DEVELOPMENT OF SUSTAINABLE GEOPOLYMER CONCRETE USING GGBS, FLY ASH, AND RECYCLED AGGREGATES TO REDUCE ENVIRONMENTAL IMPACT

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ABSTRACT

The production of cement is a major contributor to greenhouse gas emissions. Global emissions from the manufacture of cement stood at 1.7 billion metric tons of carbon dioxide (CO_2). Geopolymer concrete (GPC) is a sustainable alternative to traditional cement-based concrete that can reduce the carbon footprint of construction. This research investigated the GPC consisting of fly ash, ground granulated blast furnace slag (GGBS), recycled coarse aggregate, and alkaline solutions. The effects of varying percentages (30%, 40%, 50%, 80%, and 100%) of GGBS with fly ash, different molarities (6M, 10M, and 14M) of sodium hydroxide, and several ratios of sodium silicate to sodium hydroxide (1.5, 2.0, 2.5, and 3.0) were examined to determine the optimal combination for the splitting tensile and flexural strengths of GPC. Two curing conditions, ambient and membrane curing, were also investigated for the strengths cases. Ambient curing is conducted indoors with controlled environmental conditions and at room temperature, while membrane curing takes place outdoors under direct sun exposure. The study found that increasing the percentage of GGBS in the mix causes a higher strength of GPC. However, when 100% GGBS is used as a binder, GPC achieves its highest strength. GPC with a 50% GGBS and 50% fly ash composition was superior to that of conventional cement concrete. It was found that membrane curing is more effective than ambient curing in terms of strength development and efflorescence. This study also shows that using waste materials such as fly ash and GGBS along with recycled aggregates in GPC is an eco-friendly and affordable solution for sustainable construction practices. The study's conclusions may be applied to develop more sustainable GPC mixes, which can help reduce the carbon footprint of the construction industry.

Keywords: *Tensile strength, Flexural strength, Membrane and ambient curing, Ground granulated blast furnace slag (GGBS), Carbon footprint.*

1. INTRODUCTION

Cement is one of the most significant contributors to greenhouse gas emissions in construction. Currently, the cement production sector is responsible for 8% of carbon emissions, and it requires something to substitute for conventional concrete. In this regard, geopolymer concrete is one of the promising solutions (Posi et al., 2013). GPC is a new invention whose primary substances are fly ash, GGBS, silica fume, etc. GPC utilizes the aluminosilicate materials that cause reactions with activators like sodium silicate and sodium hydroxide to make a gel-like material, which forms a bond in aggregate and imparts strength to the concrete (Singh et al., 2015).

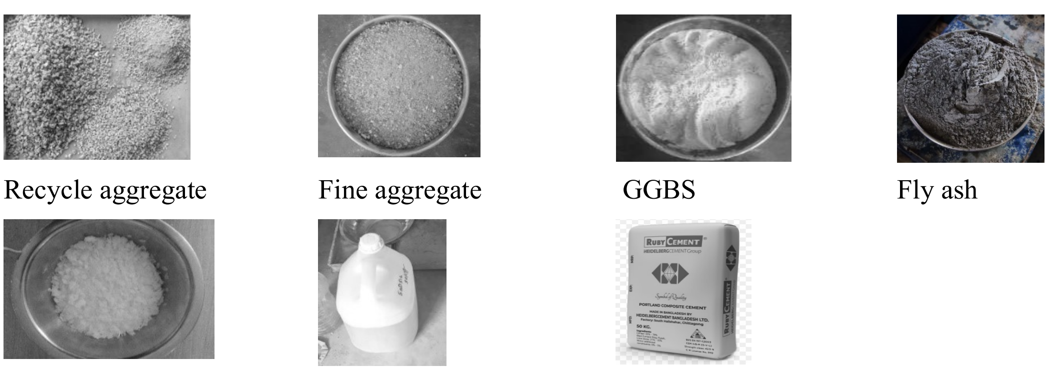
Several studies show that GPC is an environmentally friendly alternative to conventional concrete. It can reduce CO_2 emissions significantly (Podolsky et al., 2021). GPC can utilize industrial products like fly ash and GGBS, which can reduce landfill waste and play a part in sustainable development (Jwaida et al., 2023). In terms of the environment, it also has some financial benefits because it does not need extra energy or resources and is easily generated from industrial products (Wongkvanklom et al., 2021). Its strengths and durability are better compared to conventional Portland cement (Krishnan et al., 2015).

The aim of this study is to explore the feasibility of using GPC as a sustainable alternative to conventional Portland cement concrete. The main objective of the study is to observe how the strength and durability of geopolymer concrete are increasing under the influence of fly ash and GGBS percentage. Simultaneously, changes in the strength of geopolymer concrete under the effects of membrane curing and ambient curing are observed.

2. METHODOLOGY

2.1 Materials

Recycled aggregate, GGBS, fly ash, sodium hydroxide, and sodium silicate solution were used for this study. GGBS is a by-product of the iron-making industry and was collected from Premier Cement Ltd. Fly ash is the by-product of a coal thermal power plant, and it was collected from Confidence Cement Company Limited. The recycled aggregate generated from crushed concrete slabs was collected from Sanmar Properties Limited. The particle sizes of the recycled coarse aggregate (RCA) varied from 4.75mm to 12.5mm. For this investigation, Sylhet sand was chosen as the fine aggregate.



Recycle aggregate | Fine aggregate | GGBS | Fly ash

Sodium Hydroxide | Sodium silicate | Cement (As control)

Figure 1: Materials used for geopolymer concrete (GPC).

Sodium hydroxide (NaOH) is a strong base that reacts with the aluminosilicate material to form a strong geopolymer network. Sodium hydroxide is typically used in molarities of 6 to 16, although a maximum of 14 molarity has been observed. The higher the molarity, the stronger the geopolymer concrete.

Extra-alkaline sodium silicate (Na_2SiO_3) solution is frequently used to make durable geopolymer concrete. It can help make the mixture more workable and act as a supply of silicon for the geopolymer network. Sodium hydroxide and sodium silicate are very often used to create a dual activator system.

The sodium hydroxide (SH) and sodium silicate (SS) required for this study were collected from the local market. sodium silicate solution consists of 16.37% Na_2O, 34.35% SiO_2, and 49.28% H_2O. Batch formation was carried out using solutions of sodium hydroxide at concentrations of 6molarity, 10 molarity, and 14 molarity.

This study looked at different geopolymer concrete batches with different proportions of sodium silicate and sodium hydroxide, different molarities of sodium hydroxide, and different proportions of GGBS and fly ash to determine the splitting tensile strength and flexural strength of the batches. Five batches (A, B, C, D, and E) selected in this study with their proper mix ratios and curing methods are presented in **Table 1**. The mix design was done by following the ACI 211.1-91 specification.

Table 1: Proportions of mix composition and curing types for each batch.

Batch No	SS/SH ratio	NaOH	Percentage of GGBS & Fly ash in the mix	Test of strength	Types of Curing	Days	Stone chips/ Binder ratio	Binder/ Alkaline ratio
A	3	6M,10M, and 14M	30%&70% 40%&60%, 50%&50% 80%&20%, and 100%&0%	Split tensile	Membrane and Ambient curing	28	3.68	2.5
B	1.5, 2.0, 2.5, and 3	6M		Split tensile	Ambient curing	28		
C	1.5, 2.0, 2.5, and 3	10M		Split tensile	Ambient curing	28		
D	1.5, 2.0, 2.5, and 3	14M		Split tensile	Ambient curing	28		
E	3	6M,10M, and 14M		Flexural strength	Ambient curing	28		

As a control sample, 100% cement was taken.

2.2 Details Of Mold Preparation

Safety precautions were taken when preparing the solution for this test, including safe handling and preparation of the solution (24 hours before use). Sodium hydroxide at 6M, 10M, and 14M concentrations was prepared. To prepare the GPC, first, fly ash and GGBS were mixed well together for two minutes, then sodium hydroxide was added and mixed well for three minutes. Then the sodium silicate was added, and the course was mixed again for two minutes. After the addition of aggregate and fine aggregate, water was added and mixed for two more minutes, then transferred to concrete molds and covered with polythene. After one day, hard GPC was removed from the mold and kept for curing.

2.3 Details Of Tests

Splitting tensile strength: The ASTM C496/C496M-17 criteria were used in this test to evaluate the split tensile strength of GPC. Testing was done in Universal Testing Machine (UTM) at twenty-eight (28) days of curing, and the strengths reported were averages from three samples. This method seeks to assess the performance of geopolymer concrete in various curing conditions, offering important insights into the material's durability and mechanical properties.

Flexural strength: In this study, flexural strength tests were conducted as per ASTM C78/C78M-21 on 4in × 18in concrete beam specimens which were prepared and cured for 28 days.

2.4 Curing modes of specimens

The geopolymer concrete mixture was cast very carefully. The GPC specimens were covered with plastic polyethylene for 28 days at room temperature. On the other hand, for membrane curing, it was covered and exposed to the sun for 28 days. Environmental conditions (stability and humidity control) were monitored for each sample by signs of salinity, cracking, or swelling during curing days. After 28 days, tests were conducted to monitor the strength and durability of the geopolymer concrete (shown in **Figure 2**). Samples with different ratios of GGBS and fly ash were investigated to see if the color changed with the increase in GGBS.

Figure 2: A visual representation of GPC and color in the curing process.

3. RESULTS AND DISCUSSIONS

3.1 Effects Of SH (NaOH) Solutions On Splitting Tensile Strength

Geopolymer concrete was prepared with different proportions of GGBS and fly ash. Curing conditions were ambient curing at room temperature and membrane curing at direct sun exposure. In both cases, the curing process was observed for 28 days.

The results of splitting tensile strength of geopolymer concrete with different concentrations of sodium hydroxide (6M, 10M, and 14M) are shown in **Figures 3, 4**, and **5**. The highest value was observed in ambient curing when 100% GGBS was used. Splitting tensile strengths of 337 psi, 410 psi, and 525 psi were found in ambient curing for 6 molarity, 10 molarity, and 14 molarity, respectively with 100% GGBS. On the other hand, for membrane curing, the highest values observed for the same sodium hydroxide concentrations (6M, 10M, and 14M) were 392 psi, 480 psi, and 623 psi with 100% GGBS. Tabassum et al. (2015) reported similar findings that the molarity of sodium hydroxide increases, the tensile strength of geopolymer concrete always increases.

Based on the ratio of GGBS and fly ash, the geopolymer concrete exhibited different strengths. The observed results showed that splitting tensile strength increased significantly with increasing GGBS content. The highest splitting tensile strength was found when GGBS was the only binder material and fly ash was not included (see **Figures 3, 4**, and **5**). Geopolymer concrete exhibits high strength during membrane curing, which is in direct sun exposure. Solar exposure accelerates the curing process and promotes enhanced chemical reactions, resulting in stronger and more durable concrete. This observation emphasizes the significant influence of curing conditions on the strength and growth of geopolymer concrete (Abdollahnejad et al., 2020).

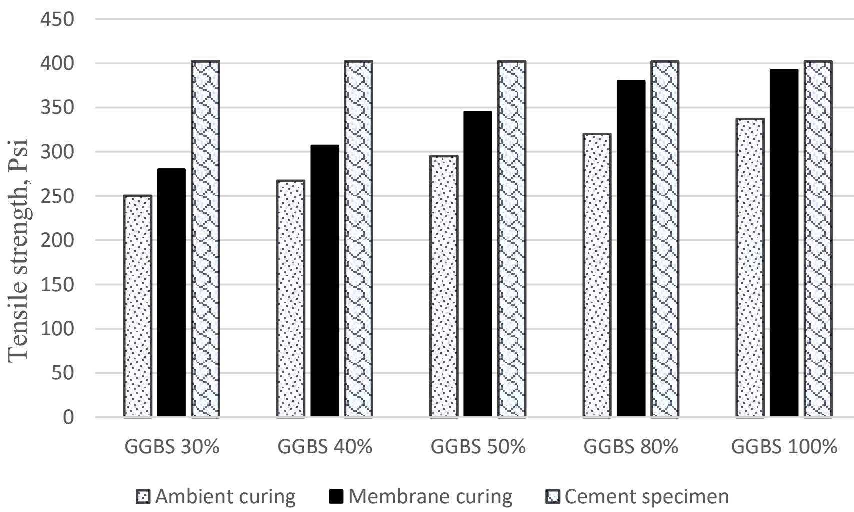


Figure 3: Splitting tensile strength at 28 days for 6 molarity of sodium hydroxide (GPC batch A).

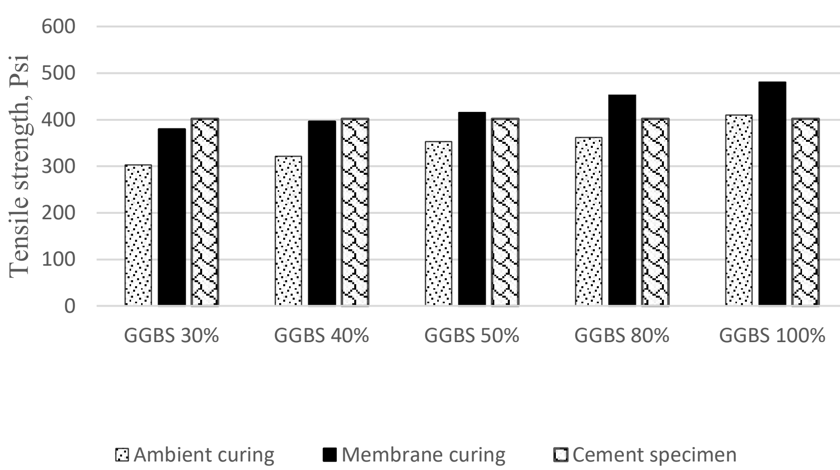


Figure 4: Splitting tensile strength at 28 days for 10 molarity of sodium hydroxide (GPC batch A).

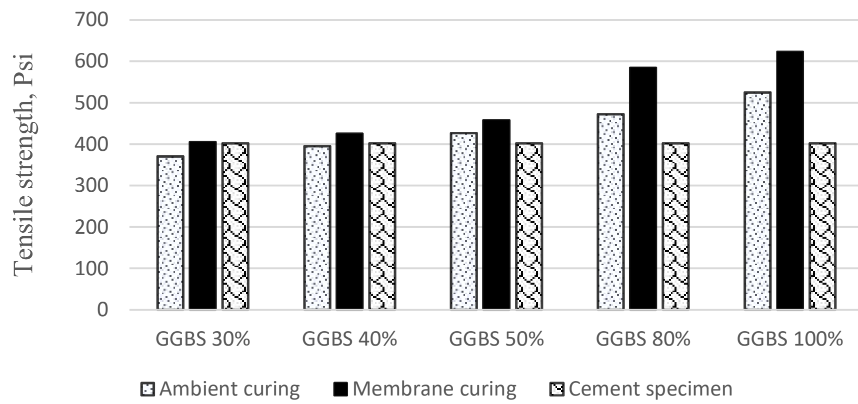


Figure 5: Splitting tensile strength at 28 days for 14 molarity of sodium hydroxide (GPC batch A).

3.2 Effects Of Sodium Silicate To Sodium Hydroxide (SS/SH) Ratios On Splitting Tensile Strength

The effect of different ratios of sodium silicate to sodium hydroxide (SS/SH) (1.5, 2.0, 2.5, and 3.0) and different molarities of sodium hydroxide (6, 10, and 14 molarity) on splitting tensile strength are shown in **Figures 6, 7**, and **8**.

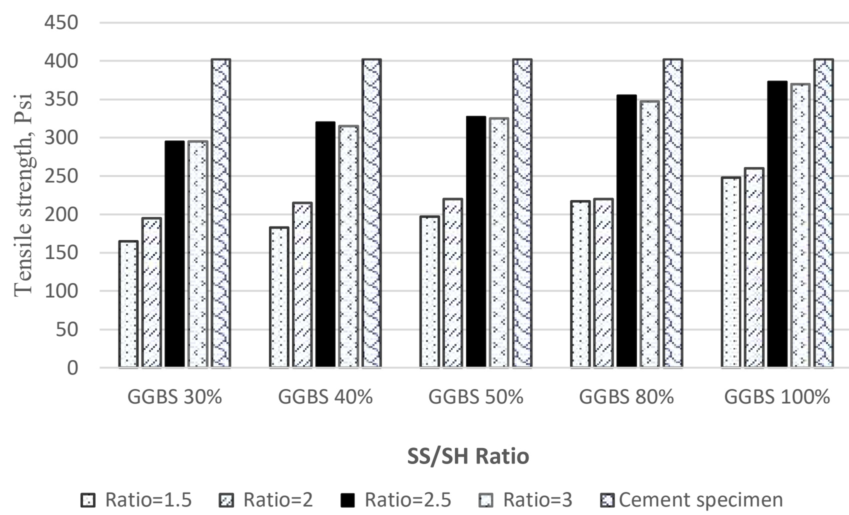


Figure 6: Splitting tensile strength at 28 days for 6 molarity of sodium hydroxide (GPC batch B).

It has been seen in **Figures 6, 7**, and **8** that the value of splitting tensile strength increases as the ratio of sodium silicate to sodium hydroxide (SS/SH) increases. Four ratios (1.5, 2.0, 2.5, and 3.0) were used in this study, and the highest strength value was found at a ratio of 2.5 (Sanni et al., 2013). A maximum strength value for the 2.5 ratio was observed when 100% GGBS was used. Tensile strength values for the 2.5 ratio (when 100% GGBS was used) were 373 psi, 480 psi, and 539 psi when molarity was 6, 10, and 14, respectively. Increasing the ratio of activator and GGBS contributes to the increase in tensile strength. This is because the sodium hydroxide and sodium silicate materials help form bonds within the materials, and GGBS-cementous materials are the strength generators of geopolymer concrete. Various researchers (Abhilash et al., 2016; Sanni and Khadiranaikar, 2013) also found better strength for GPC than conventional concrete.

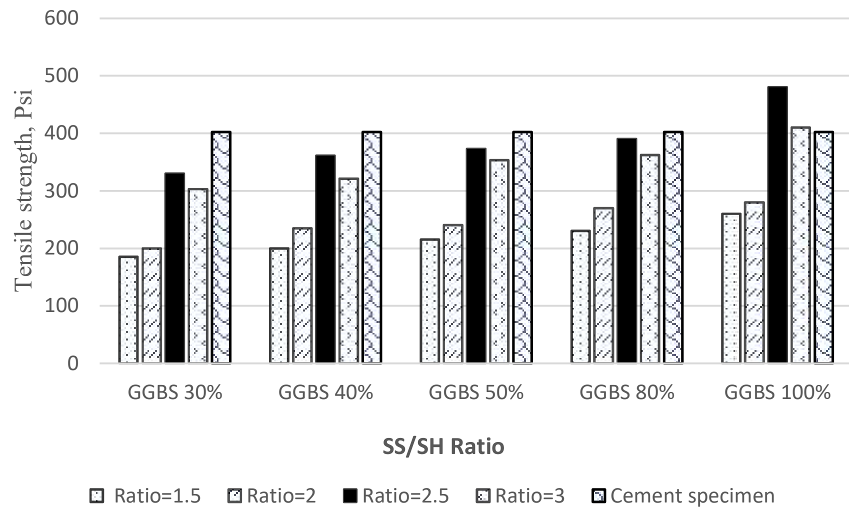


Figure 7: Splitting tensile strength at 28 days for 10 molarity of sodium hydroxide (GPC batch C).

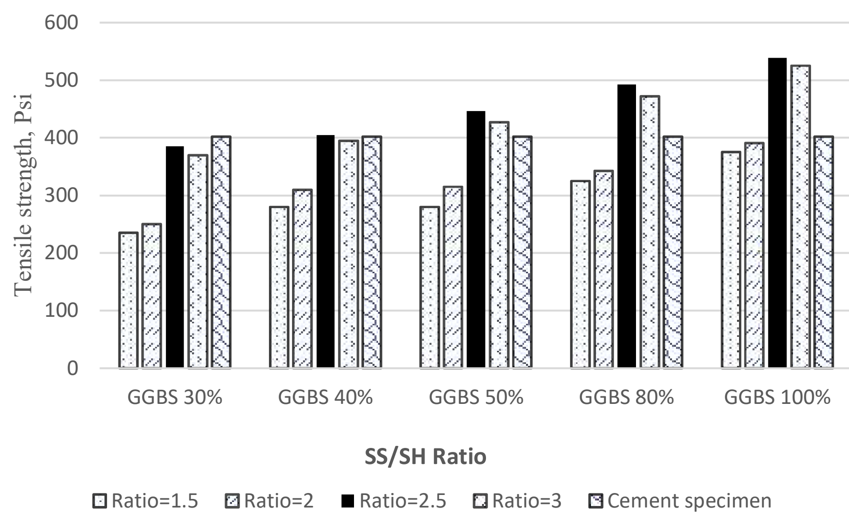


Figure 8: Splitting tensile strength at 28 days for 14 molarity of sodium hydroxide (GPC batch D).

3.3 Flexural strength

Geopolymer concrete (batch E) made with different proportions of GGBS and fly ash under ambient curing is shown in **Figure 9**. The best flexural strengths for 100% GGBS were 635 psi, 697 psi, and 747 psi for sodium hydroxide concentrations of 6, 10, and 14 molarity, respectively. The flexural strength was 570 psi, 630 psi, and 670 psi under the specified sodium hydroxide concentrations for 50% GGBS and 50% fly ash. The flexural strength for 50% GGBS mixture was higher than that of the cement specimen (609 psi) at 10M and 14M SH concentrations, meaning that it worked better in these situations.

Since the strength of geopolymer concrete is highly dependent on temperature, temperature must be considered during the curing days. Geopolymer concrete gains early strength within 24 hours of casting, so the temperature in the first 24 hours is very important. The concrete sample during curing must be covered with plastic because the alkaline solution of sodium silicate and sodium hydroxide can evaporate due to temperature. If the alkaline solution evaporates, the quality of geopolymer concrete will decrease (Chouksey et al., 2022).

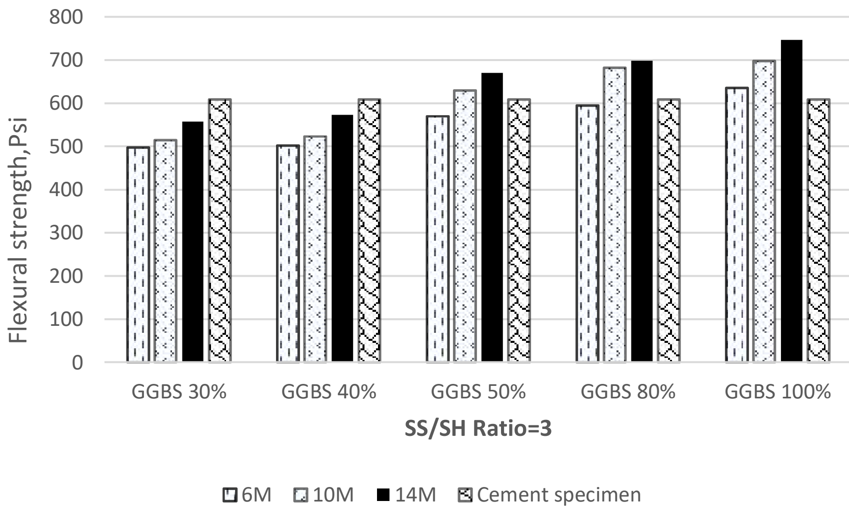


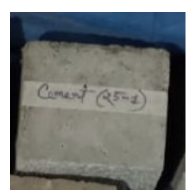
Figure 9: Flexural strength at 28 days of GPC batch E.

3.4 Effects of Curing Environment on GPC

The curing environment accelerates the properties of geopolymer concrete specimens (see **Figure 10**). Specimens cured without plastic cover exhibited detrimental effects, including swelling, salting, and strength loss. On the other hand, specimens cured with plastic covers have increased strength and minimized efflorescence (Abdollahnejad et al., 2020). The favorable curing conditions that the plastic cover provides, which accelerate silica gel formation and aid in strength development. If a plastic cover is not used on the specimen, sodium silicate and sodium hydroxide are inhibited by directly reacting with atmospheric air to form silica gel. This causes swelling and salinity within the specimen and reduces strength. Similarly, different colors were observed within the specimens. In the study, the following specimen developed a white saline swelling condition, and one specimen exhibited a white ash color (see **Figure 10**). Furthermore, the strength of specimens exposed to sunlight is much higher than that of samples kept inside the laboratory or in shaded areas. Due to environmental conditions, the study suggested protective measures such as plastic covers to increase the strength and durability of geopolymer concrete.

Specimen curing without cover

Specimen with plastic covers

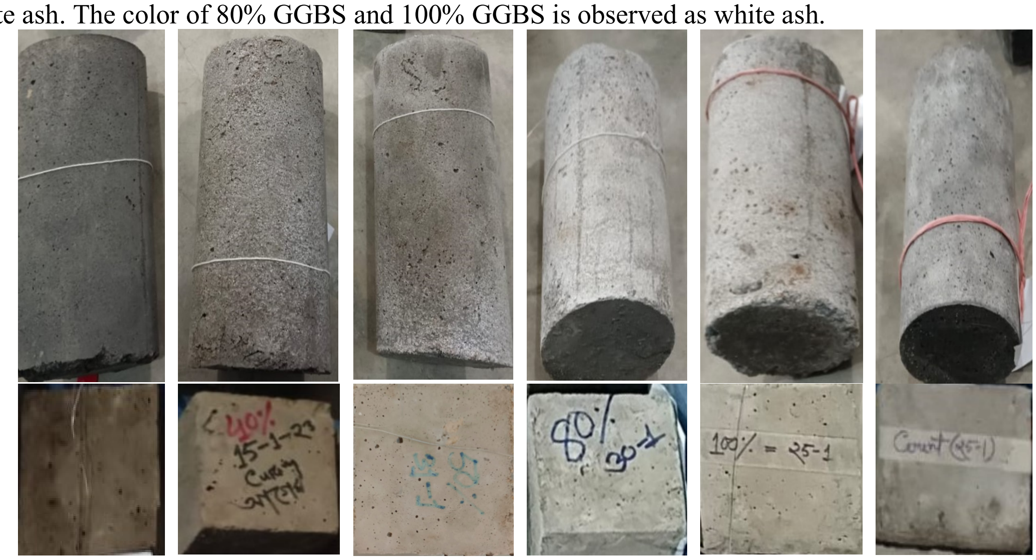


Cement specimen

Figure 10: Efflorescent effect of specimen in direct environment exposure.

3.5 Color variation of Geopolymer specimen

In this study, the color of different samples of geopolymer concrete was analyzed, as shown in **Figure 11**. 30% GGBS and 70% fly ash, 40% GGBS and 60% fly ash, 50% GGBS and 50% fly ash, 80% GGBS and 20% fly ash, and 100% GGBS and 0% fly ash were investigated, and the cement sample was observed as a control sample. The different colors of different ratios of GGBS and fly ash were found. 30% GGBS and 70% fly ash show black ash color, and as the percentage of GGBS increases, the color of geopolymer concrete changes. With increasing GGBS, the color of the sample turns to white ash. The color of 80% GGBS and 100% GGBS is observed as white ash.



30% GGBS and 70% fly ash	40% GGBS and 60% fly ash	50% GGBS and 50% fly ash	80%GGBS and 20% fly ash	100% GGBS and 0% fly ash	Cement specimen

Figure 11: Color variation of cylinder and cube specimens.

3.6 Failure modes of specimens

As shown in **Figure 12**, the cylinder specimens show longitudinal cracking introduced along the loading line under compressive loads, while flexural strength tests resulted in cracks developing along the width of the beams. Those cracks resulted from the application of various loads to the specimens (Hamidi et al., 2020).

30% GGBS and 70% fly ash | 40% GGBS and 60% fly ash | 50% GGBS and 50% fly ash | 80%GGBS and 20% fly ash | 100% GGBS and 0% fly ash

30% GGBS and 70% fly ash | 40% GGBS and 60% fly ash | 50% GGBS and 50% fly ash | 80% GGBS and 20% fly ash | 100% GGBS and 0% fly ash

Figure 12: Failure modes of specimens.

4. CONCLUSIONS

The study can infer the following conclusions based on the findings:

- Increasing the percentage of GGBS in the mix causes higher splitting tensile and flexural strength.
- After 28 days of curing with 100% GGBS, GPC exhibited higher strength when subjected to membrane curing, especially with a NaOH concentration of 14 M.
- The strength of GPC is enhanced by higher concentrations of sodium hydroxide. Additionally, an increase in the sodium silicate to sodium hydroxide ratios up to 2.5 improves both splitting tensile and flexural strength.
- Specimens containing higher proportions of fly ash displayed a dark ash color, and this coloration gradually shifted as the content of GGBS increased.

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