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FLEXURAL STRENGTH OF LOW-GRADE GGBS-BASED GEOPOLYMER CONCRETE (GPC)

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Abstract

This paper investigates the flexural performance of Geopolymer Concrete (GPC) synthesized using lower-grade Ground Granulated Blast Furnace Slag (GGBS) under ambient curing conditions. The study focuses on the impact of varying sodium hydroxide molarity (6M, 8M, 10M, and 12M) in the alkaline activator solution on the flexural strength of the developed GPC mixes. GGBS with relatively lower reactivity, characterized by moderate specific surface area and CaO content, was employed to examine its viability in sustainable GPC applications. Mix proportions were kept constant across all samples with a binder-to-aggregate ratio of 1:2.5 and a liquid-to-binder ratio of 0.50. Specimens were tested for flexural strength after 7 and 28 days using a two-point loading configuration. The results indicate a consistent enhancement in flexural strength with increasing molarity of NaOH. At 28 days, Mix M1 (6M) exhibited a flexural strength of 2.48 MPa, which increased to 3.01 MPa for Mix M4 (12M), reflecting a 21.37% improvement. This trend was similarly observed in 7-day results, although with comparatively lower strength values. The rise in molarity enhances geopolymerization, leading to better bonding and denser microstructure, thereby improving mechanical performance. However, strength gains beyond 10M were marginal, suggesting a saturation threshold for molar concentration benefits. The findings support the use of low-grade GGBS as a viable binder in GPC production for flexural applications, offering a pathway for industrial waste utilization and sustainability in concrete construction.

Keywords: Flexural Performance of Geopolymer Concrete, Lower-Grade Ground Granulated Blast Furnace Slag, Sodium Hydroxide, Alkaline and Flexural Strength.

1. INTRODUCTION

Geopolymer concrete has emerged as an innovative and eco-friendly alternative to traditional Ordinary Portland Cement (OPC) concrete. It is synthesized through the alkali activation of industrial by-products rich in aluminosilicates, such as Ground Granulated Blast Furnace Slag (GGBS). This technology significantly reduces carbon dioxide emissions and energy consumption, aligning with global goals for sustainable infrastructure. The ability to utilize industrial waste materials not only reduces environmental burden but also offers improved mechanical and durability properties. Among these properties, flexural strength—essential for resistance to bending in structural members like beams and slabs—is crucial for structural applications (George & Totar, 2022).

Several studies have investigated the performance of GGBS-based geopolymer concrete under varying curing conditions, mix designs, and the incorporation of reinforcing fibers. Polypropylene and steel fibers, when added to the geopolymer matrix, have been shown to reduce brittleness and enhance both compressive and flexural strength (Parashar et al., 2023). Research by Thakur et al. optimized various mix parameters to improve flexural strength using low alkali ratios and fiber additions, showing results comparable to M25 OPC control mixes (Thakur et al., 2022). Furthermore, ambient curing—a practical requirement in many construction scenarios—has proven effective for strength gain in GGBS-based geopolymer systems (Chithambar et al., 2019). The current work focuses specifically on low-grade mixes (M15, M20, M25), exploring their flexural performance under real-world curing and loading conditions to support broader adoption in low-cost, sustainable construction.

1.1. Sustainability And Low-Carbon Construction Materials

The construction industry is one of the largest contributors to global CO_2 emissions, primarily due to the production of OPC. Cement manufacturing accounts for approximately 8% of global carbon emissions, necessitating a shift toward alternative binders. Geopolymer concrete made with GGBS presents a sustainable and low-carbon solution. GGBS is a by-product of iron manufacturing, and its use diverts waste from landfills while minimizing reliance on virgin materials. When activated with alkaline solutions, GGBS forms a dense matrix with excellent mechanical properties and chemical durability, making it suitable for structural use (Kumar & Ramesh, 2016).

Additionally, the production of geopolymer concrete consumes significantly less energy and water than traditional cement concrete. Research shows that GGBS-based geopolymer concrete has a substantially lower embodied energy and can achieve comparable compressive and flexural strengths, even at early curing ages (Sadawy et al., 2020). The environmental advantages of this material are further amplified when natural curing (ambient conditions) is employed, reducing the energy cost associated with oven or steam curing. The cumulative effect of using industrial waste, reducing carbon emissions, and conserving resources makes GGBS-based geopolymer concrete a promising candidate for meeting environmental sustainability goals (Thakur et al., 2022).

1.2. GGBS-Based Geopolymer Concrete for Structural Use

GGBS-based geopolymer concrete offers excellent mechanical properties, including high early strength, low permeability, and good resistance to chemical attacks, making it suitable for structural applications. It is particularly effective in flexural members, where resistance to bending is critical. Research shows that GGBS-based mixes can achieve strength comparable to OPC when activated with optimized alkaline solutions. Studies by George & Totar (2022) and Kumar & Ramesh (2016) demonstrate that geopolymer beams and prisms exhibit good load-bearing capacity and improved crack resistance under bending loads (George & Totar, 2022), (Kumar & Ramesh, 2016). Furthermore, reinforced geopolymer beams incorporating GGBS and steel fibers showed increased ductility and flexural strength under cyclic and static loading conditions (Saranya et al., 2019). These advantages position GGBS-based geopolymer concrete as a reliable and durable alternative for structural frameworks in both residential and infrastructure projects.

1.3. Importance Of Flexural Strength in Bending Resistance

- **Resistance to Bending Loads:** Flexural strength determines how well concrete resists bending stresses from applied loads, crucial in beams and slabs. High flexural strength ensures the structural member can carry loads without cracking or failing prematurely.
- **Crack Control and Ductility:** Improved flexural strength enhances crack resistance and post-crack ductility, preventing brittle failure and allowing structures to deform safely under stress.
- **Design Safety and Load Distribution:** In structural design, flexural strength ensures safe load distribution, especially in reinforced concrete elements where bending moments dominate.
- **Serviceability under Repeated Loading:** Higher flexural strength improves performance under cyclic or dynamic loads, such as traffic or wind, maintaining integrity over time.
- **Indicator of Overall Structural Integrity:** Flexural strength often correlates with tensile and shear performance, serving as an indicator of a structure's overall mechanical robustness.

1.4. Influence Of Mix Grades (M15, M20, M25) On Flexural Performance

Concrete grade significantly influences its flexural performance. Low-grade mixes like M15 and M20 typically exhibit lower flexural strength compared to M25, due to reduced binder content and lower density. However, in GGBS-based geopolymer systems, even M15 mixes have demonstrated satisfactory flexural performance when optimized with appropriate alkaline ratios and fiber additions. Research by Thakur et al. (2022) confirmed that GGBS-based M25 geopolymer concrete achieved flexural strength comparable to OPC control mixes, while M15 and M20 grades showed strength increases with fiber reinforcement and higher GGBS content (Thakur et al., 2022).

Studies by Parashar et al. (2023) and Chithambar et al. (2019) show that with polypropylene or steel fiber reinforcement, even low-grade mixes gain 10–15% in flexural capacity compared to unreinforced geopolymer concrete (Parashar et al., 2023), (Chithambar et al., 2019). Optimized alkaline solution molarity (10M–13M) and GGBS percentages (80–100%) play a vital role in improving the matrix's cohesiveness and bonding, resulting in enhanced flexural strength across all grades. While M25 remains the most reliable grade for load-bearing elements, M15 and M20 GGBS-based mixes can be effectively utilized in non-critical applications or with reinforcements to meet structural demands.

1.5. Ambient Curing and Practical Construction Conditions

Ambient curing is essential for real-world applicability of geopolymer concrete, particularly in regions lacking access to elevated temperature curing. Research confirms that GGBS-based geopolymer concrete develops sufficient mechanical properties, including flexural strength, even under ambient conditions. Studies by Chithambar et al. (2019) demonstrated that polypropylene fiber-reinforced geopolymer concrete achieved high early flexural strength after just 7 days of ambient curing (Chithambar et al., 2019). Similarly, George & Totar (2022) observed effective strength development without heat curing when using optimized alkaline activators and GGBS contents (George & Totar, 2022). These findings support the feasibility of using low-grade geopolymer concrete in field conditions without compromising structural performance.

1.6. Need For Evaluating Long-Term Strength Development

Long-term strength development in geopolymer concrete is critical for ensuring structural integrity and durability over service life. Unlike OPC, which gains strength through hydration, geopolymer concrete relies on polymerization, which continues over time, especially under ambient curing. Several studies confirm that GGBS-based geopolymer concrete continues to gain flexural and compressive strength beyond 28 days. For instance, George & Totar (2022) observed substantial strength improvement between 28 and 90 days in ambient-cured specimens. Research by Sadawy et al. (2020) also highlights enhanced flexural and tensile properties over time due to fiber reinforcement and continued geopolymerization (Sadawy et al., 2020). Moreover, Parashar et al. (2023) found strong correlations between early compressive strength and long-term flexural strength, suggesting that early testing could serve as a predictor for service performance (Parashar et al., 2023). Evaluating long-term strength is especially important for low-grade mixes, which may initially show lower performance but gain substantial durability over time, enabling their use in secondary structural components or sustainable housing.

2. OBJECTIVE

To evaluate and compare the flexural strength of three different grade of concrete M15, M20, M25

3. LITERATURE REVIEW

Shafiullah et al. (2021) investigated the environmental benefits and structural performance of GGBS as a substitute for cement in concrete. Their study showed that GGBS, as a by-product of iron production, significantly reduces CO_2 emissions and energy consumption while enhancing the compressive strength of M30-grade concrete. Using IS 10262 and IS 456-2000 standards, they demonstrated that GGBS-based mixes not only met but exceeded characteristic strength requirements. Rafeet et al. (2017) explored the use of both fly ash and GGBS in alkali-activated concrete (AAC) and analyzed the effects of varying paste volume, water content, and blend ratios. While the inclusion of more GGBS improved compressive strength, it also accelerated setting time, raising challenges for workability and construction timing.

Srinivas et al. (2016) focused on optimizing mix designs for low-calcium fly ash and slag-based geopolymer concrete, specifically for G30 and G50 grades. Their study highlighted that variables such as alkaline liquid-to-binder ratio, Na_2SiO_3/NaOH ratio, and curing conditions significantly influence strength development. They achieved optimal compressive strength by calibrating these parameters. Thunuguntla et al. (2018) applied the particle packing theory to proportion aggregates in alkali-activated slag concrete, producing dense mixes with fewer voids and improved compressive strength. Kathiresan et al. (2022) evaluated the effect of incremental GGBS replacement (up to 50%) on concrete performance, concluding that although compressive strength improved, increased brittleness under flexural and tensile stress limited structural flexibility.

Poloju et al. (2020) and Naresh et al. (2024) emphasized the feasibility of ambient-cured geopolymer concrete mixes for M25 and M30 grades. Their findings confirmed that with the right balance of fly ash, GGBS, and alkaline activators, geopolymer mixes could outperform OPC concrete even without elevated-temperature curing. These studies are crucial for real-world applications, particularly in regions where heat curing is not practical. Moreover, the inclusion of fibers and refined SS/SH ratios was found to improve workability and flexural behavior, making low-grade GGBS-based mixes viable for residential and pavement construction.

Reddy et al. (2018) proposed a rational mix design methodology for geopolymer concrete that adapts ACI principles by correlating alkaline activator content to target strength. Their mix design approach offered flexibility in adjusting binder and activator content while maintaining performance under ambient conditions. Jahagirdar et al. (2022) explored the compressive strength of M40-grade mixes with varying GGBS replacement levels, finding 25% substitution optimal for strength enhancement without significant degradation. Faried et al. (2020) supported these findings by developing a stepwise design methodology and demonstrating that increasing GGBS content and curing temperature positively affect compressive strength and setting times.

Hadi et al. (2019) studied the influence of mix design parameters such as alkaline liquid-to-binder ratio, SS/SH ratio, and GGBS content on geopolymer paste strength and workability. They proposed mathematical models to predict mix performance, confirming that geopolymer pastes can outperform OPC pastes under optimal conditions. Rathanasalam et al. (2020) introduced ultrafine GGBS and copper slag in their geopolymer concrete mixes, concluding that both strength and microstructure improved with increasing GGBS content and sodium hydroxide concentration. These findings support the material's adaptability and performance in various environmental conditions.

4. METHODOLOGY

4.1. Materials And Binder Composition

This study utilizes industrial by-products such as Ground Granulated Blast Furnace Slag (GGBS) as the primary binder for geopolymer concrete (GPC). The GGBS was procured from JSW Cement Ltd, Chennai, with a specific surface area of 413.2 m²/kg and CaO content of 41.27%, making it suitable for low-calcium geopolymer reactions. Low-grade GGBS with reduced reactivity was intentionally selected to investigate its influence on flexural strength development.

4.2. Alkaline Activator Solution

The activator solution comprises sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) in varying molarities (6M, 8M, 10M, and 12M). NaOH pellets (98% purity) were dissolved in distilled water and allowed to cool for 24 hours prior to mixing. The mass ratio of Na_2SiO_3 to NaOH was maintained at 2.5 for all mixes.

4.3. Mix Proportions And Curing

GPC mixes were designed using a constant binder-to-aggregate ratio of 1:2.5, and a liquid-to-binder (L/B) ratio of 0.50. Mix codes (M1 to M4) reflect increasing molarities of NaOH. The prepared concrete was cast into prism molds of 500 mm × 100 mm × 100 mm for flexural testing. After demolding at 24 hours, specimens were subjected to ambient curing conditions (27±2°C) until testing at 7 and 28 days.

4.4. Flexural Strength Testing

Flexural strength tests were conducted according to IS: 516-1959 specifications using a two-point loading setup on a 100 kN capacity Universal Testing Machine. The span length was set at 400 mm. Load was applied at a constant rate until failure, and the flexural strength was calculated using standard bending formulae. Each mix had three replicates, and the average value was recorded.

5. RESULTS

5.1. Flexural Strength

The study is to evaluate and compare the flexural strength of three different grade of concrete M15, M20, M25 at two curing intervals of 7 days & 28 days by testing the flexural strength the aim to achieve to determine the strength and evaluate the performance of different concrete grades and increase the durability result show in the table11. Compare the avg. values of M15 at 7 days and 28 days the flexural strength increases by 18.53%, {(4.03-3.4)/3.4} *100 = 18.53 and the avg. values of M 20 at 7 days and 28 days the flexural strength increases by 4.41%, {(7.1-6.8)/6.8} *100 = 4.41%, and the avg. values of M25 at 7 days and 28 days the flexural strength increases by 24.14%, {(5.76-4.64)/4.64} *100 = 24.14%. Comparison of M25 concrete depicts that the percentage increment in flexural strength from 7 days to 28 days is very high that is equal to 24.14%. Similarly, M15 concrete has also shown a signification increment of 18.53%. again, the M20 concrete has a slightly higher percentage increase of 4.41 percent over 28 days whereas the M20 concrete has the highest absolute value of flexural strength in both 7 and 28 days. This comparative analysis brings out the fact that M20 concrete has the maximum aggregate overall flexural strength while M25 concrete experiences the maximum percentage increase over time that shown in fig.no27.

Table 1: Flexural Test Results of GGBS based GPC.

lexural Strength of Concrete (MPa)						
. No.	**I15**		**I20**		**I25**	
	days	**8 days**	**days**	**8 days**	**days**	**8 days**
	.4	.45	.7	.05	.66	.42
	.8	.05	.9		.12	.88
		.6	.8	.25	.16	
vg.	.4	.03	.8	.1	.64	.76

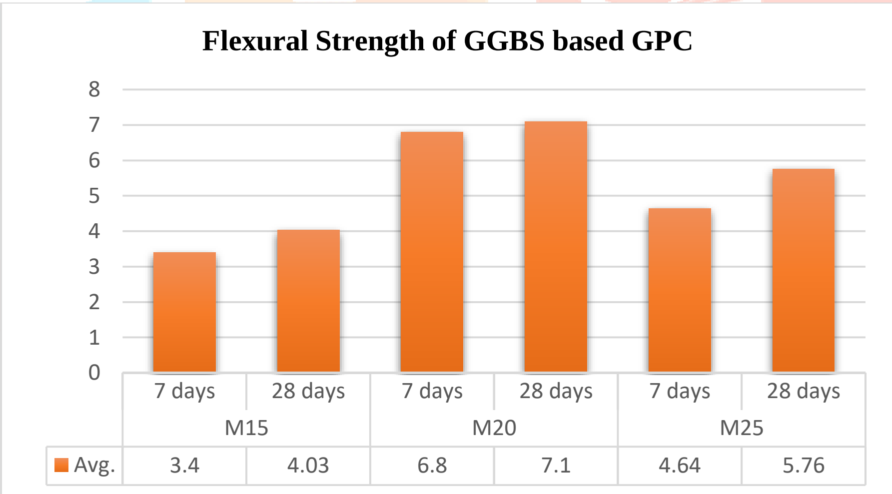
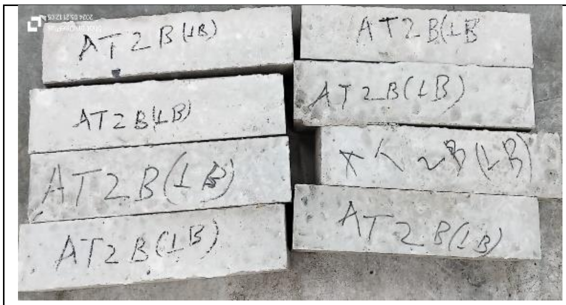


Figure 1: Flexural Strength of GGBS based GPC.

The findings will be very useful in the evaluation of the bending properties of these concrete grades and thus enable engineers and construction specialists to identify the right mix for a particular project when there is a certain level of flexural strength needed.



a) Beam sample	b) Testing of beam
	
c) Beam after load applied	d) Measuring the length of beam

Figure 2: Performing the flexural strength test of GGBS based GPC.

6. CONCLUSION

This study examined the flexural strength behavior of geopolymer concrete (GPC) developed using lower-grade Ground Granulated Blast Furnace Slag (GGBS) under ambient curing conditions. The investigation was designed to explore the influence of sodium hydroxide molarity on the development of flexural strength over 7 and 28 days. Four mix variations were studied with NaOH molarities of 6M, 8M, 10M, and 12M, maintaining constant mix design parameters. The results demonstrated a steady improvement in flexural strength with increasing molarity. At 28 days, the flexural strength increased from 2.48 MPa for M1 (6M) to 3.01 MPa for M4 (12M), marking a 21.37% enhancement. This pattern was consistent across both 7-day and 28-day curing periods, confirming the positive effect of higher alkali concentration on the polymerization process. The formation of a denser aluminosilicate network with increased molarity was responsible for the improved load-bearing capacity under bending. However, the performance increment from 10M to 12M was less pronounced compared to earlier stages, indicating that beyond a certain molarity level, additional sodium ions may not significantly influence the reaction kinetics. These findings suggest an optimal range for activator molarity to achieve balanced strength and cost-efficiency. The research highlights that low-grade GGBS can be effectively utilized in flexural applications of GPC without compromising performance. This contributes to waste valorization and opens opportunities for sustainable development in infrastructure by reducing reliance on Portland cement and enhancing circular economy practices in construction materials.

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