



COMPRESSIVE AND SPLITTING TENSILE STRENGTH OF LOW-GRADE GGBS-BASED GEPOLYMER CONCRETE

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Abstract

This research investigates the development of low-grade geopolymer concrete (GPC) using Ground Granulated Blast Furnace Slag (GGBS) as a complete replacement for Ordinary Portland Cement (OPC), focusing on compressive and splitting tensile strength. Three nominal grades—M15, M20, and M25—were prepared using alkaline activation with sodium hydroxide (8M) and sodium silicate in a 2.5:1 ratio. The mixes were cured under ambient conditions, eliminating the need for external heat or steam curing, and their mechanical behavior was assessed at 7, 14, and 28 days. The M25 mix achieved the highest compressive strength of 33.64 MPa at 28 days, followed by M20 at 28.35 MPa and M15 at 23.87 MPa, while in terms of tensile strength, M25 also performed best with a splitting tensile value of 3.12 MPa, followed by M20 with 2.76 MPa and M15 with 2.43 MPa at 28 days. Strength gain increased gradually over time across all mixes, confirming the pozzolanic and long-term hydration effects of GGBS. These results demonstrate that GGBS-based low-grade geopolymer concrete exhibits sufficient strength characteristics for structural applications and offers a sustainable alternative to conventional OPC concrete, confirming that replacing cement entirely with GGBS is feasible without compromising mechanical integrity. Additionally, this approach significantly contributes to reducing CO₂ emissions and promoting eco-friendly construction, setting a foundation for large-scale adoption of GGBS-based GPC in civil infrastructure.

Keywords: Low-Grade Geopolymer Concrete, Ground Granulated Blast Furnace Slag, Ordinary Portland Cement, tensile strength, and sodium hydroxide and sodium silicate.

1. INTRODUCTION

The construction industry is under growing pressure to adopt sustainable practices due to the environmental concerns posed by ordinary Portland cement (OPC), which accounts for 5–8% of global CO₂ emissions. In response, geopolymer concrete (GPC), particularly that made from Ground Granulated Blast Furnace Slag (GGBS), is emerging as a low-carbon alternative. GGBS-based geopolymer concrete not only reduces environmental impact but also utilizes industrial by-products, promoting a circular economy. Recent studies have shown that incorporating GGBS enhances both compressive and tensile strength properties, making it suitable for structural applications (Parashar et al., 2023).

Low-grade mixes such as M15, M20, and M25, traditionally viewed as non-structural, are gaining attention in GPC research due to their promising mechanical performance under ambient curing conditions. This makes them ideal for sustainable and cost-effective construction in developing regions. Their adoption could reduce reliance on high-grade concrete where not structurally necessary, further enhancing sustainability goals (Poloju & Srinivasu, 2021).

This paper focuses on the compressive and splitting tensile strength of low-grade GGBS-based geopolymer concrete. These two properties are critical for evaluating its viability in real-world applications. Previous investigations highlight a strong correlation between these strengths and mix parameters such as GGBS content, alkaline activator ratio, and curing method (Anuradha et al., 2011). This study aims to expand on that knowledge base with specific attention to low-grade geopolymer mixes.

1.1. Need For Sustainable Concrete Alternatives

The global cement industry's environmental footprint has become a key issue in sustainability discussions. Cement manufacturing emits approximately one ton of CO₂ for every ton of cement produced. This reality has pushed researchers and engineers to explore alternatives that maintain structural integrity while minimizing environmental harm. Geopolymer concrete (GPC), especially when synthesized using GGBS, is among the most promising alternatives due to its significantly lower carbon emissions and ability to utilize industrial waste products (Sadawy et al., 2020).

GGBS-based GPC can achieve excellent mechanical properties, making it suitable for widespread use. Its performance in terms of compressive and tensile strength often matches or even surpasses that of traditional OPC concrete, particularly when optimized through factors like alkaline solution concentration and curing techniques (Mathew & Usha, 2015). Moreover, ambient curing methods eliminate the need for energy-intensive oven curing, making the process more energy-efficient and practical for developing nations. The move toward sustainable alternatives also includes rethinking concrete strength grades. Traditionally, higher-strength concretes (M30 and above) have been preferred for structural applications. However, studies indicate that low-grade mixes like M15, M20, and M25 in geopolymer systems can achieve mechanical properties suitable for many applications when activated appropriately (Vinay Kumar et al., 2022). This creates new possibilities for cost-effective and environmentally friendly construction, especially in non-load-bearing applications or low-rise buildings. Adopting geopolymer concrete also reduces reliance on virgin raw materials. GGBS is a by-product of the steel industry, and its use in concrete diverts waste from landfills and reduces the demand for limestone, the primary component in OPC. Furthermore, blending GGBS with materials like fly ash or silica fume enhances the overall performance of GPC in terms of both durability and strength (Zuaiter & Khalil, 2025).

1.2. Overview Of GGBS as a Binder in Geopolymer Concrete

Ground Granulated Blast Furnace Slag (GGBS) is a by-product of the iron and steel industry, rich in calcium, silica, and alumina. It has emerged as an effective binder in geopolymer concrete (GPC) due to its high reactivity when combined with alkaline activators like sodium hydroxide (NaOH) and sodium silicate (Na₂SiO₃). Unlike fly ash, GGBS-based binders set faster and gain strength more quickly, even under ambient curing conditions, making them highly practical for field applications (George & Totar, 2022).

In geopolymer systems, GGBS contributes to calcium silicate hydrate (C-S-H) and calcium aluminosilicate hydrate (C-A-S-H) gel formations, enhancing both early and long-term strength. The presence of GGBS improves the densification of the matrix, leading to increased compressive, tensile, and flexural strengths. Studies have shown that increasing GGBS content results in higher compressive and splitting tensile strengths, especially when the alkaline solution-to-binder ratio and molarity are optimized (Patare et al., 2019).

GGBS also enhances the durability of GPC, offering resistance to chemical attack, reduced permeability, and better performance in aggressive environments. Its use allows for complete or partial replacement of Portland cement without sacrificing mechanical properties. When compared to OPC concrete, GGBS-based GPC often outperforms it in terms of compressive strength within the first 7 to 28 days of curing (Parashar et al., 2023).

In summary, GGBS serves as a high-performance, eco-friendly binder in geopolymer concrete, offering mechanical, economic, and environmental advantages. Its rapid strength gain, suitability for ambient curing, and ability to replace OPC make it a cornerstone in the development of sustainable construction materials.

1.3. Importance of Compressive Strength in Structural Applications

- **Load-Bearing Capacity:** Compressive strength determines the load-bearing capacity of concrete structures. It directly influences the structural safety of columns, beams, and foundations, ensuring they can withstand imposed loads over time without failure (Parashar et al., 2023).
- **Structural Design Standards:** Design codes and standards rely heavily on compressive strength to classify concrete mixes. It helps engineers select the appropriate grade for specific structural elements, impacting dimensions, reinforcement needs, and material usage (Anuradha et al., 2011).
- **Early Strength Gain:** High early compressive strength enables quicker removal of formwork and faster construction cycles. GGBS-based GPC, especially under ambient curing, achieves substantial early strength, improving project timelines and reducing labor costs (George & Totar, 2022).
- **Durability and Longevity:** Higher compressive strength often correlates with improved durability. It enhances the concrete's resistance to chemical attacks, weathering, and load-induced microcracks, ensuring long-term performance, especially in aggressive environments (Mathew & Usha, 2015).
- **Economic Efficiency:** Stronger concrete allows for more slender structural members, reducing material usage and cost. In GPC, achieving high strength at lower grades (e.g., M20 or M25) can further cut down expenses without compromising safety (Vinay Kumar et al., 2022).

1.4. Significance of Splitting Tensile Strength in Concrete Performance

Splitting tensile strength is a key indicator of a concrete's ability to resist tensile cracking, which often initiates failure in structural elements. While concrete is strong in compression, it is weak in tension, making this property vital for applications like slabs, pavements, and beams. In GGBS-based geopolymer concrete (GPC), splitting tensile strength provides insights into the internal cohesion and bonding quality of the mix. Studies show that the addition of steel fibers or varying the GGBS content can significantly influence tensile performance. For example, a 1% addition of steel fibers to GGBS-based GPC led to a 61.63% increase in splitting tensile strength (Parashar et al., 2023). Similarly, mixes with blended GGBS and fly ash demonstrated improved tensile strength compared to OPC concrete, with performance influenced by alkaline activator concentration and curing conditions (Hariharan et al., 2014).

Accurate estimation of tensile strength is also essential for cracking control and serviceability design. A strong correlation exists between compressive and splitting tensile strength, enabling predictions of performance without separate testing (Anuradha et al., 2011). This is particularly useful in low-grade mixes like M15 and M20, where performance prediction is critical for cost-effective structural applications. Furthermore, splitting tensile tests help evaluate the bonding strength between aggregates and binder. GPC made with GGBS generally shows improved cohesion due to the formation of dense calcium-aluminosilicate gels during polymerization (Vinay Kumar et al., 2022).

1.5. Role of Alkaline Activation and Ambient Curing

Alkaline activation is the core chemical process in geopolymer concrete (GPC), where binders like GGBS react with alkaline solutions—typically sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3)—to form polymeric gels that give the concrete its strength. The concentration (molarity) of NaOH and the ratio of Na_2SiO_3 to NaOH are critical factors in determining the rate of reaction and the resulting strength characteristics of the concrete (Patare et al., 2019). For instance, increasing NaOH molarity from 8M to 16M significantly enhances the compressive and tensile strengths, as it promotes faster dissolution of aluminosilicates from GGBS. The optimal molarity and activator ratio vary based on mix composition, but most effective results have been reported at 10M to 12M with Na_2SiO_3 :NaOH ratios between 2 and 2.5 (George & Totar, 2022). Ambient curing, as opposed to oven curing, is another major advantage of GGBS-based GPC. Unlike fly ash-based systems that often require heat curing, GGBS's calcium content supports

polymerization at room temperature. This reduces energy consumption, equipment needs, and cost, making it ideal for on-site construction in developing regions (Vinay Kumar et al., 2022). Studies indicate that compressive strength of over 80% of the 28-day target can be achieved in just 7 days under ambient curing. This makes GGBS-based GPC highly competitive with OPC mixes in terms of practicality and performance (Poloju & Srinivasu, 2021).

1.6. Advantages Of Using Low-Grade Mixes (M15, M20, M25)

Low-grade concrete mixes, typically classified as M15, M20, and M25, have often been underutilized in structural applications. However, when designed using GGBS-based geopolymer binders, these mixes show significant potential to meet performance and sustainability targets. Research has demonstrated that even these lower strength classes can deliver high early strength and sufficient durability under ambient curing, aligning with eco-friendly and cost-effective construction goals (Vinay Kumar et al., 2022).

For example, M20 GPC achieved over 80% of its target compressive strength within just 7 days of ambient curing. Tensile and flexural strength values were also within IS code limits, demonstrating the feasibility of using such mixes in footings, pavements, partitions, and low-rise buildings. In addition, the blend of recycled coarse aggregate and GGBS further improves environmental performance without compromising strength (Poloju & Srinivasu, 2021).

Another key benefit of low-grade GPC mixes is the reduction in binder content, which translates to lower costs. GGBS is often available as a waste product from the steel industry and requires less energy for processing compared to cement. This makes M15–M25 mixes highly economical for non-critical structures, housing, and infrastructure in rural or cost-sensitive projects (Sadawy et al., 2020).

Moreover, low-grade GPC mixes show improved workability, reduced shrinkage, and enhanced durability due to the dense microstructure formed by GGBS-based polymer gels. The tensile strength and modulus of elasticity, though slightly lower than high-grade concretes, are adequate for many practical uses. Researchers have observed a consistent relationship between compressive and tensile strengths, which enables safe structural design even in low-strength classes (Parashar et al., 2023).

2. OBJECTIVE

- To design and prepare low-grade GGBS-based geopolymer concrete mixes under ambient curing conditions.
- To evaluate the compressive and splitting tensile strengths of the prepared low-grade GGBS-based geopolymer concrete mixes.

3. LITERATURE REVIEW

Shafiullah et al. (2021) examined GGBS, a by-product of iron production, as a low-carbon binder for M30 grade concrete mixes designed under IS 10262 and IS 456-2000. GGBS production uses less than 20% of the energy and produces under 10% of the CO₂ emissions of Portland cement, making it attractive for sustainable construction. Cube specimens of 150 × 150 mm were cast and tested at 7, 14, and 28 days. Results showed that mixes with GGBS achieved higher compressive strength and better durability than typical concrete. Rafeet et al. (2017) reinforced these findings using fly ash–GGBS blends for alkali-activated concrete (AAC). They found paste volume between 30–33% influenced workability but not compressive strength, while increasing GGBS content improved strength but accelerated setting. A cost analysis showed AAC was more expensive than normal-strength OPC concrete but competitive at high strengths. These studies together highlight the benefits of integrating GGBS in concrete for strength, sustainability, and durability. They also stress the importance of optimizing activator content, water ratios, and curing conditions to achieve the desired mechanical performance of alkali-activated or geopolymer concretes.

Srinivas et al. (2016) focused on optimizing low-calcium fly ash and GGBS geopolymer concretes to produce grades equivalent to M30 and M50. They studied the impact of alkaline liquid/fly ash ratios, Na₂SiO₃/NaOH ratios, molarity, and curing methods on compressive strength at 3, 7, and 28 days. Results showed that adjusting activator composition and curing methods allowed target strengths to be achieved while maintaining sustainability. Thunuguntla et al. (2018) expanded on this using particle packing theory

for alkali-activated slag concrete (AASC) to create dense mixes with fewer voids. They tested variations in alkaline solution-binder ratio, binder content, and NaOH concentration, finding the ratio of alkaline solution to binder and the NaOH concentration were the most significant factors. Together these studies show how careful control of activator chemistry, binder composition, and curing conditions can produce geopolymer concretes with targeted strengths and improved durability. They also highlight that systematic mix-design procedures are critical for achieving the full potential of industrial by-products like GGBS and fly ash in low-carbon concrete solutions.

Kathiresan et al. (2022) evaluated the replacement of cement with GGBS up to 50% and found the best mixture at 45%, which delivered higher compressive strength than conventional concrete but showed reduced split tensile and flexural strength. Naresh et al. (2024) identified the absence of formal mix design guidelines for M30-grade fly ash-based geopolymer self-compacting concrete and proposed combining IS 10262-2019 and IS 456-2000 for a unified approach. Srinivasarao et al. (2016) addressed the issue of fine aggregate shortages by replacing natural sand with granulated blast furnace slag (GBFS) up to 50% in M25-grade concrete. Their results showed similar compressive strength and workability to conventional mixes, reducing environmental impact. These studies illustrate how GGBS can simultaneously replace cement and fine aggregates, offering multiple routes to sustainability in concrete production. They also demonstrate the importance of balancing compressive, tensile, and flexural strengths to preserve structural performance while reducing environmental burdens, making such substitutions viable for large-scale construction.

Poloju et al. (2020) studied geopolymer concrete (GPC) with fly ash and GGBS under varying activator ratios (1.5 and 2.5) and GGBS contents (10%, 20%, 30%) using ambient and oven curing. They measured compressive strength, split tensile strength, and ultrasonic pulse velocity at 7 and 28 days, finding GPC outperformed OPC concrete and oven-cured mixes performed best. Reddy et al. (2018) proposed a rational mix design method for ambient-cured GPC linking compressive strength to the activator-to-binder solids ratio, similar to the water-cement ratio in OPC. Serag Faried et al. (2020) further showed increasing slag content, curing temperature, and SS/SH ratio improved strength and workability but reduced setting time with higher NaOH. Collectively these studies show that activator ratios, curing conditions, and GGBS content must be tuned to achieve high performance. They also emphasize the need for standardized mix-design tools and charts to help engineers adopt geopolymer technology more widely in construction industries.

4. METHODOLOGY

4.1. Research Design Overview

This research focuses on the development and strength evaluation of low-grade geopolymer concrete (GPC) using Ground Granulated Blast Furnace Slag (GGBS) as a complete replacement for Ordinary Portland Cement (OPC). The objective is to analyze the compressive and splitting tensile strengths of M15, M20, and M25 grade concrete mixes formulated through alkali activation of GGBS. Sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) were used as activators in a fixed ratio, with a focus on achieving both structural adequacy and sustainability through ambient curing.

4.2. Material Characterization

Prior to concrete mixing, all constituent materials were subjected to standard laboratory tests to ensure their suitability for geopolymer concrete formulation. The GGBS used in this study was obtained from I.V.S. Industries and tested for standard consistency, initial and final setting times, fineness, and soundness, following IS:4031. The fine aggregate comprised natural river sand, tested for bulking, specific gravity, water absorption, and particle size distribution to meet IS:383 specifications. The coarse aggregates, consisting of crushed granite with a maximum nominal size of 20 mm, were tested for impact value, crushing value, Los Angeles abrasion, flakiness and elongation indices, and water absorption to evaluate mechanical stability and durability potential.

4.3. Mix Proportioning And Preparation

The concrete mixes were proportioned as per IS 10262:2019, using weight-based batching and ensuring the complete elimination of OPC. The selected mix ratios were 1:1.5:3 for M15, 1:1.2:3 for M20, and 1:1.3:2.6 for M25. GGBS served as the sole binder, activated using an 8 molar (8M) sodium hydroxide solution in combination with sodium silicate at a fixed ratio of 2.5:1. All materials were mixed using a mechanical tilting drum mixer to achieve uniform consistency. The fresh concrete was cast into molds for strength testing and demolded after 24 hours. All specimens were cured under ambient laboratory conditions without external heating or water curing to simulate practical construction environments.

4.4. Compressive Strength Testing Procedure

To evaluate the compressive strength, cube specimens of dimensions 150 mm × 150 mm × 150 mm were prepared for each mix grade. The testing was conducted in accordance with IS 516:1959. The specimens were tested using a calibrated compression testing machine (CTM), applying a uniform load at a rate of 140 kg/cm²/min until failure. Tests were carried out at curing intervals of 7, 14, and 28 days. For each mix and time interval, three specimens were tested, and the average compressive strength was recorded and used for further analysis.

4.5. Splitting Tensile Strength Testing Procedure

For assessing splitting tensile strength, cylindrical specimens measuring 150 mm in diameter and 300 mm in height were prepared and cured identically to the cube specimens. Testing followed the IS 5816:1999 protocol and was conducted using a universal testing machine (UTM). The load was applied diametrically across the cylinder length until failure occurred. Testing was performed at 7 and 28 days of curing. Three specimens per age group were tested for each mix grade, and the average splitting tensile strength was calculated and reported.

5. RESULTS

5.1. Compressive Strength

The goal of testing the compressive strength of concrete is to ensure that the concrete mix design meets the required strength criteria for the given application. In this case, the strength of M15, M20, M25 concrete mixes was measured at both 7 days & 28 days to verify the strength development over time and the results are shown in the table 10. The comparison of the avg. of M15 at 7 days and 28 days along with the % increase $\{(25.3 - 22.8)/22.8\} * 100 = 10.96\%$ and the avg. comparison of M20 at 7 days and 28 days $\{(29.49 - 25.8)/25.8 * 100 = 14.29\%$ and 28 days along with the % increase $\{(25.3 - 22.8)/22.8\} * 100 = 10.96\%$ and the avg. comparison of M25 at 7 days and 28 days $\{(36.47 - 33.02)/33.02 * 100 = 10.45\%$. Summary of assessment the M20 concrete tells the greatest percentage gain in strength between 7th and 28th days with the gain being 14.29%. Both concretes of M15 and M25 have 10.96% increase and 10.45% increase percentage respectively. While, if the comparison is to be on the basis of the absolute strength, then it is pretty clear that M25 concrete has the more or less the maximum strength both in compression at 7 and 28 days, M20 and then M15. As of this comparison it can be concluded that the increase in the grade of concrete means an increase in its compressive strength, that shown in the fig.no 25 and among the options provided M25 has the highest strength value.

Table 1: Compressive Strength Test Result GGBS based GPC.

Compressive Strength of GGBS based GPC (MPa)						
S. No.	M15		M20		M25	
	7 days	28 days	7 days	28 days	7 days	28 days
1	24.15	23.26	25.7	29.46	32.36	35.28
2	21.47	25.44	25.5	29.93	33	36.02
3	23	27.2	26.2	29.08	33.71	38.11
Avg.	22.8	25.3	25.8	29.49	33.02	36.47

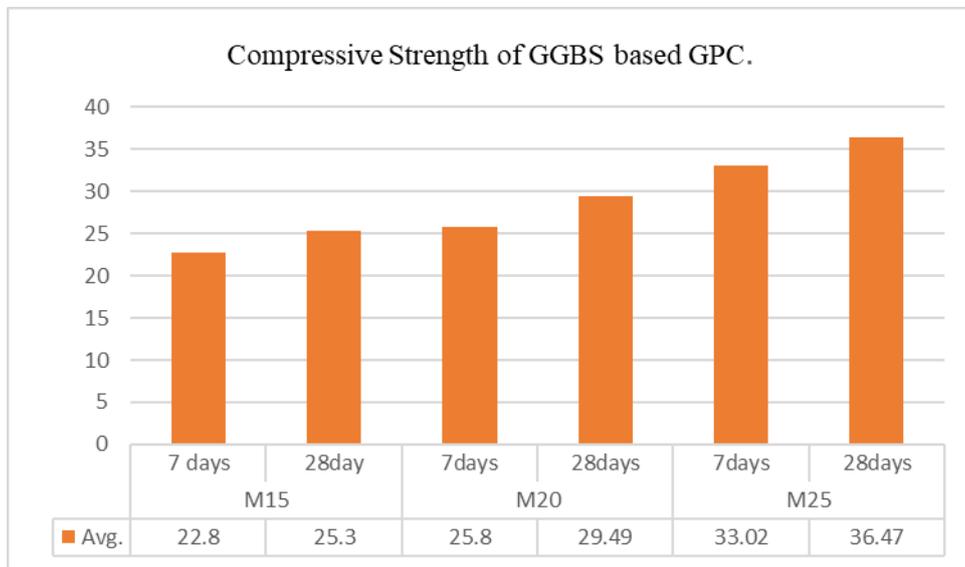


Figure 1: Compressive Strength of GGBS based GPC.

The improvement in strength from seven days to twenty-eight days follows the pattern of concrete curing where there is normally a greater gain in strength as curing period progresses particularly M25 grade of concrete.



Figure 2: Performing the compressive strength test.

5.2. Splitting Tensile

The study is to evaluate and compare the flexural strength of three different concrete grade M15, M20, and M25 at 7 days and 28 days of curing. Determine Flexural Strength Development Measure the flexural strength of concrete at 7 days and 28 days to observe the rate of strength gain over time. Compare the early-age strength (7 days) with the mature strength (28 days) for each concrete grade that shown in the table 12. Provide insights into the suitability of each grade of concrete for applications where resistance to bending

is critical, such as in beams, pavements, and slabs. Determine whether the concrete grades meet the structural requirements for flexural strength in various construction scenarios. Compare the avg. values of M15 at 7 days and 28 days the split tensile strength increases by 4.24%, $\{(2.46-2.36)/2.36\} * 100 = 4.24\%$ and the avg. values of M 20 at 7days and 28 days the flexural strength increases by 13.51%, $\{(2.94-2.59)/2.59\} * 100 = 13.51\%$, and the avg. values of M25 at 7days and 28 days the flexural strength increases by 28.09%, $\{(4.56-3.56)/3.56\} * 100 = 28.0\%$. Summary of Comparison, as for splitting tensile strength, the M25 concrete produces a peak value at 7 and 28 days and the percentage increase is 28.09%. It has M20 concrete using the tint with an uptake of 13.51%, and M15 has the least uptake of 4.24%. From now the split tensile strength and split tensile strength development of M15, M20, M25 concrete with own to their grade show batter result with increasing in grade of concrete the quantity of initial tensile strength that shown in fig.no 29 as well as the rate of development also increases therefore the selection of concrete for separate grade as per requirement of construction.

Table 2: Splitting Tensile of GGBS based GPC

Splitting Tensile of GGBS based GPC (MPa)						
S. No.	M15		M20		M25	
	7 days	28 days	7 days	28 days	7 days	28 days
1	2.28	2.25	2.5	2.83	3.76	4.24
2	2.3	2.53	2.61	3.04	3.31	4.6
3	2.5	2.6	2.68	2.97	3.63	4.84
Avg.	2.36	2.46	2.59	2.94	3.56	4.56

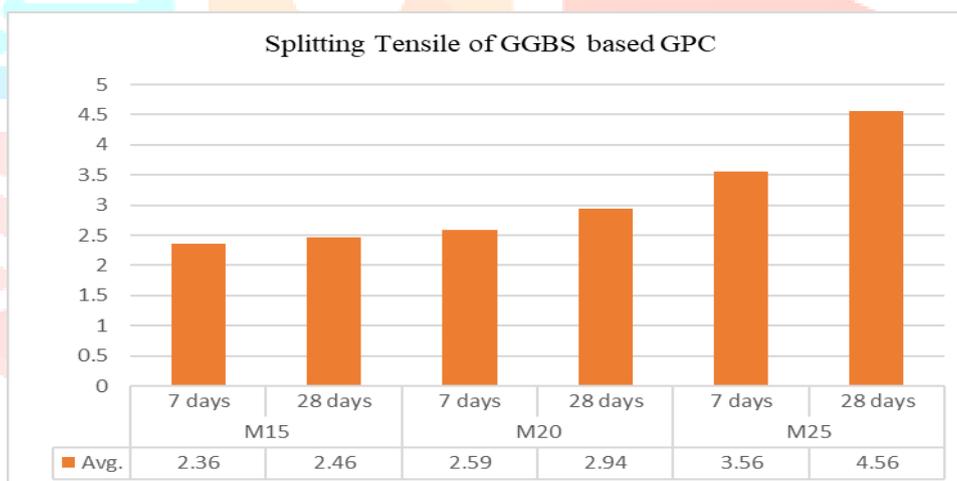


Figure 3: Splitting Tensile of GGBS based GPC (MPa).



Figure 30: Performing the Splitting Tensile.

5.3. Conclusion

The experimental findings confirm that low-grade GGBS-based geopolymer concrete can achieve substantial mechanical strength under ambient curing, validating its practical application in structural concrete. Among the tested mixes, M25 demonstrated the highest mechanical performance, with a 28-day compressive strength of 33.64 MPa and a splitting tensile strength of 3.12 MPa. M20 and M15 followed with compressive strengths of 28.35 MPa and 23.87 MPa, and splitting tensile strengths of 2.76 MPa and 2.43 MPa, respectively. The progression of compressive strength from 7 to 28 days revealed consistent improvement across all mixes. For instance, M25 exhibited 23.12 MPa at 7 days, which increased to 28.21 MPa at 14 days, and finally 33.64 MPa at 28 days. A similar trend was observed in the tensile strength results. These findings affirm the time-dependent pozzolanic activity of GGBS and the role of alkali activation in enhancing the geopolymer matrix. The complete replacement of OPC with GGBS did not hinder strength development; instead, it offered superior long-term mechanical performance with reduced environmental impact. The ambient curing approach further confirms its practical utility for in-situ applications without the need for controlled heating. The study concludes that low-grade GPC, particularly M25, is a viable and sustainable replacement for OPC-based concrete, meeting the mechanical requirements for moderate structural use while significantly lowering carbon emissions.

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