The 2015 World Congress on
Advances in Structural Engineering and Mechanics (ASEM15)
Incheon, Korea, August 25-29, 2015

The Effect on Compressive Strength of Fly Ash-Based Geopolymer Concrete with Crumb Rubber Replacing Fine Aggregates

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ABSTRACT

This study presents rubberized 'geopolymer' concrete as an environmentally friendly and durable product. Crumb rubber, from recycled tires, was employed as a lightweight replacement for fine aggregates in geopolymer concrete. Fly ash (Class C) and an alkaline liquid (mix of sodium hydroxide and sodium silicate) were used as the basic constituents of the geopolymer. The crumb rubber particles replaced from 5 to 20% (by volume) of the fine aggregates in the high calcium fly ash-based geopolymer concrete. Different factors, such as ratio of sodium silicate (Na_2SiO_3) to sodium hydroxide (NaOH), size of aggregates, as well as amount of crumb rubber that influence the compressive strength, were studied in accordance with American Standard Testing and Material (ASTM) C39. The results showed that up to 15% of fine aggregates can be replaced with an equal volume of crumb rubber in geopolymer concrete without significant reduction of the compressive strengths.

INTRODUCTION

Due to the versatile applications of concrete such as buildings, highways, and bridges, it is the most widely used building material in the world. One of the ingredients used as the binder in concrete is Portland Cement (PC), which is not considered an environmentally friendly material. The production of PC emits a substantial amount of carbon dioxide (CO_2) and other greenhouse gases (Mehta 2002). The production of one ton of PC consumes 4 GJ energy (Mehta 2001) and emits approximately one ton of CO_2 into the atmosphere (Salloum 2007). Moreover, the global production of PC increases every year and has shown no sign of slowing down (USGS 2013). In an effort to produce more environmental friendly binders replacing PC in concrete, the geopolymer technology has been proposed and is considered as one of the

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revolutionary developments that results in a low-cost and greener substitute for PC (Davidovits 1991). Geopolymers are formed by an alkali-activated binder produced by a polymeric reaction of alkaline liquids with the silicon and the aluminum oxides in source materials of geological origin like metakaolinite (calcined kaolinite) or industrial by-product materials such as fly ash (Class F and Class C) and rice husk ash (Davidovits 1999 and Topark-Ngarm 2014). The use of fly ash in geopolymer concrete reduces the environmental pollution caused by the disposal of fly ash, since a considerable amount of it is disposed of in landfills or surface impoundments, which are lined with compacted clay soil, a plastic sheet, or both. Some researchers have shown an increase in compressive strength with an increase in the molarity of a sodium hydroxide solution (Hardjito 2005 and Raijiwala 2011), while others have shown a negative impact on the strength with the increase in molarity (Bakri 2011). The effects of these parameters have not yet been completely proven. However, 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 faster strength development and higher compressive strength (Lloyd 2009).

In an effort to produce an environmental friendly concrete, several studies have been conducted to evaluate the effect of using recycled rubber from used tires in concrete mixes since a significant number of automotive tires are disposed of each year as solid waste in the United States (Khaloo 2008 ,Siringi 2013 and Siringi 2015). It was reported that the addition of crumb rubber to the concrete increases the toughness and impact resistance, while it decreases the modulus of elasticity, splitting tensile strength, and the modulus of rupture (Topçu 2007). It was found that rubberized concrete with fine rubber particles exhibits an acceptable workability and more ductility than plain concrete (Khaloo 2008). Unfortunately, however, limited studies have been conducted on the effect of crumb rubber on fly ash-based geopolymer concrete (especially Class C with a high calcium ratio). This paper investigates the effects of different types of parameters, including sizes of aggregates (9.5 mm or 16 mm), ratios of sodium silicate to sodium hydroxide, and amounts of crumb rubber on the compressive strength of fly ash-based (Class C) rubberized geopolymer concrete.

EXPERIMENTAL WORKS

Materials

In this study, Class C fly ash, obtained from Jewett, Texas (USA), was used as a source material. Class C fly ash is designated in ASTM C618 (Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete) and has a higher calcium content than Class F fly ash ($CaO < 8.0$ % for Class F and $8.0 < CaO < 20.0$% for Class C). Table 1 shows the chemical composition of the different types of fly ash, as determined by X-ray Fluorescence (XRF) analysis.

Crumb rubber, from automotive and truck scrap tires, has particles ranging from 1 mm to 2 mm with a bulk density of 480 kg/m^3 (30 lb./ft^3), as shown in Fig.1. Since the mineral aggregates have a higher unit weight than the crumb rubber particles, the unit weight of the concrete mixture was reduced by the addition of crumb rubber to the mixture. Crumb rubber was used to replace partially fine aggregates in the geopolymer concrete.

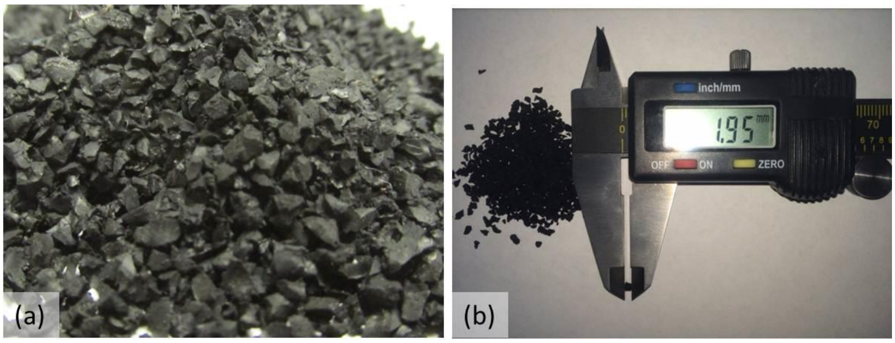

Fig. 1. (a) Crumb rubber and (b) Particle size of crumb rubber

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

Class of Fly ash Name of Place	Class - C Jewett (TX)
Silicon Dioxide (SiO_2)	50.67%
Aluminum Oxide (Al_2O_3)	18.96%
Iron Oxide (Fe_2O_3)	6.35%
Magnesium Oxide (MgO)	3.12%
Calcium Oxide (CaO)	14.14%
Loss on Ignition	0.17%

Alkali-activated solutions

A combination of sodium silicate (Na_2SiO_3) solution and sodium hydroxide (NaOH) solution was used as the alkaline liquid to form the binder between the aggregates and other unreacted materials in the geopolymer concrete. 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 in this study. The molarity is defined as the number of moles of solute per litre of solution. In order to prepare the solution of 1M, 40 g of NaOH flake (molecular weight of NaOH = 40) was dissolved in one litre of distilled water. In this study, 14 Molar sodium hydroxide (NaOH) was used for all specimens, and it was prepared a day before it was mixed with the fly ash in order to cool it down sufficiently.

Table 2. Calculation of moles of solute

Molarity of solution (*M*)	Moles of solute (g)
1	40
14	560

Mix design

The geopolymer mixtures were designed to achieve the average compressive strength of 28 MPa (4000 psi). The nominal sizes of the coarse aggregates (limestone) were 9.5 mm (3/8 in.) and 16 mm (5/8 in.), respectively, with a bulk density of 2700 kg/m^3 (170 lb./ft^3) and a specific gravity of 2.7. In order to produce the rubberized geopolymer concrete, fine aggregates, with a bulk density of 1500 kg/m^3 (95 lb/ft^3), were replaced by crumb rubber of equal volume (5, 10, 15 and 20%). The ratio of sodium silicate to sodium hydroxide was 0.5 and 2.0. The following mixing procedure was employed: 1) fine aggregates and fly ash were mixed in dry state for 30 seconds; 2) half of the total amount of rubber was added to the mixer manually to ensure uniform distribution of the rubber in the mixture, and was mixed for 30 seconds; 3) coarse aggregates were added and mixed for 30 seconds; 4) the remaining half of the total amount of rubber was put into the mixer (See Fig.2.(a)); 5) the prepared alkali liquid was added and mixed well for 60 seconds, as shown in Fig.2 (b). Finally the extra water was added to the mixture, and it was mixed again for 30 seconds. Mix compositions in terms of weight are shown in Table 3. The cylinders were cured at 30 °C temperature with relative humidity of 70%.

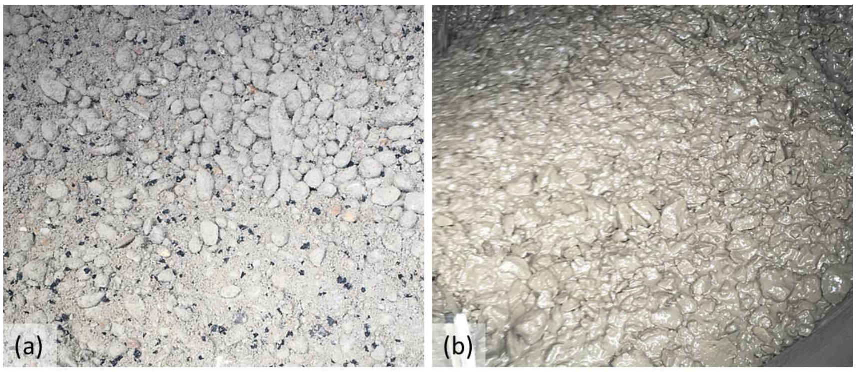

Fig. 2. (a) Mix without alkaline solutions and (b) Mix with alkaline solutions (20% rubber)

Compressive strength test

Compressive cylinders with dimensions of 100 mm × 200 mm (4 in. × 8 in.) were tested in accordance with ASTM C39 "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens," as shown Fig. 3. All specimens were compacted with the help of a table-type vibrator 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/sec (35 ± 7 psi/sec).

Table 3. Mix design of rubberized geopolymer concrete

Mixture	Class-C Fly-Ash (kg/m^3)	C.A. (9.5mm) (kg/m^3)	C.A. (16mm) (kg/m^3)	F.A. (kg/m^3)	Rubber (kg/m^3) (% Vol.)	Na_2SiO_3 (kg/m^3)	NaOH (kg/m^3)	Extra Water (kg/m^3)
Mix-1	408	1280	-	630	0.0 (0)	42	84	40
Mix-2	408	1280	-	599	9.7 (5)	42	84	40
Mix-3	408	1280	-	567	19.7 (10)	42	84	40
Mix-4	408	1280	-	535	29.7 (15)	42	84	40
Mix-5	408	1280	-	504	39.4 (20)	42	84	40
Mix-6	408	-	1280	630	0.0 (0)	42	84	40
Mix-7	408	-	1280	599	9.7 (5)	42	84	40
Mix-8	408	-	1280	567	19.7 (10)	42	84	40
Mix-9	408	-	1280	535	29.7 (15)	42	84	40
Mix-10	408	-	1280	504	39.4 (20)	42	84	40
Mix-11	408	1280	-	630	0.0 (0)	84	42	40
Mix-12	408	1280	-	599	9.7 (5)	84	42	40
Mix-13	408	1280	-	567	19.7 (10)	84	42	40
Mix-14	408	1280	-	535	29.7 (15)	84	42	40
Mix-15	408	1280	-	504	39.4 (20)	84	42	40
Mix-16	408	-	1280	630	0.0 (0)	84	42	40
Mix-17	408	-	1280	599	9.7 (5)	84	42	40
Mix-18	408	-	1280	567	19.7 (10)	84	42	40
Mix-19	408	-	1280	535	29.7 (15)	84	42	40
Mix-20	408	-	1280	504	39.4 (20)	84	42	40

*Note: Three specimens were cast in each mix design

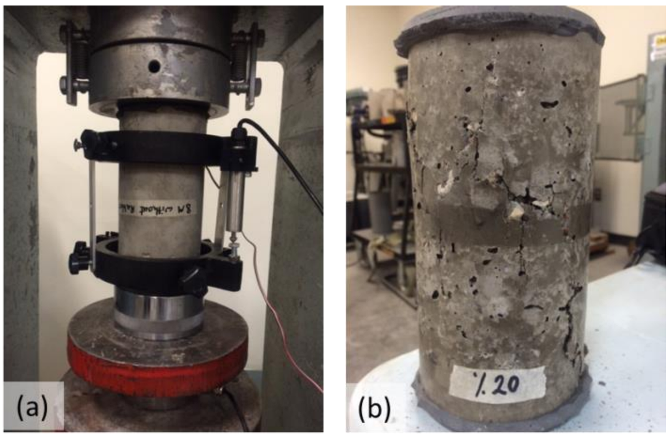

Fig. 3. (a) Compressive strength test set up and (b) Failure of cylinders (20%: rubber)

TEST RESULTS

The compressive strengths and setting times of the tested geopolymer concrete, with difference amounts of crumb rubber and different sizes of aggregates, are presented in Table 4 and Fig. 4. Compared with the test results of the low-calcium fly ash (Class F) by Hardjito (2005), the setting (hardening) time of the geopolymer concrete (Class C) in this study was relatively short, regardless of the amount of crumb rubber and aggregate size. Higher calcium oxide (CaO) content in the Class C fly ash led to a faster setting time than that of the Class F fly ash. This was consistent with the results of Topark-Ngarm (2014). The different setting time, which refers to the development of rigidity, was observed based on the ratio of sodium silicate to sodium hydroxide (0.5 and 2.0). An average of 4.3 minutes of setting time was observed for mixes 1 through 10, with 0.5 of the ratio of sodium silicate (Na_2SiO_3) to sodium hydroxide (NaOH). In the mixes 11 through 20, with 2.0 of the ratio of sodium silicate (Na_2SiO_3) to sodium hydroxide (NaOH), however, an average 10.7 minutes of setting time was observed. Setting time increased with the increase of the ratio of sodium silicate (Na_2SiO_3) to sodium hydroxide (NaOH) in the rubberized geopolymer concrete. The addition of crumb rubber did not affect the setting time.

Table 4. Compressive strength and setting time

Mixture	Rubber % (Vol.)	Na_2SiO_3 kg/m^3	NaOH kg/m^3	Na_2SiO_3 /NaOH	Comp. Strength MPa (Std.)	Setting Time (Minute)
Mix-1	0	42	84	0.5	30.8 (2.84)	4
Mix-2	5	42	84	0.5	30.6 (1.57)	4
Mix-3	10	42	84	0.5	29.7 (0.67)	5
Mix-4	15	42	84	0.5	30.1 (3.36)	4
Mix-5	20	42	84	0.5	25.9 (1.81)	4
Mix-6	0	42	84	0.5	33.6 (1.12)	4
Mix-7	5	42	84	0.5	33.9 (4.24)	5
Mix-8	10	42	84	0.5	33.1 (3.70)	4
Mix-9	15	42	84	0.5	32.2 (1.89)	5
Mix-10	20	42	84	0.5	28.7 (3.05)	4
Mix-11	0	84	42	2.0	38.2 (1.12)	10
Mix-12	5	84	42	2.0	37.6 (2.79)	11
Mix-13	10	84	42	2.0	36.2 (4.74)	11
Mix-14	15	84	42	2.0	36.7 (1.35)	10
Mix-15	20	84	42	2.0	33.5 (3.01)	9
Mix-16	0	84	42	2.0	42.1 (2.55)	12
Mix-17	5	84	42	2.0	41.7 (1.67)	11
Mix-18	10	84	42	2.0	40.9 (3.67)	12
Mix-19	15	84	42	2.0	40.5 (5.64)	10
Mix-20	20	84	42	2.0	37.1 (1.94)	11

*Note: Setting time was measured in accordance with ASTM C807-13

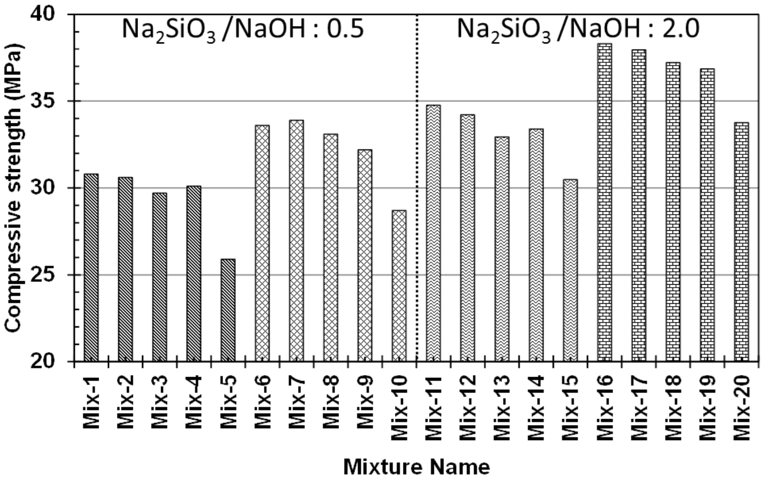

Fig. 4. Compressive strength by the ratio of Na_2SiO_3 to NaOH

As shown in Fig. 4 and Table 4, the compressive strength of the rubberized geopolymer concrete increased as the ratio of sodium silicate (Na_2SiO_3) to sodium hydroxide (NaOH) increased from 0.5 to 2.0. Based on the comparison of mix 1/11, mix 5/15, mix 6/16 and mix 10/20, increased compressive strengths of 24%, 29%, 25% and 29%, respectively, were observed with the increased ratio of sodium silicate (Na_2SiO_3) to sodium hydroxide (NaOH).

In order to study the effect of size and amount of aggregates on the compressive strength of the concrete, mixes 1 through 10 in Table 3 were prepared from two types of coarse aggregates (9.5 mm and 16 mm). As shown in Fig. 4, the presence of larger size aggregates (16 mm) increased the compressive strength of the rubberized geopolymer concrete. This might be because the interlocking between the well-graded and different-sized aggregates with rough surfaces is closer, thus improving the compressive strength. Regardless of the amount of crumb rubber, larger aggregates and a higher ratio of Na_2SiO_3 to NaOH result in a higher compressive strength.

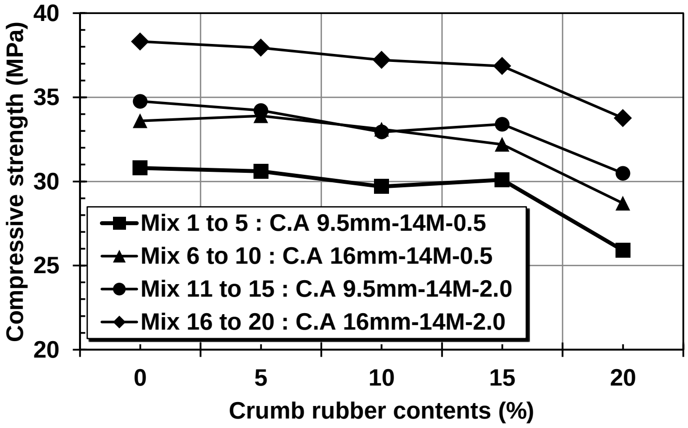

Fig. 5. Compressive strength by amount of crumb rubber

The substitution of crumb rubber for fine aggregates in the rubberized geopolymer concrete affected the compressive strength, as shown in Fig. 5. The addition of rubber weakened the compressive strength of rubberized geopolymer concrete. If the crumb rubber content increased up to 15%, the compressive strength decreased insignificantly, with a maximum reduction of 4.2% (Mix 9). However, as the rubber content was increased to 20% replacing fine aggregates by volume, significant reduction of the compressive strength was observed. Mixes 5, 10, 15 and 20 showed 16%, 16%, 13% and 11% reduction, respectively, of the compressive strength. The smaller ratio of sodium silicate (Na_2SiO_3) to sodium hydroxide (NaOH) showed a slightly higher reduction rate of the compressive strength. This might be attributed to the longer setting with the higher ratio of sodium silicate (Na_2SiO_3) to sodium hydroxide (NaOH) since a fast setting time, within 5 minutes, might lead to an uneven dispersion of crumb rubber in the geopolymer mixture. In the rubberized geopolymer concrete mix, an appropriate amount of rubber exhibited an insignificant reduction of the compressive strength. However, too much content of crumb rubber, over 15%, showed a significant negative effect on the compressive strength. It was observed that crumb rubber can be replaced with an equal volume of fine aggregates, up to 15%, in geopolymer concrete without a significant reduction in the compressive strength.

CONCLUSION

This paper presents the parameters that significantly influence the compressive strength of high calcium, Class C fly ash-based, rubberized geopolymer concrete. The results were obtained from the experimental tests of cylinders prepared in the laboratory. The following conclusions can be drawn from this study:

- Setting time increases with the increase of the ratio of sodium silicate (Na_2SiO_3) to sodium hydroxide (NaOH) in the rubberized geopolymer concrete. The addition of crumb rubber did not affect the setting time.
- The compressive strength of the geopolymer increases with the use of larger sized aggregates (16 mm). Less strength reduction with the use of larger sized aggregates (16 mm) was observed with the increase of crumb rubber in the geopolymer concrete.
- Regardless of the amount of crumb rubber, the higher ratio of sodium silicate (Na_2SiO_3) to sodium hydroxide (NaOH) results in a higher compressive strength.
- An appropriate amount of rubber may be replaced with an equal volume of fine aggregates in rubberized geopolymer concrete (Class C, fly ash-based) without significant reduction of the compressive strength. It is suggested that fine aggregates can be replaced with an equal volume of crumb rubber, up to 15%, in geopolymer concrete (Class C, fly ash-based) without a significant reduction in the compressive strength.

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