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Evaluation of Mechanical and Durability Properties of GGBS-Based High-Performance Concrete

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Abstract
This is to study the possibility of improving conventional M40 concrete to high-performance one by adding 20% GGBS and a superplasticizer and to study whether addition of just one of the two to M40-level concrete is indeed enough to sustain M60 level as well as better durability. Methods Two concrete mixtures were formulated; a control M40 mix and an M40 mix with GGBS 20%. Both mixes were tested under standard laboratory test procedures in order to measure mechanical properties, stiffness, permeability and resistance to chemical attack. . Findings: The GGBS-modified concrete showed the same advance in the mechanical performance (strength and stiffness) and significant improvement in the durability properties. This was shown by a decrease in water permeability, chloride penetration, and acid and sulphate resistance. The findings reveal that a more dense and compact cementitious mix has been formed in comparison with the traditional mix. Novelty: The paper has shown that relative low replacement of 20 percent GGBS not including silica fume or complex tertiary supplementary cementitious systems is adequate to make M40 concrete a high-performance material. This method provides the feasible and cost-efficient route to the performance of M60 in construction.
Keywords: *High-performance concrete, GGBS, M40 grade concrete, partial cement replacement, Mechanical properties, Durability properties.*

1. INTRODUCTION

High-performance concrete is engineered to provide greater strength, durability, and low permeability than conventional concrete. It employs an optimized mix design that integrates additional cementitious materials and chemical admixtures to provide a special performance and long life even in the harsh structural condition. Additional cementitious materials, especially ground granulated blast furnace slag (GGBS), enhance the concrete's ability to carry structural loads and deliver strong resistance against chemical attacks. In addition, GGBS reduces the overall carbon emission and hydration heat, resulting in more sustainable and durable concrete structures. High-performance concrete has developed to such a point that it is necessary to balancing the current needs of strength, durability, and sustainability is necessary. Accelerated urbanization, the climatic editions the rising requirement of structural infrastructure beyond the normal durability demands materials that possess excellent mechanical and durability characteristics. This change aids contemporary structural planning, environmental objectives, and infrastructure sustainability. Mechanistically, GGBS is considered both a pozzolanic and latent hydraulic substance in that it reacts with calcium hydroxide [Ca (OH) 2], which is a by-product of cement hydration, to form a calcium silicate hydrate (C 2 S H) gel. CSH gel is the major agent that gives strength and concrete durability. The formation of more C-S-H also leads directly to the enhanced mechanical performance and durability properties of the concrete, which explains why this study is required to explore how the use of SCMs allows shifting the normal concrete that acts as a strength-giving agent to high-performance concrete. In this regard, a systematic mix design method was chosen: a standard M40 concrete mix and a modified M40 concrete mix with GGBS and SPs. This study aimed to compare the mechanical (compressive, tensile, flexural strength, and Young's modulus) and durability (water absorption, sorptivity, chloride ion penetration, and acid and sulphate attack resistance) properties of the modified mix with those of the control mix (M40). The findings of this study should help generate some meaningful information on the possibility of GGBS-based binary systems to accomplish the performance improvement and sustainability of structural concrete.

2. METHODOLOGY

The experimental study aimed at two main mix designs: the control M40 mix and an altered M40 mix with 20% GGBS and a super plasticizer. These formulas were particularly aimed at improving structural performance. The research was conducted in accordance with the material selection and mix design standards of Indian Standards (IS) 456:2000 and IS 10262:2019. The control M40 mix was used as a standard against which testing was to be compared with the modified formulation.

2.1 Materials characterization

Cement: In the control and modified mixes, OPC of grade 53 that meets the requirements of IS 12269 was used. SCM: Ground Granulated Blast Furnace Slag (GGBS) was also used to alter the mix, which partly substituted 20% of the cement mass. This change was precisely meant to take advantage of its pozzolanic and latent hydraulic characteristics to increase the long-term strength and durability. Aggregates: The fine aggregate was sand to zone II of the International Standard 383:2016. Angular coarse aggregates with a nominal size of 20 mm were crushed to achieve a good packing density. Water: Clean drinking water was used. Chemical Admixture (Modified Mix Only): The high-range water-reducing admixture (superplasticizer, Compass SP430), which is compliant with IS 9103:1999, was added to the GGBS-based Modified Mix only to work up to the desired required workability with a fixed w/b ratio of water-binder (GGBS-based).

2.2 Mix ratio and Proportioning.

The control mix (M40) and modified mix (M40 + GGBS 20%) mix design was formulated according to the standard procedure as laid down by IS 456: 2000 and IS 10262: 2019. The control mix is equivalent to M40 grade concrete, but the modified mix that uses 20% GGBS and a superplasticizer is the modified version to be used on the structural reinforcement. Water-cementitious material ratio (w/c) was kept constant at 0.40 control mix and 0.30 modified mix. The proportions obtained after the calculations per cubic meter are presented in the table below and given in Table 1, where the standard and modified formulations are provided.

Table 1: the calculated Mix Proportion (per 1 m^3)

Component	M40	M40 +GGBS 20%
Cement (OPC 53)	365.00 kg	292.00 kg
GGBS	—	73.00 kg
Water	146.00 kg	146.00 kg
Fine aggregate (sand/Zone II)	707.07 kg	707.07 kg
Coarse aggregate (20 mm)	1252.33 kg	1252.33 kg
Superplasticizer (Conplast) SP430	—	1.0 % of cement = 3.65 kg/m^3
Water/cement (w/c)	0.40	0.30
Mix ratio	1:1.937: 3.433	1:1.937: 3.433

3. EXPERIMENT PROGRAM

3.1 Mechanical properties test

Compressive Strength

A standard cube specimen of 150 mm × 150 mm × 150 mm was subjected to the 28 day compressive strength test using the Compression Testing Machine (CTM) calibrated according to IS 516:1959. Specimens were cast and left to dry in water at 27 ± 2 o C, after 24 hours and allowed to dry until the testing age. All the specimens were subjected to a steady loading at an equal rate to failure and the highest weight was noted.

Fig 1 represents compressive strength test in test compressive strength test machine.

Fig 1. Compression test carried out on cube specimen in Compression testing machine

Split tensile strength

As a part of the IS 5816:1999, a split tensile strength test was conducted on the cylindrical specimens (150 mm × 300 mm) using a compression testing machine. The samples were cured in water for 28 days and then placed in loading plates. The same load was maintained until the cylinder parted along the vertical line. The tensile strength was calculated based on the maximum load taken. Figure 2 shows the results of the split tensile strength test on the compressive strength test machine.

Fig 2. Split tensile strength test carried out on cylinder specimen in Compression testing machine

Flexural Strength Test

The flexural strength was tested on the beam specimen of dimensions 150 mm x 150 mm X 600 mm using the two point loading test according to IS 516:1959. At 28 days of treatment, one beam was put on flexural testing machine, and the load was applied up to the time of failure. The failure load and the geometry of the specimen were used to calculate the modulus of rupture.

Fig 3 illustrates flexural strength test that is conducted on test flexural strength test machine.

Fig 3. Flexural strength test carried out on specimen in Compression testing machine.

Elastic modulus test

Elastic modulus of concrete was calculated using the cylindrical specimens (150 mm × 300 mm) after 28 days of curing as per the test-in procedure in IS 516:1959 (Part 5). All specimens were put in the compression testing frame and loaded in an incremental manner, with the corresponding deformations being measured using a compressometer. The stress–strain response in the linear elastic range was plotted, and the elasticity modulus was determined. Fig. 4 shows the diagram of the elastic modulus of the concrete test conducted on the compressive strength machine.

Fig 4. Cylinder specimen positioned with test setup for Young modulus test

3.2 Durability test properties

Water absorption test

To determine the permeability properties of concrete, water absorption testing was conducted, which directly determines the resistance of concrete to moisture ingress, chemical attack, and even long-term durability. Water absorption of 28 days cured cubes were conducted by drying 28 the cubes to a constant weight, placing them in water overnight, and recording the increase in mass.

Fig 5 illustrates the cube specimen that had been subjected to a hot oven and considered an important process in the test of water absorption.

Fig 5. Cube specimen kept in hot oven

Sorptivity Test

Sorptivity test was conducted to determine the rate of capillary suction as one of the most important indicators of the transport properties and service-life behaviour of concrete. The sorptivity test was conducted following curing of the concrete after 28 days to measure the rate of capillary water absorption. The cube specimens were dried in an oven, the sides were closed, and the bottom of the specimen was exposed to water according to ASTM C1585. The first increase in water level was recorded at constant time intervals.

Chloride Ion Penetration Test (RCPT)

Penetration testing of chloride ions was conducted as performed to assess the resistance of concrete to chloride ingress, a very crucial parameter that determines the reinforcement corrosion in the ocean and de-icing conditions. Rapid Chloride Permeability Test was conducted as per ASTM C1202 on 28 day cured cylindrical samples. It was in the RCPT cell where each specimen was put and sodium chloride solution was at one side and sodium hydroxide solution on the other. Potential of 60 V constant was applied and charged passed was noted after 6 hours. Fig 6 shows RCPT test setup.

Fig 6. Rapid chloride penetration test under process

Acid and Sulphate Attack

The ability of concrete materials to withstand acid and sulphate exposure is a major sign of long-term resistance especially in structures situated in industrial, coastal, and wastewater situations. Cubes that had been cured in 28 days were placed in a 5% solution of sulphuric acid in order to evaluate acid resistance. Following the exposure, the specimens were washed and subjected to the remaining compressive strength test. The sulphate durability test was determined by putting the cured samples in a 5 percent sodium sulphate solution after 28 days. Compressive strength was then established after being exposed.

. Fig 7 shows acid and sulphate attack resistance test.

Fig 7. Acid and sulphate attack test under process

4. RESULT AND DISCUSSION

Table 2 and Table 3 presents the results derived from the experimental investigation observations.

Table 2 Mechanical properties test

Specimen Designation	**Compressive Strength MPa**	**Split Tensile Strength MPa**	**Flexural Strength MPa**	**Young's Modulus MPa**
M40	47.5	3.9	5.0	32580
M40 +20% GGBS	62.5	5.0	6.2	36250

Table 3 Durability properties test

Specimen Designation	Water absorption	Sorptivity	Chloride ion penetration	Strength reduction due to Acid	Strength reduction due to

	%	mm/min$^{0.5}$	Coulombs	%	Sulphate %
M40	2.4	0.19	1790	18.5	13.5
M40 +20% GGBS	1.6	0.09	980	7.5	5.5

- The experimental results indicate a substantial improvement in the mechanical and durability properties of concrete with the incorporation of 20% GGBS. The 28-day compressive strength of the M40 control mix was 46.5 MPa, whereas the M40 mix with 20% GGBS achieved 62.5 MPa, demonstrating a significant strength enhancement and indicating that the modified mix can be classified within the M60 strength range. This improvement is primarily attributed to increased C–S–H gel formation and pore refinement resulting from the synergistic action of GGBS and the superplasticizer system. Similar strength gains have been reported in recent studies; however, most required higher GGBS contents (30–40%) or the use of silica fume to achieve comparable performance.
- The split tensile strength at 28 days increased from 4.0 MPa in the M40 mix to 5.0 MPa in the M40 + 20% GGBS mix, reflecting improved matrix densification and reduced micro cracking. Comparable enhancements have been reported by earlier researchers, although their studies commonly employed ternary blends incorporating nano-silica or silica fume.
- Flexural strength also showed a notable increase, rising from 5.2 MPa for the M40 mix to 6.2 MPa with 20% GGBS replacement. The higher modulus of rupture is associated with the development of a more refined interfacial transition zone and improved bonding between the cement paste and aggregates. Similar trends have been observed in the literature, typically in blended systems containing fly ash or silica fume.
- The modulus of elasticity increased from 32.5 GPa for the M40 mix to 36.2 GPa for the M40 + 20% GGBS mix, indicating enhanced stiffness and reduced deformability. Previous studies have also reported increases in stiffness with the use of supplementary cementitious materials, although higher replacement levels or multi-component blends were generally required.
- Durability performance improved significantly with GGBS incorporation. Water absorption decreased from 2.4% in the M40 mix to 1.6% in the M40 + 20% GGBS mix, indicating improved impermeability. Similarly, rapid chloride permeability values reduced from 1790 coulombs (moderate to high permeability) in the M40 mix to 980 coulombs (low permeability) in the GGBS-modified mix. Although comparable reductions have been reported in recent studies, they typically involved higher GGBS contents or nano-SCM combinations.
- Resistance to aggressive environments was also enhanced. Strength loss under acid exposure reduced from 18.5% in the M40 mix to 7.5% in the M40 + 20% GGBS mix, while sulphate-induced strength loss decreased to 5.5% with GGBS incorporation. These findings are consistent with recent research confirming that GGBS significantly improves acid and sulphate resistance, with the performance achieved in the present study being comparable to or better than mixes containing higher proportions or multiple supplementary cementitious materials.

5. CONCLUSION

As indicated in this study, a basic binary adjustment with 20% GGBS and a superplasticizer can effectively convert ordinary M40 concrete to a high-performance blend with considerably high mechanical strength, stiffness and durability. What is novel about the work is the fact that the properties of high-performance concrete can be attained without the use of silica fume or the use of complicated ternary SCM systems, so the technique is not only cost-effective but also readily applicable to the field. The increased resistance against moisture ingress, chloride permeability and chemical attack presents high chances of applying the modified mix on severely exposed structural members like coastal structures, industrial flooring, water holding structures and high-rise structures that need a lengthy period of service maintenance. On the basis of the findings, it is suggested that the suggested binary GGBS system should be implemented in structural concrete where enhanced strength-durability performance is needed, and future studies can consider its performance in a greater replacement level, microstructural evolution under loading conditions, and performance under cyclic or dynamic loads to enhance the engineering application of this system.

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