Construction and Building Materials 118 (2016) 43–51

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Compressive strength of fly ash-based geopolymer concrete with crumb rubber partially replacing sand

Yeonho Park [a], Ali Abolmaali [a], Young Hoon Kim [b,*], Masoud Ghahremannejad [a]

[a] Department of Civil Engineering, The University of Texas at Arlington, Arlington, TX 76019, USA
[b] Department of Civil and Environmental Engineering, The University of Louisville, Louisville, KY 40292, USA

HIGHLIGHTS

- Rubber replacement plays a key role in strength reduction of geopolymer concrete.
- Appropriate rubber amount may be replaced without significant strength reduction.
- The fly ash type and $Na_2SiO_3/NaOH$ also leads to the strength reduction.
- The regression models are used to identify critical parameters and interactions.

ARTICLE INFO

Article history:
Received 9 February 2016
Received in revised form 1 May 2016
Accepted 2 May 2016
Available online 11 May 2016

Keywords:
Geopolymer
Fly ash
Alkaline liquid
Alkaline-activated mix designs
Compressive strength
Crumb rubber

ABSTRACT

This study presents the feasibility of geopolymer concrete to which crumb rubber from recycled tires has been added. Geopolymer concrete utilizes industrial by-products like fly ash. Therefore, the use of rubberized geopolymer as a binder in concrete production not only reduces the emission of carbon dioxide, because of the elimination of cement, but also utilizes an industrial disposal of recycled tires to produce a sustainable construction material. In this research, fly ash, an alkaline liquid mix of sodium hydroxide and sodium silicate, and crumb rubber were used as the basic constituents of the geopolymer. Various factors that influence the compressive strength were studied, such as molarity of sodium hydroxide, size of aggregates, amount of rubber, and types of fly ash. An appropriate amount of rubber may be replaced with an equal volume of fine aggregates in rubberized geopolymer concrete. The analysis of variance (ANOVA) indicates that fine aggregates can be replaced with an equal volume of crumb rubber, up to 5% in three types of fly ash-based geopolymer concrete at the 95% confidence level. The regression model indicates that the correlation between rubber replacement and other parameters are not statistically significant.

1. Introduction

Concrete is the most extensively used construction material in the world because of its versatile applications. However, the essential ingredient of concrete is Portland Cement (PC), which is not considered an environmentally friendly material and consumes natural raw materials such as limestone and natural sand. The production of PC not only uses a considerable amount of energy, but also emits a substantial amount of carbon dioxide (CO_2) and other greenhouse gases [1]. The production of one ton of PC requires 4 GJ of energy and emits approximately 1.35 billion tons of CO_2 into the atmosphere annually [2–5]. Due to the production of PC, it is estimated that by the year 2020, emissions of CO_2 will increase approximately 50% from the current levels [6]. Moreover, production of one ton of PC consumes about 2.8 tons of raw materials, including fuel and other natural resources [7].

Geopolymer concrete, an inorganic polymer concrete, has emerged as a viable low cost and greener substitute for PC-based concrete, with good properties such as high compressive strength, low creep, superior acid resistance, and low shrinkage [8–11]. Geopolymer binds the loose fine aggregates, coarse aggregates, and other unreacted materials together to form the geopolymer concrete (Hardjito et al. 2004) [5]. It is an alkali-activated binder produced by a polymeric reaction of alkaline liquids with the silicon and aluminum oxides in source materials of geological origin, like metakaolinite (calcined kaolinite) or industrial by-product materials such as fly ash and rice husk ash (Davidovits 1999)

---

* Corresponding author.
E-mail addresses: ypark@uta.edu (Y. Park), abolmaali@uta.edu (A. Abolmaali), yhkim005@louisville.edu (Y.H. Kim), masoud.ghahremannejadm@uta.edu (M. Ghahremannejad).

http://dx.doi.org/10.1016/j.conbuildmat.2016.05.001
0950-0618/

[12]. It not only generates less CO_2 than PC, but also reuses industrial by-products of alumino-silicate composition to produce added-value construction material products (Hardjito et al. 2004; Malhotra 2002) [5,9]. It has been reported that coal combustion production (CCP) constitutes the nation's second largest waste stream after municipal solid waste. About 130 megatons (MT) of CCP were produced in 2011 and 56.57 MT (43.50%) of 130 MT were utilized (ACCA 2002) [13]. The main types of CCPs are fly ash, bottom ash, boiler slag, and flue gas desulfurization materials (FGD). About 59.9 MTs of total CCP were categorized as fly ash. About 22.9 MTs (38.36%) of fly ash were utilized, and the rest was disposed of in landfills or surface impoundments, which are lined with compacted clay soil, a plastic sheet, or both. Utilization of fly ash in geopolymer concrete replaces PC and assists in producing a green construction material. Several researchers studied the effects of parameters such as molarity of sodium hydroxide solution, curing temperature, curing method, and time on the compressive strength of fly ash-based geopolymer concrete. The effects of these parameters have not yet been completely identified. Some researchers have shown that the increase in compressive strength is in direct relation to an increase in molarity of the sodium hydroxide solution [14,15], while others have shown a negative impact on the strength with an increase in molarity [16]. Van Jaarsveld et al. (2003) reported that the particle size, calcium content, alkali metal content, amorphous content, and morphology and origin of the fly ash affected the properties of geopolymers [17]. It was revealed that the calcium content in fly ash plays an important role in strength development and final compressive strength, as the higher calcium content results in accelerated strength development and higher compressive strength. Lloyd and Rangan (2009) found that the presence of calcium could result in flash setting, and therefore must be carefully controlled [18]. Fernandez-Jimenez and Palomo (2003) claimed that in order to obtain the optimal binding properties of the material, fly ash, as a source material, should have low calcium content [19]. Hardjito and Rangan (2005) observed that a longer curing time and higher curing temperature resulted in greater compressive strength [14].

The use of crumb rubber, recycled from automotive and truck scrap tires, in concrete mixes was introduced in the past two decades to reduce another environmental impact of concrete caused by the waste of natural resources [20,21]. Approximately 275 million rubber tires are disposed of annually in the United Sates [22] and about 180 million in the European Union [23]. The heavy metals and other pollutants in tires create an environmental risk when the tires are placed in wet soils in the landfill, resulting in the leaching of toxins into the groundwater. In response to these concerns, many countries have made it illegal to dispose of tires in landfills and have established strict controls on size and operations of scrap tire collection facilities [24]. Therefore, structural applications of rubberized concrete have drawn attention as an effective way to reduce an environmental risk. The findings from several early studies indicated that rubberized concrete improves ductility and impact resistance, but reduces compressive and flexural strength [20,21,23,25–27]. There is a consensus about a severe reduction in strength and ductility due to excessive rubber content; however, there is still limited data and information on the interaction between rubber and the other constituents in geopolymer concrete. Limited studies have been conducted on the effect of crumb rubber on fly ash-based geopolymer concrete mixtures even though it has gained much attention in structural applications among the numerous experimental studies conducted in the literature references. In addition, the rubber content has a significant effect on the mechanical properties of rubberized concrete, but the limited information available on the mechanical behaviors of rubberized geopolymer concrete still leaves things unclear, and additional evidences are needed to verify the possibility of producing geopolymer concrete composites (fly ash-based), where crumb rubber is a partial replacement of fine aggregates. This paper investigates the effects of different types of parameters, including molarity of sodium hydroxide solution, sizes and amounts of aggregates, curing temperatures, curing methods, and time on the compressive strength of rubberized geopolymer concrete, depending on the types of fly ash.

2. Experimental program

2.1. Materials

The main constituents of geopolymer are the source materials (metakaolinite, kaolinite, fly ash, and slag) and the alkaline liquids, which serve as the activator. Since the calcium content in fly ash is the best indicator of how the fly ash will behave in concrete mixtures, in this study, class F and class C fly ashes (low and high calcium contents, respectively) obtained from three different resources were examined as source materials that are rich in silicon and aluminum [28]. Table 1 shows the chemical composition of the different types of fly ash, as determined by X-ray fluorescence (XRF) analysis.

A combination of sodium hydroxide and sodium silicate solutions was used as the activator (the alkaline liquid). Sodium hydroxide in the form of flakes (NaOH with 98% purity), and sodium silicate solution ($Na_2O = 10.6\%$, $SiO_2 = 26.5\%$ and density = 1.39 g/ml at 25 °C) were used. To prepare the sodium hydroxide solution, sodium hydroxide flakes, depending on the molarity, were first weighed and dissolved in one liter of distilled water. The molarity is defined as number of moles of solute per liter of solution. In order to prepare the solution of 1 M, 40 g of NaOH flakes (molecular weight of NaOH = 40) were dissolved in one liter of water (see Table 2). The hydroxide solution was left for about two hours to allow the exothermically heated liquid to cool to room temperature. The sodium silicate solution was added to the required amount of hydroxide solution to prepare the alkaline solution. The alkaline solution was prepared 24 h prior to use. On the next day, a super plasticizer (SP), based on polycarboxylic ether (PCE) with pH-value (20 °C) from 6.5–8.5 and water to create 20% of SP-solution, was added to the hydroxide solution. The aggregates and fly ash were mixed in the concrete mixer for about 4 min. The solution was shaken properly, poured into the mixer, and mixed for 4–5 min.

Table 1
Composition of different types of fly ash as determined by XRF (mass %).

Type of Fly ash	Type I Class C	Type II (Ultra-fine) Class C	Type III Class F
Silicon Dioxide (SiO_2)	50.67%	58.05%	54.70%
Aluminum Oxide (Al_2O_3)	18.96%	21.59%	29.00%
Iron Oxide (Fe_2O_3)	6.35%	5.10%	6.74%
Magnesium Oxide (MgO)	3.12%	1.86%	0.80%
Sulfur Trioxide (SO_3)	0.74%	0.39%	0.10%
Available Alkalis as Na_2O	0.69%	0.92%	1.88%
Calcium Oxide (CaO)	14.14%	9.42%	1.29%
Loss on Ignition	0.17%	0.46%	2.72%

Table 2
Calculation of moles of solute.

Molarity of solution (M)	Moles of solute (g)
1	40
8	320
12	480
14	560

Particle shapes and sizes were analyzed using a scanning electron microscope (SEM: Model S-4800), and the obtained images are presented in Fig. 1. The particle shapes were primarily solid spheres with irregular-shaped particles, and sizes ranged from 50 μm to 200 μm for Type I (Class C with CaO of 14.14%) and Type III (Class C with CaO of 1.29%) fly ash. However, Type II fly ash (Class C with CaO of 9.42%) showed finer particle size distribution, ranging from 1 μm to 60 μm, respectively.

Shredded crumb rubber is obtained from used automotive tires and has particles ranging from 0.075 mm (0.003 in.: No. 200 Sieve) to 4.75 mm (0.19 in.: No. 4 Sieve) (see Fig. 2). The addition of crumb rubber reduces the unit weight of the concrete mixture because the mineral aggregates have a higher unit weight than the crumb rubber particles. Crumb rubber with different replacement ratios of 5–20% (by volume) for sand (fine aggregate) was used in the geopolymer concrete mixture (see Fig. 2).

2.2. Mix designs

Based on the limited past research on rubberized geopolymer mixtures available in the literature and the experience gained during the preliminary experimental works, the parameters considered for the constituents of the mixtures were as follows:

- Amount of crumb rubber (5, 10, 15, and 20%: replacement of fine aggregate by volume)
- Type of fly ash – varies with the percentage of CaO (14.14%, 9.42%, 1.29%)
- Concentration (molarity) of sodium hydroxide solution (8 M and 14 M)
- Ratio of sodium silicate (Na_2SiO_3) to sodium hydroxide (NaOH): 2 and 1/2
- Sizes and amounts of coarse aggregates (9.5 mm or 16 mm) constituted 75–80% of entire mix by mass
- Super Plasticizer constituted (20% solution) = 2% of entire mix (except fine aggregate) by mass.

2.3. Compressive test method

Compressive cylinders were prepared for each mix design and tested in accordance with *ASTM C39 "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens"* [29]. The dimensions of the cylinders were 100 mm × 200 mm (4 in. × 8 in.), and all specimens were compacted with the help of a table-type vibrator, demolded after 24 hours (after production) during the curing period (Steam-Curing : 100% Relative Humidity, 46 °C (115 °F)), and tested 7 days after production. For the cylinder compression tests, the compressive load was applied axially to the cylinder at a rate within a prescribed range of 0.25 ± 0.05 MPa/s (35 ± 7 psi/s). This was applied continuously and slowly, without shock, throughout the test, until the load indicator showed that the load decreased steadily.

3. Results and discussion

After completion of all cylinder tests, data was accumulated and compressive strengths were compared, depending on the variable parameters. The data corresponded to the mean value of the compressive strengths of the three tested cylinders. The 7-day compressive strength of geopolymer concrete with different amounts of crumb rubber, ratios of sodium silicate (Na_2SiO_3) to sodium hydroxide (NaOH), concentration of NaOH solution (molarity), and sizes of aggregates are presented in Table 3.

The highest compressive strength was found to be 42.5 MPa (6.2 ksi), obtained when Class C fly ash-based geopolymer concrete (Type I: CaO = 14.14%) was activated by the mixed alkali solution (activator : Na_2SiO_3/NaOH = 2.0) containing larger size aggregates (16 mm) with 14 M concentration of sodium hydroxide (NaOH), without any crumb rubber. The lowest strength was found to be 16.5 MPa (2.4 ksi), obtained when Class F fly ash-based geopolymer concrete (Type III: CaO = 1.29%) was activated by the mixed alkali solution (activator: Na_2SiO_3/NaOH = 0.5), containing larger

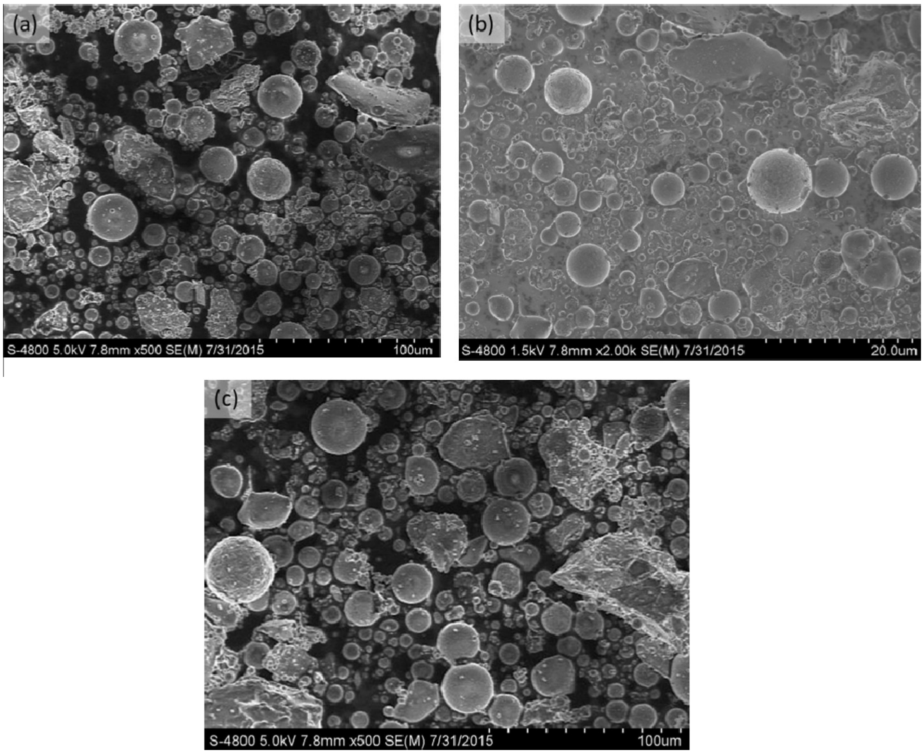

Fig. 1. Fly-ash particle size (SEM image): (a) Type I (CaO: 14.14%), (b) Type II (CaO: 9.42%)-Ultra fine particle, and (c) Type III (CaO: 1.29%).

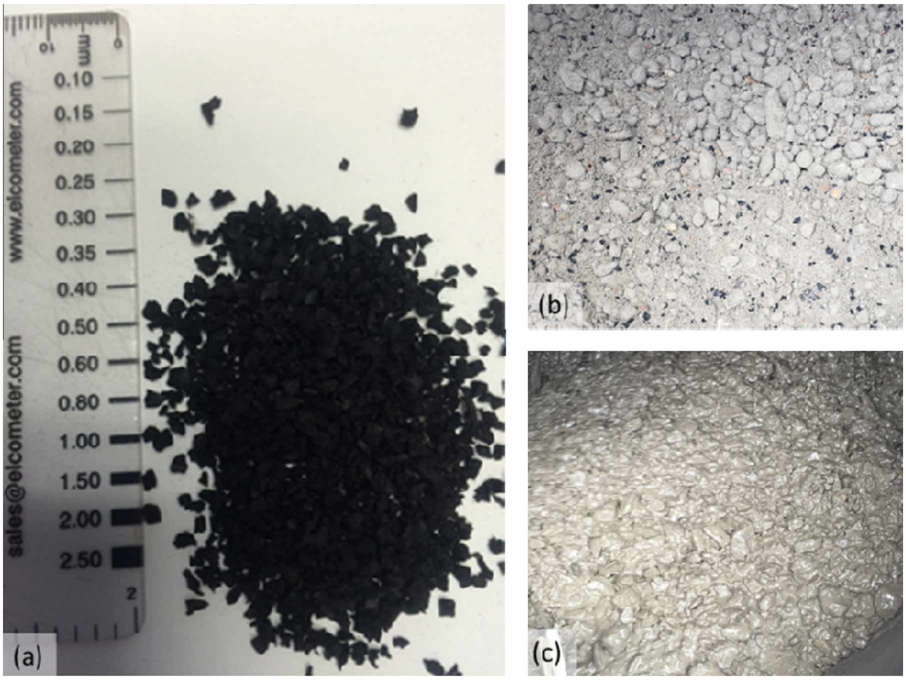

Fig. 2. (a) Crumb rubber, (b) Rubberized geopolymer concrete mixture (before adding alkaline solution), and (c) Rubberized geopolymer concrete mixture (after adding alkaline solution).

size aggregates (16 mm), with 14 M concentration of sodium hydroxide (NaOH), with 20% of crumb rubber to partially replace the sand (fine aggregates) by volume. Regardless of the amount of crumb rubber, the compressive strength of the rubberized geopolymer increased with the use of larger-sized aggregates (16 mm), the higher ratio of sodium silicate (Na_2SiO_3) to sodium hydroxide (NaOH), and the higher concentration of sodium hydroxide (14 M) for all types of fly ash. This is consistent with other geopolymer concrete studies by Diaz-Loya et al. (2011), Hardjito et al. (2004), Guo et al. (2010), and Al Bakri et al. (2011).

3.1. Type of fly ash varying with the percentage of CaO (14.14%, 9.42%, and 1.29%)

Mixes 1 through 5 (Type I), 20 through 23 (Type II), and 28 through 31 (Type III) were made from three different types of fly ash as shown in Table 3. Under the same concentration of NaOH and the ratio of alkaline solutions, Mix 1 (CaO = 14.14%) had a strength of 42.5 MPa – 7 days after casting. Mix 20 (CaO = 9.42%) and Mix 28 (CaO = 1.29%) showed 37.9 MPa and 28.6 MPa, respectively, corresponding to values of 89% and 67% of Mix 1 compressive strength (See Table 3). The compressive strength of geopolymer concrete increased with the increase of the CaO content. The addition of the same amount of crumb rubber, replaced by 5–20% (by volume) of fine aggregates in the geopolymer mixture, weakened the axial compressive strength, as shown in Fig. 3. Mix 5 (CaO = 14.14%), with 20% rubber replacement had the strength of 32.3 MPa, with a reduction rate of 24%. Mix 23 (CaO = 9.42%) and Mix 31 (CaO = 1.29%) showed 31.8 MPa and 22.2 MPa, with the strength reduction rates of 16% and 22%, respectively. The smallest strength reduction rate with 20% rubber replacement was 16% ((37.9–31.8) MPa/37.9 MPa), occurring in Mix 23 (Cao = 9.42%, fine fly ash particles), as shown in Fig. 3. The degree of compressive strength reduction was greater for larger fly ash particle sizes (50–200 μm) than for smaller fly ash particle sizes (1–60 μm). However, under the same concentration of NaOH and ratio of alkaline solutions, the compressive strength of rubberized geopolymer concrete increased with the increase of the CaO content. The content of CaO plays a significant role in the compressive strength of the rubberized geopolymer concrete.

3.2. Molarity of sodium hydroxide (NaOH) solution (8 M and 14 M)

Type I-based mixes 1 through 5 and 11 through 15, Type II fly ash-based mixes 28 through 31, and Type III-based mixes 36 through 38 were made from two types of molarity of NaOH solutions (See Table 3). Fig. 4 shows that for both types of fly ash, the mix with a higher concentration of NaOH solution (14 M) yielded a higher compressive strength at 7 days than the mix with the lower concentration of NaOH solution (8 M). In the case of Type I fly ash, the mix with a lower concentration of NaOH solution (8 M) yielded, on the average, 70% (29.9/42.5) of compressive strength than the higher concentration of NaOH solution (14 M). As in the case of Type III fly ash, the mix with a lower concentration of NaOH solution (8 M) yielded, on average, 87% (24.9/28.6) of compressive strength of the higher concentration of NaOH solution (14 M). This indicates that the compressive strength of the geopolymer concrete varies with the molarity of the NaOH solution, depending on the type of fly ash. This is thought to be due to the different chemical reactions involved and the formation of different compounds while using two different types of fly ash that vary in their chemical composition. This is probably a calcium aluminosilicate glass structure that is significantly more reactive with water than the siliceous glass structure [30] and leads to the formation of calcium silicate hydrate compounds, in addition to the geopolymerization products, augmenting the mechanical strength of the hardened matrix.

The same tendency was observed after the addition of crumb rubber to the geopolymer mixture; however, the reduction rate of compressive strength seemed to increase with the decrease of the concentration of NaOH. (See the reduction rate comparisons in Table 3.) Statistical analysis confirms this observation mentioned.

Table 3
Mix designs and compressive strength of specimens (water: 40 kg/m^3, SP: 3 kg/m^3).

Mix No.	Fly Ash* (kg/m^3)	Sand (kg/m^3)	Rubber (kg/m^3)	Conc. of NaOH (M)	Na_2SiO_3/NaOH	f'_c (MPa)					Strength Reduction
						1	2	3	Ave	Std.	
1	$408^{(I)}$	630	0.0 (0)	14	2	40.2	44.6	42.7	42.5	2.2	1
2	$408^{(I)}$	599	9.7 (5)	14	2	37.7	42.3	41.8	40.6	2.5	0.96
3	$408^{(I)}$	567	19.7 (10)	14	2	37.2	36.7	42.4	38.8	3.2	0.91
4	$408^{(I)}$	535	29.7 (15)	14	2	34.9	39.5	35.5	36.6	2.5	0.86
5	$408^{(I)}$	504	39.4 (20)	14	2	31.6	36.1	29.3	32.3	3.5	0.76
6	$408^{(I)}$	630	0.0 (0)	14	0.5	27.8	30.3	32.4	30.2	2.3	1
7	$408^{(I)}$	599	9.7 (5)	14	0.5	32.4	24.8	26.7	28	4	0.93
8	$408^{(I)}$	567	19.7 (10)	14	0.5	26.6	29.6	25.2	27.1	2.2	0.9
9	$408^{(I)}$	535	29.7 (15)	14	0.5	23.8	22.3	27.6	24.6	2.7	0.81
10	$408^{(I)}$	504	39.4 (20)	14	0.5	25.7	22.3	16.6	21.5	4.6	0.71
11	$408^{(I)}$	630	0.0 (0)	8	2	29.3	26.8	33.7	29.9	3.5	1
12	$408^{(I)}$	599	9.7 (5)	8	2	32.4	27.4	24.1	28	4.2	0.93
13	$408^{(I)}$	567	19.7 (10)	8	2	27.3	27.1	22.1	25.5	2.9	0.85
14	$408^{(I)}$	535	29.7 (15)	8	2	18.3	21.7	28.1	22.7	5	0.76
15	$408^{(I)}$	504	39.4 (20)	8	2	16.6	17.9	23.6	19.4	3.7	0.65
16**	$408^{(I)}$	630	0.0 (0)	14	2	39.8	32.8	31.7	34.8	4.4	1
17**	$408^{(I)}$	567	19.7 (10)	14	2	30.4	36.6	32.1	33	3.2	0.95
18**	$408^{(I)}$	535	29.7 (15)	14	2	29.6	30.6	26.4	28.9	2.2	0.83
19**	$408^{(I)}$	504	39.4 (20)	14	2	27.9	28.7	27.4	28	0.7	0.81
20	$408^{(II)}$	630	0.0 (0)	14	2	40	35.5	38.1	37.9	2.3	1
21	$408^{(II)}$	567	19.7 (10)	14	2	30.4	37.8	39.9	36	5	0.95
22	$408^{(II)}$	535	29.7 (15)	14	2	39.1	34.1	29.5	34.2	4.8	0.9
23	$408^{(II)}$	504	39.4 (20)	14	2	31.6	25.3	38.6	31.8	6.7	0.84
24	$408^{(II)}$	630	0.0 (0)	14	0.5	28.8	32.6	25.2	28.9	3.7	1
25	$408^{(II)}$	567	19.7 (10)	14	0.5	31.8	24.6	24.8	27.1	4.1	0.94
26	$408^{(II)}$	535	29.7 (15)	14	0.5	25.5	22.8	27.1	25.1	2.2	0.87
27	$408^{(II)}$	504	39.4 (20)	14	0.5	20.8	27.1	19.4	22.4	4.1	0.78
28	$408^{(III)}$	630	0.0 (0)	14	2	34.3	25.8	25.7	28.6	4.9	1
29	$408^{(III)}$	567	19.7 (10)	14	2	30.6	25.9	20.4	25.6	5.1	0.9
30	$408^{(III)}$	535	29.7 (15)	14	2	29.6	27.3	18.9	25.3	5.6	0.88
31	$408^{(III)}$	504	39.4 (20)	14	2	19.5	29.8	17.3	22.2	6.7	0.78
32	$408^{(III)}$	630	0.0 (0)	14	0.5	20.8	23.8	27.1	23.9	3.2	1
33	$408^{(III)}$	567	19.7 (10)	14	0.5	20.9	20.4	16.3	19.2	2.5	0.8
34	$408^{(III)}$	535	29.7 (15)	14	0.5	18.9	20.6	15.6	18.4	2.5	0.77
35	$408^{(III)}$	504	39.4 (20)	14	0.5	17.3	14.6	17.6	16.5	1.7	0.69
36	$408^{(III)}$	630	0.0 (0)	8	2	25.3	20.3	29.1	24.9	4.4	1
37	$408^{(III)}$	535	29.7 (15)	8	2	16.9	24.8	18.3	20	4.2	0.8
38	$408^{(III)}$	504	39.4 (20)	8	2	16.3	21.8	14.4	17.5	3.8	0.7

* Note: (Type I) CaO: 14.14%, (II) CaO: 9.42%, and (III) CaO: 1.29%.
** Note: 9.5 mm of coarse aggregate size (16 mm of coarse aggregate were used except mixes of 16 through 19).

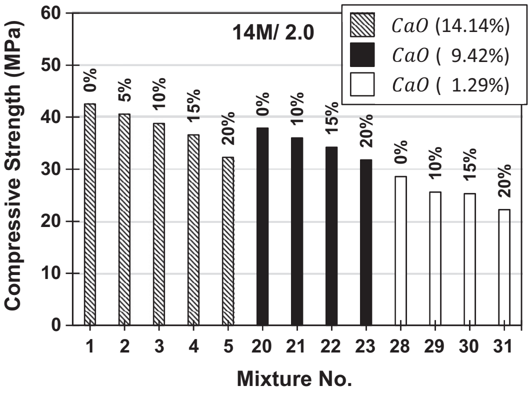

Fig. 3. Comparison of compressive strength with respect to type of fly ash.

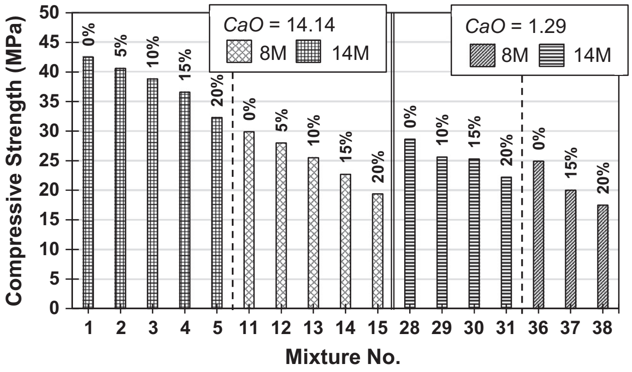

Fig. 4. Comparison of compressive strength with respect to type of molarity.

3.3. Size and amount of aggregates (9.5 mm or 16 mm)

To study the effects of the size and amount of aggregates on the compressive strength of the rubberized geopolymer concrete, Mixes 1 through 5 and 16 through 19 in Table 3 were prepared from Type I fly ash (CaO = 14.14%). Table 3 shows that the presence of larger size aggregates (16 mm) increased the compressive strength of the geopolymer concrete. This may be because the use of large size aggregates with rough surfaces provides better interlocking between them. Similarly, the compressive strength of cement-based concrete were found to increases as the size of coarse aggregate increases [31].

3.4. Ratio of sodium silicate (Na_2SiO_3) to sodium hydroxide (NaOH)

The variations of compressive strength are presented with different ratios (2.0 and 0.5) of sodium silicate (Na_2SiO_3) to sodium hydroxide (NaOH) and the amount of crumb rubber in Fig. 5 and Table 3. Mixes 1 through 10, 20 through 27, and 28 through 35 for Types I (CaO = 14.14%), II (CaO = 9.42%), and III (CaO = 1.29%), respectively, were compared. A higher ratio (2.0) of Na_2SiO_3 to NaOH provided 40.7%, 31.1% and 19.6% higher compressive strength than the lower ratio (0.5) of Na_2SiO_3 to NaOH for Types I, II, and III, respectively, since the higher quantity of Na_2SiO_3 influenced change in the microstructure of geopolymer, and a lower quantity of Na_2SiO_3 caused an insufficient dissolution process of geopolymer formation. The same tendency was observed with the addition of crumb rubber. However, the Type II fly ash (CaO = 9.42%) showed a smaller reduction rate of compressive strength with the increase of crumb rubber. This indicates that smaller particle sizes of fly ash lead to a small loss of compressive strength.

3.5. Rubber content

The influence of crumb rubber content on the average compressive strength of geopolymer concrete is shown in Fig. 6. Generally, the compressive strength with 0.5 ratio of sodium silicate to sodium hydroxide is lower than 30 MPa even without crumb rubber. Therefore, rubberized geopolymer concrete with the ratio of sodium silicate to sodium hydroxide 0.5 is not recommended. When considering the 2.0 ratio of sodium silicate to sodium hydroxide (14 M), the rubber may be replaced up to 15, 20 and 15%, in Type I, Type II, and Type III fly ash-based geopolymer concrete, respectively, to exhibit less than approximately 15% reduction of compressive strength. Further investigation of the mean difference is conducted in the following section.

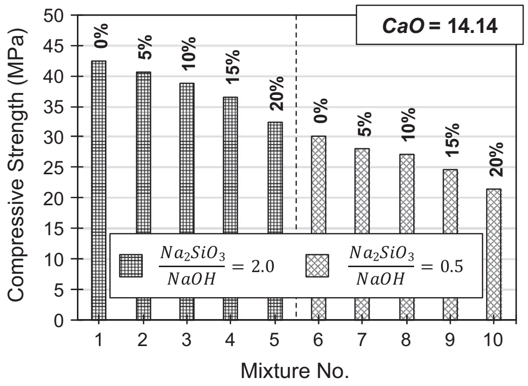

Fig. 5. Comparison of compressive strength with respect to ratio of alkaline solutions.

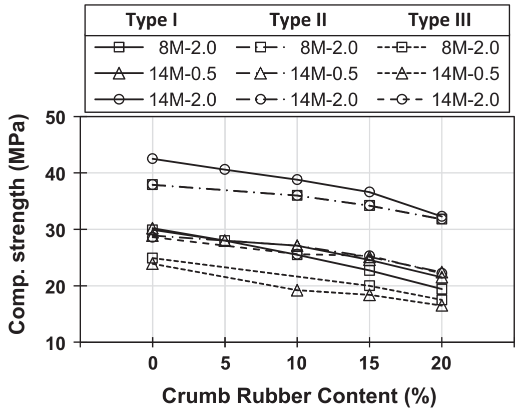

Fig. 6. Reduction ratio of compressive strength (Nomenclature of legend: Fly-ash Type-NaOH (M)-$\frac{Na_2SiO_3}{NaOH}$).

4. Statistical analysis

The regression analysis and analysis of variance (ANOVA) provided the information of the statistical importance of explanatory terms (i.e., predictors in the regression model) and interactions between predictors.

4.1. Regression model development

The authors performed the preliminary analysis with design parameters. It was found that the reduction of strength is solely affected by the ratio of rubber to sand. The other parameters, such as the type of fly ash (CaO contents), the ratio of sodium silicate (Na_2SiO_3) to sodium hydroxide (NaOH), and the concentration of the sodium hydroxide solution do not interact with the ratio of rubber contents. Therefore, the regression model was set up in two steps. First, the regression model was used to predict the strength of concrete without rubber content. Second, the strength of concrete was assumed, and the strength reduction was evaluated as a function of rubber content. Finally, both compressive strengths of geopolymer, f_{crc0} and f_{crc_R} were predicted with one regression model.

The regression model of f_{crc0} is presented as follows. There are significant interactions between CaO contents (in decimal) and other parameters ($\frac{Na_2SiO_3}{NaOH}$ and $NaOH$ (M)) to aid in predicting the strength of concrete without rubber content, f_{crc0} (MPa). The regression analysis, using the step-wise reduction procedure, was performed. The procedure excluded the least important parameter, which exhibited the p-value of less than 0.05. The parameters used to predict the strength of concrete are presented in Table 4. The adjusted R-squared coefficient of determination (R^2-value) was estimated to be 0.89. This indicates that the proposed equation exhibited the rational model with the least parameters. However, it should be noted that the model is only applicable with the ranges of values in parameters in this study. The compressive strength of geopolymer concrete without any rubber content, f_{crc0}, can be formulated as follows:

$$f_{crc0} = \theta_0 + CaO\left[\theta_1 \frac{Na_2SiO_3}{NaOH} + \theta_2 NaOH + \theta_3 CaO\right] \tag{1}$$

As shown in Eq. (1), the CaO content plays an important role in increasing the strength of geopolymer concrete. At the same time, the strength is increased with a higher value of $\frac{Na_2SiO_3}{NaOH}$.

Table 4
Parameters in Regression Model to Predict f_{crc0}.

Parameter	Estimate	Standard Error	p-value
θ_0	11.45	2.85	0.0001
θ_1	24.42	6.06	0.0001
θ_2	7.89	1.59	2.65e−06
θ_3	−748.9	153.4	3.69e−06

As seen in the interaction term between (CaO) and ($NaOH$) in Eq. (1) the increase of NaOH with higher CaO content tends to increase effectively the compressive strength.

The intent of this model development was to evaluate the impact of rubber replacement on the reduction of strength, and it was clear that the strength of the concrete was reduced by an increase in the rubber replacement. There is no significant statistical evidence that the interaction between the rubber replacement and other parameters determines the strength of concrete, $f_{crc0_{avg}}$, of any of the mix designs. In this study, the ratio of rubber to sand by weight (kg/m^3) ranged from 0.016 to 0.078. These values are equivalent to the volume replacement of 5–20%, respectively. The parameters to predict the strength of concrete are presented in Table 5. The compressive strength of geopolymer concrete containing rubber, f_{crcR}, can be expressed as follows:

$$f_{crcR} = \theta_0 + \theta_1 f_{crc0\_avg} + \theta_2 (Rubber/Sand) \qquad (2)$$

The model exhibited the R^2 value of 0.79. This indicates that the rubber replacement reduced the compressive strength. Since the p-value of θ_0 is less than 0.05, the intercept seems insignificant, and the value of intercept can be considered as the error term of the model.

$$f_{crcR} = f_{crc0\_avg} - 97(Rubber/Sand) \qquad (3)$$

Finally, the regression model was proposed to predict the f_{crcR} and f_{crc0} by using all of the parameters considered in this study. This analysis enabled the investigation of the correlation between rubber replacement and other parameters determining geopolymer strength. In particular, the analysis attempted to investigate the correlation between the addition of crumb rubber and the ratio of sodium silicate (Na_2SiO_3) to sodium hydroxide (NaOH). This was not clearly identified in the existing dataset. Statistically, the interaction of these parameters was insignificant based on the p-value of greater than 0.05. The stepwise regression model is shown in Eq. (4), excluding the less important parameters and interactions. The regression model is presented as follows:

$$f_{crcR,0} = \theta_0 + \theta_1\left(\frac{Rubber}{Sand}\right) + \theta_2\left(\frac{Na_2SiO_3}{NaOH}\right) + CaO[\theta_3 NaOH + \theta_4 CaO] \qquad (4)$$

Eq. (4) exhibits the R^2-value of 0.74. Table 6 shows the estimated values for predicting the compressive strength of geopolymer concrete with rubber content ranging from 0 to 20%. As shown in Eq. (4), the rubber content is not strongly correlated with other parameters to determine the compressive strength, f_{crc0} for determining θ_2 θ_3, and θ_4. As the rubber replacement increased, the compressive strength of geopolymer concrete clearly reduced, with the value of 101.3 times the replacement ratio by weight.

Table 5
Parameters in Regression Model to Predict f_{crcR}.

Parameter	Estimate	Standard Error	p-value
θ_0	0.30	1.84	0.86
θ_1	1.00	0.06	9.23e−35
θ_2	−97.0	11.0	1.55e−14

Table 6
Parameters in Regression Model to Predict f_{crcR} and f_{crc0}.

Parameter	Estimate	Standard Error	p-value
θ_0	3.15	4.40	0.475
θ_1	−101.3	12.23	3.67e−13
θ_2	5.46	0.538	2.26e−17
θ_3	6.52	2.75	0.0200
θ_4	−1099	292	0.0002

4.2. Evaluation of rubber replacement

Even though the replacement of rubber is a significant factor in reducing the compressive strength of geopolymer concrete, a statistical evaluation was needed to determine the threshold of replacement to meet the specified performance such as compressive strength. The result of ANOVA is presented in this section. Fig. 7 shows the box plot of geopolymer concrete with respect to the weight (volume) replacement ratio of rubber to sand. Box plot displays the distribution of data with minimum, first quartile, mean, third quartile, and maximum. The value of y-axis is the normalized compressive strength of geopolymer concrete ($= \frac{f_{crc0}}{f_{crc0\_avg}}$ or $\frac{f_{crcR}}{f_{crc0\_avg}}$).

Table 7 shows the summary of statistical analysis, comparing the two means. The differences of the two means (A-B) and 95% confidence intervals are presented. When the p-value is less than 0.05, it indicates that the difference of the means of groups is significant. For example, the difference of 0% rubber replacement and 5% rubber replacement are statistically not significantly different at the 95% confidence level (p-value > 0.05). However, the p-value of 10% and 0% rubber replacement clearly indicates that the difference of compressive strength is significant at the 95% confidence level. Therefore, the threshold for the replacement level to ensure no significant change in compressive strength reduction can be found between 5 and 10%. The additional replacement of 5% apparently exhibits no reduction in the compressive strength compared to both 10 and 15% replacement level at the 95% confidence level. However, the 5% additional replacement significantly reduces the strength in the change of volume from 15 to 20%.

Interestingly, the additional replacement of 10% exhibits no reduction of strength statistically in the change from 5% to 15% replacement (p-value = 0.123 < 0.05). In summary, a 10–15% interval of replacement level is generally required to confirm that the mean of the compressive strength is reduced by the volume change. However, in the high volume replacement, a 5% increase in rubber replacement significantly affects the strength change (e.g., 15% versus 20% replacement). Lower volume change levels of at least 10% are needed to observe the significant change of strength (e.g., 0 versus 10% replacement, 10% versus 20% replacement).

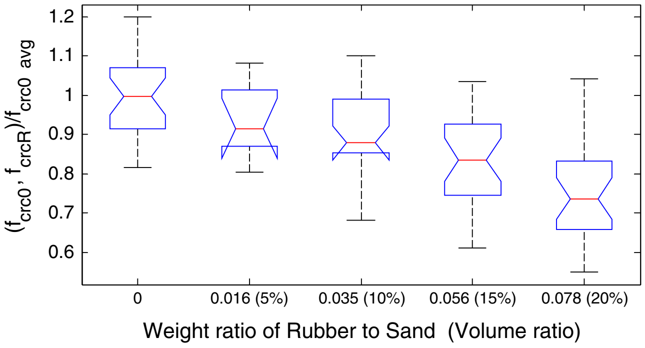

Fig. 7. Box plot of normalized compressive strength.

Table 7
Statistical Analysis: Group Comparisons.

Group Comparisons Replacement %		Lower Bound of C. I. of Mean Difference (95%)	Mean Difference (A-B)	Upper Bound of C. I. of Mean Difference (95%)	p-value
A	B				
0%	5%	−0.0612	0.0611	0.1834	0.6380
0%	10%	0.0105	0.0997	0.18888	0.0203
5%	10%	−0.0856	0.0386	0.1628	0.9103
5%	15%	−0.0162	0.1061	0.2285	0.1213
5%	20%	0.0705	0.1929	0.3152	0.0003
10%	15%	−0.0216	0.0676	0.1567	0.2268
10%	20%	0.0651	0.1543	0.2435	0
15%	20%	0.0002	0.0867	0.1732	0.049

5. Conclusions

This paper focuses on the performance-based investigation of the parameters that significantly influence the mechanical properties of high and low calcium (Classes C and F that are rich in silicon and aluminum), fly ash-based, rubberized geopolymer concrete, in which recycled tire rubber was used to partially replace sand (fine aggregates), ranging in volume from 0 to 20% by volume. The following conclusions can be drawn from this study:

1. The cylinder compressive strength of the geopolymer concrete decreases with the increase in crumb rubber content. Regardless of the type of fly ash, the concentration of the sodium hydroxide solution, or the ratio of the alkali-activator, the addition of crumb rubber decreases the compressive strength of geopolymer concrete.
2. The type of fly ash and the ratio of sodium silicate (Na_2SiO_3) to sodium hydroxide (NaOH), as the mixed activator, leads to a significant reduction of compressive strength. Larger strength reduction due to the addition of crumb rubber is observed with a lower ratio of sodium silicate (Na_2SiO_3) to sodium hydroxide (NaOH). Type II-based geopolymer concrete with finer particle size exhibits less reduction of compressive strength than Types I and III-based geopolymer concrete.
3. The regression models were proposed to understand the critical parameters and to determine the compressive strength of geopolymer concrete and the impact of rubber replacement on strength reduction. A stepwise regression model enabled the identification of key parameters and the correlation between parameters without a significant sacrifice of accuracy of the model. Rubber replacement plays a significant role in the reduction of compressive geopolymer concrete strength. For example, the compressive strength is reduced by 97–101 times the ratio of rubber to sand by weight (kg/m^3). In addition, there is no significant statistical evidence that the interaction between the rubber replacement and other parameters of the mix designs. However, it should be noted that the model is only applicable with the ranges of values in parameters in this study.
4. An appropriate amount of rubber may be replaced with an equal volume of fine aggregates in rubberized geopolymer concrete without significant reduction of the compressive strength. The range of replacement level from 10 to 15% is required to ensure that the mean of compressive strength is statistically reduced by the volume change. Otherwise, it cannot be statistically significant for 5% intervals of replacement, except for the change from 15 to 20%. The rubber replacement of at least 10% leads to reducing the significant change of compressive strength in the basis of the control (0% replacement).

References

[1] P.K. Mehta, Greening of the concrete industry for sustainable development, Concr. Int. (2002) 23–28.
[2] P.K. Mehta, Reducing the environmental impact of concrete, Concr. Int. (2001) 61–66.
[3] T. Salloum, Effect of fly ash replacement on alkali and sulphate resistance of mortars, Concordia University, Montreal, Quebec, Canada, 2007. pp. 1–2.
[4] J. Davidovits, High-alkali cements for 21st century concretes, Concrete Technology: Past, Present and Future, ACI, 1994. sp-144, pp. 383-397.
[5] D. Hardjito, S.E. Wallach, D.M. Sumajouw, B.V. Rangan, On the development of fly ash-based geopolymer concrete, ACI Mater. J. 101 (6) (2004) 467–472.
[6] T.R. Naik, Sustainability of Cement and Concrete Industries, Center for By-Products Utilization, Global Construction, Ultimate Concrete Opportunities, Dundee, Scotland, 2005.
[7] X. Guo, H. Shi, W.A. Dick, Compressive strength and microstructural characteristics of class c fly ash geopolymer, Cem. Concr. Compos. 32 (2010) 142–147.
[8] E. Ivan Diaz-Loya, Erez N. Allouche, Saiprasad Vaidya, Mechanical properties of fly-ash-based geopolymer concrete, ACI Mater. J. 108 (3) (2011) 300–306.
[9] V.M. Malhotra, Introduction: sustainable development & concrete technology, Concr. Int. (2002) 22–23.
[10] J. Davidovits, Geopolymer chemistry & sustainable development. The poly (silicate) terminology: a very useful and simple model for the promotion and understanding of green chemistry, in: Geopolymer Green Chemistry and Sustainable Development Solutions, Proceedings of the World Congress Geopolymer, Saint Quentin, France, 2005, pp. 9–15.
[11] M.M. Al Bakri, H. Mohammed, H. Kamarudin, I.K. Niza, Y. Zarina, Review of fly ash-based geopolymer concrete without portland cement, J. Eng. Technol. Res. 3 (1) (2011) 1–4.
[12] J. Davidovits, Chemistry of geopolymeric systems, terminology, in: Geopolymere '99 Proceedings, Saint-Quentin, France, 1999, pp. 9–22.
[13] ACAA, 2011 Coal Combustion Product (CCP) Production Use Survey Report, 2012. <http://www.acaa-usa.org/Portals/9/Files/PDFs/Final2011CCPSurvey.pdf>.
[14] D. Hardjito, B.V. Rangan, Development and properties of low-calcium fly ash-based geopolymer concrete, research report GC 1, Curtin University of Technology, Perth, Australia, 2005.
[15] D.B. Raijiwala, H.S. Patil, Geopolymer concrete: a concrete of next decade, J. Eng. Res. Stud. II (I) (2011) 19–25.
[16] A.M.M.A. Bakri, H. Kamarudin, M. Bnhussain, I.K. Nizar, A.R. Rafiza, Y. Zarina, Microstructure of different NaOH molarity of fly ash-based green polymeric cement, J. Eng. Technol. Res. 3 (2) (2011) 44–49.
[17] J.G.S. Van Jaarsveld, J.S.J. Van Deventer, G.C. Lukey, The characterization of source materials in fly ash-based geopolymers, Mater. Lett. 57 (7) (2003) 1272–1280.
[18] N.A. Lloyd, B.V. Rangan, Geopolymer concrete – sustainable cementless concrete, in: 10th ACI International Conference on Recent Advances in Concrete Technology and Sustainability Issues, ACI Special Publication, 2009, pp. 33–53. SP-261-3.
[19] A. Fernandez-Jimenez, A. Palomo, Characterization of fly ashes. Potential reactivity as alkaline cements, Fuel 82 (18) (2003) 2259–2265.
[20] Z.K. Khatib, F.M. Bayomy, Rubberized portland cement concrete, J. Mater. Civ. Eng. 11 (3) (1999) 206–213.
[21] H.A. Toutanji, The use of rubber tire particles in concrete to replace mineral aggregates, Cem. Concr. Compos. 18 (2) (1996) 135–139.
[22] C.G. Papakonstantinou, M.J. Tobolski, Use of waste tire steel beads in portland cement concrete, Cem. Concr. Res. 36 (9) (2006) 1686–1691.
[23] G.A. Issa, G. Salem, Utilization of recycled crumb rubber as fine aggregates in concrete mix design, Constr. Build. Mater. 42 (2013) 48–52.
[24] Y. Park, A. Abolmaali, M. Mohammadagha, S. Lee, Structural performance of dry-cast rubberized concrete pipes with steel and synthetic fibers, Constr. Build. Mater. 77 (2015) 218–226.

[25] L. Lijuan, R. Shenghua, Z. Lan, Mechanical properties and constitutive equations of concrete containing a low volume of tire rubber particles, Constr. Build. Mater. 70 (2014) 291–308.

[26] Y. Park, A. Abolmaali, M. Mohammadagha, S. Lee, Flexural characteristics of rubberized hybrid concrete reinforced with steel and synthetic fibers, Adv. Civil Eng. Mater. (ACEM) 3 (1) (2014) 495–508.

[27] F. Hernandez-Olivares, G. Barluenga, M. Bollati, B. Witoszek, Static and dynamic behavior of recycled tire rubber-filled concrete, Cem. Concr. Res. 32 (10) (2002) 1587–1596.

[28] M.D.A. Thomas, P.B. Bamforth, Modeling chloride diffusion in concrete: effect of fly ash and slag, Cem. Concr. Res. 29 (1999) 487–495.

[29] ASTM C39M-12a, Standard test method for compressive strength of cylindrical concrete specimens, Annual Book of ASTM Standards, ASTM International, West Conshohocken, PA, 2008.

[30] A. Palomo, M.W. Grutzeck, M.T. Blanco, Alkali-activated fly ashes a cement for the future, Cem. Concr. Res. 29 (1999) 1323–1329.

[31] S.A. Issa, M.S. Islam, M.A. Issa, A.A. Yousif, M.A. Issa, Specimen and aggregate size effect on concrete compressive strength, Cem. Concr. Aggregates 22 (2) (2000) 103–115.