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THEMATIC ISSUE

Natural Pozzolan-based geopolymers for sustainable construction

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Abstract The study presented herein evaluates effects of alkaline activator (sodium hydroxide) concentration, solution (sodium hydroxide solution)-to-binder ratio (S/B), and curing condition on properties of alkali-activated natural Pozzolan mortars (geopolymers). To this end, several mixtures were made having natural Pozzolan as their binder with different concentrations of alkaline activator solution including 2.5, 5, 7.5, 10, and 12.5 molar (M) at various S/B of 0.50, 0.54, and 0.58. The produced mortars were cured at 80 °C under three different conditions of exposed (dry), sealed (wrapped), and moist until testing at ages of 1, 3, and 7 days. Multiple tests were conducted on the alkali-activated natural Pozzolan mortars including flow spread, compressive strength, flexural strength, PH measurement, absorption, and rapid chloride migration. Test results showed the sealed curing condition to be most conducive to strength gain, whereas the exposed curing condition caused dehydration and/or carbonation within the samples and the moist curing condition did not allow for full removal of excess water resulting in reduced bond formations. The moist oven-cured mortars produced higher strength than the exposed cured mortars when alkaline activator with lower molarities was used. The opposite trend was observed for the higher molarities mortars. The compressive and flexural strengths, absorption, and depth of penetrated chloride improved when NaOH concentration increased and S/B decreased.

Keywords CO_2 emission · Sustainability · Geopolymers · Natural Pozzolan · Sodium hydroxide concentration · Solution-to-binder ratio · Curing condition

Introduction

Concrete is the most widely used man-made construction material with approximately 1 ton produced per person every year. Production of Portland cement (PC), as a main component of concrete, accounts for nearly 5 % of the world's total carbon dioxide (CO_2) emissions (Huntzinger and Eatmon 2009). Almost half of the CO_2 emissions are produced as calcium carbonate ($CaCO_3$) transforms to calcium oxide (CaO) in the kiln and the other half result from energy usage (Huntzinger and Eatmon 2009). Pacheco-Torgal et al. (2012) provided another assessment of the global CO_2 emissions due to PC production, finding an estimate around 7 %. They also predicted that the demand for PC will double in the next 40 years (Pacheco-Torgal et al. 2012).

Contrary to the common belief, PC concrete is not free of severe degradation problems. The actual costs of corrosion-induced repairs in the US highway bridges exceed billions of dollars (per annum). The indirect repair costs, due to traffic delays and the resulting productivity lost, are estimated to be tenfold as much (ACI 222 2001). The problem is not limited to the concrete bridges. Several problems have also been observed in concrete pavements. They have shown varying signs of deteriorations due to age, harsh environment, excessive loading, and other

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detrimental factors. It was reported that one-third of the US road system is in poor condition or worse (Van Dam et al. 2011). Hence, the US transportation network is expected to face several challenges due to the deterioration and aging of the network components (ASCE 2013). The need for production of long-lasting concrete has never been more urgent.

The desire to reduce CO_2 emissions and to produce more durable concrete has given impetus to search for supplementary cementitious materials (SCM) or new binders. Accordingly, various research studies have been conducted in recent decades to find alternatives for PC. For several years, these studies mainly focused on the use of SCM including natural Pozzolans or industrial by-products such as fly ash and silica fume (artificial Pozzolans). As the major constituents of Pozzolans are silica, alumina, and iron oxide with a calcium oxide (CaO) content of usually less than 20 %, they cannot naturally react and hydrate with water (Pacheco-Torgal et al. 2008; ACI 232.1 2000). They need some forms of catalysts or additional ingredients to initiate the hydration reactions. In SCM-contained concretes, Portland cement typically plays this role. The calcium hydroxides, produced during PC hydration, react with Pozzolanic oxides and produce C–S–H gel. Findings of different research studies have proven that SCM can be considered a viable option to replace a portion of PC, to decrease CO_2 emission, and to increase longevity of concrete. Use of SCM, however, results in partial replacement of PC, as the majority of the concrete binder is still PC.

Recent research has shown alkaline activators to be successful as catalysts that initiate hydration reactions for Pozzolans (Bondar et al. 2011a). Therefore, it is possible to replace whole PC in a mixture by alkali activation of Pozzolanic materials, which is also known as geopolymerization. The process of geopolymerization, production of alkaline-aluminosilicate hydrate gel, is considered to be consisted of three major steps, namely, destruction coagulation or dissolution, coagulation condensation or hydrolysis, and condensation crystallization or condensation (Weng and Sagoe-Crentsil 2007; Sagoe-Crentsil and Weng 2007). For the alkali-activated Pozzolans using sodium hydroxide as the only alkaline activator, the first stage, “destruction coagulation,” begins with the breakdown of the Pozzolan bonds such as Si–O–Si, Al–O–Al, and Al–O–Si. Once the activator is added to the Pozzolans, the dissolution process begins instantly in order to supplement the aluminate ions needed for the rest of the activation process. Al^{3+} and Si^{4+} ions result from the dissolution process in addition to water. The amount of Al^{3+} and Si^{4+} ions made available is dependent on the concentration of the activator, with the amount increasing with increase in the concentration of the activator. In the next step, referred to as the hydrolysis process, the water, Al^{3+}, and Si^{4+} ions from the previous step are used to develop $[Al(OH)_4]^-$ ions as well as $[SiO_2(OH)_2]^{2-}$ and $[SiO(OH)_3]^-$ ions. The general equations for these reactions are as follows, if only mass and charge balances are considered (Weng and Sagoe-Crentsil 2007; Sagoe-Crentsil and Weng 2007):

$$Al_2O_3 + 3H_2O + 2OH^- \rightarrow 2Al(OH)_4^- \quad (1)$$

$$SiO_2 + H_2O + OH^- \rightarrow \left[SiO(OH)_3\right]^- \quad (2)$$

$$SiO_2 + 2OH^- \rightarrow \left[SiO_2(OH)_2\right]^{2-} \quad (3)$$

The mechanisms of the condensation step are not as simple as the previous two steps because of its dependency on the evolution of silicate ions; $[SiO_2(OH)_2]^{2-}$ and $[SiO(OH)_3]^-$. In general, the condensation step involves the condensation between $[Al(OH)_4]^-$ with $[SiO_2(OH)_2]^{2-}$ and/or $[SiO(OH)_3]^-$. The dependency relies on the concentration $[SiO_2(OH)_2]^{2-}$ and $[SiO(OH)_3]^-$, which is dependent on the pH of the system or the concentration of the activator. With that said, the end reaction varies with the concentration of the two silicate ions, but in general, following equations depict the chemical reactions of the condensation processes (Weng and Sagoe-Crentsil 2007; Sagoe-Crentsil and Weng 2007).

$$\left[Al(OH)_4\right]^- + \left[SiO(OH)_3\right]^- \rightarrow \left[(OH)_3Al - O - SiO(OH)_2\right]^{2-} + H_2O \quad (4)$$

$$\left[Al(OH)_4\right]^- + \left[SiO_2(OH)_2\right]^{2-} \rightarrow \left[(OH)_3Al - O - SiO_2(OH)\right]^{3-} + H_2O \quad (5)$$

There are, however, a number of influential factors affecting such replacement. These factors include, but not limited to, alkaline activator types and concentrations; type, chemical compositions, and source of Pozzolans; curing condition, curing temperature, solution-to-binder ratio, and curing age. Alkaline concentration plays an important role in the geopolymerization process. As the hydroxide ion concentration increases, there is also an increase in aluminosilicate solubility, leading to an increase in compressive strength of alkali-activated binders (Khale and Chaudhary 2007). There are, however, some studies showing opposite trend when extra hydroxides were available in the mixture. Xu and Van Deventer (2000), Palomo et al. (1999), and Cheng and Chiu (2003) reported that the excess of alkaline did not improve or reduce the compressive strength of alkali-activated binders (mainly fly ash). In addition to the alkali concentration, temperature is another contributing factor to the strength development of alkali-activated binders. It has been found that elevated temperatures catalyze the geopolymerization process. Lemougna et al. (2011) showed increases in the compressive strength as the curing temperature increased up to

90 °C. It was also found that condition of samples in oven considerably affected their properties (Lemougna et al. 2011; Bondar et al. 2011a).

Although the replacement of PC with alkali-activated binders may significantly reduce the amount of CO_2 emission of concrete production, these newly developed binders are still at an early stage of development. There are currently no standards available in relation to their mixing procedures and curing conditions. For the most part, majority of the past studies dealt with strength properties using alkali-activated slag and fly ash with a few reported results on alkali-activated natural Pozzolans. The study presented herein focused on evaluating effects of five activator concentrations, three solution-to-binder ratios, three curing conditions, and three curing ages on the strength properties of mortars produced with alkali-activated natural Pozzolans as their primary binder. This study also assessed transport properties of sealed oven-cured alkali-activated natural Pozzolan mortars using five and three activator concentrations and solution-to-binder ratios, respectively.

Experimental program

Materials

The materials used in this study included natural Pozzolan as the binder, sodium hydroxide solution as the alkaline activator, and fine aggregates. The used natural Pozzolan was from a source having vitrified rhyolite deposit. The material was naturally amorphous, and as a felsic volcanic, high in silica and aluminum. The chemical properties of the natural Pozzolan, obtained by XRF analysis, are presented in Table 1. Table 2 documents the chemico-physical requirements of natural Pozzolan based on ASTM C618 (2012). Tables 1 and 2 also report chemical and physical properties of a typical class F fly ash for comparison purposes. As can be seen, the used natural Pozzolan contained 78.4 % of Pozzolanic oxides (silica, alumina, and iron oxides). The calcium oxide content was low (3.2 %), indicating that the used natural Pozzolan was not cementitious on its own. The 7- and 28-day strengths of mortars having 20 % natural Pozzolan were 85 and 92 % of those of the prepared standard reference mortar, respectively. These strength results are well above the minimum requirement of 75 % specified in ASTM C618 (2012). The used natural Pozzolan had a considerably high specific surface (6088 cm^2/gr) as only 13.5 % was retained on sieve #325 (45 µm). The particle size distribution of natural Pozzolan is shown in Fig. 1, indicating its finer particle size in comparison with that of a commonly used fly ash.

The fine aggregates used in this study had an oven-dry specific gravity of 2.76, absorption of 0.81 %, and fineness modulus of 2.64.

For the purpose of this study, sodium hydroxide solution with different concentrations was selected as an alkaline activator. There were a number of reasons behind this selection: (1) In nearly all previous studies on natural Pozzolan-based geopolymers, combinations of sodium or potassium hydroxide with sodium silicate were used. These studies have given the readers the perception that use of sodium silicate is an inevitable part for a successful activation. As there has not been any fundamental research using only sodium hydroxide for activation of natural Pozzolan, this study used sodium hydroxide as the sole activator. (2) Sodium silicate costs at least 15$ per liter (reported from the US supplier and price varies among different producers) which is significantly higher than the cost for sodium hydroxide solution (a liter of sodium hydroxide solution can definitely be made with less than a dollar). (3) Recent research studies show that it is better to shift toward one-part activators (preferably solid) (Pacheco-Torgal et al. 2015). And (4) for some applications which does not require high strength, geopolymers can be more practical and less expensive using only sodium hydroxide than combined with sodium silicate.

NaOH solutions were made by dissolving NaOH pellets in distilled water. In order to make a liter of solution with molarities of 2.5, 5, 7.5, 10, and 12.5 M, 100, 200, 300, 400, and 500 g of NaOH pellets were dissolved in enough water to produce one total liter of solution, respectively. The amounts of water and NaOH used to make a liter of

Table 1 Chemical composition of natural Pozzolans and a typical class F fly ash (in percent)

Material	Silicon dioxide (SiO_2)	Aluminum oxide (Al_2O_3)	Iron oxide (Fe_2O_3)	Sulfur trioxide (SO_3)	Calcium oxide (CaO)	(Na_2O)eq	Loss on ignition
Natural Pozzolan	68.8	8.5	1.1	0.1	3.2	5.2	3.7
Class F fly ash	59.9	22.2	5.2	0.4	4.7	1.3	0.3

Obtained by XRF analysis

Table 2 Chemical and physical properties of natural Pozzolan and a typical class F fly ash according to ASTM C618 (2012)

Requirements	Class N, ASTM C618	Natural Pozzolan results	Fly ash results
Chemical requirements			
$SiO_2 + Al_2O_3 + Fe_2O_3$, %	Min, 70.0	78.4	87.3
Sulfur trioxide (SO_3), %	Max, 4.0	0.1	0.4
Moisture content, %	Max, 3.0	0.7	0.04
Loss on ignition, %	Max, 10.0	3.7	0.3
Physical requirements			
Amount retained when wet-sieved on 45-µm sieve (%)	Max, 34	13.5	21.2
Strength activity index, at 7 days, percent of control[a]	Min, 75	85	83
Strength activity index, at 28 days, percent of control[a]	Min, 75	92	79
Water requirement, percent of control	Max, 115	103	97
Autoclave expansion or contraction (%)	Max, 0.8	0	−0.02
Specific gravity	–	2.29	2.31
Specific surface (cm^2/g)	–	6088	–

[a] Note that, the strength activity index is determined based on ASTM C311 (2013) by replacing 20 % of cement with natural Pozzolan

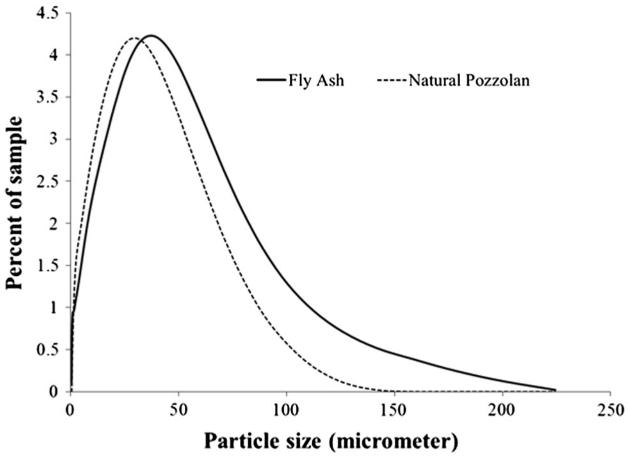

Fig. 1 Particle size distribution of natural Pozzolan and fly ash

solution are shown in Table 3. NaOH pellets were added in incremental amounts and underwent vigorous swirling to ensure complete dissolution throughout the distilled water. The NaOH solutions were allowed to cool down in a water bath before being added to the mortar mixture.

Mixture proportion

Table 3 also presents the mixture proportion of the selected alkali-activated mortars. These mixtures include 5 different sodium hydroxide concentrations of 2.5, 5, 7.5, 10, and 12.5 M, and 3 different solution-to-binder ratios of 0.50, 0.54, and 0.58. The fine aggregate-to-binder ratio was kept constant and equal to 2 for all the selected mixtures. This ratio was chosen based on a preliminary study conducted on different fine aggregate-to-binder ratios of 1.5, 2, 2.5, and 3. It should be noted that it was not possible to cast mixture with molarity of 12.5 M and S/B of 0.50 due to its low flow, resulting in unsuitable compaction of samples.

Sample preparation

A single-axis industrial pan mixer was used to prepare fresh mortars. Mortar mixtures were prepared by adding one-half of the NaOH solution in the mixing bowl, followed by carefully adding in the natural Pozzolans and fine aggregates. It was found that adding the NaOH solution first allowed for easier and more thorough mixing. The fine aggregates, natural Pozzolans, and NaOH solution were mixed for 2 min on the slow speed (140 ± 5 r/min according to ASTM C305) (ASTM C305 1999). The remaining one-half of the NaOH solution was added, and the mortar was mixed on the slow speed for an additional 2 min before turning on medium speed [285 ± 10 r/min according to ASTM C305 (1999)] for 30 s to ensure that the materials were uniformly mixed. Fresh mortars were tested for flow according to ASTM C1437 (2001) before cube-, disk-, and beam-shaped specimens were cast for assessments of compressive strength, PH, absorption, rapid chloride migration, and flexural strength.

Each mixture underwent four different curing conditions: standard moist curing room (sealed; 7 and 28 days) and oven (exposed, sealed, and moist cured; 1, 3, and 7 days). The moist curing room samples were de-molded after a day, wrapped in plastic wrap three times, and placed

Table 3 Mixture proportions and flow of alkali-activated mortars

NaOH concentration (M)	S/B	W/B	W/ GS	Natural Pozzolan (g)	Fine aggregate (g)	Activator solution (g)	Weight per liter of solution (g)		Flow (cm)
							Water	Sodium hydroxide pellets	
2.5	0.50	0.454	0.434	4740.3	9480.6	2370.2	989.1	100	9.9
	0.54	0.490	0.467			2559.8			13.0
	0.58	0.527	0.500			2749.4			13.0
5	0.50	0.415	0.382	4740.3	9480.6	2370.2	973.9	200	6.5
	0.54	0.450	0.410			2559.8			8.3
	0.58	0.481	0.438			2749.4			10.7
7.5	0.50	0.380	0.339	4740.3	9480.6	2370.2	950.3	300	5.7
	0.54	0.410	0.363			2559.8			7.5
	0.58	0.441	0.387			2749.4			7.6
10	0.50	0.347	0.300	4740.3	9480.6	2370.2	903.4	400	3.7
	0.54	0.374	0.321			2559.8			5.0
	0.58	0.402	0.341			2749.4			6.8
12.5	0.50	0.316	0.267	4740.3	9480.6	2370.2	858.8	500	–
	0.54	0.341	0.285			2559.8			3.5
	0.58	0.367	0.302			2749.4			5.7

W/B water-to-binder ratio, *W/GS* water-to-geopolymer solid (fly ash plus sodium hydroxide powder) ratio

in a curing room at ambient temperatures with constant moisture. The remaining samples were cured initially at 60 °C for 3 h in an oven prior to de-molding. Samples were then removed from the molds and maintained at 80 °C in their respective curing conditions. The exposed cured samples were placed directly on the oven racks, completely exposed to the oven environment. The sealed cured samples were wrapped three times in plastic to retain moisture within the sample and then placed on the oven racks. The moist cured samples were placed on a rack inside of a pot that had 5 cm of water beneath the rack where the samples rested on. There was no contact between samples and water that was maintained at a constant level throughout the testing period. The flexural strength beams were underwent sealed oven curing and tested at the age of 7 days.

Testing

The flow test was conducted according to ASTM C1437 (2001) to evaluate the effects of S/B and molarity of solution on workability of the selected mortars.

Compressive strength test was performed on 5-cm cube samples in a procedure similar to ASTM C109 (ASTM 2002b). In addition, some cubes were also cut and their PH was measured using a commercially available PH indicating spray.

The flexural strengths of the 5 × 5×20 cm beams were measured in accordance with ASTM C78 (ASTM 2002a). Four beams were tested for each mixture. A strain gauge was attached to the extreme tension side of one beam to measure bending strain.

Absorption, density, and volume of permeable voids were measured according to ASTM C642 (2013) using disks having diameter of 10 cm and height of 5 cm. Similar size disks were used for measurement of rapid chloride migration in accordance with NT BUILD 492 (1999).

Results and discussion

Flow

The results of the flow test are presented in Table 3. As can be seen, the flow of alkali-activated mortars decreased when NaOH concentration increased. The decreases in flow were averagely 29, 17, 26, and 23 % when molarity of solution increased from 2.5 to 5, 5 to 7.5, 7.5 to 10, and 10 to 12.5, respectively. An explanation for this trend can be due to the amount of alkaline and water in the prepared solution. An increase in the activator concentration allowed for more sodium hydroxide pellets and less free water for a given volume, resulting in the reduction of flow spread.

The flow of the studied mortars increased with increases in solution-to-binder ratio. The increases were averagely 31 and 26 % when S/B increased from 0.50 to 0.54 and 0.54 to

0.58, respectively. This trend was similar to the typical behavior of PC mixtures. As the mixtures with higher S/B contained more water, they became more plastic and workable, allowing for ease of mixing and placement.

Compressive strength

Table 4 shows the results of the compressive strength test for all the tested mixtures under oven curing conditions. Overall, curing condition, age of testing, molarity, and solution-to-binder ratio were all influential on the compressive strength test results. These parameters and their effects are discussed in details in the following subsections.

Effect of NaOH concentration

The concentration of alkaline activator has been known as the most important factor affecting properties of alkali-activated binders. In general, increases in hydroxide ion concentration lead to increases in solubility of aluminosilicates, which in turn result in higher compressive strengths. The effects of alkaline concentration, however, have not always been that simple. While some studies suggested that a minimum amount of alkaline is needed for a successful activation, there are different studies showing adverse effects of high alkaline concentrations on the strength properties of alkali-activated binders. Bondar et al. (2011a) showed little dissolution of natural Pozzolans and thus insufficient activation, when alkali activators with concentrations of less than 5 M were used. Similarly, Kaps and Buchwald (2002) confirmed that measurable strength could not be gained below a minimum NaOH content. They also reported no strength improvements for more than a certain amount of NaOH. Similarly, Xu and Van Deventer (2000) concluded that extra alkaline could not lead to strength improvements. Palomo et al. (1999) stated that an excess of OH^- concentration in the system could result in a strength reduction of alkali-activated fly ash. In a study conducted by Cheng and Chiu (2003), the strength of alkali-activated slag decreased when KOH concentration increased from 10 to 15 M. This investigation looked into the effect of alkaline concentration on the strength properties of studied alkali-activated natural Pozzolan mortars by changing molarity of solution from 2.5 to 12.5 M with incremental increases of 2.5 M. The results are presented in Table 4. The 7-day compressive strengths are also shown in Figs. 2, 3, and 4. As can be seen, increases in NaOH concentration led to improvements in compressive strength of alkali-activated natural Pozzolan mortars for all the selected molarities. The improvements, however, were not consistent among NaOH concentrations due to dependency on other parameters, including curing condition, solution-to-binder ratio, and age of samples.

On average, the 7-day compressive strength of the exposed cured mortars increased by 2.8, 4.9, 12.2, and 5.7 MPa, when NaOH concentration increased from 2.5 to 5, 5 to 7.5, 7.5 to 10, and 10 to 12.5 M, respectively. Similar increases in molarity of solution led to averagely 5.6, 7.0, 11.3, and 5.2 MPa improvements for the sealed cured samples and 1.0, 3.6, 6.5, and 6.5 MPa improvements for the moist cured samples, respectively. With the change of S/B, there was less variance in the improvements of compressive strength due to increases in the molarity of solutions. On average, when solution concentration increased from 2.5 to 5 M, the 7-day compressive strength increased by 4.0, 3.0, and 2.5 MPa for S/B of 0.50, 0.54, and 0.58, respectively. These improvements were averagely 6.9, 4.8, and 3.8 MPa when molarity of solution increased from 5 to 7.5 M, and 9.3, 10.1, and 10.6 MPa when it increased from 7.5 to 10 M, respectively. As matter of age effect, the 1-, 3-, and 7-day compressive strengths increased by averagely 1, 2.4, and 3.2 MPa when molarity of solution increased from 2.5 to 5 M, respectively. The improvements in 1-, 3-, and 7-day compressive strengths increased to 2.4, 4.6, and 5.8 MPa when molarity increased from 5 to 7.5 M, and 2.4, 7.6, and 10 MPa when molarity increased from 7.5 to 10 M, respectively. After that, for increases of molarity from 10 to 12.5 M, lower improvements of averagely 1.0, 4.7, and 5.8 MPa were observed in 1-, 3-, and 7-day compressive strengths, respectively.

The observed improvements by increases in the molarity of solution can be related to the greater solubility of aluminosilicate in higher NaOH concentration (Khale and Chaudhary 2007; Bondar et al. 2011a). Since one of the main steps of geopolymerization process is the breakdown of aluminosilicates (Si–O–Si and Al–O–Si bonds) in alkaline environment, higher concentrations led to increased breakdowns. As more aluminosilicates bonds broke down, there were further opportunities for hydrates to be formed, thus increasing the compressive strength. Unlike the research conducted by Palomo et al. (1999) and Xu and Van Deventer (2000), there were improvements in the strength of alkali-activated mortars for all increases in the molarities of up to the 12.5 M which was used in this study. However, lower improvements observed when molarity increased from 10 to 12.5 M in comparison with those observed for increases in molarity from 7.5 to 10 M. This observation could suggest that the activation may not increase after a maximum level of NaOH concentration. It can also be seen that, similar to the pervious conducted research (Bondar et al. 2011a; Kaps and Buchwald 2002), a certain amount of alkaline was needed for a considerable activation. The low compressive strength of mixtures having molarities of 2.5 and 5 M proved that these molarities provided insufficient activation for the natural Pozzolans. The observed behavior can be related to the

Table 4 Compressive strength of alkali-activated mortars cured in the oven

S/B	NaOH concentration (M)	Age (days)	Exposed (MPa)	Moist (MPa)	Sealed (MPa)
0.50	2.5	1	3.8	4.2	4.6
		3	5.2	6.2	5.4
		7	4.6	10.0	5.9
	5	1	7.2	4.8	5.4
		3	9.0	7.5	9.7
		7	8.8	11.2	12.5
	7.5	1	10.4	6.6	7.4
		3	14.5	11.2	16.5
		7	15.3	17.3	20.5
	10	1	13.6	8.7	9.4
		3	27.7	15.9	22.3
		7	26.2	22.9	31.9
0.54	2.5	1	3.5	4.2	4.5
		3	5.0	5.9	5.7
		7	4.6	9.5	5.7
	5	1	6.0	4.1	4.4
		3	6.6	6.8	8.4
		7	6.8	10.5	11.4
	7.5	1	9.8	5.3	5.8
		3	11.0	9.2	14.8
		7	11.5	13.7	17.9
	10	1	12.8	6.7	7.9
		3	25.3	13.5	21.6
		7	24.2	21.1	28.2
	12.5	1	15.7	7.3	10.4
		3	30.8	16.3	24.1
		7	27.6	25.7	30.8
0.58	2.5	1	2.4	2.6	2.9
		3	3.0	3.9	3.4
		7	3.0	6.1	3.9
	5	1	4.7	2.5	3.0
		3	5.5	4.6	6.8
		7	5.1	7.0	8.4
	7.5	1	8.1	3.3	3.5
		3	10.1	6.5	12.6
		7	8.6	8.5	14.9
	10	1	11.9	5.0	5.7
		3	21.9	8.9	17.5
		7	21.6	15.0	27.1
	12.5	1	14.0	5.7	7.4
		3	32.4	17.4	23.3
		7	31.8	26.6	37.7

little dissolution of the natural Pozzolans for concentrations of less than 5 M resulting in low compressive strengths as stated by Bondar et al. (2011a). Also, it could be attributed to the higher concentrations of $[SiO(OH)_3]^-$ when lower concentrations were used (see Eqs. (2) and (3)), leading to further condensation of $[Al(OH)_4]^-$ and ultimately lowering the rate of reaction products (Weng and Sagoe-Crentsil 2007; Sagoe-Crentsil and Weng 2007).

Figures 2, 3, and 4 also highlight the highest rate of increase in the compressive strength for different curing conditions, S/B, and ages of curing. As can be seen, the highest improvements were observed when molarity of

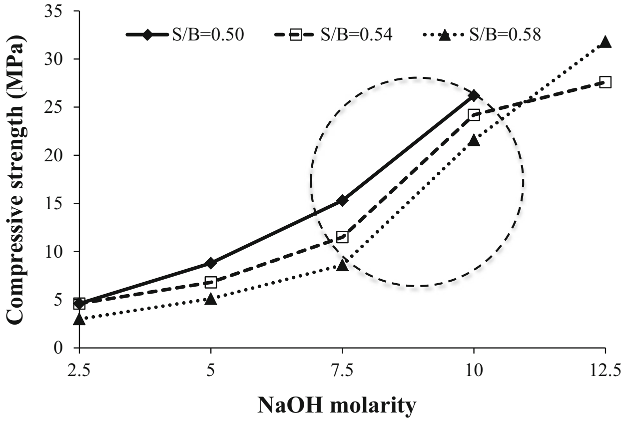

Fig. 2 The 7-day compressive strength of the exposed cured samples

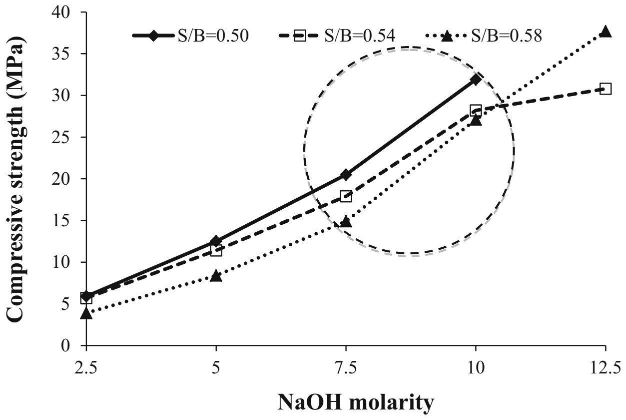

Fig. 3 The 7-day compressive strength of the sealed cured samples

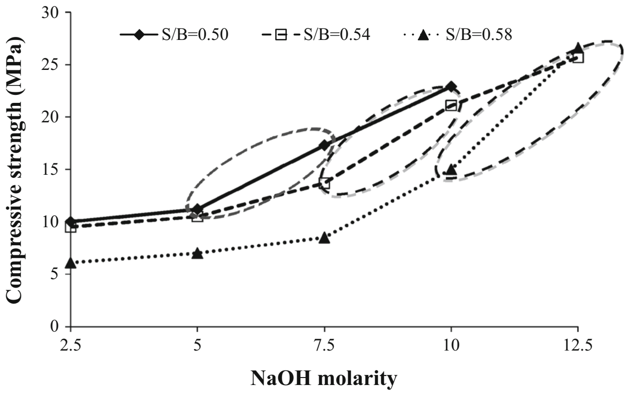

Fig. 4 The 7-day compressive strength of the moist cured samples

alkaline solution changed from 7.5 to 10 M (approximately 10 MPa for the 7-day strength). This observation is particularly true for average improvements under the exposed and sealed curing condition in all the tested S/B and at different ages of testing. For the moist cured condition, the main strength gradient varied for different S/B. The highest increases in strengths of the moist cured samples were observed when molarities increased from 5 to 7.5, 7.5 to 10, and 10 to 12.5 M for S/B of 0.5, 0.54, and 0.58, respectively. The observed behaviors can similarly prove that a minimum alkalinity is needed for un-bonding Pozzolanic oxides and activations. It also proves that increases in the molarity from 10 to 12.5 M may not be as effective as increases from 7.5 to 10 M. The different trend observed for different S/B under the moist cured condition can be most likely occurred due to the increases in excess water in the produced mortars. As S/B increased, the excess water, which needed to evaporate, also increased resulting in lower bond formation. Therefore, a higher concentration of NaOH was required to increase the activation.

Effect of curing condition and age

It has been suggested that curing temperature, curing conditions, and age are of the influential parameters which can significantly affect properties of alkali-activated binders. Use of elevated temperatures catalyzes reactions of alkali-activated binders to help them to form a strong network of hydrates, which in turn substantially increase their compressive strengths. The previously conducted research has shown improvements in the compressive strength of alkali-activated binders when temperatures increased in the ranges of 30–90 °C. Beyond 90 °C, however, increases in temperature may result in adverse effects. Lemougna et al. (2011) found that while strength improved by increases in the temperatures of up to 90 °C, it significantly reduced beyond that temperature. In their studies, as temperature rose to 250 °C, the strengths were nearly halved as a result of loss of structural water as well as formation of micro-cracks. Hence, it was concluded that an oven curing environment ranging in temperature from 30 to 90 °C is most conducive to strength development (Khale and Chaudhary 2007). For the purpose of this study, a constant temperature of 80 °C was selected as it was aimed to assess effects of other influential factors. Curing condition, i.e., condition of samples in the oven, can also affect properties of alkali-activated binders. Lemougna et al. (2011) found that alkali-activated natural Pozzolan (volcanic ash) mortars which cured dry (exposed) in the oven produced higher strengths than those cured wet in the oven (inside water). Bondar et al. (2011b) stated that sealed curing was better than fog (moist) curing. Van Jaarsveld et al. (2002) claimed that alkali-activated fly ash samples cured in the sealed bags developed lower strengths than those cured without sealed bags. Three different conditions of exposed, sealed, and moist cured in the oven were selected for this study. The wet condition, i.e., samples inside water in the oven, was not considered for this research as results of preliminary studies, showing the

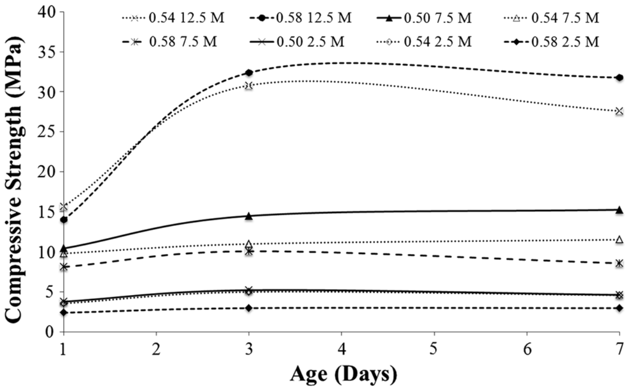

Fig. 5 Effect of age and S/B on compressive strength of the exposed cured mortars

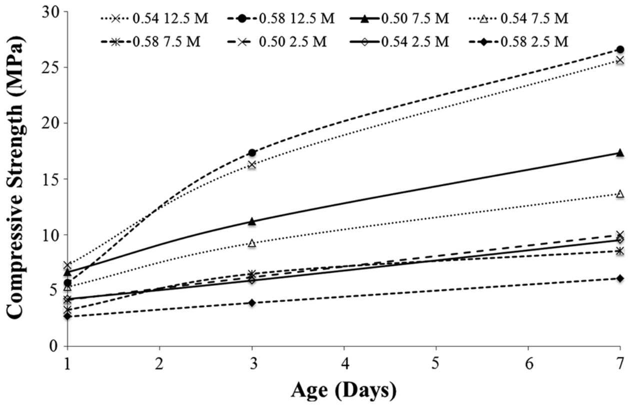

Fig. 6 Effect of age and S/B on compressive strength of the moist cured mortars

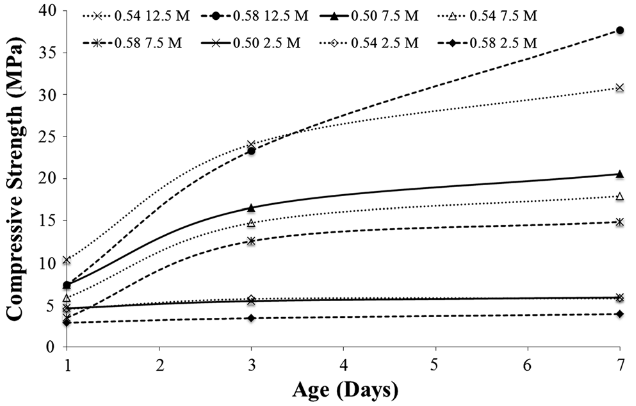

Fig. 7 Effect of age and S/B on compressive strength of the sealed cured mortars

lowest compressive strengths under this condition. In addition to these factors, curing time is another important influential variable to consider. In most of the past studies on alkali-activated binders, the majority of strength was gained within 48 h of curing in the oven. It was also reported that curing in the oven for long time may even reduce the compressive strength (Van Jaarsveld et al. 2002). This study used ages of 1, 3, and 7 days for curing time of samples in the oven. Effects of curing condition and age on the compressive strength of alkali-activated natural Pozzolan mortars are shown in Table 4 and Figs. 5, 6, and 7. In general, there were significant differences in behavior of alkali-activated mortars under different curing conditions. The exposed cured mortars gained their highest strength in their first day or first 3 days of curing depending on the molarity of solution. On the other hand, the moist and sealed cured mortars continuously gained strength up to 7 days. The sealed cured samples achieved higher compressive strengths than the moist and exposed cured samples. The moist cured samples produced higher strength than the exposed cured mortars for lower molarities (2.5, 5, and 7.5 M), whereas opposite trend was observed for higher molarities (10 and 12.5 M).

The exposed cured mortars having molarities of 2.5, 5, and 7.5 M gained most of their compressive strength after 1 day of curing, obtaining values ranging from 68 to 89 % of their maximum strengths. Mixtures with molarities of 10 and 12.5 M gained 43–54 % of their maximum compressive strengths after 1 day of exposed curing. This led to a larger increase in strength between one and 3 days of curing. From 3 to 7 days, most of the exposed cured mortars did not gain any more strength or experienced decreases in their compressive strengths. The moist cured mortars showed a different trend than the exposed cured mortars. After 1 day of curing, the moist cured samples achieved 21–44 % of their ultimate strengths, indicating that the moist oven curing allowed for slower strength development when compared to the exposed condition. For the sealed cured samples, 2.5 M mortars followed a trend similar to that of the exposed cured mortars. They achieved most of their maximum strength (74–78 %) after 1 day of curing. The remaining 5, 7.5, 10, and 12.5 M mortars followed a trend more similar to that of the moist cured mortars. At 1 day, the samples attained 20–43 % of their 7-day strengths. They also continued to gain strength up to 7 days. The observed behaviors can be explained as follows.

There was no humidity available under the exposed curing condition, which allowed strength to develop quickly in all the samples. The mixtures made with lower concentrations of NaOH (2.5, 5.0, and 7.5 M) allowed for evaporation of excess water after 1 day of curing, resulting in reaching to the majority of their highest compressive strengths within 1 day. In the mixtures with molarities of 10 and 12.5 M, more time was required for the excess water to evaporate from the system to form a monolithic geopolymer layer (Bondar et al. 2011a). Exhaustion of all the water did not let any more reaction to occur after 3 days. Therefore, at 3 days of curing, most of the exposed cured mortars had attained their maximum strengths. After 3 days of curing, compressive strengths dropped as dehydration or carbonation occurred and micro-cracks developed. As mortars were exposed to the elevated temperatures for too long, the aluminosilicate gel began to dehydrate and break apart, causing the samples to lose mechanical strength. These reductions can also be related to the development of micro-cracks due to the excessive shrinkage in high temperatures (Khale and Chaudhary 2007). Carbonation of samples in the oven can be another source of the strength reduction (Criado et al. 2005). The PH measurements (presented in section "PH measurements") suggest the occurrence of carbonation for the exposed samples. Their PH was reduced from an absolutely basic mortar with PH of 13 to PH of 9 to 10 at the age of 3 or 7 days, with the PH of 9 for the outer part of samples. Under the same curing conditions (exposed), carbonation was also observed by Criado et al. (2005) for alkali-activated fly ash. Criado et al. (2005) stated that carbonation happens for oven-dry-cured samples, resulting in reductions of pH and strength development. The authors also stated that carbonation can be minimized by providing a high humidity environment.

For the sealed cured mortars, more time was needed to exhaust the extra water, causing fewer bonds to form at early age (1 day) or formation of bonds with a slower rate. In fact, the plastic wrap protected the samples from the dry oven environment, allowing some moisture to be retained within the samples. As such, their strength development occurred at a slower rate than the exposed cured samples due to the presence of moisture, which allowed for the continued reactions and formation of matrix bonds at all ages of curing. In contrast to the exposed cured samples, the sealed cured samples did not experience dehydration or carbonation. The reason that higher molarity mortars achieved majority of their strength at later ages can be related to the delay in polymer formation. Alonso and Palomo (2001) stated increases in the ionic species concentration by increases in molarity of solution limit the ion's mobility and delay the formation of coagulated structures. Bondar et al. (2011a) also reported that mixtures with higher molarities needed longer time or higher temperatures to remove (evaporate) the excess water to allow for proper bonding. The moist cured samples were cured in a high humidity environment, so the extra water within the samples took longer to be removed, causing formation of bonds with a slower rate. These led to lower rate of strength gain within the moist cured samples in comparison with the sealed and exposed cured samples. The PH measurements of sealed and moist cured samples (presented in section "PH measurements") proved that no or minimal carbonation happened under these curing conditions.

It can also be seen that the sealed cured mortars achieved the highest overall compressive strengths. The 7-day compressive strength of the sealed cured mortars was averagely 58.1, 54.3, 21.2, and 15.1 % higher than those of the exposed cured mortars, and 13.4, 41.5, 51.2, and 30.8 % higher than those of the moist cured mortars for molarities of 5, 7.5, 10, and 12.5, respectively. This observation confirms the results observed by Bondar et al. (2011b). It also confirms Criado et al. (2005) suggestion that isolation helps the strength development of samples as carbonation would arise under certain conditions to halt strength development. On the other hand, it contradicts the results observed by Van Jaarsveld et al. (2002) where the exposed curing was superior to the sealed curing. It can also be seen that the exposed cured samples produced higher strengths than the moist cured samples for higher molarities. The reason that moist cured mortars produced the lowest strength can be related to the more water being retained in the pores resulting in a more open microstructure.

The superior performance under sealed cured condition suggests that in order to achieve the highest compressive strengths, some level of moisture content must be retained within the samples. However, too much moisture, in the case of moist curing condition, has adverse effects on alkali-activated natural Pozzolans in reaching their optimal strengths.

Effect of solution-to-binder ratio

The ratio of liquid materials to binder expressed in the form of solution-to-binder ratio (S/B), water-to-binder ratio (W/B), or water-to-geopolymer solid ratio (W/GS) is another variable that has been found to influence properties of alkali-activated binders. Past studies have found its effects on the strength properties contradictory. Hardjito et al. (2004) reported improvements in compressive strength by decreases in W/GS. Mandal and Majumdar (2009), Ravikumar et al. (2010) stated increases in strength by reducing S/B, whereas Joseph and Mathew (2012) noticed increases in strength by reduction in either S/B or W/GS. Bondar et al. (2011b) also showed that alkali-activated natural Pozzolan mortars made with W/B of 0.45 performed superior to those made with W/B of 0.55. In the contrary, Palomo et al. (1999) concluded that S/B was not a relevant parameter to affect strength properties. Katz (1998) also concluded that reduction of water-to-fly ash ratio (W/B) resulted in a reduced compressive strength. For the purpose of this study, the effect of S/B on the strength properties of alkali-activated natural Pozzolan mortars was considered by using three different S/B of 0.50, 0.54, and 0.58. The W/B and W/GS of these mixtures were also reported and discussed as well. These effects are shown in Table 4 and Figs. 2, 3, and 4 as well as Figs. 5, 6, and 7. In general, the compressive strength reduced with increases in S/B. This trend was similar to the general trend of PC and previous studies conducted on geopolymers by Hardjito et al. (2004), Mandal and Majumdar (2009), Ravikumar et al. (2010), Bondar et al. (2011b), Joseph and Mathew (2012).

When S/B increased from 0.50 to 0.54, the strength of alkali-activated mortars having molarities of 2.5, 5, 7.5, and 10 reduced by averagely 2, 15, 17, and 11 %, respectively. Increases in S/B from 0.54 to 0.58 resulted in a more significant reduction in compressive strength than what observed when S/B increased from 0.50 to 0.54. On average, increases in S/B from 0.54 to 0.58 caused 36, 27, 25, 19, and 1 % reduction in the compressive strength of alkali-activated mortars having molarities of 2.5, 5, 7.5, 10, and 12.5, respectively. The observed reductions in compressive strengths can be related to entrapment of more water within the alkali-activated paste which made a looser micro-structure (Bondar et al. 2011b). The exposed cured mortars experienced less of an impact on compressive strength due to change in S/B than the moist and sealed cured mortars. This can be explained by the dry condition of the exposed curing. The excess water was able to evaporate more easily under the exposed curing condition, causing the S/B to have less of an impact.

It is worth mentioning that the mixtures with a similar S/B or W/B or W/GS did not produce equal compressive strengths. An example can be found when comparing results of 7.5 M mortars (S/B = 0.50, W/B = 0.380, and W/GS = 0.339) with those of different 10 M mortars (1. S/B = 0.50, W/B = 0.347, and W/GS = 0.300, 2. S/B = 0.54, W/B = 0.374, and W/GS = 0.321, and 3. S/B = 0.58, W/B = 0.402, and W/GS = 0.341). The 7-day sealed cured compressive strength of 7.5 M mortar was 20.5 MPa, whereas the above-mentioned 10 M mortars had strengths of 31.9, 28.2, and 27.1 MPa, respectively. These results prove that the amount of sodium hydroxide (or NaOH concentration in mixture) is a key contributor to the strength of the studied mortars.

Compressive strength of standard moist cured samples

Table 5 documents the compressive strength of companion samples cured under standard curing conditions without use of elevated temperatures. As can be seen, there was not any significant strength development under standard curing condition. The additional activation provided by the higher concentrations did not improve the overall performance of the standard cured mixtures. There was no common trend among the samples other than increases in the compressive strength by increases in curing time from 7 to 28 days and decreases in S/B.

Table 5 Compressive strengths of standard moist cured mortars

S/B	NaOH concentration (M)	Compressive strength (MPa)	
		7 days	28 days
0.50	2.5	2.8	3.8
	5	3.2	5.3
	7.5	3.2	5.6
	10	3.8	5.6
0.54	2.5	3.4	5.1
	5	2.2	3.6
	7.5	2.9	4.8
	10	2.7	4.4
	12.5	2.5	3.4
0.58	2.5	2.0	2.9
	5	1.6	3.0
	7.5	1.5	3.0
	10	1.6	3.6
	12.5	1.6	2.4

The 7- and 28-day compressive strengths of standard cured mortars ranged from 1.6 to 3.8 and 2.4 to 5.6 MPa, respectively. The low strength gain can be related to little formation of monolithic geopolymers. Since the curing room did not allow for evaporation of the excess water, little monolithic geopolymer was formed producing samples with low compressive strengths. The observed compressive strength test results confirm that the elevated temperatures are necessary for alkali-activated natural Pozzolans to allow the formation of the monolithic geopolymer layer and strength development (Bondar et al. 2011a). These results also confirm Bakharev (2005) statement that a day of curing at elevated temperature can develop strength as much as a month of curing in ambient temperatures.

Flexural strength

Modulus of rupture of the studied alkali-activated mortars was evaluated on the 7-day sealed oven-cured beams. Strain gauges were attached at samples' extreme tension side to measure flexural strains with loading. The obtained stress–strain curve was used to calculate modulus of elasticity of the studied mortars. The ultimate strain, modulus of rupture, and elastic modulus are presented in Table 6. Overall, the flexural strength and modulus of elasticity showed a similar trend to that of the compressive strength. They increased with increases in NaOH concentration and

Table 6 Flexural strength test results

NaOH concentration (M)	S/B	Ultimate strain (με)	Modulus of rupture (MPa)	Modulus of elasticity (MPa)	Modulus of rupture/compressive strength
2.5	0.50	533	1.329	4330	0.23
	0.54	353	1.135	3616	0.20
	0.58	200	0.732	3481	0.19
5	0.50	270	2.766	13,431	0.22
	0.54	795	2.783	9307	0.24
	0.58	335	2.524	8750	0.30
7.5	0.50	392	6.174	18,155	0.30
	0.54	507	5.740	14,694	0.32
	0.58	594	5.476	14,018	0.37
10	0.50	385	7.074	19,146	0.22
	0.54	458	6.562	17,251	0.23
	0.58	431	6.665	16,789	0.25
12.5	0.54	386	8.490	21,554	0.28
	0.58	273	6.040	21,137	0.16

Table 7 Results of PH measurements

NaOH concentration (M)	S/B	Fresh state	After 3-h curing in oven inside molds	Exposed oven cured			Sealed oven cured			Moist oven cured			28-day standard curing
				1 day	3 day	7 day	1 day	3 day	7 day	1 day	3 day	7 day	
2.5	0.50	13	13	10.5	10	10	12	11.5	10	12.5	12	12	13
	0.58	13	13	11	9.5	9	12.5	11	11.5	12.5	11.5	10.5	13
5	0.50	13	13	11	11	10.5	12	12	11.5	12	12	12	13
	0.58	13	13	11.5	11	10	12	11.5	12	12	11.5	11	13
7.5	0.50	13	13	12	12	11	12.5	12.5	12	12	12	12	13
	0.58	13	13	12	12	10.5	12.5	12	12	12.5	11.5	11	13
10	0.50	13	13	12	12	12	13	12.5	12.5	12.5	12	11.5	13
	0.58	13	13	12	12	11	13	12.5	12	12.5	11.5	11.5	13
12.5	0.58	13	13	12	12	12	12.5	12	12	12	12	12	13

decreases in S/B. The largest stiffness and modulus of rupture were exhibited by the mixture having molarities of 12.5 M and S/B of 0.54, and the smallest results were observed in the mixture having molarities of 2.5 M and S/B of 0.58. The amount of strain varied among the samples, with no trend relative to NaOH concentration or S/B.

Modulus of rupture of alkali-activated mortars having S/B of 0.50 increased by 108, 123, and 15 % when molarities of solution increased from 2.5 to 5, 5 to 7.5, and 7.5 to 10, respectively. These increases were 210, 35, and 5 % for modulus of elasticity, respectively. Increases in molarity of solution from 2.5 to 5, 5 to 7.5, 7.5 to 10, and 10 to 12.5 led to 145, 106, 14, and 29 % improvements in modulus of rupture and 157, 58, 17, and 25 % increases in modulus of elasticity of mixtures having S/B of 0.54, respectively. For S/B of 0.58, similar increases in molarity led to 245, 117, 22, and −9 % improvements in modulus of rupture and 151, 60, 20, and 26 % increases in modulus of elasticity, respectively.

Reduction in S/B also led to increases in the stiffness and modulus of rupture. The increases in stiffness were negligible when S/B was reduced from 0.58 to 0.54, ranging from 2 to 7 %. By reducing S/B from 0.54 to 0.50, these increases ranged from 11 to 44 %. Modulus of rupture increased by up to 55 and 17 %, when S/B reduced from 0.58 to 0.54 and 0.54 to 0.50, respectively.

It should be mentioned that the lower NaOH concentration samples did not fail in a brittle manner. As the crack formed, the low concentration samples continued to bend without breaking fully apart. In contrast, the high concentration samples, such as those with molarity of 10 and 12.5, broke quickly and rigidly with little bending. This trend in failure showed that the lower concentration solutions produced mortars with more ductility, whereas the higher concentrations led to more brittle behavior. The brittleness as a weak point for higher alkaline concentrations was also stated by Bondar et al. (2011a). The flexural-to-compressive strength ratio was also calculated, and the results are presented in Table 6. This ratio varying in the range of 0.16–0.37 depends on the molarity of solution and S/B.

PH measurements

PH measurements were conducted in this study to monitor alkalinity of the alkali-activated natural Pozzolan mortars on different occasions, from fresh state till different ages of hardened state. In order to measure PH, a PH indicating solution was sprayed on the split samples and the PH was detected based on the change in color. The spray indicator consisted of different colors for PH levels of 5, 7, 9, 11, and 13. After each sample was cut and PH indicator was sprayed, each sample was divided into 4 zones and averages of PH of these zones were calculated. The results of these measurements are presented in Table 7 for S/B of 0.5 and 0.58 to represent lower and upper solution-to-binder ratios, respectively. As can be seen, the selected mortars were totally basic (PH of approximately 13) at their fresh state, after 3 h of sealed curing in the oven, and also when they were cured in the curing room without use of elevated temperatures. The PH of samples, however, reduced when they were cured in the oven. The PH reduction was higher for the exposed curing condition than the moist and sealed curing conditions. In particular, PH of the exposed samples reduced by increases in age of testing. On average, PH of the exposed cured samples after 7 days of curing in the oven was 9.5, 10.25, 10.75, 11.5, and 12 for molarities of 2.5, 5, 7.5, 10, and 12.5 M, respectively. For similar activator concentrations, PH was averagely 10.75, 11.75, 12, 12, and 12 for the sealed cured samples and 11.25, 11.5, 11.25, 11.5, and 12 for the moist cured samples, respectively. This observation may be related to occurrence of carbonation within the exposed cured samples. Previous studies showed that the dry elevated temperatures can increase the probability of carbonation, whereas the contrary occurs under moist conditions (Criado et al. 2005). The occurrence of carbonation can reduce pH and interfere with the activation process for which the intrinsic strength of the matrix is negatively impacted. The majority of carbonation and resulting pH reduction occur at early age due to high availability of moisture and weaker matrix (Criado et al. 2005).

It can also be seen that the PH of mixtures was increased with increases in NaOH concentration. The PH of mixtures slightly decreased when S/B increased from 0.5 to 0.58. Their differences were, however, in the range of 0–1.

Transport properties

Nearly all investigations on alkali-activated natural Pozzolans have been on strength properties, while only one study was conducted to assess transport properties using potassium hydroxide and sodium silicate for activation purposes (Bondar et al. 2012). In their research, oxygen permeability, rapid chloride penetration test (RCPT), and chloride diffusion were measured which showed reduction in permeability with reduction in S/B. They also found that

Table 8 Results of absorption test

NaOH concentration (M)	S/B	Absorption after immersion (%)	Absorption after immersion and boiling (%)	Bulk density, dry	Bulk density after immersion	Volume of permeable voids (%)
2.5	0.5	12.40	13.62	1.898	2.133	25.84
	0.54	13.41	15.28	1.877	2.129	28.68
	0.58	13.82	15.66	1.84	2.095	28.83
5	0.5	10.33	11.82	1.943	2.144	22.95
	0.54	11.26	12.88	1.903	2.094	24.25
	0.58	11.52	13.17	1.907	2.13	25.16
7.5	0.5	7.70	8.42	2.074	2.234	17.47
	0.54	8.42	9.38	1.962	2.106	18.22
	0.58	9.92	12.17	1.961	2.168	24.01
10	0.5	3.94	4.66	2.1	2.18	9.54
	0.54	5.47	7.33	2.038	2.149	14.94
	0.58	6.41	9.14	1.961	2.087	17.93
12.5	0.54	2.38	4.36	2.071	2.12	9.01
	0.58	2.41	5.70	2.069	2.119	11.78

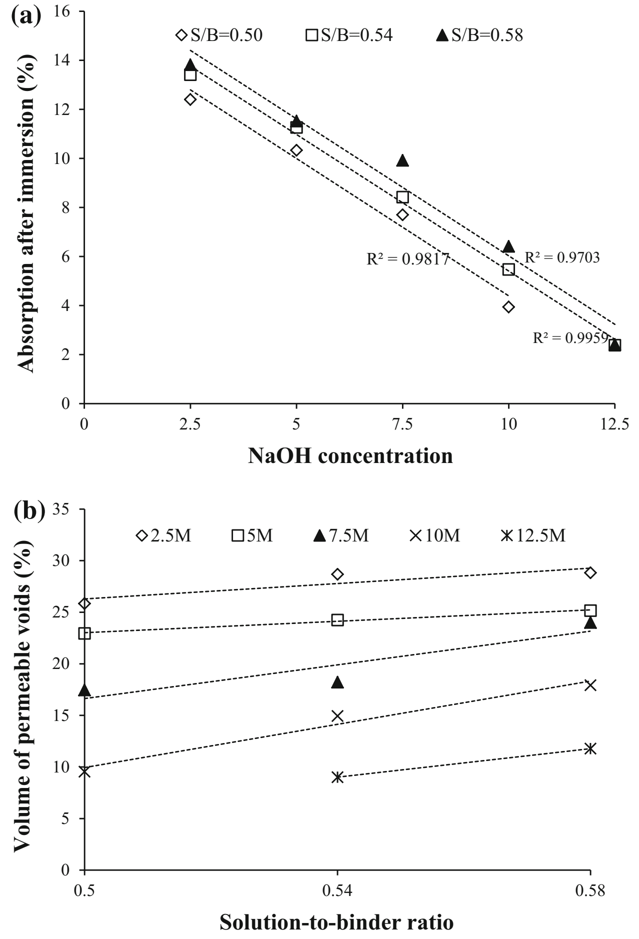

Fig. 8 Results of absorption test on the studied alkali-activated mortars; **a** absorption after immersion, **b** volume of permeable voids

the RCPT gives misleadingly high results for the alkali-activated concretes. For the purpose of this study, absorption, rapid chloride migration, and RCPT tests were conducted on the 7-day sealed oven-cured alkali-activated natural Pozzolan mortar samples.

Absorption

ASTM C642 was used to determine the density, absorption, and volume of permeable voids of the studied alkali-activated mortars. Table 8 and Fig. 8 present the results of this test. The results showed that both molarity of alkaline activator and S/B had significant effects on absorption and volume of permeable voids. Absorption and void percentages reduced by increases in molarity and reduction in S/B, whereas opposite trend was observed for density.

As can be seen, there was an almost linear trend in the results of absorption percentage with increases in molarity of solution. On average, for each 2.5 M increases in molarity, the absorption percentage was reduced by 2.7 %, starting from averagely 13.2 % for mixtures with molarity of 2.5 M to 2.4 % for mixtures having 12.5 M. Similarly, volume of permeable voids significantly reduced with increases in NaOH concentration. When molarity of solution increased from 2.5 to 5, 5 to 7.5, 7.5 to 10, and 10 to 12.5 M, volume of voids decreased by averagely 13, 18, 30, and 37 %, respectively. Reduction in S/B also led to improvements in absorption properties. Absorption improved averagely 7.3 and 13.1 % when S/B reduced from 0.58 to 0.54 and 0.54 to 0.50, respectively. Similar reductions in S/B led to 13.7 and 13.9 % improvements in

Table 9 Results of rapid chloride migration and rapid chloride penetration tests

NaOH concentration (M)	S/B	Rapid chloride migration			RCPT (charge passed for voltage of 10 V)
		DNSSM × 10^{-12} (m^2/s)	Rate of chloride penetration (mm/Vh)	Chloride penetration depth (mm)	
2.5	0.5	194.77	0.538	32.29	6118
	0.54	214.57	0.587	35.19	6308
	0.58	285.21	0.760	45.62	6800
5	0.5	112.56	0.331	19.88	6625
	0.54	121.01	0.352	21.09	–
	0.58	181.20	0.503	30.17	6776
7.5	0.5	41.33	0.144	8.63	6239
	0.54	64.55	0.206	12.38	6433
	0.58	71.65	0.225	13.48	7080
10	0.5	21.38	0.088	5.26	2407
	0.54	21.80	0.089	5.33	3463
	0.58	23.10	0.092	5.53	6397
12.5	0.54	15.63	0.071	4.23	1054
	0.58	17.08	0.075	4.49	1065

The voltage and test duration for rapid chloride migration test were 10 V and 6 h, respectively volume of permeable voids, respectively. Higher hydroxide concentration resulted in greater alkali activation and a more compact matrix with less voids to allow for moisture penetration (decreased absorption). Ravikumar et al. (2010) also reported a similar behavior for volume of permeable voids as affected by reduction in solution-to-binder ratio.

Rapid chloride migration test

For the purpose of measuring resistance against chloride permeation, RCPT was conducted. Similar to the observations of Bondar et al. (2012), the passed current and charge were misleadingly high. As the test could not be carried out with the standard voltage of 60 V, tests were conducted with 10 V and the results are presented in Table 9. These results show that even with use of 10 V, the passed charge was significantly high.

Rapid chloride migration test was used to measure the actual depth of penetrated chloride, and the results are also shown in Table 9. Unlike RCPT, this test method provided valuable data. It can be seen that chloride penetration (presented as penetrated depth, diffusion coefficient, and penetrated depth per volt. hour) considerably decreased by increases in molarity of solution or reduction in S/B. There were averagely 14.1 and 11.4 % reduction in depth of penetrated chloride when S/B reduced from 0.58 to 0.54 and 0.54 to 0.50, respectively. The improvements were more significant when NaOH concentration increased. The depth of penetrated chloride reduced by 37, 51, 52, and 20 %, when molarity of solution increased from 2.5 to 5, 5 to 7.5, 7.5 to 10, and 10 to 12.5 M, respectively.

Conclusions

Based on the results of this study, the following conclusions can be drawn:

- Majority of the sealed oven-cured alkali-activated natural Pozzolan mortars produced 7-day compressive strength well beyond the structural compressive strength requirement of 20 MPa.
- The flow of the studied mortars had an inverse relationship with NaOH concentration, but a direct relationship with solution-to-binder ratio.
- Room temperature water-cured samples showed no significant strength gain. These samples would have little applications in the construction industry due to their low compressive strengths. Use of elevated temperatures was necessary for activations of natural Pozzolans.
- The exposed oven curing environment allowed for the most rapid strength gain due to the faster evaporation of excess water. After 3 days of curing, the exposed oven-cured mortars achieved their highest compressive strengths. Both sealed and moist oven-cured samples required longer curing times to reach their optimum strengths.
- The sealed curing samples achieved the highest compressive strengths after 7 days. The moist oven-cured mortars produced higher strength than the exposed oven-cured mortars with lower NaOH molarities (2.5, 5, and 7.5 M), whereas opposite trend was observed for the mortars prepared with higher NaOH molarities (10 and 12.5 M). The superior performance under sealed oven-cured condition suggests that in order to achieve optimum compressive strength, some moisture must be retained within the samples, whereas too much moisture, in the case of moist oven curing, has the opposite effect.
- The PH measurements suggested carbonation within the exposed oven-cured mortars, while there was minimal or no carbonation within the sealed and moist oven-cured samples.
- Increases in NaOH concentration produced mortar samples with greater compressive strengths. Solution-to-binder ratio had an inverse relationship with compressive strength. As S/B increased, compressive strength decreased.
- Use of higher NaOH concentrations and lower S/B led to greater flexural strengths and elastic modulus.
- Absorption, volume of permeable voids, and depth of penetrated chloride improved considerably by increases in molarity of alkaline activator. There are, however, varying opinions on this observation in the literature. Reduction in solution-to-binder ratio was useful in improving transport properties of the studied alkali-activated natural Pozzolan mortars.

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