Flexural and Abrasion Performance of High Volume GGBS Concrete Pavements

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ABSTRACT

Ground Granulated Blast Furnace Slag (GGBS) is an effective supplementary cementitious material because of its pozzolanic properties and positive environmental impact. This research explores the flexural strength of concrete pavements by analyzing several high-volume formulations of GGBS concrete against conventional mixes. The study aims to assess the viability of incorporating high-volume GGBS mixes in pavement construction, with a particular emphasis on their flexural performance. The study employs various GGBS content levels (60%, 65%, 70%, and 75%) in concrete mixes, with the control mix containing ordinary Portland cement. Specimens are prepared according to standard procedures, and flexural testing is conducted to evaluate their performance. Statistical analysis is performed to compare the flexural strength and behavior of GGBS mixes with the control mix. The results obtained from the experiments revealed that the GGBS concrete mixes had better flexural performance than the control mix, with more strength and less cost. The results provide the performance of large-volume GGBS concrete mixes under flexural loading circumstances, which helps to understand whether these mixes are suitable for use in concrete pavements. Ultimately, this research sheds light on the possibilities of utilizing large-volume GGBS concrete mixes as long-term substitutes for traditional concrete pavements, which may help in the promotion of greener and more long-lasting infrastructure solutions.

Keywords-cementitious materials; concrete; Portland cement; flexural strength; abrasion resistance; GGBS; fly ash

I. INTRODUCTION

Concrete durability and strength are crucial for ensuring the longevity and safety of these constructions, particularly in high-traffic areas like pavements. However, conventional ways of making concrete are very harmful to the environment since they consume a lot of energy and release large amounts of greenhouse gases. Considering these issues, scientists and businesspeople have been looking for new cementitious materials that may improve concrete's performance without negatively impacting the environment. The iron manufacturing by- product GGBS is one such material, which may partially replace Portland cement in concrete mixes. GGBS improves the strength and durability of concrete while also decreasing its carbon impact. Being greater than half of the cementitious materials, a high-volume GGBS concrete mix has increased individuals' attention in recent years. In terms of mechanical qualities and sustainability, these blends have shown encouraging results. The findings of this research can inform decision-making processes in the construction industry, helping to promote the adoption of sustainable concrete materials and practices [1]. The abrasion resistance of concrete pavement is influenced by various factors, including the mix design, curing methods, aggregate properties, and surface finishing techniques. By improving the longevity and sustainability of concrete pavements, this research might lead to less frequent repairs and replacements, lower maintenance costs, and better transportation infrastructure performance [2].

GGBS concrete has exhibited better abrasion resistance compared to Ordinary Portland Cement (OPC) concrete, especially under aggressive environmental conditions, due to its enhanced chemical resistance and durability [3]. Incorporating GGBS has improved the surface hardness and abrasion resistance of concrete. Authors in [4] highlighted the importance of optimal GGBS content and curing conditions to maximize these benefits. The combined effects of GGBS and other Supplementary Cementitious Materials (SCMs) on concrete properties have been also explored. The results indicated that combining GGBS with fly ash or silica fume could synergistically enhance both flexural and abrasion properties, offering a more robust solution for concrete pavements [5, 6]. When compared to control mixtures, concrete mixes that included up to 50% GGBS had a greater flexural strength. The enhanced durability was attributed to the concrete's improved microstructure and the pozzolanic reaction [7]. Filling gaps and aiding in the development of more Calcium Silicate Hydrate (CSH) gel, GGBS increases the overall matrix density, and thus the flexural performance of concrete. Concrete with 40% GGBS has significantly improved abrasion resistance, attributed to the denser microstructure and reduced porosity. However, at higher GGBS contents (above 60%), the resistance does not increase proportionally, possibly owing to the reduction in early strength development. Various GGBS replacement levels have been investigated and it was found that a 40%-50% replacement ratio provides the best balance between flexural strength and abrasion resistance. This ratio ensures adequate early strength while maintaining long-term durability [8]. High volume GGBS mixes (over 50%) could result in a reduction of flexural strength if not adequately cured, due to the slower hydration rate of GGBS compared to OPC [9]. In [2], the research findings revealed that increased compressive strength of concrete corresponds to enhanced abrasion resistance. The focus of this study was placed on assessing the durability of concrete pavements through abrasion resistance testing. The latter is also valuable for evaluating how different mixture proportions, finishing techniques, and surface treatments affect the surface properties of concrete. However, this test does not provide an estimation of the concrete pavement's service life. Additionally, the procedure is designed to be suitable for practical on-site testing. In [1], the authors observed that adding GGBS as a mineral additive positively impacts the quality of concrete and improves its workability. The study revealed notable outcomes, with the peak compressive strength recorded at 77.4 MPa, the highest tensile strength at 5.1 MPa, and the flexural strength after 28 days was measured at 9.1 MPa. In [10], the authors developed Geopolymer Concrete (GC) by incorporating fly ash and GGBS, adjusting the binder content in the process. They investigated how curing temperature influenced the concrete's properties. Their findings displayed that GC cured at ambient temperature, containing 70% of fly ash and 30% of GGBS, achieved a compressive strength like that of M20 concrete. However, specimens cured at elevated temperatures demonstrated superior strength compared to those cured at ambient conditions. Authors in [11] explored the impact of different percentages of GGBS ranging from 30% to 50%, as well as varying amounts of steel and carbon fiber, each up to 1.5%, in twenty-five distinct concrete mix designs with a constant water-to-cement ratio of 0.40. The study involved a series of tests on the concrete, including slump tests, and measurements of compressive strength, flexural strength, split tensile strength, water absorption, and abrasion resistance at various ages. Additionally, the research included evaluations of CO_2 emissions and a cost analysis.

A. Research Objectives

This research achieves the following objectives:

- The identification of the ideal proportions of cement, GGBFS, water, and chemical admixtures to achieve both durability and workability in concrete.
- The examination of the mechanical properties, specifically the flexural strength, of M40 PQC (Pavement Quality Concrete) mixes with different levels of GGBFS at various curing ages, and the comparison of these properties with those of conventional concrete.
- The evaluatation of the abrasion resistance of concrete specimens with high GGBFS content in comparison to conventional concrete.

II. RESEARCH METHODOLOGY

Since previous studies have primarily explored GGBS replacements for OPC of up to 50%, this research extends the investigation to higher GGBS volumes. Specifically, it examines the effects of using GGBS in proportions of 60%, 65%, and 70% as a replacement for OPC, aiming to evaluate its performance beyond the previously studied levels. The experimental program of the research is segmented into the following stages:

- GGBFS Cement Replacement: It creates PQC mixtures with 60%, 65%, and 70% of cement replaced by GGBFS. It uses a superplasticizer to ensure proper workability, maintaining a water per cement ratio of 0.4 and identifies the most durable mix.
- Chemical Admixture Development: It develops a superplasticizer in the MAPEI Concrete R and D Lab for incorporation into the concrete mix.
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- Mix Design*:* M40 grade PQC concrete mixes were prepared in accordance with the IS 10262:2009, using materials like cement, sand, aggregates, GGBFS, chemical additives, and water. A quantity of 0.4% PC-based superplasticizer was used along with a water per cement ratio of 0.40. Material properties such as specific gravity and fineness modulus were evaluated.
- Experimental Procedure*:* It produces concrete cubes with the designed mixes. It Tests their mechanical properties at

7, 28, 56, and 90 days and examines the workability, drying shrinkage, and resistance to abrasion.

- Results Analysis*:* It compares the results of flexural strength and abrasion resistance acquired from the lab tests with those of the standard mixes.

III. MATERIALS AND METHODS

GGBFS is known for its high calcium silicate content and beneficial cementitious properties. As shown in Table I, GGBFS results from the iron-making process and has been widely used as a substitute for OPC in the construction sector. It is particularly valuable for managing the rise of temperature during large concrete pours, as it generates less heat due to its slower hydration compared to OPC. GGBFS has a lower amount of free lime and a higher proportion of CSH, which contribute to increased concrete strength. There is an ongoing research to determine if GGBFS can function as a pozzolana, the results of which will be compared against the criteria set by IS-3812 Part 1, which specifies the existing requirements for materials to be classified as pozzolanas.

Portland cement is the main ingredient in concrete, mortar, and plaster, consisting primarily of calcium, aluminum, and silicon oxides. It is produced by heating a mixture of clay and limestone, followed by the addition of a sulfate. When this fine powder is mixed with water, it hardens over time. Table II details the physical properties of both GGBFS and cement, including specific gravity, fineness, and strength activity index. Aggregates, constitute approximately the 70%–75% of concrete. They serve two main purposes, reducing the volume of cement paste needed to fill voids and providing structural strength to the concrete. In India, commonly used aggregates include granite, quartzite, sandstone, basalt, and limestone, with river sand being a prevalent choice for fine aggregate. The 4.75 mm IS sieve size is used to distinguish between fine and coarse particles.

Aggregates are categorized based on their grading, which refers to the proportion of aggregate mass passing through specific IS sieves. Coarse aggregates can be classified as single-sized, where particles are mostly retained between adjacent sieves, or graded, where particles vary in size. The physical characteristics of coarse aggregates are outlined in Table III, and the Fineness Modulus (FM) of the aggregate can differ.

Superplasticizer is employed to achieve specific characteristics in concrete mixtures. In this study, Dynamon NRG 9040, a superplasticizer developed by MAPEI Construction Products India Pvt. Ltd., is deployed. This superplasticizer is based on second-generation polycarboxylic ether polymers. Table II presents the physical properties of Dynamon NRG 9040, including specific gravity, solid content, pH, and dosage percentage.

A. Mix Proportion of Concrete

According to IS 10262:2009, the mix design for PQC M40 grade concrete is prepared in the laboratory using materials such as cement, sand, aggregates, GGBFS, chemical additive, and water, as shown in Table IV. A 0.4% PC-based superplasticizer is incorporated into the concrete mix, maintaining a water per cement ratio of 0.40 to achieve sufficient workability.

TABLE I. CHEMICAL COMPOSITION OF GGBS

Components	**GGBS**	**FLY ASH**
	Per (%)	**Per (%)**
Silicon dioxide	34.04	59.94
Aluminium oxide	18.8	22.87
Ferric oxide	0.7	4.67
Calcium oxide	32.4	3.08
Magnesium oxide	10.75	1.55
Sulphur trioxide	0.85	0.55
Potassium oxide	0.98	0.62
Sodium oxide	0.31	2.19
S	0.65	3.64

TABLE II. PHYSICAL PROPERTIES OF INGRADIENTS

GGBS	**Fly Ash**	**Cement**	**Superplasticizer (Dynamon NRG 9040)**
Specific Gravity: 2.88	Specific Gravity: 2.65	Specific Gravity: 3.13	Specific Gravity: 1.115
Fineness: 372 Kg/m3	Fineness: 320 Kg/m3	Standard Consistency: 27%	Solid Content: 43.37%
Strength Activity Index (At 28 Days): 110 Min	Strength Activity Index (At 28 Days): 80 Min	fcm (7-Days):39.57 MPa fcm (28-Days): 49.23MPa	Dosage :0.40% pH: 7.81

TABLE III. PHYSICAL PROPERTIES OF AGGREGATE

Particulars	**Coarse aggregates**		
	20 mm	**10 mm**	**Standards**
Specific Gravity	2.94	2.87	
Water Absorption	0.40%	0.60%	<2% (MORTH 2013)
Impact Value	16.06	15.55	<20% IS: 2386 Part-4 (1963)
Abrasion Value	18.01	16.24	
Crushing Value	15.55	14.76	
Flakiness Index	27.65%	-	

TABLE IV. MIX PROPORTION OF CONCRETE SPECIMEN (WT. IN KG)

Ingredients	**Control Concrete**	**60% GGBS**	**65% GGBS**	**70% GGBS**
Cement	330	176	157	138
Fly Ash	80	0	0	0
GGBS	0	264	293	322.5
10 mm	485.43	467.77	459.16	457.03
20 mm	688.08	720.22	706.96	703.68
River Sand	768.32	777.4	763.08	759.55
Water	6.71	6.11	164.76	163.68
Super plasticizer	1.64	1.76	1.8	1.84
Total Density (kg/m^3)	2521.17	2559.94	2545.76	2546.27

IV. RESULTS AND DISCUSSION

The experimental investigation was completed and the Flexural Performance and Abrasion Resistance assessment of the varied High Volume GGBS Concrete Mixes (Table V) compared to that of the control mix was performed. To address this knowledge vacuum, this research compares a control mix typically used in concrete pavements to the flexural performance of concrete specimens (100 mm × 100 mm × 500 mm) mixes with varying percentages of GGBS (60%, 65%, 70%, and 75% replacement levels). Flexural strength is a critical parameter for pavements as it determines the ability of concrete to resist bending and cracking under traffic loads. This research aims to provide useful insights into the acceptability of various concrete mixes for use in concrete pavements by systematically analyzing their flexural performance via experimental testing and analysis. The purpose of this research is to determine how well concrete pavement specimens measuring 70.6 mm × 70.6 mm × 70.6 mm withstand abrasion. Standardized abrasion tests were used to evaluate the specimens' performance in a simulated real-world setting. This research intends to optimize concrete pavement design and maintenance techniques by analyzing test data to get insights into the elements impacting abrasion resistance. Figure 1(a) demonstrates that flexural strength is enhanced and Figure 1(b) shows that abrasion resistance is improved when GGBS replacement is increased. The composition of mixtures with different GGBS replacement percentages are depicted in Table V.

TABLE V. COMPOSITION OF MIXES WITH % REPLACEMENT OF GGBS

Mix Type	% Replacement	Grade Mix	Specimen	Composition/ W/C Ratio	Testing Duration	No. of cubes
M1	0%	M40	Flexural Beam (100×100×500mm)	1:1.87:2.86/0.40	28, 56,90, 180 Days	12
M2	60%			1:1.77:2.70/0.35		12
M3	65%			1:1.70:2.59/0.37		12
M4	70%			1:1.65:2.52/0.35		12
M5	75%			1:1.57:2.40/0.315		12
M1	0%	M40	(70.6×70.6×70.6 mm)	1:1.87:2.86/0.40	28 Days	3
M2	60%			1:1.77:2.70/0.35		3
M3	65%			1:1.70:2.59/0.37		3
M4	70%			1:1.65:2.52/0.35		3

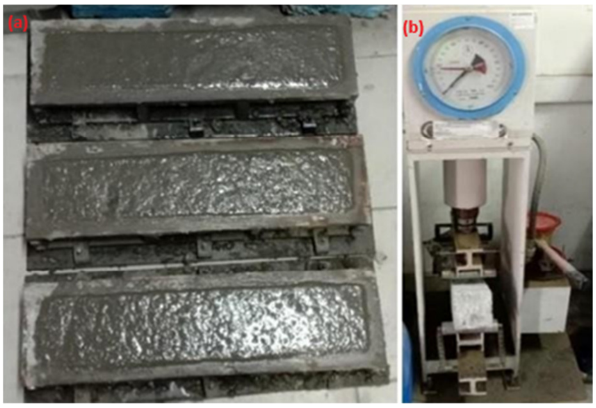

Fig. 1. Laboratory performance of experimental work.

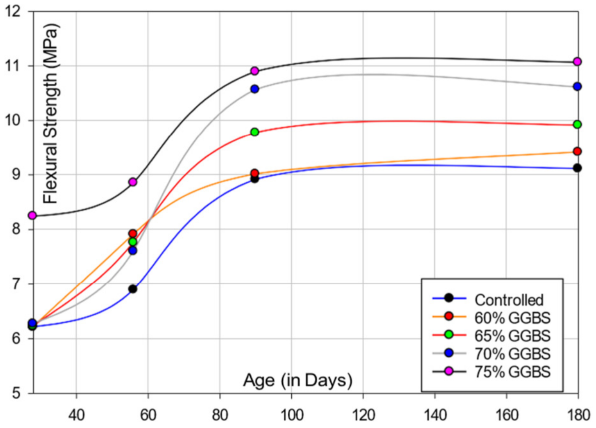

Fig. 2. Flexural strength with % replacement of GGBS.

To determine flexural strength, standard cube specimens measuring 100 mm × 100 mm × 500 mm (Figure 1) are prepared and subjected to axial flexure tests with a 100 kN load. The manual pumping method recommended by IS 516:1999 is deployed for this process. The strength values recorded at 7, 28, 56, 90, and 180 days represent the average of the results obtained from the two cube specimens. Comparisons between concrete with 60% GGBFS replacement and conventional concrete are made based on compressive strength values. These comparisons help assess the economic viability of the concrete mixes. The experimental results, which are detailed in Section IV and are displayed in Table V and Figure 2, illustrate the strength progression over time for four different mixes, including the control mix.

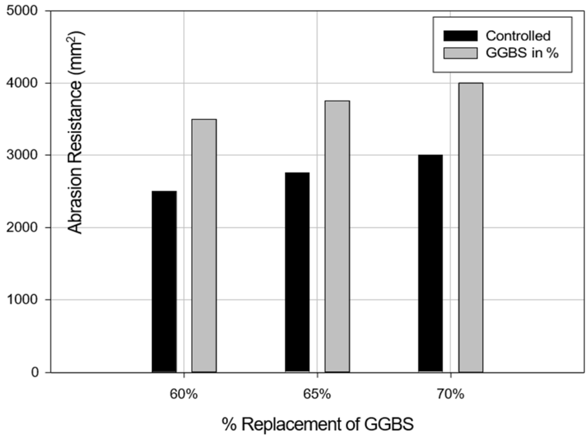

Fig. 3. Abrasion resistance with % replacement of GGBS.

V. CONCLUSION

The Research findings reveal that concrete containing high proportions of GGBS exhibits advantageous mechanical and durability properties, which are crucial for the long-term performance of concrete structures, ensuring that they meet or exceed the industry standards. GGBS, known for its pozzolanic and latent hydraulic properties, improves the long-term strength and durability of concrete. This enhancement results in longer lasting and more resilient concrete structures, potentially reducing maintenance costs over their lifespan. Additionally, incorporating GGBS in concrete lowers the carbon footprint of its production. As GGBS is a by-product of the steel industry, its utilization lessens the dependence on OPC, which is a major contributor to CO_2 emissions during production. By adopting GGBS concrete, the construction industry can better align with sustainability goals, including reducing greenhouse gas emissions, conserving resources, and minimizing waste. The cost savings per cubic meter, combined with its beneficial mechanical and durability properties, make GGBS concrete a viable choice for large- scale infrastructure projects.

The research offers an in-depth analysis of the use of high proportions of GGBS in PQC mixes, highlighting both the advantages and considerations involved. Here is a concise overview of the findings:

- Improved Performance: Incorporating substantial amounts of GGBS into PQC mixes leads to notable enhancements in both flexural strength and abrasion resistance. These improvements are particularly beneficial for applications requiring durable pavements.
- Flexural Strength Trends: For M40 grade concrete, mixes with GGBS percentages of 60%, 65%, and 70% exhibit similar flexural strength after 28 days. Over extended curing periods, 56, 90, and 180 days, the flexural strength increases by approximately 10%, demonstrating the long-term advantages of using GGBS.
- Abrasion Resistance: Concrete with various levels of GGBS content shows improved resistance in abrasion. Specifically, the reduction in abrasion is 28.58% for mixes with 60% GGBS, 26.67% for 65%, and 25% for 70%, compared to that of a standard control mix after 28 days.
- Optimization Needs: To be the benefits of GGBS maximized, it is important to carefully adjust its proportion to the concrete mix. This adjustment must also take curing conditions and environmental factors into account. Further studies are needed to optimize these variables for enhanced performance.
- Curing Requirements: High-GGBS concrete mixes necessitate longer curing periods due to the slower hydration of GGBS. An excess of GGBS can result in reduced early strength. Additionally, local climate conditions affect curing efficiency and overall durability, thus requiring precise management of curing practices.

In conclusion, while high GGBS content can significantly improve the concrete performance, especially in terms of strength and abrasion resistance, achieving optimal results requires careful mix design and curing strategies. Ongoing research will help fine-tune factors to maximize practical benefits. Incorporating GGBS into PQC holds the potential to significantly alter conventional concrete mix designs. This industrial byproduct can enhance both the sustainability and performance of pavement structures, offering a way to lessen the environmental footprint of concrete production while improving PQC's durability and strength. Nonetheless, when GGBS replaces up to 75% of OPC, there is a marked decrease of compressive strength even though flexural strength remains satisfactory. To address this issue, further investigation should be directed towards identifying new supplementary cementitious materials for the substitution of OPC in concrete. This approach aims to reduce reliance on OPC and advance the sustainability and efficiency of concrete production.

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