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Original article

Fresh properties and compressive strength of high calcium alkali activated fly ash mortar

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ABSTRACT

This paper reports the fresh properties and compressive strength of high calcium alkali-activated fly ash (AAFA) mortar. Two different sources of class C fly ash, with different chemical compositions were used to prepare alkali-activated mortar mixtures. Four different sodium silicate to sodium hydroxide (SS/SH) ratios of 0.5, 1.0, 1.5, and 2.5 were used as alkaline activators with a constant sodium hydroxide concentration of 10 M. Two curing regimes were also applied, oven curing at 70 °C for 24 h, and ambient curing at 23 ± 2 °C. The rest time, i.e., the time between casting the mortar cubes and starting the oven curing was 2 h. The results revealed that the setting time, and workability of mortar decreased with increasing the alkali to fly ash ratio, and decreasing the water to fly ash ratio. The optimum sodium silicate to sodium hydroxide ratio was 1.0, which showed the highest compressive strength and setting time. An increase of sodium silicate to sodium hydroxide ratio to 2.5 led to a significant reduction in the setting time, and workability of mortar. The 7-day compressive strength of the mortar approached 20.80 MPa for ambient cured regime and 41.10 for oven cured regime.

1. Introduction

There is a current momentum around the world to increase concrete sustainability through using recycled materials in concrete manufacturing. For example, recycled tires were used to replace natural aggregates in concrete (Gheni et al., 2017; Youssf et al., 2016; Moustafa and ElGawady, 2016; 2015; Youssf et al., 2015). Furthermore, the current manufacture process of one ton Portland cement consumes about 100 kWh and released approximately 1.0 ton of CO^2 emissions into the atmosphere (Temuujin et al., 2014). Hence, there is an urgent need to partially or completely replace Portland cement as a binder with an alternative material that consumes less manufacturing energy and has less harmful effects on environment as well as display superior performance. One of the currently used alternatives to Portland cement is fly ash.

Alkali activated fly ash (AAFA) is another type of concrete where the Portland cement has been completely replaced with fly ash. When pozzolanic materials are activated with alkali material such as sodium hydroxide and/or sodium silicate, polymer chains are formed creating alkali activated cement. These materials provide behavior comparable/superior to ordinary Portland cement (OPC) concrete in terms of compressive (Rangan, 2005), splitting tensile (Komljenović, 2015), flexural (Nath and Sarker, 2017), bond between the concrete and rebar strength (Pattanapong et al., 2015), but lower modulus of elasticity (Komljenović, 2015; Nath and Sarker, 2017). Moreover, the durability properties of these materials showed higher corrosion resistance (Bastidas et al., 2008), fire resistance, low thermal conductivity, and chemical attack resistance (Davidovits and Davidovics, 2008) than OPC concrete. They also showed high freeze and thawing cycles resistance (Pacheco-Torgal et al., 2012). In addition, no sign of Alkali silica reaction associated with them (Pacheco-Torgal et al., 2012). The alkali activated materials had a reduced permeability to chloride penetration (Shi, 2004) compared with OPC concrete.

Fly ash is classified, per the ASTM C618-15 (Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete, 2015), as either Class F or Class C depending on the contents of the pozzolanic compounds (silica oxide, alumina oxide, and iron oxide). The former is produced by burning bituminous or anthracite coals (Palomo et al., 1999; Swanepoel and Strydom, 2002) while the later is produced from burning lignite or sub-bituminous coals (Guo et al., 2010a). Class F fly ash contain at least 70% pozzolanic compounds, while Class

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C fly ash contains at least 50% of the pozzolanic compounds. Another major difference between both types is the calcium content; fly ash Class C has higher calcium content than Class F. However, the ASTM C618-15 (Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete, 2015) does not consider the calcium content in fly ash classification. Other standard such as the CSA A3001 uses a different approach for classification of fly ash based on the calcium oxide content. The CSA A3001 classifies fly ash into three classes, namely, F for calcium oxide content not exceeding 8%, CI for calcium content between 8% to 20%, and CH or calcium content exceeding 20% of the fly ash.

High calcium content in a precursor causes the chemical reaction to produce calcium silicate hydrate (CSH), aluminium-modified calcium silicate hydrate (CASH), and sodium aluminosilicate hydrate (NASH) (Yip and van Deventer, 2003; Yip et al., 2005; Guo et al., 2010b; Chindaprasirt et al., 2012). The former two types of gels are similar to those produced during the hydration process of Portland cement while the latter type is geopolymeric gel. Formation of CSH and CASH increase the early age strength of ambient cured geopolymer concrete; however, the high level of calcium content decreases the setting time and workability (Temuujin et al., 2009; Rattanasak et al., 2011; Diaz et al., 2010; Lee and van Deventer, 2002a). The existence of a high level of calcium interferes with the geopolymerization process by reacting with the dissolved silicate and aluminate species originating from the precursor (Duxson et al., 2007). This hydration process leads to water shortage, which in turn causes an increase in the alkalinity of the mixture, leading to faster dissolution of the precursor and increasing the rate of geopolymerization at the price of rapid setting time and low workability.

This study investigated the effects of water to fly ash (W/FA) ratio, alkali activators to fly ash (Alk/FA) ratio, sodium silicate to sodium hydroxide (SS/SH) ratio, and two different curing regime on the fresh properties and early age strength of alkali activated mortar.

2. Experimental program

2.1. Material

2.1.1. Fly ash and fine aggregate

High calcium fly ashes from two different sources namely Labadie (LB) and Kansas City (KC) power plants located in the state of Missouri, U.S. were used in this study. The chemical compositions of both types of fly ashes, shown in Table 1 were determined using the X-ray Fluorescence analysis, following ASTM D4326-13 (Standard Test Method for Major and Minor Elements in Coal and Coke Ash By X-ray Fluorescence, 2013). Both types of fly ashes were classified as Class C with pozzolanic compounds of 59.05% and 66.30% for Labadie and Kansas City fly ashes, respectively.

Missouri river sand with specific gravity of 2.6 in saturated surface dry (SSD) condition was used for mortar mixtures. Fig. 1 illustrates the results of the sieve analysis of the used sand.

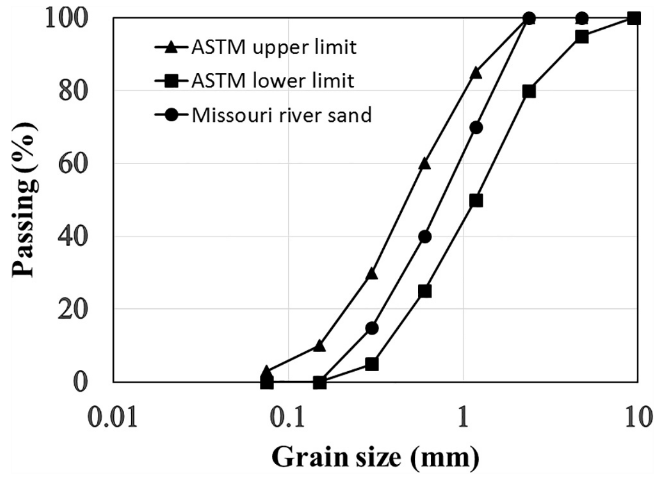

Fig. 1. Sieve analysis of Missouri river sand.

2.1.2. Alkali activators

The alkali activated solutions used during this study consisted of SS (Na_2SiO_3) and SH (NaOH). SS solution type D, produced by PQ Corporation, had amount of solid sodium silicate 44.1% by weight (SiO_2 = 14.7% and NaO_2 = 29.4%) and water content of 55.9% by weight. SH in solid pellets form, produced by Bulk Apothecary, was mixed with distilled water at room temperature of 23 ± 2 °C and left to cool down at least 24 h prior to the mortar-mixing day. The selected molarity of the SH is 10 M obtained by mixing 686 gm of water and 314 gm of SH solids.

2.2. Mix proportions

Thirteen mixtures were prepared to examine the effects of W/FA, Alk/FA, SS/SH, and curing regime on the setting time, workability, and early age compressive strength of AAFA mortar. The W/FA ranged from 0.350 to 0.450. The water content included both the water in the mixed alkali activators and the extra water added to each mixture. The Alk/FA ranged from 0.250 to 0.300. The SS/SH ranged from 0.5 to 2.5. Table 2 shows the details of the mixture ratios. The ratio between the sand and FA was fixed at 2.75.

2.3. Mixing and curing conditions

The mixing procedure of the mortar consists of the following four steps. 1) The fly ash and sand were mixed for 30 S. to homogenously spread the particles with low mixing speed of 136 rpm. 2) The water was added while mixing at the same mixing speed for one min. which helped in wetting all fly ash and sand particles and preventing the agglomeration of the mortar ingredients. 3) The sodium silicate and sodium hydroxide were mixed together before adding them to the mix with the same mixing speed for another one min. 4) The mixture continued for another four min. while the mixing speed was increased to 281 rpm which was found to increase the mortar slump flow and prevent flash setting where

Table 1
Chemical composition of fly ashes.

Composition	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	TiO_2	LOI[a]	MC[b]
LB (%)	37.56	17.47	7.02	25.33	7.93	3.28	0.00	1.42	0.60	0.09
KC (%)	42.27	17.30	6.73	22.54	6.54	3.04	0.17	1.41	0.19	0.03

[a] LOI: Loss on ignition.
[b] MC: Moisture content.

Table 2
AAFA mortar mixture proportion and details.

Mix No.	W/FA	Alk/FA	SS/SH	FA (kg/m^3)	Sand (kg/m^3)	SS (kg/m^3)	SH (kg/m^3)	Extra water (kg/m^3)
1	0.350	0.250	1.0	552	1518	69	69	108
2	0.375	0.250	1.0	545	1499	68	68	121
3	0.400	0.250	1.0	537	1477	67	67	132
4	0.400	0.300	1.0	536	1474	80	80	116
5	0.425	0.300	1.0	529	1455	79	79	127
6	0.450	0.300	1.0	522	1436	78	78	139
7	0.400	0.275	1.0	537	1477	74	74	124
8	0.400	0.250	0.5	538	1480	45	90	130
9	0.400	0.250	1.5	537	1477	81	54	134
10	0.400	0.250	2.5	537	1477	96	38	136
11	0.450	0.300	0.5	522	1436	52	104	136
12	0.450	0.300	1.5	522	1436	94	63	140
13	0.450	0.300	2.5	522	1436	112	45	142

the mixing time and speed had an effect on the leaching and dissolution of silica and alumina ions from the fly ash to the solution (Chindaprasirt et al., 2014). During the mixing process, after adding the water and the chemicals, the mixing was stopped to scrap the parts of the mortar that attached to the wall of the pan for 40 S. The mixing was done at the room temperature, i.e. 23 ± 2 °C.

The fresh AAFA mortar was casted into 50 × 50 × 50 mm. cube molds as per the ASTM C109-16a (Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens), 2016). After casting the molds, two different curing regimes were applied to the AAFA mortar. 1) Oven curing at 70 °C for 24 h. The molds have been encased in plastic oven bags to prevent moisture loss during the curing period inside the oven. 2) Ambient curing at 23 ± 2 °C. All the cubes were demolded after 24 h then left in the room temperature until the testing day.

2.4. Setting time, workability, and compressive strength tests

The initial and final setting times of the AAFA mortars were measured using the modified Vicat needle per the ASTM C807-13 (Standard Test Method for Time of Setting of Hydraulic Cement Mortar by Modified Vicat Needle, 2013). The initial setting time was measured from the mixing time of the FA with the SS and SH solutions until the penetration of 2 mm diameter needle was equal to 10 mm, while the final setting time was determined when there was no remarkable penetration. The workability (flow) of the mortar mixtures were tested per the ASTM C1437-15 (Standard Test Method for Flow of Hydraulic Cement Mortar, 2015). The workability was measured after placing two layers of mortar inside a standard cone then lifting the cone away from the mortar following immediately by dropping the table 25 times in 15 S. The reported workability is the mean of four diagonal measurements. The compressive strengths of the AAFA mortar mixtures were determined at the age of 7 days following the ASTM C109-16a. The compressive strengths presented in this paper are the mean of three cubes.

3. Results and discussion

3.1. Setting time and workability

In general, the setting time and workability values of LB fly ash are lower than KC fly ash as the calcium content of LB fly ash is higher than that of KC fly ash. The higher calcium content caused additional nucleation sites for precipitation of the fly ash dissolved species which accelerated the setting time and hardening process of the AAFA (Lee and van Deventer, 2002b; Pangdaeng et al., 2014). The results of the initial and final setting times and workability of AAFA mortars are shown in Figs. 2 through 6. The results showed that the setting times and workability depended on the W/FA, Alk/FA, and SS/SH. As shown in Figs. 2 and 3, for Alk/FA of 0.300 and 0.250, and SS/SH of 1.0, the setting time and the workability were increased with increasing the ratio of W/FA.

As shown in Fig. 4, for W/FA of 0.400 and SS/SH of 1.0, the setting time and workability decreased with increasing the Alk/FA. The increase in concentration of NaOH and Na_2SiO_3 in the mixture increased the viscosity of the mortar as well as leaching, and dissolution of fly ash species which reduce the setting time and workability of the mixture (Pattanapong et al., 2015; Rattanasak and Chindaprasirt, 2009; Provis and Bernal, 2014).

For given W/FA and Alk/FA the workability decreased with increasing the SS/SH ratio from 0.5 to 1.0, 1.5, and 2.5 as shown in Fig. 5(b) and 6(b). The sodium silicate solution has high viscosity which result in poor workability of AAFA mortar (Provis and Bernal, 2014; Vail). For W/FA of 0.400 and Alk/FA of 0.250, the longest setting time was at SS/SH of 1.0 as shown in Fig. 5(a). Increasing the SS content in the mixture increases the soluble silica (SiO_2) and Alkali (Na_2O) content in the mixture. Therefore, increasing the silica by adding more SS decreases the setting time as the geopolymerization process was enhanced by the more free silicate and it took less time to complete the dissolution reaction, resulting in decreasing the setting time (Chindaprasirt et al., 2012; Siyal et al., 2016). Increasing the amount of SH in the mixture, increases hydroxide ions (OH^-) concentration in the mortar which accelerates dissolution of fly ash and resulted in reduction in the setting time (Somna et al., 2011). For W/FA of 0.450 and Alk/FA of 0.300 as shown in Fig. 6(a), the setting time of mortars with SS/SH of 0.5, 1.0, 1.5 are almost the same because the W/FA and Alk/FA increased in the mortar at the same time, which made the effect of increasing the soluble silica or hydroxide ion concentration on the setting time was similar. However, with SS/SH of 2.5, the soluble silica significantly increased and the setting time was decreased for KC FA only. This may be because it has less calcium content and more pozzolanic compounds that made the FA more sensitive for changing the silica that was more significant for the geopolymerization process.

3.2. Compressive strength

The 7-day compressive strengths of the AAFA mortars synthesized with different W/FA, Alk/FA, and SS/SH are shown in Figs. 7 through 11. As shown in the figures, the oven-curing regime showed higher compressive strengths compared to those of the similar specimens cured at ambient temperature. because to obtain a higher AAFA mortar strength, an elevated curing temper-

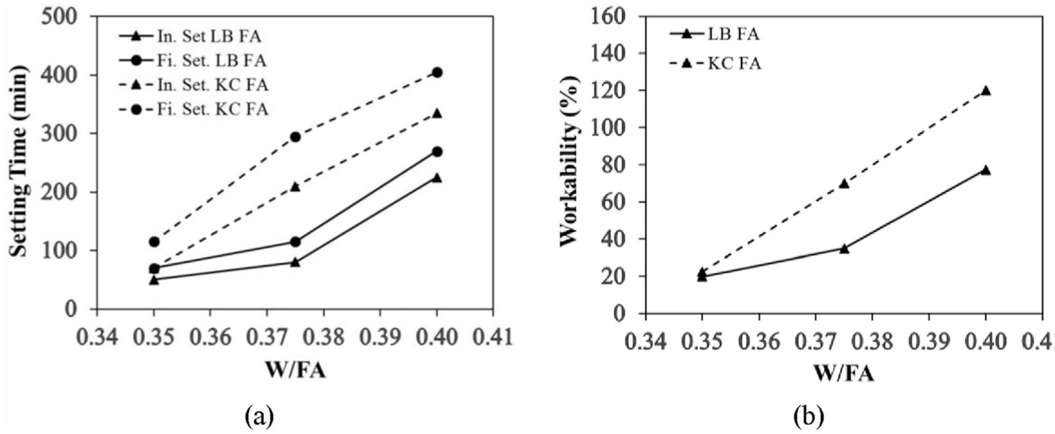

Fig. 2. Effect of W/FA on (a) setting times, and (b) workability for Alk/FA of 0.250 and SS/SH of 1.0.

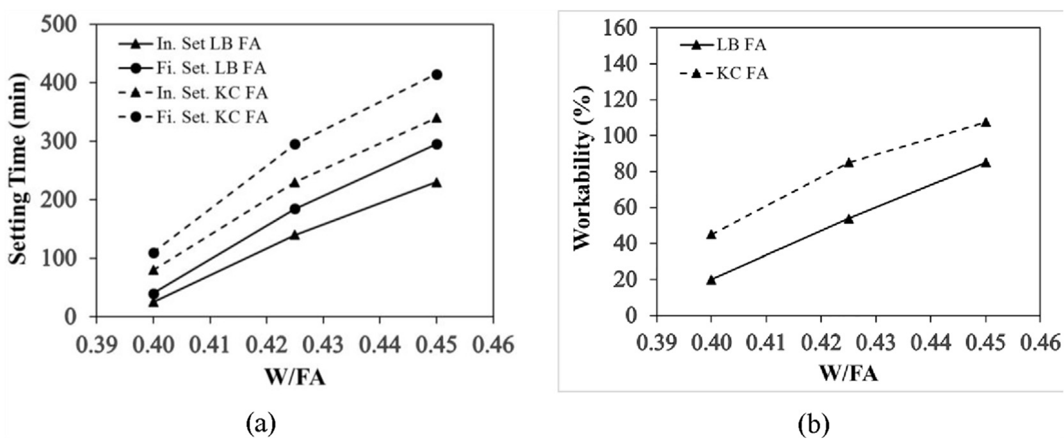

Fig. 3. Effect of W/FA on (a) setting times, and (b) workability for Alk/FA of 0.300 and SS/SH of 1.0.

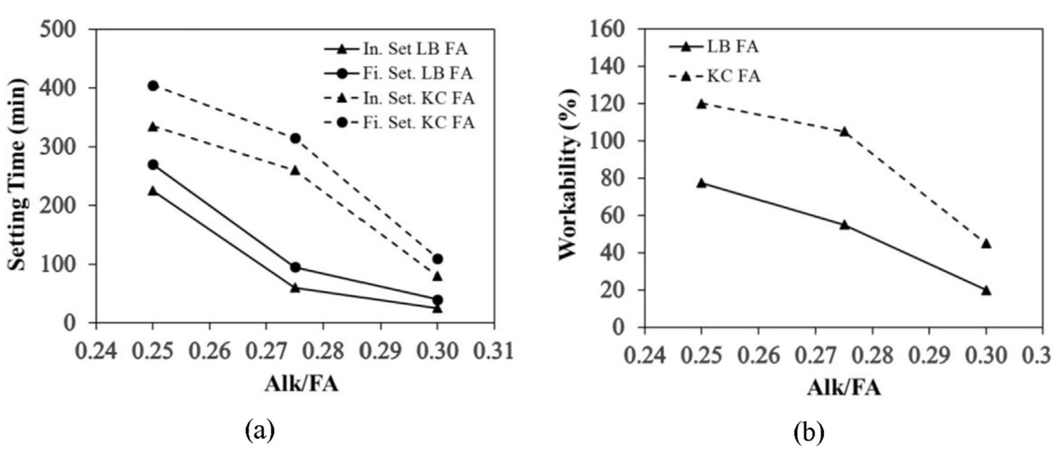

Fig. 4. Effect of Alk/FA on (a) setting times, and (b) workability for WA/FA of 0.400 and SS/SH of 1.0.

ature is required for the reaction to take place (Bakharev, 2005). Ambient cured specimens gained their strength without elevated heating mainly because presence of high calcium content which has the ability to harden at ambient temperature (Temuujin et al. 2009). The calcium reacts with the silica, in addition to the water and formed calcium silicate hydrate (CSH) (Guo et al., 2010a; Yip et al., 2005) which increased the mechanical strength at early ages compared with low calcium fly ash. The compressive strength of the ambient curing regime specimens were ranged from 6.75 to 20.69 MPa for LB fly ash-based mortar and from 8.03 to 20.80 MPa for KC fly ash-based mortar. While the compressive strength of the oven curing regime specimens ranged from 22.46 to 41.10 MPa for LB fly ash-based mortar and from 20.08 to 40.23 MPa for KC fly ash-based mortar.

The compressive strength of KC fly ash-based mortar decreased with increasing the mortar water content while keeping the Alk/FA and SS/SH constants as shown in Figs. 7 and 8. However, for LB fly ash-based mortar that has higher calcium content, the presence of

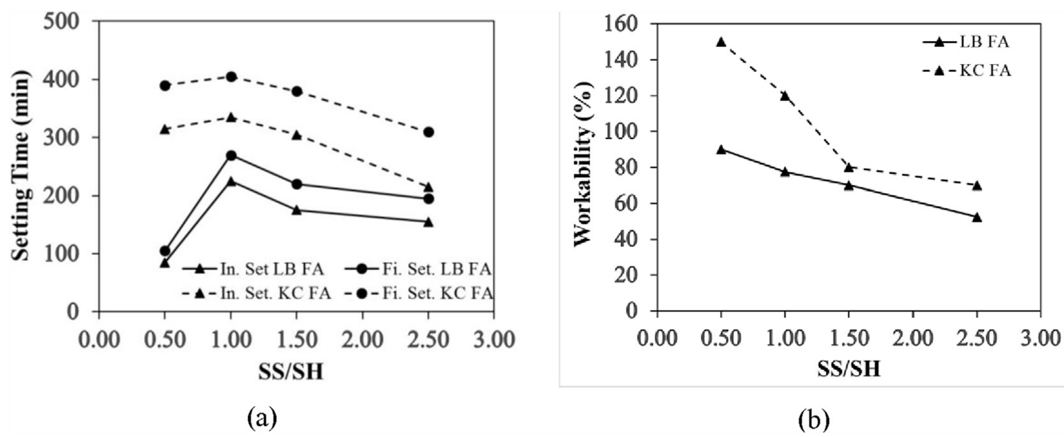

Fig. 5. Effect of SS/SH on (a) setting times, and (b) workability for WA/FA of 0.400 and Alk/FA of 0.250.

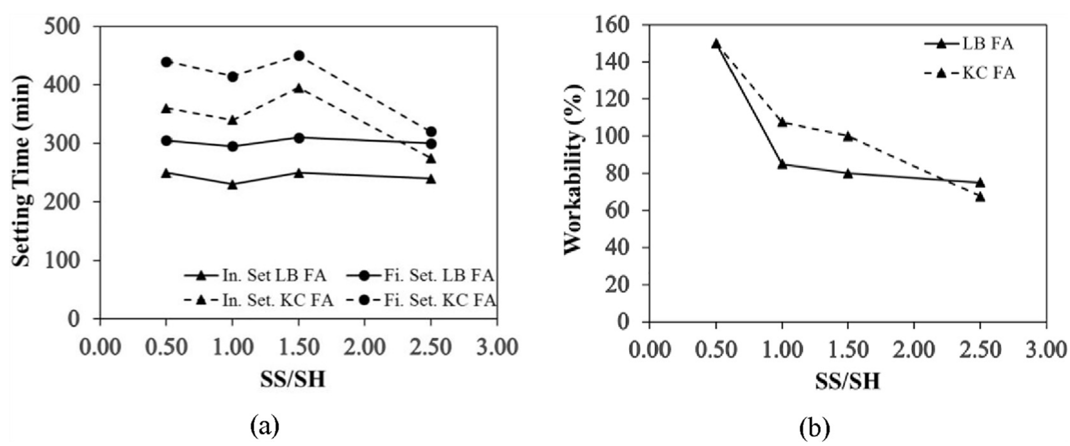

Fig. 6. Effect of SS/SH on (a) setting times, and (b) workability for WA/FA of 0.450 and Alk/FA of 0.300.

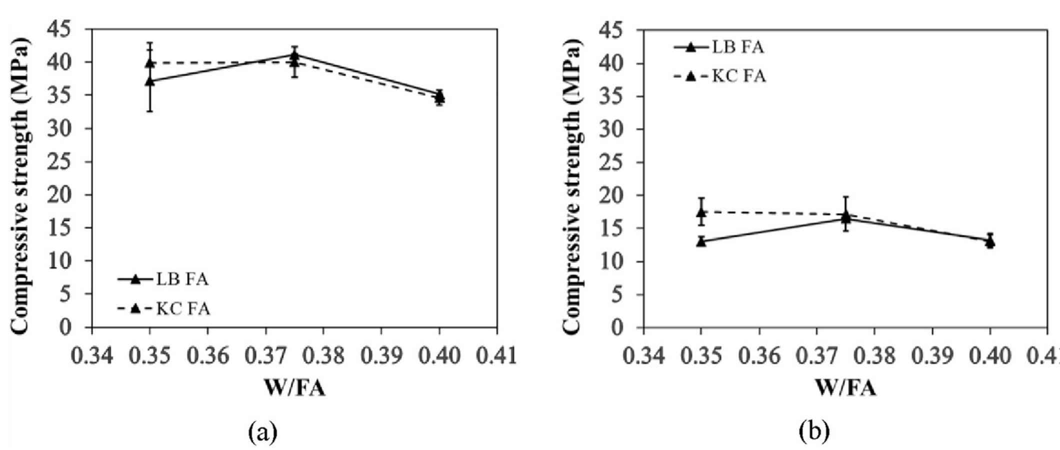

Fig. 7. Effect of W/FA on compressive strength of (a) oven, and (b) ambient cured mortar having Alk/FA of 0.250 and SS/SH of 1.0.

water was essential for formation of CSH. So, the compressive strength increased with increasing the W/FA from 0.350 to 0.375 as shown in Fig 7 and from 0.400 to 0.450 as shown in Fig. 8.

Increasing the Alk/FA from 0.250 to 0.300, resulted in higher compressive strength from 35.17 MPa to 37.07 MPa for LB fly ash-based mortar and from 34.65 MPa to 40.23 MPa for KC fly ash-based mortar as shown in Fig. 9. For a given W/FA of 0.400, increasing the Alk/FA increased the Na_2O concentration which increased the solubility of the silica and alumina (Guo et al., 2010b).

As shown in Figs. 10 and 11, in the case of ambient cured mortar, increasing the SS/SH from 0.5 and 1.0 to 1.5 and 2.5 reducing the compressive strength from 13.93 MPa to 6.75 MPa for LB fly ash-based mortar and from 15.57 MPa to 9.49 MPa for KC fly ash-based mortar of W/FA of 0.400 and Alk/FA of 0.250. The same phenomena took place for W/FA of 0.450 and Alk/FA of 0.300, the compressive strength reduced from 20.69 MPa to 10.62 MPa for LB fly ash-based mortar and from 17.22 MPa to 8.03 MPa for KC fly ash-based mortar. This was due to increasing the silica content in the mortar which hindered the structure formation

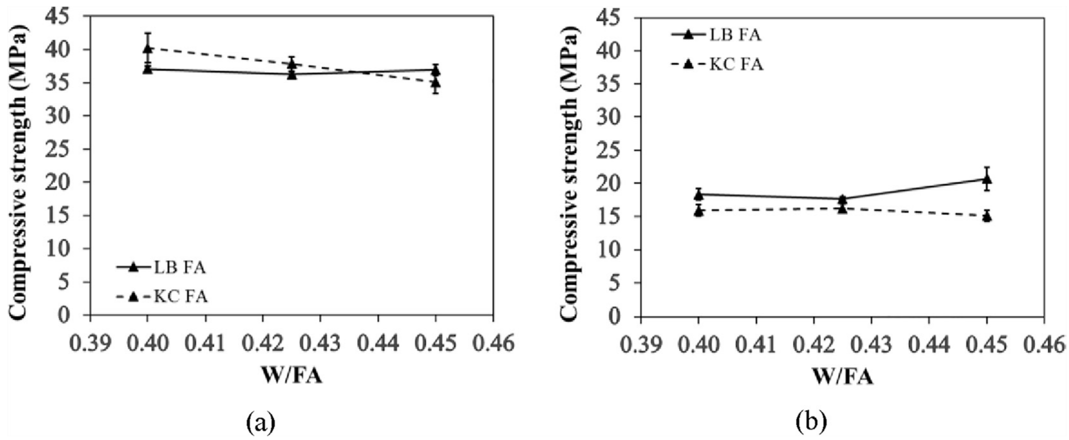

Fig. 8. Effect of W/FA on compressive strength of (a) oven, and (b) ambient cured mortar having Alk/FA of 0.300 and SS/SH of 1.0.

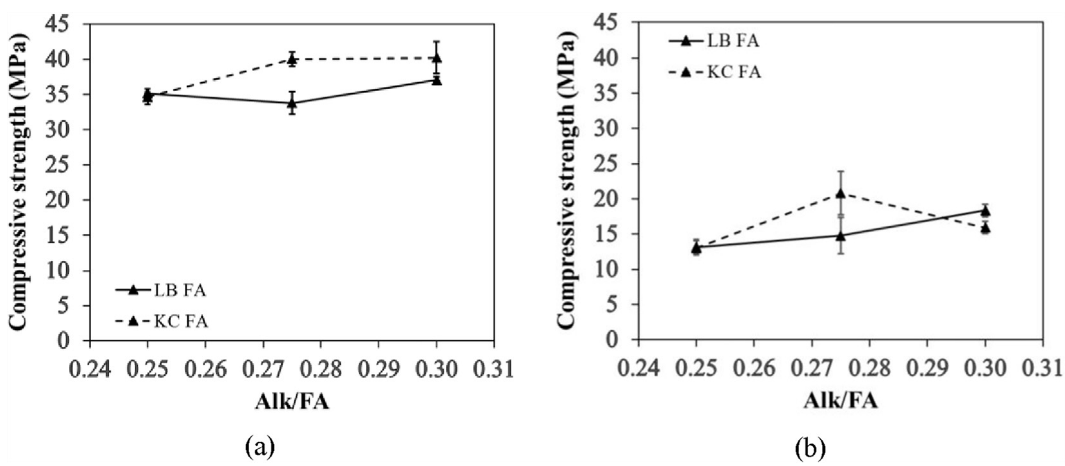

Fig. 9. Effect of Alk/FA on compressive strength of (a) oven, and (b) ambient cured mortar having W/FA of 0.400 and SS/SH of 1.0.

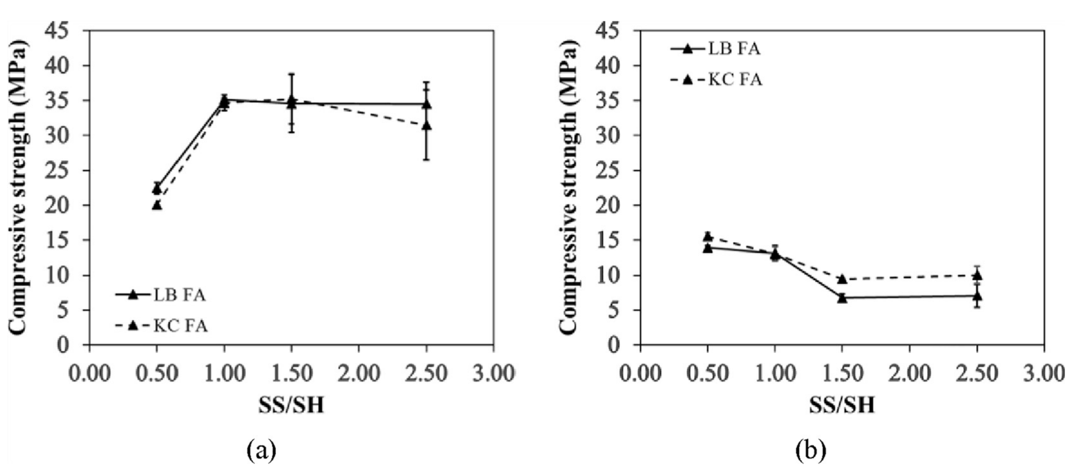

Fig. 10. Effect of SS/SH on compressive strength of (a) oven, and (b) ambient cured mortar having W/FA of 0.400 and Alk/FA of 0.250.

(Chindaprasirt et al., 2012; Morsy et al., 2014). The increase of the hydroxide ions and alkali concentration by adding more SH than SS, increased the ambient cured mortar compressive strength where the increased hydroxide and alkali ions had an ability to leach the silica and alumina from the fly ash at higher rate compared to the soluble silica from the SS. In the case of oven curing, decreasing the sodium silicate to sodium hydroxide ratio increases the free hydroxide ions in the mortar which accelerate the dissolution of the fly ash and precipitate the aluminosilicate gel at very early stages, thus resulting in lower strength AAFA mortar (Chindaprasirt et al., 2012; Part et al., 2015). It was found that the optimum SS/SH for ambient curing regime was 0.5 and 1.0 where the compressive strength reached up to 19.95 and 20.69 for LB fly ash-based mortar, and 17.22 MPa and 15.12 MPa for KC

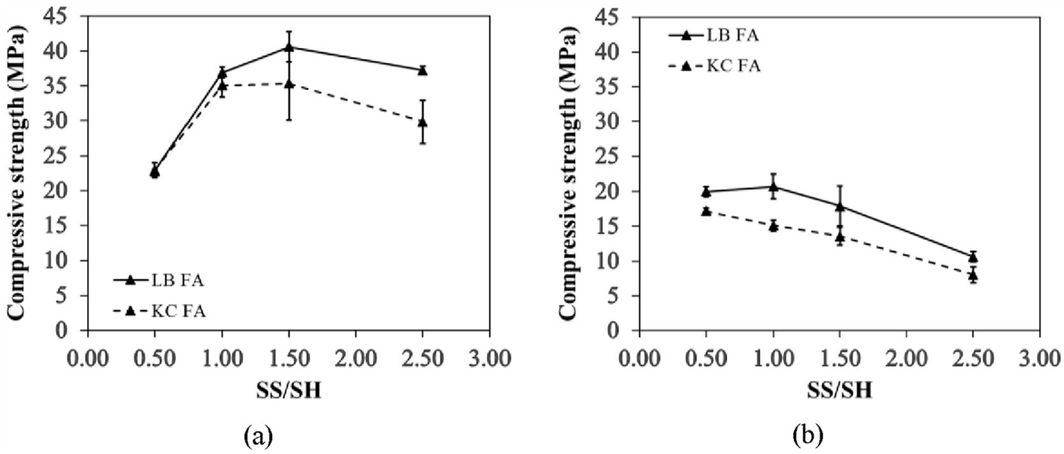

Fig. 11. Effect of SS/SH on compressive strength of (a) oven, and (b) ambient cured mortar having W/FA of 0.450 and Alk/FA of 0.300.

fly ash-based mortar, respectively. While for oven curing were 1.0 and 1.5 where the compressive strength reached up to 36.9 MPa and 40.59 MPa for LB fly ash-based mortar and, 35.06 MPa and 35.36 MPa for KC fly ash-based mortar.

Tables 3–6 shows the statistical analyses of the compressive strength results. As shown in the tables, the coefficient of variation of most of the results is less than 15% with few results that passed this ratio.

4. Conclusion

This paper presents the fresh properties and 7-day compressive strength of alkali activated high calcium fly ash-based mortars. Two types of fly ashes obtained from two different power plants located in the state of Missouri, U.S. were used during this study. The alkaline solution was prepared as a mixture of sodium silicate (SS) and sodium hydroxide (SH). Water-to-fly ash ratios (W/FA) ranging from 0.350 to 0.450, alkaline-to-fly ash ratios (Alk/FA) ranging from 0.250 to 0.300, sodium silicate to sodium hydroxide ratio (SS/SH) ranging from 0.5 to 2.5 were investigated during the course of this study. All mortar cubes were cured and tested at 7 days to determine their compressive strengths. The specimens were cured at either oven for 24 h at 70 °C or ambient temperature at 23 ± 2 °C. Based on this study the following conclusions can be drawn:

- For both fly ashes, with constant Alk/FA and SS/SH, Increasing the W/FA resulted in higher setting time and workability. While the compressive strength increased with increasing the W/FA ratio from 0.350 to 0.375 with Alk/FA of 0.250 and from 0.400 to 0.450 with Alk/FA of 0.300 for LB fly ash as the extra water was used to form more CSH.
- For both fly ashes, with constant W/FA and SS/SH, Increasing the Alk/FA decreased the setting time and workability. While the compressive strength increased due to increasing the alkali (Na2O) concentration which increased the solubility of the silica and alumina.
- Increasing the SS/SH from 0.5 to 2.5, the workability started to reduce gradually due the high viscosity of the sodium silicate.
- The setting time increased with increasing the SS/SH from 0.5 to 1.0. Thereafter, it decreased with increasing the ratio from 1.0 to 2.5 with W/FA ratio of 0.400 and Alk/FA ratio of 0.250. While the setting time for the SS/SH ratios 0.5, 1.0, and 1.5 were almost the same with W/FA ratio of 0.450 and Alk/FA ratio of 0.300.
- Generally, the highest compressive strengths for the ambient cured mixtures were at SS/SS of 0.5 and 1.0, while the highest compressive strengths for the oven cured mixtures were at SS/SS of 1.0 and 1.5 for both fly ashes.
- For the ambient cured mixtures, the highest compressive strength was 20.69 MPa at W/FA of 0.450, Alk/FA of 0.300, and SS/SH of 1.0 for LB fly ash based-mortar. While the highest compressive strength was 20.80 MPa at W/FA of 0.400, Alk/FA of 0.275, and SS/SH of 1.0 for KC fly ash-based mortar.
- For the oven cured mixtures, the highest compressive strength was 41.1 MPa at W/FA of 0.375, Alk/FA of 0.250, and SS/SH of 1.0 for LB fly ash based-mortar. While the highest compressive strength was 40.23 MPa at W/FA of 0.400, Alk/FA of 0.300, and SS/SH of 1.0 for KC fly ash-based mortar.

Table 3
Details and compressive strength results for oven cured mixtures of LB FA.

Mix No.	W/FA	ALK/FA	SS/SH	Compressive Strength (MPa)	Range	Variance	SD[a]	% CV[b]
1	0.35	0.25	1	37.19	8.36	21.65	4.65	12.51
2	0.375	0.25	1	41.10	0.27	0.02	0.13	0.33
3	0.4	0.25	1	35.17	0.27	0.02	0.15	0.44
4	0.4	0.3	1	37.07	0.88	0.20	0.45	1.22
5	0.425	0.3	1	36.25	12.51	0.20	0.44	1.22
6	0.45	0.3	1	36.90	1.46	0.62	0.79	2.13
7	0.4	0.275	1	33.80	2.95	2.73	1.65	4.89
8	0.4	0.25	0.5	22.46	1.52	0.71	0.84	3.75
9	0.4	0.25	1.5	34.57	6.89	17.05	4.13	11.94
10	0.4	0.25	2.5	45.78	5.63	9.88	3.14	6.86
11	0.45	0.3	0.5	22.79	0.50	0.07	0.26	1.13
12	0.45	0.3	1.5	40.59	4.28	4.61	2.15	5.29
13	0.45	0.3	2.5	37.22	2.70	0.33	0.57	1.53

[a] SD: standard deviation.
[b] CV: coefficient of variation.

Table 4
Details and compressive strength results for oven cured mixtures of KC FA.

Mix No.	W/FA	ALK/FA	SS/SH	Compressive Strength (MPa)	Range	Variance	SD[a]	% CV[b]
1	0.35	0.25	1	39.92	5.96	8.91	2.99	7.48
2	0.375	0.25	1	40.02	4.63	5.41	2.33	5.81
3	0.4	0.25	1	34.65	2.15	1.18	1.09	3.13
4	0.4	0.3	1	40.23	4.45	4.98	2.23	5.55
5	0.425	0.3	1	37.83	2.17	1.19	1.09	2.88
6	0.45	0.3	1	35.06	3.08	2.81	1.68	4.78
7	0.4	0.275	1	40.03	1.74	0.96	0.98	2.44
8	0.4	0.25	0.5	20.08	1.45	0.52	0.72	3.61
9	0.4	0.25	1.5	35.23	7.14	12.87	3.59	10.18
10	0.4	0.25	2.5	31.49	9.41	25.10	5.01	15.91
11	0.45	0.3	0.5	22.94	1.99	1.10	1.05	4.58
12	0.45	0.3	1.5	35.36	10.51	28.18	5.31	15.01
13	0.45	0.3	2.5	29.87	5.93	9.55	3.09	10.35

[a] SD: standard deviation.
[b] CV: coefficient of variation.

Table 5
Details and compressive strength results for ambient cured mixtures of LB FA.

Mix No.	W/FA	ALK/FA	SS/SH	Compressive Strength (MPa)	Range	Variance	SD[a]	% CV[b]
1	0.35	0.25	1	13.02	1.28	0.48	0.70	5.34
2	0.375	0.25	1	16.49	0.44	0.05	0.23	1.37
3	0.4	0.25	1	13.18	2.01	1.03	1.02	7.71
4	0.4	0.3	1	18.35	4.30	4.87	2.21	12.03
5	0.425	0.3	1	17.67	0.48	0.11	0.34	1.90
6	0.45	0.3	1	20.69	3.42	3.11	1.76	8.52
7	0.4	0.275	1	14.76	3.64	6.63	2.57	17.45
8	0.4	0.25	0.5	13.93	0.39	0.07	0.27	1.96
9	0.4	0.25	1.5	6.75	1.02	0.33	0.58	8.55
10	0.4	0.25	2.5	7.08	3.18	2.73	1.65	23.34
11	0.45	0.3	0.5	19.95	1.35	0.51	0.71	3.57
12	0.45	0.3	1.5	17.92	5.58	7.99	2.83	15.77
13	0.45	0.3	2.5	10.62	1.45	0.52	0.72	6.82

[a] SD: standard deviation.
[b] CV: coefficient of variation.

Table 6
Details and compressive strength results for ambient cured mixtures of KC FA.

Mix No.	W/FA	ALK/FA	SS/SH	Compressive Strength (MPa)	Range	Variance	SD[a]	% CV[b]
1	0.35	0.25	1	17.51	2.87	4.11	2.03	11.58
2	0.375	0.25	1	17.18	5.14	6.79	2.61	15.17
3	0.4	0.25	1	13.04	1.87	0.97	0.99	7.56
4	0.4	0.3	1	15.92	1.21	0.73	0.85	5.36
5	0.425	0.3	1	16.21	1.32	0.48	0.69	4.26
6	0.45	0.3	1	15.12	1.48	0.64	0.80	5.30
7	0.4	0.275	1	20.80	6.01	9.43	3.07	14.76
8	0.4	0.25	0.5	15.57	1.04	0.27	0.52	3.34
9	0.4	0.25	1.5	9.49	0.34	0.03	0.17	1.79
10	0.4	0.25	2.5	10.03	2.48	1.61	1.27	12.66
11	0.45	0.3	0.5	17.22	0.87	0.20	0.44	2.58
12	0.45	0.3	1.5	13.59	2.39	1.74	1.32	9.72
13	0.45	0.3	2.5	8.03	2.35	1.41	1.19	14.81

[a] SD: standard deviation.
[b] CV: coefficient of variation.

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References

Bakharev, T., 2005. Geopolymeric materials prepared using Class F fly ash and elevated temperature curing. Cem. Concr. Res. 35 (6), 1224–1232. http://dx.doi.org/10.1016/j.cemconres.2004.06.031.

Bastidas, D.M., Fernández-Jiménez, A., Palomo, A., González, J.A., 2008. A study on the passive state stability of steel embedded in activated fly ash mortars. Corros. Sci. 50 (4), 1058–1065. http://dx.doi.org/10.1016/j.corsci.2007.11.016.

Chindaprasirt, P., De Silva, P., Sagoe-Crentsil, K., Hanjitsuwan, S., 2012. Effect of SiO2 and Al2O3 on the setting and hardening of high calcium fly ash-based

geopolymer systems. J. Mater. Sci. 47 (12), 4876–4883. http://dx.doi.org/10.1007/s10853-012-6353-y.
Chindaprasirt, P., De Silva, P., Hanjitsuwan, S., 2014. Effect of high-speed mixing on properties of high calcium fly ash geopolymer paste. Arab. J. Sci. Eng. 39 (8), 6001–6007. http://dx.doi.org/10.1007/s13369-014-1217-1.
Davidovits, J., Davidovics, M. 2008. Geopolymer: Room-Temperature Ceramic Matrix for Composites. In: Proceedings of the 12th Annual Conference on Composites and Advanced Ceramic Materials: Ceramic Engineering and Science Proceedings. John Wiley & Sons Inc, pp 835–841. doi: 10.1002/9780470310496.ch34.
Diaz, E.I., Allouche, E.N., Eklund, S., 2010. Factors affecting the suitability of fly ash as source material for geopolymers. Fuel 89 (5), 992–996. http://dx.doi.org/10.1016/j.fuel.2009.09.012.
Duxson, P., Fernández-Jiménez, A., Provis, J.L., Lukey, G.C., Palomo, A., van Deventer, J.S.J., 2007. Geopolymer technology: the current state of the art. J. Mater. Sci. 42 (9), 2917–2933. http://dx.doi.org/10.1007/s10853-006-0637-z.
Gheni, A.A., ElGawady, M.A., Myers, J.J., 2017. Mechanical characterization of concrete masonry units manufactured with crumb rubber aggregate. Mater. J. 114 (01). http://dx.doi.org/10.14359/51689482.
Guo, X., Shi, H., Chen, L., Dick, W.A., 2010a. Alkali-activated complex binders from class C fly ash and Ca-containing admixtures. J. Hazard. Mater. 173 (1–3), 480–486. http://dx.doi.org/10.1016/j.jhazmat.2009.08.110.
Guo, X., Shi, H., Dick, W.A., 2010b. Compressive strength and microstructural characteristics of class C fly ash geopolymer. Cement Concr. Compos. 32 (2), 142–147. http://dx.doi.org/10.1016/j.cemconcomp.2009.11.003.
Komljenović, M. 2015. Mechanical strength and Young's modulus of alkali-activated cement-based binders. In: Handbook of Alkali-Activated Cements, Mortars and Concretes. Woodhead Publishing, Oxford, pp 171–215. doi: 10.1533/9781782422884.2.171.
Lee, W.K.W., van Deventer, J.S.J., 2002a. The effect of ionic contaminants on the early-age properties of alkali-activated fly ash-based cements. Cem. Concr. Res. 32 (4), 577–584. http://dx.doi.org/10.1016/S0008-8846(01)00724-4.
Lee, W.K.W., van Deventer, J.S.J., 2002b. The effects of inorganic salt contamination on the strength and durability of geopolymers. Colloids Surf., A 211 (2–3), 115–126. http://dx.doi.org/10.1016/S0927-7757(02)00239-X.
Morsy, M.S., Alsayed, S.H., Al-Salloum, Y., Almusallam, T., 2014. Effect of sodium silicate to sodium hydroxide ratios on strength and microstructure of fly ash geopolymer binder. Arab. J. Sci. Eng. 39 (6), 4333–4339. http://dx.doi.org/10.1007/s13369-014-1093-8.
Moustafa, A., ElGawady, M.A., 2015. Mechanical properties of high strength concrete with scrap tire rubber. Constr. Build. Mater. 93, 249–256. http://dx.doi.org/10.1016/j.conbuildmat.2015.05.115.
Moustafa, A., ElGawady, M.A., 2016. Strain rate effect on properties of rubberized concrete confined with glass fiber-reinforced polymers. J. Compos. Construct. 20 (5). http://dx.doi.org/10.1061/(ASCE)CC.1943-5614.0000658.
Nath, P., Sarker, P.K., 2017. Flexural strength and elastic modulus of ambient-cured blended low-calcium fly ash geopolymer concrete. Constr. Build. Mater. 130, 22–31. http://dx.doi.org/10.1016/j.conbuildmat.2016.11.034.
Pacheco-Torgal, F., Abdollahnejad, Z., Camões, A.F., Jamshidi, M., Ding, Y., 2012. Durability of alkali-activated binders: a clear advantage over Portland cement or an unproven issue? Constr. Build. Mater. 30, 400–405. http://dx.doi.org/10.1016/j.conbuildmat.2011.12.017.
Palomo, A., Grutzeck, M.W., Blanco, M.T., 1999. Alkali-activated fly ashes: a cement for the future. Cem. Concr. Res. 29 (8), 1323–1329. http://dx.doi.org/10.1016/S0008-8846(98)00243-9.
Pangdaeng, S., Phoo-ngernkham, T., Sata, V., Chindaprasirt, P., 2014. Influence of curing conditions on properties of high calcium fly ash geopolymer containing Portland cement as additive. Mater. Des. 53, 269–274. http://dx.doi.org/10.1016/j.matdes.2013.07.018.
Part, W.K., Ramli, M., Cheah, C.B., 2015. An overview on the influence of various factors on the properties of geopolymer concrete derived from industrial by-products. Constr. Build. Mater. 77, 370–395. http://dx.doi.org/10.1016/j.conbuildmat.2014.12.065.
Pattanapong, T.-N., Prinya, C., Vanchai, S., 2015. Setting time, strength, and bond of high-calcium fly ash geopolymer concrete. J. Mater. Civ. Eng. 27 (7). http://dx.doi.org/10.1061/(ASCE)MT.1943-5533.0001157.
Provis, J.L., Bernal, S.A., 2014. Geopolymers and related alkali-activated materials. Annu. Rev. Mater. Res. 44, 299–327. http://dx.doi.org/10.1146/annurev-matsci-070813-113515.
Rangan, DHaBV, 2005. Development and Properties of Low-Calcium Fly Ash-Based Geopolymer concrete. Research Report GC 1, Curtin University of Technology, Perth, Australia.
Rattanasak, U., Chindaprasirt, P., 2009. Influence of NaOH solution on the synthesis of fly ash geopolymer. Miner. Eng. 22 (12), 1073–1078. http://dx.doi.org/10.1016/j.mineng.2009.03.022.
Rattanasak, U., Pankhet, K., Chindaprasirt, P., 2011. Effect of chemical admixtures on properties of high-calcium fly ash geopolymer. Int. J. Miner., Metal. Mater. 18 (3), 364. http://dx.doi.org/10.1007/s12613-011-0448-3.
Shi, C., 2004. Effect of mixing proportions of concrete on its electrical conductivity and the rapid chloride permeability test (ASTM C1202 or ASSHTO T277) results. Cem. Concr. Res. 34 (3), 537–545. http://dx.doi.org/10.1016/j.cemconres.2003.09.007.
Siyal, A.A., Azizli, K.A., Man, Z., Ullah, H., 2016. Effects of Parameters on the Setting Time of Fly Ash Based Geopolymers Using Taguchi Method. Procedia Engineering 148, 302–307. http://dx.doi.org/10.1016/j.proeng.2016.06.624.
Somna, K., Jaturapitakkul, C., Kajitvichyanukul, P., Chindaprasirt, P., 2011. NaOH-activated ground fly ash geopolymer cured at ambient temperature. Fuel 90 (6), 2118–2124. http://dx.doi.org/10.1016/j.fuel.2011.01.018.
Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete (2015). ASTM International.
Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens) (2016). ASTM International.
Standard Test Method for Flow of Hydraulic Cement Mortar (2015). ASTM International.
Standard Test Method for Major and Minor Elements in Coal and Coke Ash By X-Ray Fluorescence (2013). ASTM International.
Standard Test Method for Time of Setting of Hydraulic Cement Mortar by Modified Vicat Needle (2013). ASTM International.
Swanepoel, J.C., Strydom, C.A., 2002. Utilisation of fly ash in a geopolymeric material. Appl. Geochem. 17 (8), 1143–1148. http://dx.doi.org/10.1016/S0883-2927(02)00005-7.
Temuujin, J., van Riessen, A., Williams, R., 2009. Influence of calcium compounds on the mechanical properties of fly ash geopolymer pastes. J. Hazard. Mater. 167 (1–3), 82–88. http://dx.doi.org/10.1016/j.jhazmat.2008.12.121.
Temuujin, J., Minjigmaa, A., Davaabal, B., Bayarzul, U., Ankhtuya, A., Jadambaa, T., MacKenzie, K.J.D., 2014. Utilization of radioactive high-calcium Mongolian flyash for the preparation of alkali-activated geopolymers for safe use as construction materials. Ceram. Int. 40 (10, Part B), 16475–16483. http://dx.doi.org/10.1016/j.ceramint.2014.07.157.
Vail JG Soluble Silicates – Their Properties and Uses. New York: Reinhold.
Yip, C.K., van Deventer, J.S.J., 2003. Microanalysis of calcium silicate hydrate gel formed within a geopolymeric binder. J. Mater. Sci. 38 (18), 3851–3860. http://dx.doi.org/10.1023/a:1025904905176.
Yip, C.K., Lukey, G.C., van Deventer, J.S.J., 2005. The coexistence of geopolymeric gel and calcium silicate hydrate at the early stage of alkaline activation. Cem. Concr. Res. 35 (9), 1688–1697. http://dx.doi.org/10.1016/j.cemconres.2004.10.042.
Youssf, O., ElGawady, M.A., Mills, J.E., 2015. Experimental Investigation of Crumb Rubber Concrete Columns under Seismic Loading. Structures 3, 13–27. http://dx.doi.org/10.1016/j.istruc.2015.02.005.
Youssf, O., ElGawady, M.A., Mills, J.E., 2016. Static cyclic behaviour of FRP-confined crumb rubber concrete columns. Eng. Struct. 113, 371–387. http://dx.doi.org/10.1016/j.engstruct.2016.01.033.