Sustainable Concrete: Enhancements and Challenges

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ABSTRACT

Fly ash-based geopolymer concrete or alkali-activated fly ash-based concrete is a sustainable concrete that reduces CO_2 emissions and also utilizes waste materials such as fly ash, metakaolin, or blast furnace slag. This paper summarizes the recent improvements on mechanical properties of fly ash-based geopolymer concrete; its activating solution is a combination of sodium hydroxide, silica fume, and water. The results showed that the average compressive strength was reached up 103 MPa (15,000 psi) when the fly ash source was changed from Belews Creek to Wateree Station. The need for external heat was overcome when up 15% of fly ash weight replaced by Portland cement. The initial and final setting time was extended due to using sucrose (granulated sugar), 3%-9% of fly ash weight. In addition, the cost of fly ash-based geopolymer concrete was reduced by 40% when three mix designs were introduced. The cost of fly ash-based geopolymer concrete is similar to Portland cement counterpart approximately.

Keywords: improvement of mechanical properties, cost reduction, fly ash-based geopolymer concrete, alkali-activated fly ash concrete, silica fume activating solution

1 INTRODUCTION

Portland cement is a primary construction material that is responsible for 5% to 7% of the total CO_2 emissions worldwide [1]. The need for a new sustainable material that fully or partially replaces Portland cement has become urgent. Geopolymer concrete or alkali activated cementitious material is a sustainable concrete that reduces CO_2 emissions and also utilizes waste materials including but not limited to fly ash, metakaolin, and blast furnace slag. Previous studies found that geopolymer concrete requires lowest fuel and minimizes CO2 emmisions compared to conventional concrete [2,3].

Geopolymer concrete consists of aluminate silicate source materials including fly ash (type C&F), metakaolin, or blast furnace slag, and an activating solution, fine and coarse aggregates. The activating solution is either a combination of sodium hydroxide, sodium silicate, and water (most common) [4,5], or a mixture of sodium hydroxide, silica fume, and water [6,7]. Several studies have been conducted to investigate the mechanical properties of geopolymer concrete. Results showed that geopolymer concrete has superior mechanical properties such as high early and final compressive strength, acid and sulfate resistance, high performance under high temperatures [5,8–10].

Even though geopolymer concrete showed having several issues should be resolved to make it feasible for civil construction applications, onsite or concrete plants. For instance, one of the major issues that prevetns geopolymer concrete from being widely used in the market is the cost. The cost of geopolymer concrete is 1.5 of Portland cement concrete cost [3]. Furthermore, it has short initial and final setting time due to a rapid geopolymerization process reaction. Geoploymer concrete needs an external heat in order to gain strength and this made its use limited and best for precast and prestressed concrete products only.

Extensive recent studies have been conducted on fly ash based geopolymer concrete in the engineeing laboratories at Univeristy of South Carolina. A mixture of sodium hydrxide, silica fume, and water was used as an activating solution. The achieved resutls showed that the early and final compressive strength were improved significntly w/o of external heat presence. The initial and final setting time was extended by 100% and 160% respectively. There mix designs were interoduced to reduce the cost up to 50% [11]. This paper summarizes the challenges and developments that are made on the recently published study.

2 MATERIALS AND SAMPLES PREPARATION

Fly ash, silica fume (or soduim silicate), and soduim hydroxide were used togather as a binding material instead of cement. The fly ash that is used to prepare samples was brought from two sources: Wateree Station, SC and Belews Creek Power Station, NC. More information regarding the chemical composition of the fly ash from both sources can be found in Assi et al [11]. Condensed silica fume powder (Sikacrete 950DP) was purchased from a local supplier. Sodium hydroxide (97-98 purity) was brought from DudaDiesel. Crushed granite, Vulcan quary, was used as an aggreagte to prepare the concrete mix. It was brought from a local quarry in a saturated surface dry condition.

The activation solution was first prepared by dissolving sodium hydroxide in water. Silica fume was then added to the solution and stirred for five minutes. Mixing of those chemicals with water resulted in an exothermic reaction with an internal temperature up to 80 ^{0}C. The activation solution was stored in a closed container in the oven at 75 ^{0}C overnight. The dry fly ash, coarse and fine aggregate were mixed for three minutes and then the activation solution was added to the mixture and mixed throughly for an additional five minutes. A dosage of superplastisizer was added to the mixture to increase the workability. The mix design proportions are shown in Table 1.

The obtained mixture was cast in 3” x 6” cylindrical molds to be tested for compressive strength. The samples were cured under ambiant conditions for two days and then were further cured thermally in the oven at 70 ^{0}C for two days. Another samples were prepared by repalcing the fly ash with some percentages of portland cement (5%, 10%, and 15%) and just left to be cured under ambiant conditions.

All tests were conducted according to ASTM C39/C39M-18 and ASTM C403/C403M-16 at the engineering lab/ University of South Carolina [12,13].

Table 1: Concrete Mixture Ingradiants

Materials	Proportions
Fly ash	474 kg/m^3
Water	163 kg/m^3
Sodium hydroxide	61.6 kg/m^3
Silica fume	46.2 kg/m^3
Coarse aggregate	793 kg/m^3
Fine aggregate	793 kg/m^3
Superplastisizer / fly ash	1.5%
Water/binder ratio	28%

3 RESULTS AND DISCUSSIONS

3.1 Improvement of Compressive Strength

In this work, the main goal was to improve the final compressive strength. The fly ash source and activation solution type were found to have a high influence on compressive strength [11]. The samples were tested at seven-day age and the results are illustrated in Figures 1 and 2. From Figure 1, it can be noticed that the average compressive strength was 105 MPa for alkali-activated fly concrete (AAFC)/silica fume and 59 for AAFC/sodium silicate. The compressive strength was enhanced by 77% when the soduim silicate is replaced by silica fume.

The effect of fly ash source on compressive strength can be noticed in Figure 2. The compressive strength was 38 MPa for samples prepared with Belews Creek fly ash and 105 MPa for those prepared with Wateree fly ash. The compressive strength was enhanced by 176% when Wateree fly ash was used.

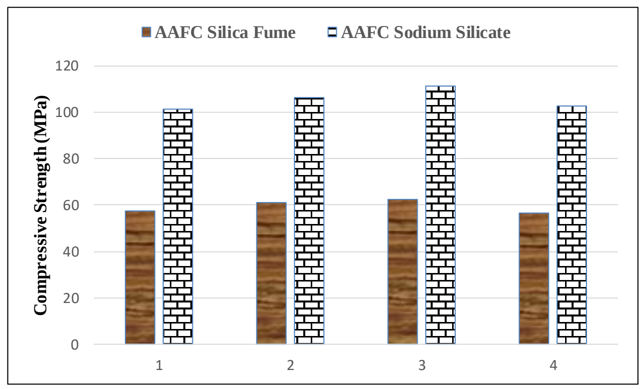

Figure 1: Effect of activating solution on compressive strength

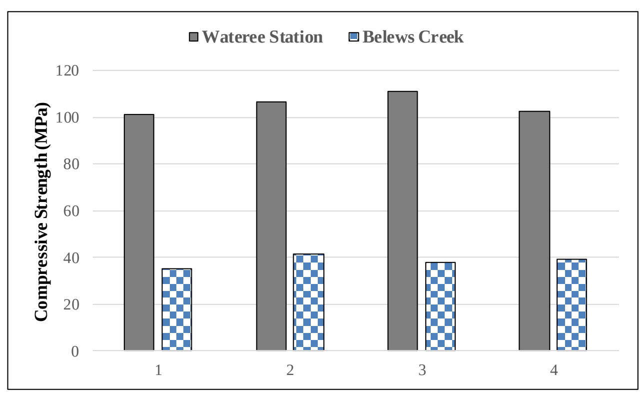

Figure 2: Effect of fly ash source on compressive strength of AAFC/silica fume samples

3.2 Enhancing Early and Final Compressive Strength at Ambient Curing Conditions

In this section, the main intent was to eleminate the need for external heat that is usually used to cure AAFC to speed up the geopolymerization process [7]. Portland cement reaction is an exothormic and 18%-20% of the reaction products is calicium hydroxide. Therefore, including Portland cement will not only provide internal heat, but it also dispenses extra alkaline, sodium hydroxide. The samples that are prepared by replacing Fly ash with some percentages of cement were tested at different ages.

The resutls showed that the early and final compressive strength was increased by partially replacing of Portland cement as shown in Figure 3. The compressive strength was 29 MPa for samples with 0% of Portland cement and 62 MPa for samples with 15% of Portland cement at age 28 days. Portland cement replacement also reduces the microcracks as presnted in Assi et al. [7].

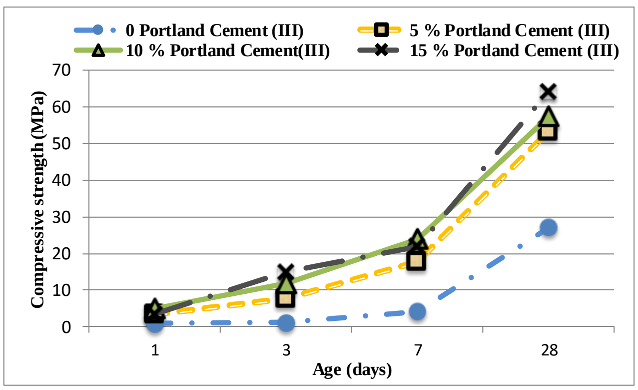

Figure 3: Effect of Portland cemetent replacement on compressive strength of AAFC

3.3 Delaying Initial and Final Setting Time

One of the primary issues is the initial and final setting time of geopolymer concrete. Using high percent of a strong alkaline, sodium hydroxide, will acceleraate the geopolymerization process leading to a sudden hardening. In practical applications, having a reasonable initial and final setting time will allow enough time for the concrete to be mixed, transported, and cast in place. Therefore, it is essential to control the initial and final setting time.

The sucrose (granulated sugar) was included in the mix as 3%, 6%, and 9% of fly ash weight in addition 10% of Portalnd cement. More information can be found in Assi et al. [14]. Utilization sucrose increases the viscosity of the solution leading to a delay in particles movement, which results in retarding the initial and final setting time. The experimental results are shown in Figure 4. The results showed that the initial setting time was improved from 10 minutes to 530 minutes when 0%-9% of sucrose was included. Final setting time was increased from 25 minutes to 755 minutes.

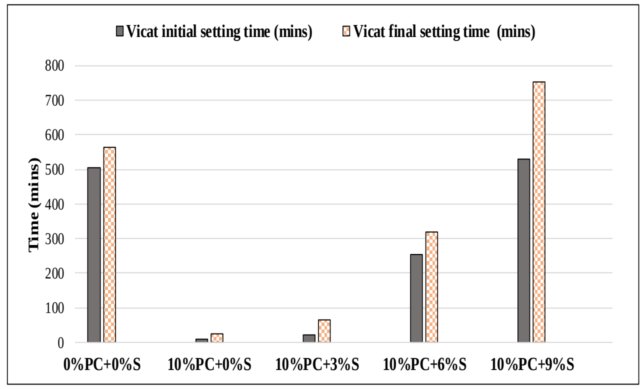

Figure 4: Effect of sucroe content on setting time of AAFC

3.4 Reduction of Alkali Activiated Fly Ash - based Geopolymer Concrete Cost

Geopolymer concrete revealed superior properties such as high compressive strength, fire and sulfate attack resistance, and good durability properties. However, the cost of geopolymer concrete may stand as a barrier against its thrive in the concrete market. A research showed that cost of geopolymer concrete might reach up to 1.5 of Portland cement concrete cost [2]. The main component that drives the cost was sodium hydroxide, which is having a high fuel energy consumption as well.

In this study, three mix designs were introduced to reduce the cost of geopolymer concrete. The sodium hydroxide weight was minimized up to 75% in comparison with the mix design presented in Table 1. To offset the hinder in the geopolymerization process, Portland cement was blended with fly ash up to 35% replacement. The presence of Portland cement in the geopolymer concrete mixture will supply external heat as well as an alkaline, sodium hydroxide. Figure 5 shows the obtained results in comparison with some selected conventional concrete types. The cost was reduced by more than 40% in comparison with fly ash-based concrete in section 3.1. For instance, the price was around \$118 and became \$65 while it was keeping suitable mechanical properties.

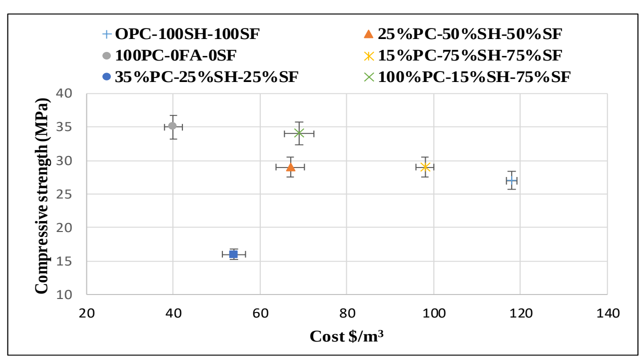

Figure 5: Cost optimization

4 CHALLENGES AND CONCLUSIONS

The results showed that alkali-activated fly ash concrete showed superior properties when compared with Portland cement concrete. The compressive strength at seven days reached up to 105 MPa by thermal curing. The early and final compressive strength were improved when fly ash was partially replaced by Portland cement. The use of Portalnd cement eleminated the need of thrermal curing. One of the major problems, rapid initial and final setting time, was overcome by including sucrose (granulated sugar) up to 9% of fly ash weight. The optimum dosage amount was 6% of sucrose in the mixture. The initial cost would be one of the challenges that can be mitigated if the sodium hydroxide amount were reduced. The cost of alkali-activated fly ash concrete was dropped by more than 40% when sodium hydroxide amount was decreased while keeping sufficient mechanical properties. To resolve the slowing down in the geopolymerization process due to sodium hydroxide amount reduction, Portland cement was introduced to the mixture as a partial replacement.

Some of the challenges, which should be solved or think about to make alkali cementitious materials being used in the civil engineering practical applications, are including but not limited to:

1. The common understanding that alkali activated fly concrete is resulting in corrosion to reinforcing steel bars. This problem can be solved by running a corrosion test on a reinforced sample and report detailed results.
2. New material or product usually has a hard time to penetrate the market because customers like to buy what they know. Hence, a marketing and communication plan is essential to inform customers about alkali cementitious properties and make them sure about them.
3. Large scale samples are required to investigate and verify the structural performance for the geopolymer concrete and com pare it with the conventional concrete.

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