GBFS mortars at 25% and 50% demonstrated the ability to use ceramic in alkali activated mortar and concrete industry. Alkali activated mortar mixed with WC and GBFS binder showed higher compressive strength at ambient temperature curing compared with mortar cured at elevated temperature. Most samples of alkali activated mortar showed higher tensile and flexural strength than OPC after 28 d.

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