



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



Yeonho Park<sup>a</sup>, Ali Abolmaali<sup>a</sup>, Young Hoon Kim<sup>b,\*</sup>, Masoud Ghahremannejad<sup>a</sup>

<sup>a</sup> Department of Civil Engineering, The University of Texas at Arlington, Arlington, TX 76019, USA

<sup>b</sup> 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.

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## 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](mailto:ypark@uta.edu) (Y. Park), [abolmaali@uta.edu](mailto:abolmaali@uta.edu) (A. Abolmaali), [yhkim005@louisville.edu](mailto:yhkim005@louisville.edu) (Y.H. Kim), [masoud.ghahremannejadm@uta.edu](mailto:masoud.ghahremannejadm@uta.edu) (M. Ghahremannejad).

[12]. It not only generates less CO<sub>2</sub> than PC, but also reuses industrial by-products of aluminosilicate 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 States [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<sub>2</sub>O = 10.6%, SiO<sub>2</sub> = 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 <sub>2</sub> )	50.67%	58.05%	54.70%
Aluminum Oxide (Al <sub>2</sub> O <sub>3</sub> )	18.96%	21.59%	29.00%
Iron Oxide (Fe <sub>2</sub> O <sub>3</sub> )	6.35%	5.10%	6.74%
Magnesium Oxide (MgO)	3.12%	1.86%	0.80%
Sulfur Trioxide (SO <sub>3</sub> )	0.74%	0.39%	0.10%
Available Alkalis as Na <sub>2</sub> O	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

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