

INVESTIGATION ON APPLYING GEOPOLYMER MORTAR INCORPORATING GGBS TO PRECAST PRODUCT

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ABSTRACT

The application of fly-ash based geopolymer mortar incorporating ground granulated blast furnace slag (GGBS) presents a promising alternative to traditional Portland cement in precast concrete products, especially when it involves CO₂ emissions. To be a competitive replacement, it requires further study and development regarding its durability and mechanical properties. The purpose of this study is to promote it as a competitive substitute for precast concrete products. Utilizing fly ash as the basis material, mixing with different weight percentages of GGBS (0%, 20%, and 30%). Evaluating the final mixes' compressive strength, porosity, shrinkage, and efflorescence susceptibility. The results showed that compressive strength was greatly increased over 50 MPa at 7 days observed at 30% GGBS content. Moreover, increased GGBS content also leads to reduced porosity. However, the addition of GGBS promotes issues, especially in shrinkage and efflorescence, which can potentially lower durability and aesthetics. More specifically, the faster hydration rate of GGBS compared to fly ash plays a part in increased shrinkage, while its higher calcium content promotes efflorescence formation creating undesirable surface salt deposits. In summary, the addition of GGBS content offers several advantages, however it also highlights certain problems. The study underscores the need for further optimization to mitigate these drawbacks and promote universal acceptance in precast concrete applications.

Keywords: Precast, Fly ash, Geopolymer, GGBS, Durability.

INTRODUCTION

The construction sector has considerable challenges in adopting sustainable advancements, particularly in precast concrete production, due to the negative environmental impact of traditional cement production. Geopolymer alternative, applying industrial by-products such as fly ash (FA) and ground granulated blast furnace slag (GGBS), offers a viable option that has a high chance to pursue green construction goals [1,2]. However, their popularization in precast concrete production has been obstructed by some critical performance issues such as its durability [3].

Precast concrete products, which are manufactured in controlled factory environments and then transported to construction sites for assembly, offer major benefits over traditional in-situ concrete, including better quality control and quicker construction time periods. This research aims to address the current problems by examining the effects of adding GGBS to FA geopolymers, enhancing the mechanical and durability attributes needed for precast applications. The goal is to enhance these materials' performance under controlled laboratory conditions with the utilization of heat curing. This can lead to high initial strength [4], strengthening them suitable for precast elements, supporting their industry standard viability, and solving critical performance issues in precast concrete manufacturing.

RESEARCH SIGNIFICANCE

This study emphasizes the significance of environmentally friendly construction by enhancing fly ash-based geopolymer with GGBS (FA-GGBS GP). The goal of this study is to enhance material performance, including durability, workability, and mechanical qualities. This advancement eliminates the impact on the environment and promotes eco-friendly activities by providing practical and affordable substitutes to produce precast concrete. The results support innovation in the building sector and encourage the applying of more eco-friendly and effective building materials and methods.

MATERIALS AND METHODS

In this research, geopolymers are synthesized using industrial by-products, specifically FA, JIS type II, and GGBS with 6000 Blaine Fineness, without gypsum addition, as the primary active fillers. The process involves activating these alumina-silica powders with an alkali activator solution, composed of sodium hydroxide and water glass (sodium silicate). GGBS is used in a limited amount (up to 30%) to supplement FA due to its higher reactivity. In this study, the percentage of GGBS substitution ranged from 0% to 30%. The upper limit of 30% was selected because preliminary observations indicated that specimens with 30% GGBS addition exhibited rapid

hardening. This rapid hardening could potentially complicate the experimental procedures.

Although FA and GGBS being sourced from the same production facility, variability may occur due to their by-product nature. To ensure consistency and minimize material differences, this study utilized FA and GGBS from the same production batch.

To investigate the incorporation of FA with GGBS product, significant tests were carried out.

Mortar specimens measuring 40 mm by 40 mm by 160 mm were cast and heat-cured at 60°C. Compressive strength was tested according to JIS R 5201, while shrinkage was measured using JIS A 1129-2. Additionally, efflorescence and Archimedes Porosity Tests were conducted. All tests were performed in a controlled laboratory environment to simulate precast production conditions.

Mix Design Considerations.

Selection of significant parameters.

In the preliminary stages of geopolymer (GP) testing, critical parameters such as the alkali solution to FA with GGBS binder mass ratio (L/B), water glass/sodium hydroxide solution mass ratio (SS/SH), liquid/solid mass ratio, slag/mixed cementitious material mass ratio (slag content), and curing method were carefully selected to assess their impact on the workability and compressive strength of GP product. These parameters, crucial for expressing the influence of alkali stimulants on GP properties, are standardized across different regions, although specific measurement methods may differ by country. Notably, in Japan, parameters for alkali stimulants are expressed using the molar mass ratio of sodium ions to silica ions in sodium hydroxide/water glass solutions (Si/A) and the sodium ion concentration in the alkali stimulant, alkaline stimulant to water (A/W), as in [5]. Building on prior research findings, which highlighted the importance of parameters involving L/B close to 0.5, Sp/Ss close to 1:1, and Si/A close to 0.6 for optimal GP strength and workability [6], this study conducted preliminary tests based on these parameters.

In this research, A/W ratios ranging from 0.12 to 0.15 are preferred, with higher alkali concentrations leading to increased strength. Optimal Si/A ratios of 0.5 and 0.6 have been established. Subsequent investigations in this study were focused on fixed parameters outlined in Table 1 for specimen preparation.

Table 1 Selection of parameters

L/B	Sp/Ss	Si/A	A/W
0.5	1:1	0.6	0.12/0.15

Explanation of mix used

The alkali stimulant was given priority in the

calculation process formulations, which calculate its total mass per cubic meter with the L/B and Sp/Ss ratios. The stimulant's Si/A molar mass ratio was chosen, and then the Si⁴⁺/Na⁺ ratio was adjusted using SH and a water glass, and the Na⁺ concentration (A/W) was controlled with the water.

This determined the additional amounts of water glass, SH, and water in the binder relative to the total mass of the alkali stimulant.

The specimens of GP mortar were prepared according to the formulations shown in Table 2.

Table 2 Mix proportions.

	GGBS (%)*	A/W	Unit Amount (kg/m ³)		
			JIS3 Na ₂ SiO ₃ Solution	NaOH	Water
FA100	0%	0.12	213.6	39.4	106
FA80	20%				
FA70	30%				
FA100 HA	0%	0.15	247.6	45.7	68
FA80HA	20%				
FA70HA	30%				

Note: L/B = 0.5, Si/A=0.6, HA = High Alkaline Stimulant, *GGBS (% by weight)

Experiment Setup

Preparing the test specimen

In geopolymers, the liquid component must be prepared prior to mixing with cement and aggregates, similar to traditional cement. Geopolymers require extended setting times for the alkali stimulant, with reaction durations typically ranging from 4 to 12 hours following the addition of solid sodium hydroxide to water glass. Reaction times shorter than 4 hours may lead to inconsistencies, while those exceeding 12 hours can result in precipitation. To optimize the process, this study standardized the preparation period to 4 hours [7,8].

Due to their high viscosity and tendency to trap air, geopolymers require extended mixing times, approximately double the usual duration, for optimal blending. Specimens need at least one day of heat curing before demolding, as geopolymers set gradually and adhere strongly to molds. Inadequate use of releasing agents can complicate demolding and increase the risk of specimen damage [8,9].

RESULTS AND DISCUSSION

Strength Evaluation

Fig.1 shows the compressive strength of FA-GGBS GP addition at 28 days of age. The results show that the compressive strength of FA-GGBS GP can be enhanced by adding more amount of GGBS and alkali concentration (A/W) to the mixture as well as by utilizing heat curing, reflecting that extremely high initial strength for GP mortar. Promoting the polycondensation reaction in GP mortar, thereby enhancing the strength of the specimens. Lee, W. K. W., and van Deventer, J. S. J [10], support that heat-cured samples achieved high early strength, within 1-3 days, while air-cured samples exhibited a gradual increase, reaching moderate strength by 28 days.

The incorporation of GGBS into geopolymer mixtures enhances strength through several mechanisms. GGBS reacts with alkali stimulants to form additional hydration products, such as C-A-S-H gel, which reinforce the geopolymer structure. It also reduces voids, fills pores, and increases microstructure density. Additionally, GGBS’s fine particles act as nucleation sites, promoting further hydration. In fly ash-based geopolymers, GGBS’s high calcium content improves alkali stimulation, leading to more extensive reactions, as in [2,4,7].

On the other hand, Fig.1 presents that, for FA100, even with the ideal Si/A ratio, L/B ratio, and aggregate quantity, without incorporating GGBS and applying heat curing, the strength of GP was found to be lower than that of conventional silicate cement. Considering the greater difficulty in manufacturing GP compared to cement products. Heat curing and the addition of GGBS are thought to be necessary to achieve basic usage requirements.

Fig.1 also shows that after 1 day of heat curing, the compressive strengths are relatively low, with FA70 HA being the highest and FA100 the lowest. After 7 days, there is a notable increase, with FA70 HA (~75 MPa) and FA80 HA (~71 MPa) showing the high strengths, while FA100 remains the lowest. The compressive strengths peak at 10 days of heat curing, with FA70 achieving the highest strength. Overall, extended heat curing significantly enhances concrete mixtures’ compressive strength.

Fig.2 shows the strength development of FA-GGBS GP up to 42 days of age with 1-day heat curing. The results show that strength development almost stops after 14 days. Continuous heat curing in a high-temperature environment can further catalyze reactions within FA-GGBS GP. Therefore, while heat

curing is a well-established method to improve the low strength of FA-GGBS GP, it significantly increases power consumption and complicates the construction process. Hence, the issue of heat curing is a more critical challenge for FA-GGBS GP.

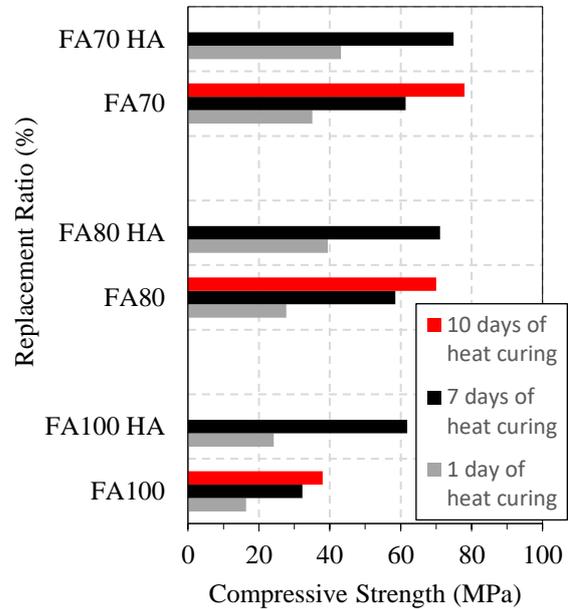


Fig 1. Compressive Strength at 28 Days

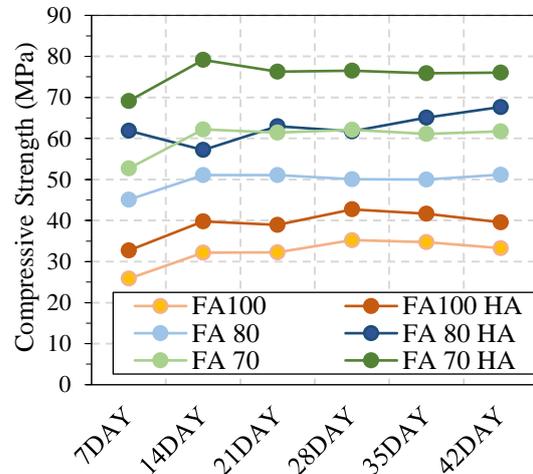


Fig 2. Compressive Strength Development

Efflorescence Evaluation

A large amount of Ca²⁺ in GGBS can present several kinds of issues. The addition of GGBS may potentially cause internal expansion, cracking, and efflorescence in GP. Internal expansion occurs because, when Ca²⁺ interacts with sulfates, it can form expansive products such as calcium sulfate (gypsum) or sulfoaluminate compounds. [11]. These expansive products undergo volumetric expansion due to water

absorption, which weakens the GP's sulfate resistance, cause cracking and reduced strength. Additionally, soluble calcium salts formed by the reaction of Ca^{2+} with water can migrate to the surface of FA-GGBS geopolymer concrete along with water, leaving behind white deposits after evaporation. Furthermore, Ca^{2+} in FA-GGBS geopolymer concrete may leach into the environment, potentially impacting nearby water or soil. [11]. Specimen with efflorescence confirmed visually is showed in Fig.3.

Thus, the presence of free Ca^{2+} in FA-GGBS geopolymer concrete can significantly increase the risk of deterioration. Addressing this issue is a critical challenge in a field of geopolymer concrete.



Fig.3 Image of Efflorescence.

Shrinkage Evaluation

The data for FA-GGBS GP's autogenous shrinkage are presented in Fig.4 These findings do not clearly show how altering A/W (alkali concentration) affects shrinking. However, it was observed that GGBS considerably increases shrinkage, and the shrinkage increases with the amount of GGBS added.

The effect of GGBS addition on shrinkage is shown in Fig.4, which indicates that GGBS incorporation considerably raises shrinking. More specifically, FA70 has shrunk around three times more than FA100 has. FA80's shrinking value falls between FA70 and FA100's. According to the findings, GGBS has a noticeable influence on shrinkage, with the amount of shrinkage rising depending on the amount of GGBS added. FA70 exhibits the maximum shrinkage, while FA80 displays an intermediate level in this Figure.

This may occur because of differences in the reaction rates of GGBS and FA, leading to hydration effects, Poisson effects and structural changes associated with GGBS addition.

GGBS tends to hydrate more quickly than FA, indicating that it may produce more hydration products in the early stages of hydration. These hydration products fill the pores of FA-GGBS GP, leading to volume expansion. However, as water continues to evaporate, the spaces previously

occupied by hydration products shrink, contributing to increased autogenous shrinkage in FA-GGBS GP. This phenomenon is known as “hydration-induced Poisson effect” [12,13].

Incorporating GGBS can alter the pore structure of FA-GGBS GP, potentially increasing porosity, restricting water evaporation, and enhancing capillary action, potentially resulting in increased autogenous shrinkage. The differing reactivity of GGBS and FA affects hydration products and rates, impacting shrinkage behaviour. Mehta, P. Kumar, and Paulo J. M [14], excessive shrinkage can cause interface detachment with reinforcing bars, diminishing the protective effects of geopolymer concrete and raising concerns about its use with reinforcement, controlling shrinkage remains a critical issue for geopolymer applications.

In contrast to regular cement products, precast elements are frequently subject to controlled curing conditions and tight tolerances. Excessive shrinkage may have an adverse effect on the precast product's overall performance and longevity by causing problems such as warping, cracking, and impaired fit within built buildings.

Moreover, when compared to other curing regimes. The faster reaction and denser microstructure of heat-cured samples resulted in a decrease in autogenous shrinkage. In contrast, air-cured samples exhibited moderate levels of shrinkage, consistent with their slower reaction rates. [15].

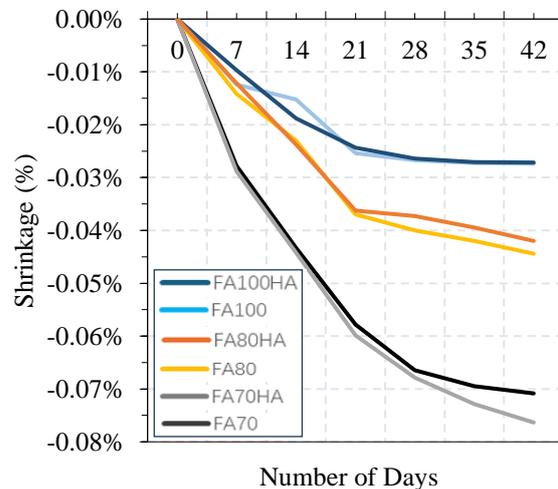


Fig.4 Shrinkage (%)

Porosity Evaluation

Data on the void ratio of FA-GGBS GP mortar are presented in Fig.5 and Fig.6, these findings clearly show that reducing the void ratio can be achieved by both raising the A/W ratio (alkali concentration) and the amount of GGBS incorporated.

Fig.5 shows that the porosity of FA70 and FA70 HA is reduced by approximately 6% compared to FA100 and FA100HA. The porosity values of FA80 and FA80HA fall between those of the FA70 and FA100 mixtures. This shows a distinct pattern whereby the addition of GGBS reduces overall porosity, with FA70 and FA70HA showing the greatest reduction.

Increasing the A/W ratio affects the hydration and microstructure of GP by enhancing the alkaline environment. This environment promotes the dissolution of silicates and aluminates from FA and GGBS, leading to more hydration products such as C-S-H and C-A-S-H gels, which fill pores and reduce porosity. Higher alkaline concentrations facilitate uniform reactions of reactive components from FA and GGBS, decreasing unreacted particles and voids [16]. The reduction in void ratio with higher GGBS content is due to its physical and chemical properties, which improve the GP microstructure through interaction with FA and alkali stimulants. The following are potential the primary causes of this effect [17].

Firstly, when slag and water combine in an alkaline environment, calcium silicate hydrate (C-S-H gel) and other hydration products are produced. These products assist to minimize the porosity of the geopolymer by inserting in its interior pores.

Furthermore, GGBS, with its fine particle size, functions as a micro-filler, reducing voids and improving compactness by filling larger pores. It also enhances particle size distribution, leading to tighter packing and improved overall compaction. This better dispersion facilitates denser packing of particles, minimizing gaps and improves overall compaction.

GGBS enhances the geopolymer's hydration rate, leading to more consistent hydration and fewer unreacted particles. This results in increased density and fineness, reducing capillary voids and overall porosity. Consequently, the geopolymer becomes denser, more compact, and less porous [17].

While not conclusively proven, it is speculated that the factors discussed collectively reduce the void ratio in geopolymers with GGBS addition. Additionally, geopolymers typically have fewer small voids and more large-entrained air voids compared to conventional concrete, as in Fig. 6. Therefore, Neville, Adam M [18] shows, the void ratio of laboratory-prepared cement mortar is around 15% and increases in concrete, the void ratio in FA-GP is notably high, highlighting the importance of void reduction. Fig. 4

confirms that GGBS addition and an increase in the A/W ratio effectively diminish the void ratio.

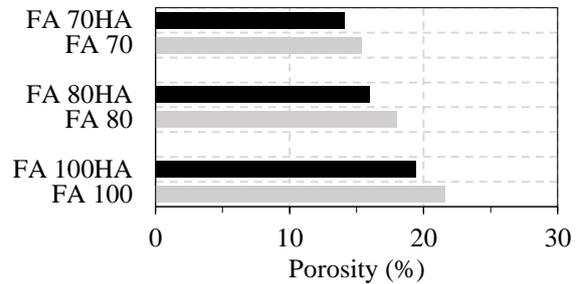


Fig.5 Porosity (%) at 14 Days curing

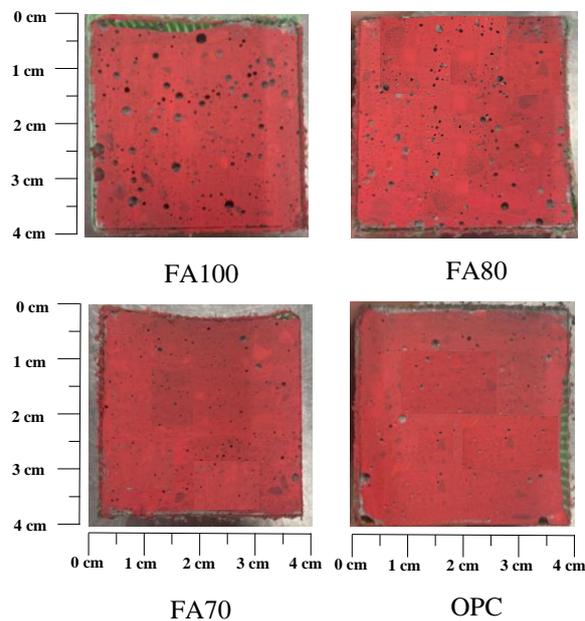


Fig.6 Images of porosity

Potential methods to mitigate the negative effects

This study suggests the following measures to mitigate the negative aspects identified in the findings.

Implementing carbonation curing

Positioning the geopolymer mortar in a CO₂-rich environment initiates a reaction between CO₂ and the calcium in GGBS, strengthening the mortar's microstructure and reducing shrinkage. This carbonation process also minimizes surface salt formation, thereby reducing efflorescence [19].

Implementing additive agents

Superplasticizers can enhance mortar workability without additional water, leading to denser particle packing, reduced porosity, and lower shrinkage [20]. Efflorescence-control admixtures react with soluble salts to form insoluble precipitates, thus minimizing salt migration and reducing efflorescence [21].

CONCLUSION

Geopolymers reinforced with GGBS offer significant benefits for precast construction. Increasing GGBS content and alkali concentration enhances compressive strength and reduces porosity. Specifically, 30% GGBS results in about twice the compressive strength and improves compaction as a micro-filler. However, GGBS's faster hydration rate compared to fly ash leads to greater autogenous shrinkage, with FA70 showing about three times the shrinkage of FA100. Additionally, the Ca^{2+} in GGBS can cause efflorescence and reduce sulfate resistance.

This study suggest that further optimization is required to lessen these disadvantages and produce a geopolymer precast product that is more durable, aesthetically stable, and appropriate for border construction.

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