



Influence of selected parameters on compressive strength of geopolymer produced from ground glass fiber

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HIGHLIGHTS

- Ground glass fiber (GGF) was alkali activated to produce geopolymer.
- Compressive strength of GGF and fly ash-based geopolymer were compared together.
- Effect of different curing temperatures on the compressive strength was studied.
- Effect of activators' compositions on the compressive strength was studied.

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ABSTRACT

In this study, ground glass fiber (GGF), manufactured by milling waste glass fiber, was used to produce geopolymer mixtures. The effect of using different alkali content and different combinations of alkali activator solutions on the compressive strength and micro-structure of GGF-based geopolymer mixtures were investigated and compared with fly ash-based geopolymer mixtures. Furthermore, the effect of temperature (from ambient to 110 °C) and duration of heat-curing on the compressive strength and micro-structure of GGF-based geopolymers was studied. Results of this study showed that for all the levels of alkali content, GGF-based geopolymers showed a higher compressive strength in comparison to the fly ash-based specimens; prepared with a same solution and heat-curing method. It was also seen that the strength gain in GGF-based geopolymers does not depend on the presence of sodium silicate in the activator solution; and high compressive strength (as high as 80 MPa) can be achieved by using sodium hydroxide solution alone. The temperature of heat curing was also seen to affect the early-age (i.e. 3–7 days) strength of the GGF-based samples, but had no significant effect on the later-age (i.e. 28–56 days) strength. Finally, it was concluded that GGF has a good potential to be used as a precursor to produce high strength geopolymers even at the low curing temperatures as the ambient temperature (23 °C).

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1. Introduction

In recent years the use of geopolymer concrete as a potential replacement for Portland-cement based concrete is attracting more attention to not only address growing environmental concerns [1–5] but also to provide a better alternative as a construction material of choice in resisting aggressive chemical environments [5–7]. Utilization of geopolymer concrete in precast concrete products, including sewer pipes, culverts, railway sleepers, pre-fabricated units for housing market, etc. [8–10], repair or a retrofitting mate-

rial for existing Portland-cement-concrete elements or structures [11,12], using as a fire resisting material [13,14] and as a repair coating or a construction material in marine sites [15–16] are some examples of the geopolymer applications.

To produce geopolymers, silica and alumina-rich precursors are chemically activated using alkaline activators such as sodium hydroxide or sodium silicate solutions. This process results in the formation of an amorphous three-dimensional alumino-silicate network, which is known as the geopolymer [4]. Thus far materials such as slag, fly-ash, meta-kaolin, and various combinations of these materials are the most widely used precursors to produce geopolymer concrete [17–20]. However, in recent years, several other waste or industrial by-products such as: waste paper sludge ash [21], glass produced from the DC plasma treatment of air pol-

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lution control residue [22], spent fluid catalytic cracking catalyst [23], Oil palm shell [24] sugar cane straw ash [25], waste glass-powder [26,27], combination of sugarcane bagasse ash and blast furnace slag [28], palm oil fuel Ash [29], combinations of natural pozzolan and slag [30], and blends of clay and fly ash [31] have been used as a precursor for geopolymer. In addition to these materials, recent studies have shown that ground glass fiber (GGF) can be effectively activated by an alkali activator to produce a geopolymer mortar [27,32].

Each year, a large amount of glass fiber is commercially produced to be used in various applications. However, this process generates millions of tons of waste glass fiber around the world. According to a 2005 report by Hemmings [33], each year around 250,000 to 500,000 tons of waste glass fiber end-up in landfills of the U.S. This waste glass fiber has a chemical composition which is rich in glassy silica, alumina, and calcium. Therefore, if milled to a fine powder, this material might potentially be used as a supplementary cementitious material (SCM) or as a precursor to produce geopolymers. Chen et al. [34] investigated the use of waste E-glass (the most commonly used type of fiber glass) as cement replacement material in concrete mixtures. Utilization of GGF as a cement replacement and its effect on the mechanical and durability properties of concrete are also reported by Rangaraju et al. and Rashidian-Dezfouli and Rangaraju [35,36]. Furthermore, recent research by the authors has shown that GGF can be effectively activated by sodium hydroxide solution, producing a geopolymer mortar mixture with the high early strength as high as 80 MPa after 3 days [27,32].

The purpose of this work is to study the influence of several activation parameters that affect the strength gain of GGF-based geopolymer mixtures. Earlier studies on geopolymer mixtures have identified some of a large number of parameters that can affect the mechanical properties of the final product [8,20,37–41]. Based on their characteristics, some of the most important parameters can be divided into three main categories: (i) parameters related to the properties of the activator solutions, such as combination and concentration of activator solutions [10,37,38]; (ii) parameters related to the physical and chemical properties of precursors, such as fineness and chemical composition [8,18–20]; and (iii) parameters related to the curing condition such the temperature and duration of the heat curing process, have been reported to affect the mechanical properties of the geopolymers considerably [10,38,39–41].

The alkali concentration of the activator solution is one of the most important parameters that affect the strength of geopolymers. Generally, it has been reported that increase in the alkali concentration results in the increase in the mechanical properties of the geopolymers [10,24,37,53]. However, it also has been reported that the excessive amount of alkali content of the activator solution will negatively influence their strength [13,24,43]. In addition to the alkali content, presence of soluble Si, mostly in the form of sodium silicate solution, in the activator solution can influence the compressive strength of the geopolymer mixtures. Several works have shown that the manufacturing of geopolymer mixtures using combinations of sodium hydroxide (NaOH) and sodium silicate solution resulted in a higher compressive strength in comparison to the mixtures that were activated using sodium hydroxide alone [28,38,44].

It has been shown that the $\text{SiO}_2/\text{Na}_2\text{O}$ ratio of the activator (or mixtures) plays an important role in the final compressive strength of geopolymer mixtures. According to Hardjito et al. [10], increase in the sodium silicate/NaOH liquid mass ratio from 0.4 to 2.5 resulted in the higher compressive strength ratio for both NaOH concentration of 8 M and 14 M. Nonetheless, it should be noted that despite its beneficial effect at lower dosage levels, addition of too much sodium silicate solution to mixtures has been found

to reduce compressive strength of the geopolymer samples [18,44,45]. Therefore, some studies have suggested an optimum range or ratio for the sodium silicate/NaOH of the activator solution based on the particular precursor used in their study [44,45].

Physical and chemical characteristics of the precursors have a significant influence on the compressive strength of the geopolymers. Several studies have shown that a finer particle size of a precursor can result in a higher compressive strength of the final geopolymer product; mainly due to the higher surface area of the precursors [47,48] and smaller pore sizes in the geopolymer matrix [46]. Despite this, other studies have indicated no clear trend between the particle size of precursors and the mechanical properties of geopolymers [19,48].

Chemical composition of precursors plays an important role in determining the structure and mechanical properties of geopolymers. According to Davidovits [49], the lower atomic ratio of Si/Al ($\text{Si}/\text{Al} < 3$) leads to the formation of a rigid three-dimensional network and the higher Si/Al ratios ($\text{Si}/\text{Al} > 15$) gives a polymeric characteristic to the geopolymer systems. Effect of Si/Al and the ratio or the Al content of the geopolymer mixtures on the mechanical properties of geopolymers has been investigated in a number of studies [50–52]. Based on these studies, it is evident that Si/Al ratio plays a significant role in affecting the compressive strength and Young's modulus of elasticity of geopolymer concrete, with Si/Al ratio (~ 2.0) being optimal for providing the highest mechanical properties.

In addition to the Si/Al ratio, the presence of calcium oxides also affects the fresh and hardened properties of geopolymer mixtures [19,53]. While the exact mechanism is not yet clear, several works have shown that the presence of calcium oxide accelerates the setting procedure [54,55] and also improves the mechanical properties of geopolymer mixtures [53,54,56–58]. In efforts to explain the role of calcium oxides in geopolymer systems, several mechanisms have been proposed, such as: 1) formation of C-S-H (calcium silicate hydrate) or C-A-S-H gel (calcium aluminosilicate hydrate) which densifies the structure of the paste [2,20], 2) effect of calcium compounds in creating a nucleation site for the precipitation of the geopolymer compound [54,57,59], and 3) charge balancing capacity of Ca in the alumino-silicate structure [58,60].

Effect of temperature and duration of heat curing on the mechanical properties of geopolymer mixtures has been discussed in several studies [10,38,39,45]. Based on these studies, it is generally observed that the compressive strength of geopolymer mixtures increases with an increase in the temperature. However, the effect is more significant in lower temperature ranges (i.e. up to 60 to 75 °C); and the further increase in the heat-curing temperature did not show a notable increase in the strength [10,41,42]. However, in other studies [39,40,45], it was shown that very high curing temperatures (i.e. more than 80 °C to 90 °C) could lead to the reduction in the strength of geopolymer. According to Muñoz-Villarreal et al. [39], the reduction in the compressive strength at the higher temperature can be explained through the fast evaporation of water in the system that occurs, which not only increases the porosity but also causes geopolymerisation to take place on the surface of precursors which hinders the further dissolution of Si and Al. Prolongation of the heat-curing of samples has been shown to improve the mechanical properties of geopolymers, as more time is provided for the polymerisation to take place [10]. Nonetheless, it should also be mentioned that a few studies performed on the fly ash-based geopolymers have reported a reduction in the compressive strength with the extension in the heat-curing period [45].

The use of GGF as a precursor in geopolymer mixtures is a relatively new concept and only limited numbers of research have been conducted in this regard [27,32]. The aim of this work is to present some fundamental understandings on the parameters

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