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Performance Evaluation of Concrete with Binary and Ternary Blends of Fly Ash, Silica Fume, and Fiber Reinforcement

Neelesh Nagle[1,*], Harsh Rathore[2]

Abstract

This study evaluates the effect of ground granulated blast furnace slag (GGBS) as a partial replacement for cement on the mechanical properties of concrete, focusing on compressive and split tensile strength. Concrete mixes were prepared with GGBS replacement levels of 0%, 25%, and 50% and subjected to different curing methods, including water curing, steam curing, and conceal curing. These curing methods were selected to investigate their impact on hydration, strength development, and long-term performance. The results indicate that incorporating 25% GGBS provides an optimal balance between strength and sustainability, offering improvements in durability and reduced environmental impact, whereas a 50% replacement reduces both compressive and tensile strength due to slower pozzolanic reactions and insufficient early-age strength. Among the curing methods, concealed curing exhibited the highest strength development due to enhanced hydration and internal moisture retention, which promotes the continued reaction of cementitious materials, while steam curing led to the lowest strength values, likely as a result of rapid moisture loss and limited hydration. The split tensile strength followed a similar trend, confirming the beneficial role of GGBS in enhancing bond strength and crack resistance through improved matrix density and reduced porosity. The study highlights the significance of appropriate curing techniques and optimal GGBS content in achieving durable and high-performance concrete, which is essential for modern construction practices. These findings contribute to the sustainable use of industrial by-products in construction while maintaining structural integrity, promoting eco-friendly construction materials, and encouraging the adoption of green building technologies in the civil engineering sector.

Keywords: GGBS, compressive strength, split tensile strength, curing methods, sustainable concrete, pozzolanic reaction, mechanical properties

***Author for Correspondence**
Neelesh Nagle
E-mail: neelesh.workspace@gmail.com

[1]Research Scholar, Department of Civil Engineering, Sanjeev Agarwal Global Educational University, Bhopal, Madhya Pradesh, India
[2]Associate Professor, Department of Civil Engineering, Sanjeev Agarwal Global Educational University, Bhopal, Madhya Pradesh, India

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INTRODUCTION

The growing demand for sustainable construction materials has led to increased interest in the utilization of industrial by-products, such as ground granulated blast furnace slag (GGBS), as a partial replacement for cement. The use of GGBS in concrete enhances its durability, reduces carbon emissions, and improves its mechanical properties through pozzolanic reactions. However, the effectiveness of GGBS depends largely on its replacement level and the employed curing method. Appropriate curing plays a crucial role in strength development by ensuring adequate hydration and minimizing shrinkage. This study investigated the influence of GGBS replacement (0%, 25%, and

50%) on the compressive and split tensile strengths of concrete under different curing conditions, including water curing, steam curing, and concrete curing. Understanding the relationship between the GGBS content, curing methods, and mechanical performance is essential for optimizing mixed designs and promoting sustainable concrete solutions in structural applications [1–4].

OBJECTIVES

The objective of this study is to assess the impact of incorporating GGBS as a partial replacement for cement at 0%, 25%, and 50% on the compressive and split tensile strengths of concrete. Additionally, the study examined the influence of different curing methods, including water curing, steam curing, and concrete curing, on strength development. This study aims to identify the optimal GGBS replacement level and curing method to enhance the mechanical performance of concrete [5–8].

MATERIAL

This research utilized a combination of conventional and supplementary materials to evaluate their effects on the mechanical properties of concrete. The primary materials used were as follows.

Cement

Ordinary Portland cement (OPC) of 53 grade was used as the primary binder, conforming to IS 12269:2013. Its physical properties, such as fineness, consistency, initial and final setting times, and specific gravity, were determined according to IS 4031:1988.

Supplementary Cementitious Materials

Partial replacement of cement is achieved using fly ash, silica fume, metakaolin, and GGBS to enhance durability and reduce environmental impact. Their properties were tested according to the IS 3812:2013 and ASTM C1240 standards.

Fine Aggregate

Manufactured sand (M-sand) was used as a fine aggregate to ensure a uniform particle distribution and reduced void content. The gradation and physical properties were determined through sieve analysis, as per IS 2386:1963.

Coarse Aggregate

Crushed granite (CG) is used as a conventional coarse aggregate, whereas oil palm shell (OPS) is incorporated in lightweight concrete as a full replacement. The aggregates were tested for shape, texture, and water absorption following the IS 383:2016 standard.

Crumb Rubber

Crumb rubber, obtained from recycled waste tires, is partially substituted for fine aggregates at varying percentages to enhance impact resistance and ductility.

Fibers

Hooked-end steel fibers, synthetic fibers, and crimped steel fibers were introduced at different volume fractions and aspect ratios to improve the tensile strength and crack resistance.

Water

Potable water was used for mixing and curing, conforming to IS 456:2000 standards to ensure hydration and strength development.

Admixtures

Superplasticizers and retarders are used to enhance the workability and setting time of fiber-reinforced concrete, thereby improving its performance.

These materials were systematically selected and combined to analyze their impact on concrete properties, to improve their mechanical behavior, and durability.

RESULTS

Compressive Strength

The compressive strengths of various concrete mixes were evaluated at 7 and 28 days, considering different curing methods and GGBS replacement levels. The results, as shown in Table 1, indicate that Mix-1 exhibited the highest compressive strength among all the mixes, achieving 25.0 MPa at 7 days and 30.1 MPa at 28 days. The inclusion of 25% GGBS in Mix-2 resulted in a marginal reduction in the compressive strength compared to Mix-1. However, further increasing the GGBS content to 50% in Mix-3 led to a noticeable decline in strength under all curing conditions [9–12]. Among the three curing conditions, concrete curing consistently outperformed water (W) and steam (S) curing, with an average strength increase of approximately 20–25% over steam curing. This suggests that concrete curing provides better hydration and pozzolanic activity, particularly in GGBS-based mixes. The lowest compressive strength was recorded for Mix-3 (S), reinforcing the adverse effect of high GGBS content under steam curing (Table 1) [13–17]. Figures 1 and 2 illustrate the histogram representation of the compressive strength for various concrete mixes at 28 and 56 days, respectively. Table 1 presents the compressive strength values of the different concrete mixes compared with those of the control mix.

Split Tensile Strength

The split tensile strength results followed a similar trend to the compressive strength, with Mix-1 showing the highest tensile strength at both 7 and 28 days. The inclusion of GGBS slightly reduced the tensile strength, with Mix-2 and Mix-3 exhibiting a progressive decline as the replacement percentage increased. However, the reduction was less pronounced compared with the compressive strength, indicating that GGBS still contributed to improved bonding and crack resistance [18–20]. The influence of curing methods on tensile strength mirrored the compressive strength trends, with concrete curing providing superior results. The presence of fibers in some mixes further enhanced the tensile capacity by delaying crack propagation and improving post-crack behavior.

Overall, this study demonstrates that moderate GGBS replacement (up to 25%) can maintain satisfactory strength levels while improving durability. However, excessive GGBS content (50%) can lead to a significant reduction in strength, particularly under steam curing (Figures 3 and 4).

Table 1. Compressive strength data.

Mix designation	Compressive strength (MPa)	
	28 days	***56 days***
M000	37.08	39.14
M001	38.63	43.26
M002	41.20	46.14
M003	44.50	49.54
F400	31.42	37.80
F401	34.30	40.69
F402	36.15	43.26
F403	37.90	45.73
S070	33.06	34.51
S071	35.33	37.08
S072	38.01	39.76
S073	39.96	41.92
FS470	37.60	45.32
FS471	41.72	50.37
FS472	44.60	54.08
FS473	49.44	59.23

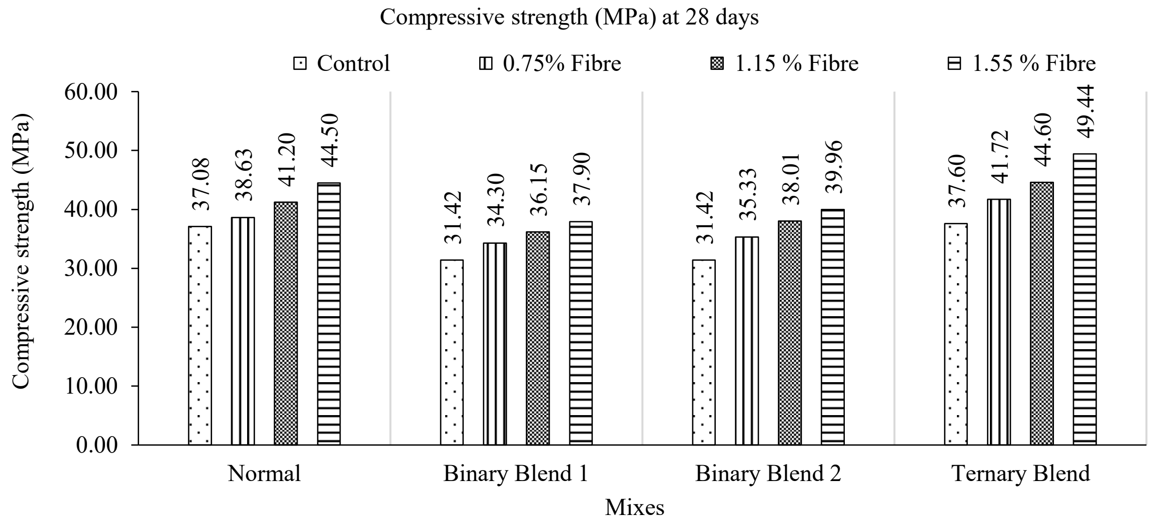

Figure 1. Compressive strength at 28 days.

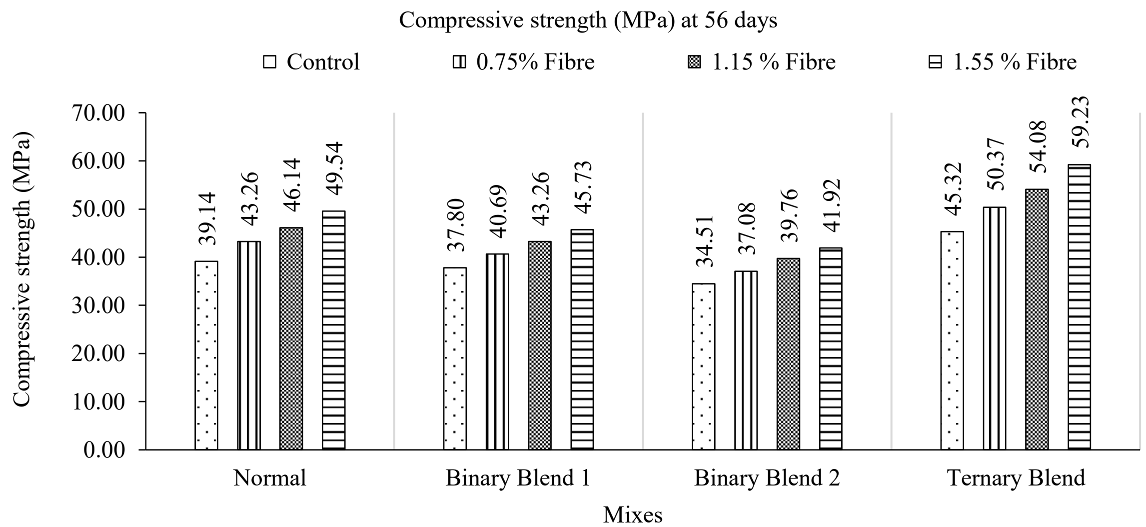

Figure 2. Compressive strength at 56 days.

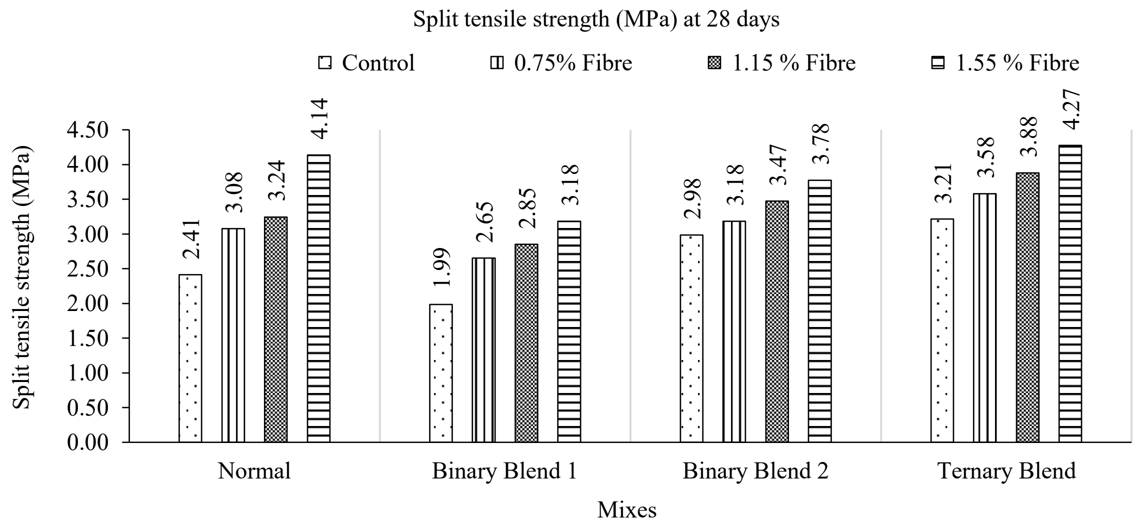

Figure 3. Split tensile strength at 28 days.

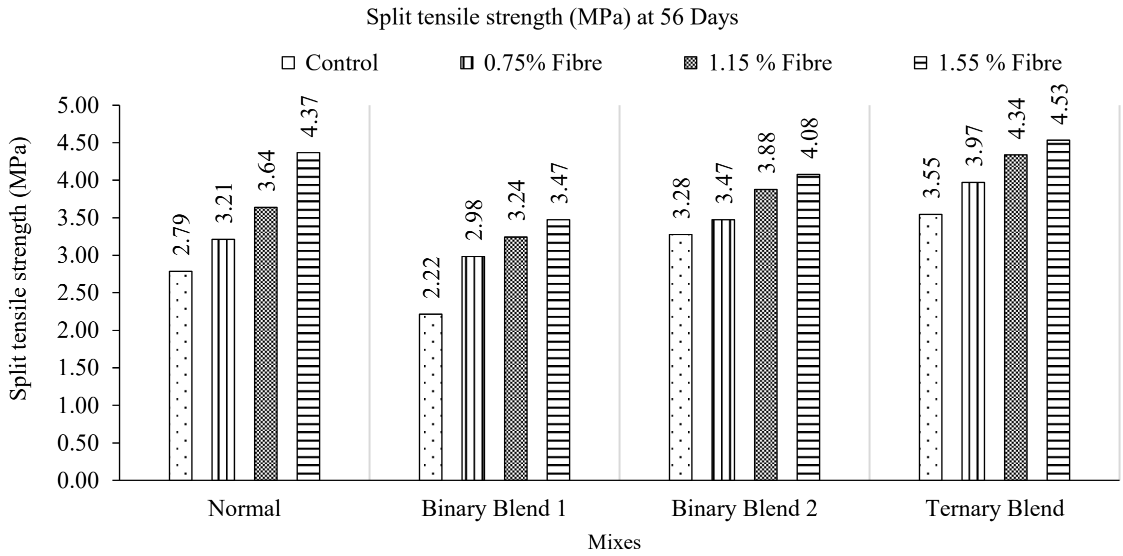

Figure 4. Split tensile strength at 56 days.

CONCLUSIONS

This study investigated the effects of GGBS replacement levels and different curing methods on the compressive and split tensile strengths of concrete. The results demonstrated that incorporating up to 25% GGBS maintained satisfactory strength characteristics, while a 50% replacement led to a significant reduction in both compressive and tensile strengths. Among the curing methods, concrete curing exhibited the highest strength values owing to enhanced hydration and pozzolanic reactions, whereas steam curing resulted in the lowest strength development. The split tensile strength trends followed a similar pattern to that of the compressive strength, indicating that GGBS contributed to improved bonding and crack resistance.

Overall, a moderate GGBS replacement (25%) can be considered optimal for achieving a balance between strength and sustainability. However, excessive GGBS content (50%) negatively affects the mechanical properties, particularly under steam curing. These findings highlight the importance of selecting appropriate curing methods and replacement levels to ensure the durability and performance of GGBS-based concrete in structural applications.

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