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Development of High Strength Geopolymer Concrete Using Silica Fume-Based Activating Solution

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Abstract - Portland cement has traditionally been an indispensable element in the concrete production industry. The process of producing cement has negative environmental effects, requires a huge amount of energy, and releases large amounts of carbon dioxide. Fly ash-based geopolymer concrete has the potential to reduce Portland cement usage while at the same time demonstrating the desirable engineering properties of Portland cement concrete. Most fly ash-based geopolymer research has studied the use of ground granulated blast furnace slag (GGBS) as a partial replacement for fly ash (FA) in combination with sodium silicate and sodium hydroxide. In this study, an alternative activating solution, made of silica fume (SF), sodium hydroxide, and water, was used. The effects of using GGBS as a partial replacement for FA and of using different curing systems were investigated. Workability, compressive strength, density, absorption, and volume of permeable pore space were the properties selected to evaluate FA-based geopolymer concrete. FA-based geopolymer paste was examined using a scanning electron microscope. It was found that the inclusion of up to 20% GGBS significantly improved the compressive strength, density, absorption, and volume of permeable pore space in both heat-cured and ambient-cured conditions and reduced the workability to an acceptable range. Scanning electron microscope observations of the geopolymer pastes revealed that the inclusion of GGBS produced a denser microstructure with fewer cracks. The current study is a step toward extending geopolymer concrete use in both precast and site applications.

Keywords: Geopolymer concrete, Fly ash, GGBS, Silica Fume, High-strength concrete

1. Introduction

There is high growth in the demand for new construction materials that are green and produce a low level of greenhouse gas emissions during their manufacture. This makes geopolymer concrete a good and potentially ideal alternative to Portland cement concrete [1]. These concretes are produced through the alkali activation of industrial alumino-silicate waste such as ashes and slags; moreover, they are considered ecofriendly materials as they have low greenhouse gas emissions in comparison with traditional cement material [2]. The geopolymerization procedure relies upon numerous parameters, such as the chemical and mineralogical composition of the primary materials, curing treatment temperature, water content, and concentration of the alkaline solution [3]. Low-calcium fly ash-based geopolymer has several advantages over Portland cement concrete: almost no drying shrinkage, very good sulfate attack resistance, low creep, and great corrosive resistance [1].

1.1. Binders In Geopolymer Concrete

Fly ash (FA): The mineral matter that is not consumed by the burning of coal, which varies from 5 to 20% by weight, collected through the electrostatic precipitation process. Low-calcium fly ash has been effectively used to produce geopolymer concrete when the silicon and aluminum oxides constituted around 80% by mass, with an Si-to-Al ratio of around two. The iron oxide content is generally from 10 to 20% by mass, while the calcium oxide content is under 5% by mass. Regarding the particle size distribution of most of fly ashes, studies have found that 80% of the fly ash particles were smaller than 50 mm [1] [3] [4].

Ground granulated blast furnace slag (GGBS): A byproduct of the production of iron in a blast furnace where iron ore, limestone and coke are heated between 1400 C and 1600 C. GGBS is normally used in the cement industry for preparing mixed concrete, where slag replaces cement clinker in the range of 6 to 95% by weight. However, large quantities of this slag are still disposed of in landfills. One alternative is to reuse the slag as a cementing material by activating it using an alkali solution instead of disposing of it in an environmentally hazardous manner [5].

Silica fume (SF): A byproduct of the silicon smelting process and one of the most pozzolanic materials used in concrete to improve its properties. Silica fume is usually used in amounts between 5 and 10% by mass of the total cementitious material. It is often included in concrete mixes as a replacement for cement to reduce its content or as an additive material to improve the performance of concrete [6] [7].

1.2. Fresh properties of geopolymer concrete

Geopolymer concrete is believed to be less workable than Portland cement concrete because of the higher viscosity of the liquids used in geopolymer concrete. FA-based geopolymer concrete with zero GGBS content retains a workable consistency for a considerable time (more than 2 hours). When GGBS is added, the geopolymer concrete becomes less workable, thereby reducing handling time. This is attributed to the rapid reaction and setting process of the FA-GGBS blended mixture and to the irregularly-shaped slag particles [8]. A recent study [9] found that the workability of FA-based geopolymer concrete was influenced by GGBS inclusion. FA-based geopolymer concrete with zero GGBS replacement caused a collapse slump due to the spherical shape of the fly ash particles and the viscous consistency of the sodium silicate and the added water. The slump of FA-based geopolymer concrete was significantly reduced by GGBS inclusion in the mix. The addition of 10% GGBS decreased the slump value by 12% from 195 mm to 172 mm. Moreover, increasing the GGBS to 30% also decreased the slump value by 11% to 152 mm. Increasing the slag content caused a decrease in setting time and flow diameter of the geopolymer mortar. The highest values of flow diameter and setting time were found in mixes containing slag at 30% of the total binder, compared to mixes with a higher percentage of slag. This is due to the calcium content, which triggers hardening reactions at early stages, as well as the irregular shapes of slag particles compared to the rounded shapes of FA [10].

1.3. Hardened properties of geopolymer concrete

Compressive strength: [8] studied the effect of GGBS as a partial replacement (up to 30%) in FA-based geopolymer concrete. The increase of GGBS in the mix increased the compressive strength. An ambient-cured FA-based geopolymer mixture with zero GGBS content reacted slowly to develop strength. The compressive strength of FA-based geopolymer concrete mixtures with 10%, 20% and 30% GGBS content reached 33.3 MPa, 43.2 MPa and 57 MPa, respectively, which are 33%, 74% and 110% greater than the strength of the zero GGBS mixture, respectively. The content of the alkaline activator also affected the compressive strength of the mixtures. [11] also found that increasing GGBS content in FA-based geopolymer concrete increased the strength. The 30% GGBS replacement had the best results in comparison to zero GGBS replacement, which is attributed to better packing and fineness. The ability to fill the voids between larger particles and the secondary hydrate formation through the pozzolanic reactions between lime and water improved the compressive strength. According to [9], an FA-based geopolymer concrete with 30% GGBS replacement achieved the highest compressive strength. It also showed a comparable compressive strength to that of normal concrete at 28 days. The use of GGBS in FA-based geopolymer concrete can offer a solution to the heat curing treatment requirement of geopolymer concrete production, as it allows FA-based geopolymer concrete to be cured at room temperature. [12] found that the compressive strength of binders containing class-F FA and GGBS increased with an increasing GGBS content. The highest compressive strength was obtained when the GGBS:FA ratio was 50:50 (about 108 MPa) at 28 days, followed by a compressive strength of 106 MPa when GGBS:FA was 60:40 at ambient temperature. The FA-slag geopolymer had an accelerated early age strength due to its high CAO content; nevertheless, the 28-day compressive strength was not affected. Moreover, the increase of alkaline solution in the mix as a percentage of binder led compressive strength values to increase in alkali-activated concretes. It was also found that the effect of water to binder ratio on OPC does not apply in the case of AAC. Designing AAC mixes for a certain compressive strength cannot be correlated with the direct effect of water to binder ratio on compressive strength in OPC [13].

Permeability characteristics: [14] stated that the long-term durability of FA-based geopolymer concrete and alkali-activated slag concrete is dependent upon the permeability characteristics of the concrete. It was observed that the water permeation resistance of FA-based geopolymer concrete improved with time due to continuing geopolymerization and performed comparably to Portland cement concrete. FA-based geopolymer concrete had a higher water permeability index than alkali-activated slag concrete in the first 90 days, but this significantly decreased with age. The increase in the packing density of the alumino-silicate gel matrix was hypothesized to positively influence the engineering performance of fly ash geopolymer concrete observed between 90 and 540 days.

Microstructural observations: [8] found that the inclusion of GGBS in FA-based geopolymer sourced additional calcium bearing compound and contributed to the additional binding product that affected the setting behavior of the resulting gel in early stages. It was revealed that the inclusion of GGBS in FA-based geopolymer increased the compactness of the gel and had a hydration product that was mostly amorphous and rich in calcium. The inclusion of GGBS in FA-based geopolymer paste significantly influenced the formation of binding gels and ultimately the hardened microstructure [12]. Observations showed that the ambient-cured FA-based geopolymer with 40% GGBS replacement had a small amount of unreacted or partially reacted FA particles, but these were firmly bonded with the resulting gel.

Furthermore, the calcium content was barely noticeable in the geopolymer gel produced in class-F FA-based geopolymer and was mainly sodium alumino-silicate hydrate gel (N-A-S-H). On the other hand, GGBS inclusion in FA-based geopolymer showed somewhat higher amounts of calcium as well as sodium and silicon. Thus, the polymerization reactions resulted in additional final products of calcium alumino-silicate hydrate (C-A-S-H) in addition to N-A-S-H gel. Therefore, a more compact and denser microstructure was formed with the inclusion of GGBS. [15] reported that compressive strength was affected by FA reactivity and calcium oxide content. The reactivity of the FA was generally controlled by the quantity of finer particles in the reactive amorphous phase and sodium alumino-silicate (N-A-S-H) gel formation. In addition, the calcium oxide content in FA reacted with the activating solution to produce calcium alumino-silicate (C-A-S-H) gel, which provides additional strength in the concrete.

1.4. Use of silica fume and nanosilica in the activating solution

A few studies have investigated the use of silica fume or nanosilica as a part of the activation solution. [16] compared the use of sodium hydroxide/silica fume as an activation solution to the use of sodium hydroxide/sodium silicate and investigated the curing procedure and the effects and source of fly ash in relation to the resulting compressive strength of FA-based geopolymer concrete. A higher compressive strength was achieved with the use of the silica fume-based activating solution (approximately 105.1 MPa). [17] studied NaOH concentration, aging time and curing time. The results of compression tests showed that two days of aging and two days of heat curing are beneficial for strength development. The highest value (67 MPa) was obtained when the concentration of NaOH was 10% of the fly ash mass. [18] studied the effects of external heat amount, sodium hydroxide ratio, and partial Portland cement replacement on fly ash-based geopolymer concrete. The study showed that external heat has an important effect on both early and final compressive strength development. It also proved that sodium hydroxide concentration has a major effect on compressive strength. A sodium hydroxide to binder ratio in the range of 60–100% in the mixture can produce acceptable compressive strength values in several civil engineering applications, and it was found that Portland cement, in the absence of external heat, improves early compressive strength as well as final compressive strength. In addition, SEM observations in the same study showed that the presence of Portland cement reduced microcracks by utilizing the expelled water produced by the geopolymerization process. The study also found a significant correlation between compressive strength and absorption after immersion. The permeable voids ratio for FA-based geopolymer concrete decreased with an increase in Portland cement replacement. [19] showed that the activation of GGBS/Metakaolin blends with by-product derived silicate-based activators can generate mechanical strengths and structures comparable to those obtained using commercial silicate solutions. SF-derived activators result in reaction products with similar characteristics to those obtained using commercial silicate solutions due to the high silicone content in the mix and the high reactivity of this precursor in early stages. [20] compared the effect of commercially produced activating solutions (alkali silicates and alkali hydroxides) with that of solutions derived from by-product materials (nanosilica and alkali hydroxides) on fly ash-based geopolymer paste and mortar in terms of compressive strength, porosity, and microstructure. Compressive strengths were somewhat higher when using commercial silicates as compared to nanosilica-based activators, especially in early stages. However, the compressive strengths of concrete prepared with nanosilica activators were comparable to those reported for the specimens using commercially produced solutions, at longer periods of curing. Nanosilica-derived activators reacted rather more slowly than did commercial sodium silicate activators. Nanosilica particles were suspended in the solution during early stages of the reaction and then released in the later reaction processes. Thus, the porosity was found to be lower when using nanosilica-based activators than when using commercial silicate activators because of the delayed release of silica from the solid nanosilica particles. Microstructural analysis was consistent with the findings that these binders had reduced porosity. The nanosilica-derived activator used a geopolymer gel that was more firmly bonded to the partially reacted FA particles. [21] revealed that, compared with the sodium silicate-based activator mortars, the nanosilica replacement resulted in an increased initial/final setting time, flowability, porosity, and shrinkage, and slightly reduced compressive strength. Mixtures with olivine nanosilica-based activators presented a higher workability than the commercial sodium silicate-based ones, and samples with a higher SiO2/Na2O ratio exhibited higher flowability in general.

Most fly ash-based geopolymer research studies have used the most common activating solution, a combination of sodium silicate and sodium hydroxide that requires high energy to be produced, especially sodium silicate, which requires high temperature (1100–1200 °C) and high pressure during its production. While a few studies have used an alternative activating solution, which is made from silica fume, sodium hydroxide, and water, none have studied the effect of replacing FA with GGBS. Therefore, further investigation is needed to determine the effect of GGBS in the presence of this alternative activating solution. Furthermore, sodium hydroxide (NaOH) and external heat are the most expensive and energy-consuming components in fly ash-based geopolymer concrete. The need for external heat during the curing process limits fly ash-based geopolymer concrete applications to pre-stressed and precast concrete applications. Therefore, the effects of ambient curing are investigated here.

2. Materials and Methodology

Low calcium fly ash (Class F) was used as the main binder, and ground granulated blast furnace slag (GGBS) was used as a replacement in the main binder. The activating solution was made of sodium hydroxide (NaOH), silica fume and tap water. The chemical properties and microstructures of FA, GGBS, and SF are shown in Table 2.1 and Figure 3.1.

Table 2.1: Chemical compositions of FA, GGBS and SF

Chemical Composition %	FA	GGBS	SF
SiO_2	58.72	31.5	95.98
AL_2O_3	28.25	16.46	-
Fe_2O_3	4.84	1.33	-
CaO	2.71	41.26	-
Na_2O	3.72	-	-
K_2O	0.78	-	2.04
MgO	-	6.2	1.88
SO_3	0.76	3.69	-
S	-	1.87	-

Natural fine aggregate and 10-mm crushed stone coarse aggregate complying with ASTM C33-03 were used. Energy dispersive x-ray analysis (EDX) was used to determine the chemical compositions, and a scanning electron microscope (SEM) was used to examine the morphology and particle shapes of FA and GGBS as well as SF. Mix proportions were determined based on a previous study [16] as shown in Table 2.2.

Table 2.2: Mix proportions for geopolymer concrete (kg/m^3)

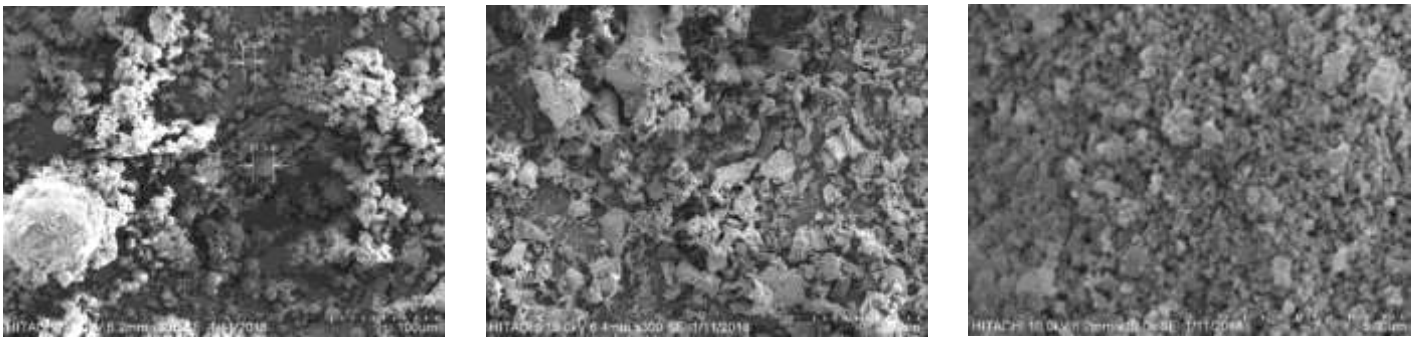
Mix No.	FA	GGBS	NaOH	SF	Water	W/B %	Course Agg.	Fine Agg.	SP
100F0G100N	474	0	61.6	46.2	163	28	793	793	14.2
90F10G100N	426.6	47.4	61.6	46.2	163	28	793	793	14.2
80F20G100N	379.2	94.8	61.6	46.2	163	28	793	793	14.2
70F30G100N	331.8	142.2	61.6	46.2	163	34	793	793	14.2

Sodium hydroxide flakes were dissolved in tap water and stirred for three minutes; silica fume powder was then added, and the solution was mixed for another five minutes. Once the mixing process was complete, the activating solution was heated overnight in an oven at 75 C to ensure that the sodium hydroxide solution and silica fume powder were completely dissolved. The coarse and fine aggregates were mixed with the binder in dry conditions for two minutes. These dry materials were then mixed with the activating solution for another two minutes. The testing samples used were 100 mm cubes. All the specimens were then vibrated for two minutes. The curing methods involved ambient and heat curing for two days preceded by two aging days. The density, absorption, and volume of the permeable pore space of the geopolymer concrete were determined according to ASTM C642-06. FA-based geopolymer paste specimens were casted at the same time and conditions and were examined with a scanning electron microscope (SEM) to understand the microstructure of the geopolymer paste.

3. Results And Discussion

Material characterization: As shown in Figure 3.1, FA has amorphous spherical-like particles ranging in size from 100 µm to less than 1 µm that are rich in silica and alumina, while GGBS is found to be rich in calcium oxide and silica and has irregular-shaped particles that are similar in size to FA particles. By contrast, SF is distinguished by its extremely fine spherical particles, and 96% of its chemical content is silica. These results agree with the observations made in the literature regarding these materials.

Workability: All mixtures were tested using the slump cone test to examine their workability. Table 3.1 shows the slump test values for different mixes. The 100% FA mixture had a very high slump value (220 mm), indicating high workability, and reached its final setting after 24 hours. As GGBS partially replaced FA, a significant decrease in workability was observed. Slump values were 190 mm and 180 mm for 10% and 20% GGBS replacement, respectively. The inclusion of 30% GGBS replacement in the mix showed normal concrete consistency with a slump value of 150 mm. The 30% GGBS replacement caused rapid setting and hardening of the mixture, which led to difficult handling during specimen molding. This was probably due to the irregular shape of the GGBS particles and the high CaO content at 30% GGBS replacement. This result agrees with previous studies [8] [9] which stated that the inclusion of GGBS in FA-based geopolymer plays a significant role in decreasing the workability of the mix.



(c) (b) (c)

Figure 3.1: SEM images of (a) fly ash, (b) GGBS, (c) SF

Table 3.1: Slump values for different GGBS replacements

Mix No.	Slump Value (mm)
100F0G100N	220
90F10G100N	190
80F20G100N	180
70F30G100N	150

Effects of GGBS: A compressive strength test was conducted at 7 and 28 days for the different mixes cured in heat and ambient conditions. Figure 3.2 shows the results of the compressive strength test after 7 and 28 days in heat curing conditions. The effect of GGBS on the compressive strength of heat-cured FA-based geopolymer concrete can be observed. The results of the 7-day compressive strength showed that 20% GGBS achieved the highest strength (60.2 MPa), which was 26% higher than the strength of the control mix (47.7 MPa), followed by 10% GGBS (57.5 MPa). The 28-day results showed a relative increase in strength compared to the 7-day results. The 20% GGBS had the highest strength value (67.6 MPa), which was 31.5% higher than the strength of the control mix (51.4 MPa), followed by 10% GGBS (64.8 MPa). On the other hand, the effect of GGBS in FA-based geopolymer cured in ambient conditions was more effective. Figure 3.3 shows the results of the compressive strength test after 7 and 28 days in ambient curing conditions. The 7-day results showed that FA replacement with 20% and 10% GGBS in the mix achieved strengths of 32.7 MPa and 22.7 MPa, respectively, which are approximately 190% and 100% higher than the strength of the control mix (11.3 MPa). The results of the 28-day strength test showed a significant increase compared to the 7-day results. The 20% GGBS replacement had the highest strength in the 28-day results (57.1 MPa), which is 75% higher than its 7-day strength as well as 70% higher than the 28-day strength of the control mix (33.6 MPa). The 10% GGBS replacement obtained a nearly 120% higher value (49.8 MPa) than its 7-day strength. It was found that the replacement of GGBS up to 20% had a positive effect in terms of developing higher early and final compressive strengths compared to the control mix with no GGBS due to the high GGBS reactivity. The reactions between the binder (FA and GGBS) and the activating solution produced more geopolymeric final products, namely sodium alumino-silicate hydrates (N-A-S-H) and calcium alumino-silicate hydrates (C-A-S-H). Moreover, the high CaO content in GGBS can be hydrated to produce calcium silicate hydrate (CSH) final products; therefore, the compressive strengths improved with the inclusion of GGBS in the mix [12] [22]. However, the 30% GGBS replacement did not contribute to increasing the compressive strength compared to the 20% GGBS replacement. The 30% GGBS replacement achieved strengths of 59.2 MPa in 7 days and 64.3 MPa in 28 days, while in ambient conditions, strengths of 32.8 MPa in 7 days and 56.8 MPa in 28 days were achieved, which are similar to the 20% GGBS replacement results.

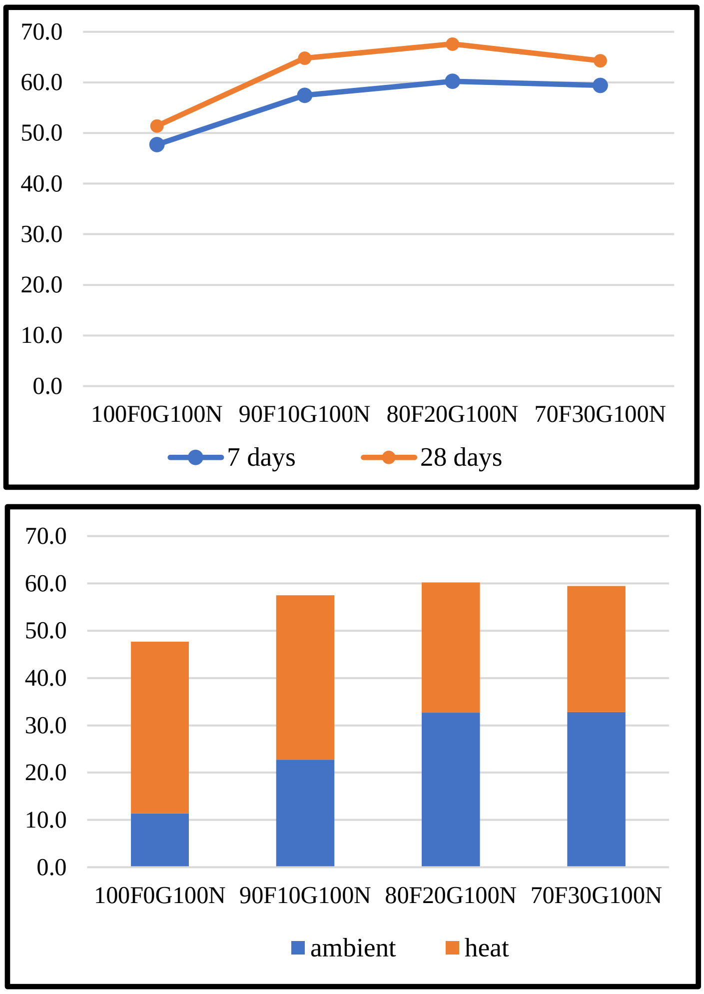


Figure 3.3: 7-day compressive strength for different GGBS content

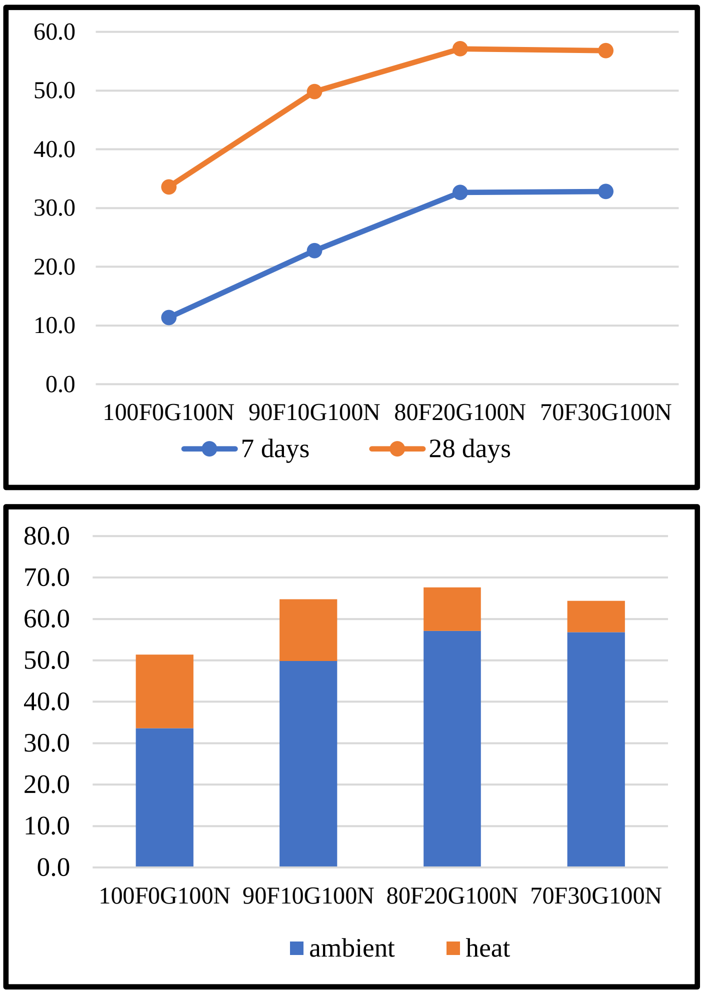


Figure 3.4: 28-day compressive strength for different GGBS content

Effect of curing conditions: The effect of different curing conditions on compressive strength was investigated. Figures 3.4 and 3.5 show the compressive strength results for 7 and 28 days in heat and ambient curing conditions. The effect of heat curing can be seen clearly in the early stages. The 7-day compressive strength for heat-cured zero GGBS replacement mix was 47.7 MPa, which is more than four times the ambient-cured mix value of 11.3 MPa. By contrast, in mixes where GGBS was included, the compressive strength values of the heat-cured mixes were approximately double those of the ambient-cured ones. The 28-day compressive strength was also improved by heat curing but with less impact than on the 7-days results. The compressive strength values of heat-cured 0%, 10%, 20% and 30% GGBS replacement mixes were 50%, 30%, 18% and 13% higher than those of the ambient-cured mixes.

It is believed that heat curing at 70 C degrees for 48 hours played a significant role in developing an early strength that was rather close to the final strength, as seen in Figure 3.2. The heat enhanced the dissolution process of the binder by increasing the solubility of the silica and therefore accelerated the geopolymerization process of the binder in the mixes [17] [23]. It is important to mention that the inclusion of 20% GGBS in the mix eliminated the heat curing effect on compressive strength compared to the control mix. The 28-day strength of ambient-cured, 20% GGBS, FA-based geopolymer concrete had a strength of 57.1 MPa, while heat-cured, zero GGBS, FA-based geopolymer concrete achieved a strength of 51.4 MPa.

Microstructural observations: The microstructures of FA-based geopolymer pastes were examined by an SEM at an age of 21 days. Figures 3.6, 3.7, 3.8, and 3.9 show SEM images for geopolymer pastes with different GGBS replacements. The FA-based geopolymer with no GGBS replacement has a slightly porous final product with unreacted FA particles (denoted as A), as seen in Figure 3.6. Obvious cracks can be noticed around the unreacted particles, which indicates that they were not well bonded with the final product. The polymer gel produced by activating low-calcium FA is basically sodium alumino-silicate hydrate (N-A-S-H). A similar observation was found in [16]. A denser microstructure can be observed with the inclusion of GGBS in the paste mix due to the existence of Ca content as GGBS increased in the mix. The 10% GGBS replacement shows fewer unreacted FA particles that are firmly bonded with the final product (Figure 3.7), which indicates that the Ca content contributed to the geopolymerization process. Hydration of GGBS can be noticed with a 20% GGBS replacement for FA in the mix (Figure 3.8). A hydrated gel product (CSH) seems to appear in the paste, and alumino-silicate gel containing calcium (C-A-S-H) is formed alongside N-A-S-H, which explains why the 20% GGBS replacement achieved the highest compressive strength, as mentioned in the previous section. This observation agrees with the observations in the literature [8] [12]. Figure 3.9 shows that more hydrated gel (CSH) was noticed when GGBS replaced FA at 30% in the mix due to the high Ca content; however, voids (denoted as B) can be found in this mix due to the very fast hardening as a result of the higher GGBS content, which explains the slight drop in compressive strength.

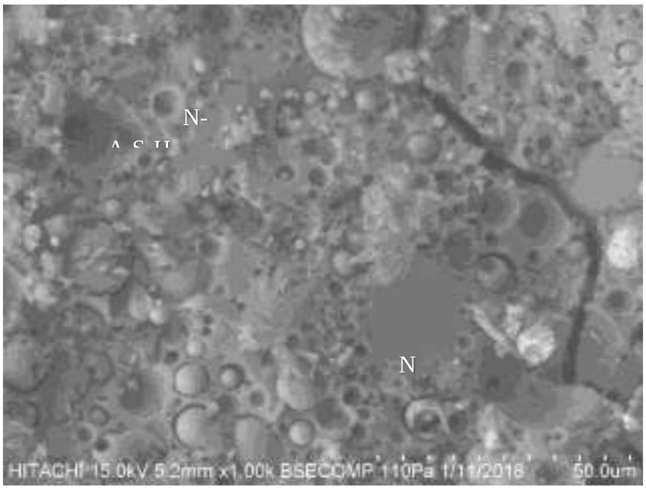


Figure 3.6: SEM image of zero GGBS replacement

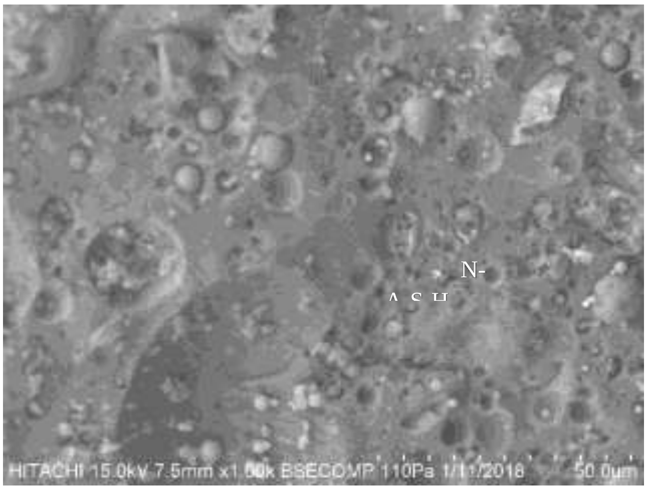


Figure 3.7: SEM image of 10% GGBS replacement

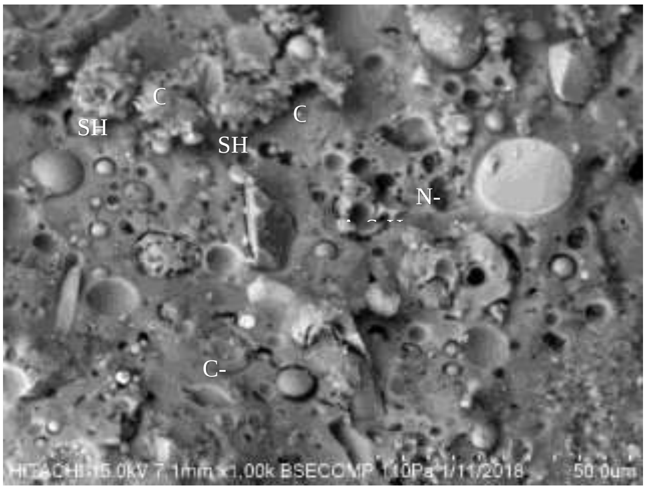


Figure 3.8: SEM image of 20% GGBS replacement

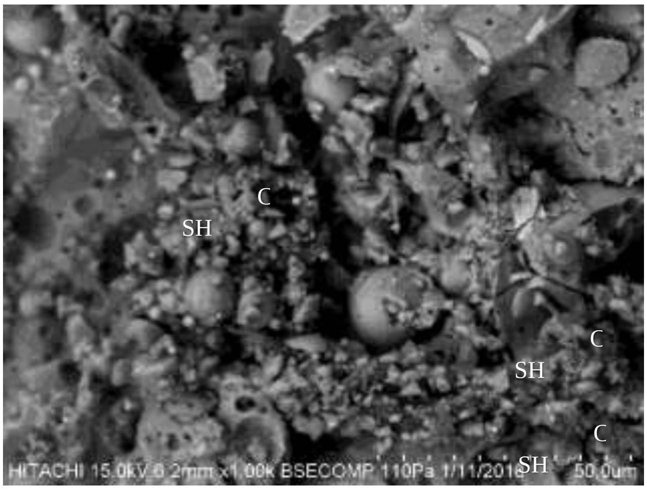


Figure 3.9: SEM image of 30% GGBS replacement

Density, absorption, and volume of permeable voids: Absorption and the volume of permeable pore space were determined by testing ambient-cured mixes. Figure 3.10 shows the absorption and voids values for different mixes. The inclusion of up to 20% GGBS in the mix had a significant effect on reducing absorption and voids ratios, which could be due to the reduction of micro cracks and porosity, as mentioned in the previous section. The 20% GGBS replacement also had the lowest absorption and voids values (3.77% and 8.47%, respectively), which were 36.7% and 36.6% less than the control mix values (5.96% and 13.37%, respectively). This result proved that FA-based geopolymer concrete, activated by silica fume and NaOH solution, could have a durability comparable to that of conventional concrete [24]. A clear correlation was seen between absorption after immersion and compressive strength, as shown in Figure 3.11. By comparing 20% GGBS replacement to zero replacement, the absorption after immersion decreased by 36.7%, and the compressive strength increased by 70%. [18] reported a similar finding of replacing FA by OPC up to 15% by weight.

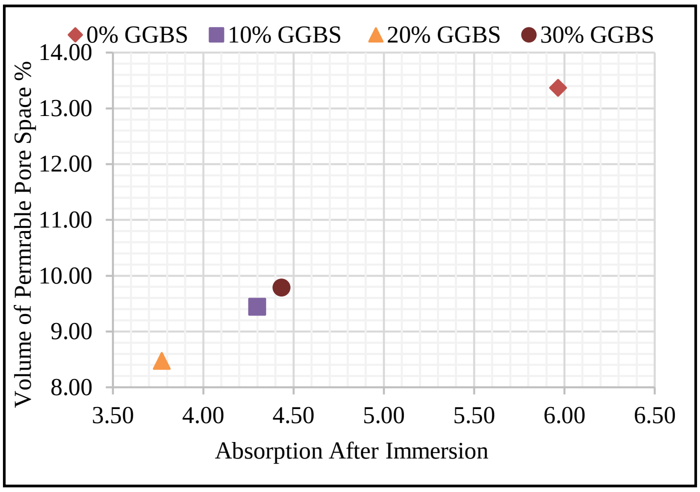


Figure 3.10: Volume of permeable pore space and absorption after immersion correlation for different GGBS replacement samples

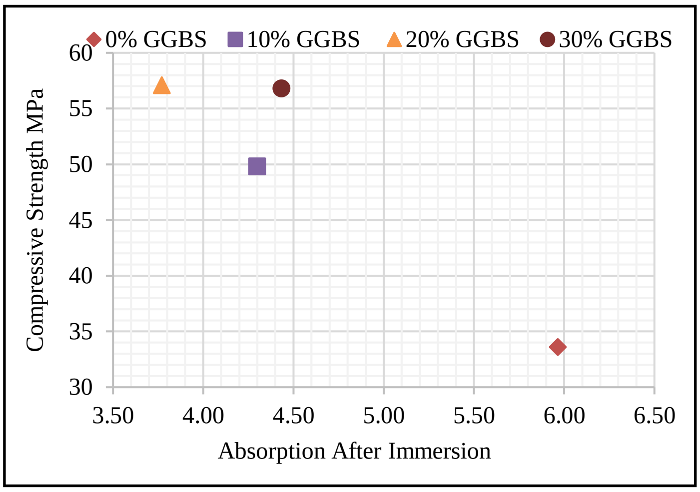


Figure 3.11: Absorption after immersion and compressive strength correlation for different GGBS replacement samples

4. Conclusion:

Most fly ash-based geopolymer research studies have used a combination of sodium hydroxide and sodium silicate as an activating solution. An alternative solution that utilizes by-product materials was used in this study, namely a silica fume and sodium hydroxide solution. GGBS replaced fly ash to a certain percentage in the mix, because it has been proven that GGBS has the ability to produce relatively high early strength due to its high CaO content and high reactivity. It can be concluded that:

1) The workability of FA-based geopolymer concrete significantly decreased with an increased GGBS replacement percentage. However, rapid setting and hardening was observed when GGBS replaced FA at 30% due to the irregular shapes of the GGBS particles and the high CaO content.
2) The replacement by GGBS had a positive effect on developing rather high early and final compressive strengths in heat curing conditions, which is considered high strength concrete. The 20% GGBS replacement achieved a 26% higher early strength (60.2 MPa) and a 12.3% higher final strength (67.6 MPa) compared to zero GGBS replacement.
3) The replacement of GGBS up to 20% played an important role in increasing the early and final compressive strengths of FA-based geopolymer concrete in ambient conditions. The compressive strength tripled in 7 days to 32.7 MPa and was 70% higher in 28 days (57.1 MPa) as compared to zero replacement. This is a promising outcome that supports widening geopolymer concrete use in on-site construction works.
4) The inclusion of 20% GGBS in the mix eliminated the heat curing effect on compressive strength compared to the control mix. The 28-day strength of ambient-cured, 20% GGBS, FA-based geopolymer concrete had a strength of 57.1 MPa, while heat-cured, zero GGBS, FA-based geopolymer concrete achieved a strength of 51.4 MPa.
5) Microstructural observations revealed that the inclusion of GGBS in FA-based geopolymer concrete resulted in a denser final product with fewer cracks due to the existence of CaO, which positively contributed to the microstructure of the geopolymer paste.
6) The inclusion of up to 20% GGBS in FA-based geopolymer concrete reduced absorption and voids rates, which indicates an improvement in geopolymer concrete durability. Absorption was reduced by 36.7% and 3.77%, and voids were reduced by 36.6% and 8.47% compared to the control mix.

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