



Investigation of early compressive strength of fly ash-based geopolymer concrete



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HIGHLIGHTS

- The fly ash source has significant effect on FGC compressive strength.
- The type of activating solution has a significant effect on FGC compressive strength.
- Curing conditions play a significant role in compressive strength gain.

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ABSTRACT

Development of sustainable construction materials has been the focus of research efforts worldwide in recent years. Concrete is a major construction material; hence, finding alternatives to ordinary Portland cement is of extreme importance due to high levels of carbon dioxide emissions associated with its manufacturing process. This study investigates the effects of activating solution type, curing procedure, and source of fly ash in relation to the resulting compressive strength of fly ash-based geopolymer concrete. The fly ash-based geopolymer paste microstructure was observed and density, absorption and voids were measured. Two activating solutions were used: a) a mixture of sodium hydroxide, silica fume, and water; and b) a mixture of sodium hydroxide solution, sodium silicate, and water. Test results indicate that the resulting concrete has the potential for high compressive strength and the compressive strength is directly affected by the source of fly ash. Results further indicate that compressive strength is not significantly affected by the curing condition when silica fume is used in the activating solution in comparison to the use of sodium silicate.

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1. Introduction

A significant amount of concrete is used in construction around the world and Portland cement is one of the main constituents. Due to the very high temperatures required for the manufacture of Portland cement, vast amounts of energy are utilized for this ubiquitous construction material. It has been stated that the production of each ton of Portland cement releases approximately

one ton of carbon dioxide [1], and that Portland cement industries contribute 5–7% of total worldwide CO₂ emissions [2]. In recent decades, a sustainable development has become a focus of scientists and engineers and, therefore, the quest for alternatives to this technology has accelerated.

One potential alternative to Portland cement based concrete is fly ash-based geopolymer concrete (FGC), which may have the potential to reduce Portland cement usage while mirroring the compressive strength and durability characteristics of Portland cement concrete [3,4]. Many studies have shown that FGC can demonstrate beneficial and diverse properties. For example, FGC has shown good resistance against acid and sulfate attack, high early age strength, and good performance in high temperatures [5–12]. It has been proven recently that FGC can achieve high early and final compressive strength in ambient curing condition, and

Abbreviations: FGC, fly ash-based geopolymer concrete; FGC-silica fume, FGC with silica fume in the activating solution; FGC-sodium silicate, FGC with sodium silicate in the activating solution; SEM, scanning electron microscopy.

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good workability when additives are incorporated such as Portland cement, calcium hydroxide, or ground granulated blast furnace slag [13]. FGC is an inorganic polymer, which is produced by the reaction of aluminosilicate materials with alkaline solutions and the addition of conventional coarse and fine aggregate. FGC makes use of fly ash, which is a good source of aluminosilicate and is also a prevalent waste material. While the study described is focused on the use of fly ash, other waste materials such as blast furnace slag may also be utilized [14,15]. FGC is generally agreed to be less deleterious to the environment than Portland cement based concrete; however, more work to quantify this assertion is warranted.

A significant number of research studies have been conducted on FGC wherein sodium silicate was utilized in the activating solution [16–19], as is also the case for alkali activated slag [20,21]. In contrast, relatively few studies have investigated the combination of silica fume and sodium hydroxide as the activating solution [22]. Issues noted with the use of sodium silicate in the activating solution include relatively low workability and lower compressive strength when compared to conventional Portland cement based concrete, considered as 21 MPa (3000 psi) to 41 MPa (6000 psi). Both activating solutions have the same major chemical components including Na_2O , and SiO_2 . However, the main differences are: 1) process of manufacturing, for instance sodium silicate solution is subjected to high temperature between 1100 °C and 1200 °C (2012 °F and 2192 °F), and then subjected to high pressure, and 2) the ratio of Si/Na in the activating solution where the ratio is higher in the silica fume based solution than the sodium silicate based solution. The strength of FGC has been noted to be improved when external heat in the range of 75 °C (167 °F) was applied early in the curing process. It is mentioned that the application of some external heat early in the curing process is feasible and relatively common for precast/prestressed concrete applications.

In addition to the materials utilized in the activating solution, the chemical composition of the fly ash itself varies considerably depending on the coal source and technological processes used, and these factors may significantly affect the resulting FGC properties [23]. Comparisons between different activating solutions and sources of fly ash are not widely available. This study aims to address some of the current gaps in knowledge by investigating the effects of activating solution type, curing procedure, and source of fly ash in relation to the resulting compressive strength of FGC.

This paper compares compressive strength results obtained for FGC using either sodium silicate or silica fume in the activating solution. One significant finding is that the use of silica fume in the activating solution increases the compressive strength in comparison to the use of sodium silicate in the activating solution, potentially due to the higher silica concentration and smaller particle size of silica fume. The effect of different fly ash sources and curing conditions (samples stored either inside or outside the molds till the test day) are also investigated. The results indicate that the fly ash source has a significant effect on the resulting compressive strength. To gain further insight, the microstructure was observed to identify the major differences between fly ash sources by Scanning Electron Microscopy (SEM). To address and gain a better understanding of potential durability considerations, density, absorption and voids were measured in general conformance with ASTM (C 642-06) [24].

2. Materials and methods

In this section two experiments have been chosen from previous studies as first step. For FGC-silica fume, the mixture proportions followed Tempest et al. 2009 [22]. FGC-sodium silicate mixture proportions followed Lloyd and Rangan 2010 [18] due to high compressive strength and moderate workability. However, the mixture proportions were slightly changed to improve the compressive strength.

The materials used for fabrication of the FGC test specimens included fly ash (ASTM class F), activating solution (either sodium hydroxide mixed with silica fume or sodium hydroxide solution mixed with sodium silicate solution), and fine aggregate,

water, and super plasticizer (Sika ViscoCrete 2100). Two fly ash sources were utilized in the investigation: a) Belevs Creek, from a power station in North Carolina, and b) Wateree Station, from a power station in South Carolina. The Wateree Station fly ash source was processed differently from the Belevs Creek source, in that the Wateree Station source was subjected to a proprietary carbon burn out process. Chemical compositions of both fly ash sources are shown in Table 1. The activating solution used was either: a) silica fume (Sikacrete 950DP, densified powder silica fume), sodium hydroxide (97–98 purity, DudaDiesel), and water; or b) sodium silicate solution ($\text{Na}_2\text{O} = 14.7\%$, $\text{SiO}_2 = 29.4\%$, and water = 55.9%, PQ Corporation), sodium hydroxide solution (14M), and water. Local crushed coarse granite aggregates (Vulcan Materials) in a saturated surface dry condition and local fine aggregates (Glasscock) were used. The gradation of coarse and fine aggregate is provided in Table 2, and the proportions of the silica fume and sodium silicate based FGC are provided in Table 3.

X-ray Florence (XRF) and Thermal Gravimetric Analysis (TGA) were conducted to investigate the effect of fly ash source materials on FGC-silica fume at the Holcim (US), Inc. laboratory in Holly Hill, South Carolina. SEM observations were conducted on fly ash-based geopolymer silica fume paste samples in the SEM Center at University of South Carolina. Density, absorption and voids for FGC (silica fume and sodium silicate based) were measured according to ASTM (C 642-06) at 7 days after casting.

2.1. Activating solutions

For the silica fume based activating solution, sodium hydroxide flakes were dissolved in water and silica fume powder was then added and stirred for two minutes. The mixing of silica fume with sodium hydroxide and water resulted in an exothermic process (in excess of 80 °C [176 °F]). The activating solution was kept in a closed container in an oven at 75 °C (167 °F) for 12 h to assure that the sodium hydroxide flakes and silica fume powder were completely dissolved. The water/binder ratio (w/b) was calculated as 28%. This ratio was calculated by dividing the water weight over summation of dried fly ash, sodium hydroxide and silica fume weight.

For the sodium silicate based activating solution, the sodium hydroxide solution (14 molarity concentration) was prepared by dissolving sodium hydroxide flakes in water and kept for at least 24 h in ambient conditions. The sodium hydroxide and sodium silicate solution were then mixed together. The resulting solution was stored at ambient temperature for a period of at least 24 h, and then the extra water was added prior to mixing of activating solution with the dry ingredients (fly ash, fine aggregates, and coarse aggregates). Therefore, the water/binder (w/b) ratio of 22% was calculated by dividing total water weight (55.9% of weight of sodium silicate, the water of sodium hydroxide solution, and the extra water [22.5 kg/m³ (1.4 lb/ft³)] by weight of fly ash, sodium hydroxide flakes, 14.7% of sodium silicate for Na_2O , and 29.4% of sodium silicate for SiO_2 weight. It is worth noting that using higher w/b for FGC-sodium silicate will reduce the compressive strength drastically.

Mixing sodium silicate and sodium hydroxide solution does not result in significant exothermic heat. Since both sodium silicate and sodium hydroxide are in liquid state, external heat was not required for solution preparation, unlike the silica fume based activating solution described above.

2.2. Casting and curing

The dry ingredients (fly ash, fine aggregates, and coarse aggregates) were mixed for three minutes. The activating solution, which include the water, was then added to the dry mixture and mixed for five minutes. Cylinders with dimensions of 76 mm × 152 mm (3 in. × 6 in.) were cast by adding three lifts of concrete and rodding 60 times per lift with a 9.5 mm (0.3 in.) diameter rod [8]. The size of cylinders was chosen according to ACI 211.1-91 [25]. All specimens were externally vibrated for a period of 10 s [8]. For FGC-silica fume, the specimens were left in ambient condition for two days and then heated for a period of two days in an oven at 75 °C (167 °F) [17]. For FGC-sodium silicate, the specimens were left for one day in ambient conditions and were then heated for a period of two days in the same oven at

Table 1
XRF chemical analysis of fly ash.

Chemical analysis	Belevs Creek Station, wt.%	Wateree Station wt.%
Silicon dioxide	50.2	53.5
Aluminum oxide	26.4	28.8
Iron oxide	10.0	7.5
Sum of silicon dioxide, aluminum oxide	86.41	89.8
Calcium oxide	4.3	1.6
Magnesium oxide	1.3	0.8
Sulfur trioxide	0.9	0.1
Loss on ignition	2.0	3.1
Moisture content	0.1	0.1
Total chlorides	<0.002	–
Available alkalies as Na_2O	0.7	0.8

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