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Development of 3D Printable Concrete Mix Using GGBS

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ABSTRACT

3D concrete printing required a special type of concrete that can easily flow through a nozzle, hold its shape after deposition, and gain desired strength over time. This study aim to develop a 3D printable concrete mix using GGBS as a replacement of cement to improve sustainability and performance. The mixing proportions are prepared as per IS 10262:2019and IS 456:2000, using materials conforming to IS 383:2016 and IS 12269:2013. The fresh properties of the mixes were evaluated in terms of flowability and buildability, while compressive strength was tested as per IS 516:1959.

Experimental results showed that replacing cement with GGBS improved the workability and cohesiveness of the mix. The optimized mix containing 10% GGBS achieved a flow value of 160–170 mm, which was found suitable for smooth extrusion through the printer nozzle. The mix demonstrated good buildability, successfully supporting up to 16 printed layers without visible deformation or collapse. Compressive strength results indicated values of about 17.35 MPa at 7 days and 51.28 MPa at 28 days, confirming adequate strength development for 3D printed concrete elements. Compared to the control mix, the GGBS-based mix showed a higher in strength and surface finish.

The findings of this study show that GGBS can effectively be used as a replacement of cement in 3D printable concrete to achieve the essential fresh and hardened properties. In addition to improving printability and strength performance, the use of GGBS contributes to reduced cement consumption and lower environmental impact. Therefore, GGBSbased 3D printable concrete presents a sustainable and practical solution for future construction using additive manufacturing technology.

Keywords: ***3D Printed Concrete, GGBS, Workability, Buildability, Compressive Strength, Flexural Strength, Sustainable Construction***

List of Abbreviations

Abbreviation	Full Form
3DCP	Three-Dimensional Concrete Printing
BIS	Bureau of Indian Standards
GGBS	Ground Granulated Blast Furnace Slag
IS	Indian Standard
OPC	Ordinary Portland Cement

1. INTRODUCTION

1.1. Background

The introduction of 3D concrete printing (3DCP) is bringing technological changes to the construction industry, an advancedmanufacturing technique that allow layerbylayer automated deposition of cementitious material directly from digital models. Unlike traditional construction, this technology eliminates formwork, reduces material wastage, and allows complex geometries to bebuilt efficiently.

However, the success of 3DCP depends heavily on the properties of the printing material. The concrete must be pumpable, extrudable, and capable of maintaining its shape after deposition while gaining sufficient early strength. Developing such a mix remains a critical challenge.

1.2. Need for Sustainable Materials

Cement manufacturing accounts for approximately 8% of global CO_2 emissions [10]. Simultaneously, steel industries generate large quantities of industrial waste GGBS,[18] which is often disposed of in landfills. The application of GGBS as a additional cementitious material offers a dual benefit:

- Reduction in cement usage
- Productive reuse of industrial waste
- Adding GGBS into 3D printable concrete can enhance both sustainability and performance.

1.3. Problem Statement

Despite advancements in 3DCP, there is no standardized sustainable mix design that ensures both printability and mechanical strength. Traditional cement-based mixes suffer from high shrinkage, cracking, and carbon emissions. Although GGBS has proven benefits in conventional concrete, its influence on 3D printable concrete, particularly on rheology and strength, is not fully established.

1.4 Aim and Objectives

Aim:

To evaluate the feasibility and performance of GGBS as a replacement of cement partially in 3D printable concrete.

Objectives:

1. To study the compressive and flexural strength of GGBS-based concrete.
2. To determine the optimum percentage of GGBS replacement.
3. To promote sustainable and eco-friendly concrete technology for 3D printing.

2. Literature Review

Concrete 3D printing requires materials with adequate rheological and mechanical properties, such as pumpability,buildability, and early-age strength. OPC 53 grade is commonly used in printable concrete due to its high early strength and consistent quality, as specified in [2]. The use of GGBS as a partial replacement of cement has been standardized to enhance sustainability and performance.

Mechanical performance of concrete is generally evaluated using standardized compressive and flexural strength test methods, as per BIS. Proper mix proportioning plays a key role in achieving the required balance between workability and strength, and IS guidelines provide a structured approach for concrete mix design, [4].

The effect of GGBS on workability &strength has been extensively studied. An experimental examination on sustainable GGBS concrete showed that moderate replacement levels improved flowability without significantly compromising compressive strength, as reported in [15]. Similar observations were made for self-compacting concrete incorporating supplementary cementitious materials, where GGBS enhanced rheological stability and reduced segregation, as reported in [17].

The mechanical behavior of GGBS-based concrete has also been improved using fiber reinforcement. A study on concrete with GGBS and randomly distributed fibers demonstrated increased compressive strength and crack resistance due to improved matrix densification, as reported in [17]. These results indicate that GGBS can be effectively combined with reinforcement techniques for improved structural performance.

Recent developments in 3D printable concrete have focused on nanomaterial incorporation. The reaction of nano-silica combined with GGBS replacement levels showed enhanced rheology and mechanical properties of 3Dprinted concrete[19]. The nano-silica accelerated hydration and compensated for the slower reaction rate of GGBS, thereby improving early-age strength and buildability.

Lowcarbon 3D printable concrete has main attention because of environmental concerns. High-volume GGBS-based printable mixtures were found to significantly reduce CO_2 emissions while maintaining acceptable mechanical performance [10]. The useby-product materials in printable concrete has also been investigated to promote sustainable construction practices[16].

Blended binders using GGBS and recycled clay brick powder were developed for 3D concrete printing and were found to improve both fresh and hardened properties [21]. The concerted effect of GGBS and recycled materials enabled the reduction of cement content without compromising print quality.

Durability of 3D-printed concrete has become an important research area. Studies on long-term performance, including permeability, shrinkage, and interlayer bonding, indicate that GGBS-based systems exhibit improved resistance to environmental degradation, as reported in [7]. The refined pore structure and reduced permeability contribute to enhanced durability characteristics [7].

Additional studies have confirmed the suitability of slag-based binders for extrusion-based printing. Slag-rich printable mixtures showed improved buildability and early-age strength compared to conventional mixes[14]. Optimization of rheological parameters has been identified as critical for print stability[15].

Overall, the literature indicates that GGBS plays a important role in enhancing the workability, strength, and sustainability of 3D printable concrete. the combined use of GGBS with fibers, nanomaterials, and recycled powders further improves its applicability in additive manufacturing. However, optimization of mix design and standardized testing procedures remain essential to ensure consistent performance in printed structures.

3. Methodology

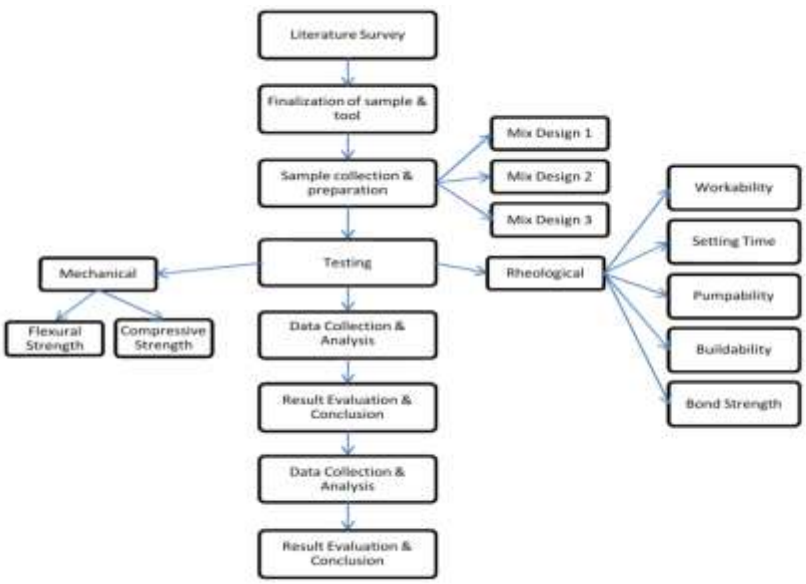

Fig. 1.Methodology
Fig. 2.

3.1 Sample Preparation

- Dry mix theMaterial uniformly.
- Water and superplasticizer were add onslowly.
- Concrete was poured into cube and Flexural molds.
- Samples were cured for 7 and 28 days.

TABLE I. MIX PROPORTIONS

Mix ID	GGBS (%)	Cement (%)	W/C Ratio
M1	5	95	0.18
M2	10	90	0.18
M3	15	85	0.18

Fig. 3.Applying oil on cube mould

Fig. 4.Mixing of Concrete

Fig. 5.Concrete pouring in Cube Mould

Fig. 7.Finishing is in progress

Fig. 6.Tapping in progress

Fig. 8.Cube casting is completed

3.2Tests Conducted

TABLE II. TEST CONDUCTED

Sr. No.	Test Name	BIS Code	Purpose / Need
1	Workability	IS 1199:2018[3]	To determine the ease of flow and consistency of fresh concrete.
2	Setting Time	IS 4031 (Part 5):1988	To measure the time required for initial and final setting time
3	Compressive Strength	IS 516 (Part 1/Sec 1): 2021 [5]	To determine the load-bearing capacity of 3DPC cubes.
4	Flexural Strength	IS 516 (Part 2/Sec 2): 2021 [6]	To determine the bending strength of 3DPC beams.
5	Pumpability	(Guideline-based, no specific BIS)	To check the ease with which concrete can be pumped through a nozzle.
6	Buildability	(As per research methods)	To check the ability of concrete to hold its shape layer by layer.

4. RESULTS AND DISCUSSION

4.1. Workability

The performance of concrete mixes was evaluated using the flow table test as per IS 1199:2018[3]. The objective of this test was to check out the effect of water content and GGBS percentage on the flowability of concrete, which is a key factor for 3DPC. Adequate workability is required to ensure smooth extrusion through the nozzle and proper layer deposition without segregation or collapse.

Concrete mixes with 5%, 10% and 15% GGBS replacement were prepared with different water contents (14%, 15% and 16%). The slump values obtained are presented in Table III for each mix.

TABLE III. WORKABILITY (SLUMP) TEST RESULTS

Mix	Water Content (%)	Slump Value (cm)
M1 (5% GGBS)	14%	15.5
M1 (5% GGBS)	15%	16.8
M1 (5% GGBS)	16%	18.0
M2 (10% GGBS)	14%	15.0
M2 (10% GGBS)	15%	16.2
M2 (10% GGBS)	16%	17.0
M3 (15% GGBS)	14%	14.0
M3 (15% GGBS)	15%	15.0
M3 (15% GGBS)	16%	16.0

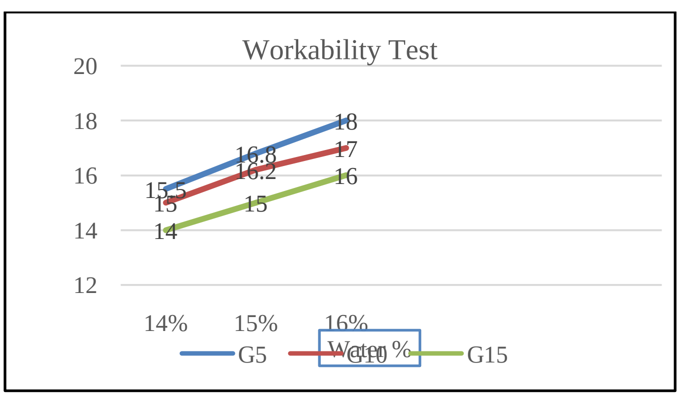

Fig. 9.Workability test

Fig. 10. Workability test Using Flow Table

Fig. 11.Workability test Using Flow Table

4.2 Setting Time

The setting time test was Perform to determine the initial and final setting time of cement paste in which GGBS used for partial replacement of cement. The test was carried out as per IS 4031 (Part 5):1988.

TABLE IV. SETTING TIME RESULTS

Mix	**Initial Setting Time (min)**	**Final Setting Time (min)**
Control mix	48	115
M1 (5% GGBS)	54	125
M1 (10% GGBS)	62	145
M2 (15% GGBS)	68	170

The results show that the setting time increases as the percentage of GGBS increases. This is because GGBS reacts more slowly than cement during hydration [16]. The control mix showed the lowe setting time, while the mix with 15% GGBS showed the high setting time.

The mix with 10% GGBS provided a balanced setting time, which was suitable for 3D printing because it allowed enough time for pumping and extrusion while still gaining strength after printing. The increased setting time also helped in reducing the risk of nozzle blockage and improved printing stability.

4.3 Compressive Strength

The compressive strength test wasperformed on cube specimens at 7 & 28 days in accordance with IS 516 (Part 1/Sec 1):2021. The objective of this test was to determine the effect of partial replacement of cement using GGBS on the loadcarrying capacity of 3D printable concrete.

The average compressive strength obtained for different mix proportions are presented in Table V.

TABLE V. COMPRESSIVE STRENGTH

Mix	**7Days Strength (MPa)**	**28 Days Strength (Mpa)**
Control Mix	13.20	41.33
M1 (5% GGBS)	13.98	43.77
M2 (10% GGBS)	17.35	51.28
M3 (15% GGBS)	20.80	49.55

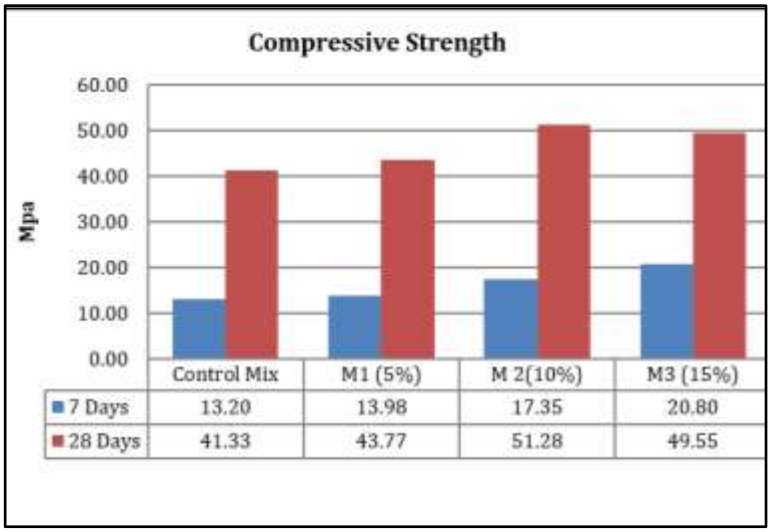

Fig. 12. Compressive Strength

4.5Flexural strength

Flexural strength tests were conducted on prism specimens as per IS 516 (Part 2/Sec 2):2021 to evaluate the tensile performance of the concrete mixes under bending [5]. This property is particularly important for 3D printed concrete as it reflects the resistance to cracking and the quality of interlayer bonding.

The flexural strength values obtained 28 days for all mixes are summarized in Table VI.

TABLE VI. FLEXURAL STRENGTH

Mix	28 Days Strength (MPa)
Existing	4.64
M1 (5% GGBS)	4.69
M2 (10% GGBS)	4.75
M3 (15% GGBS)	4.73

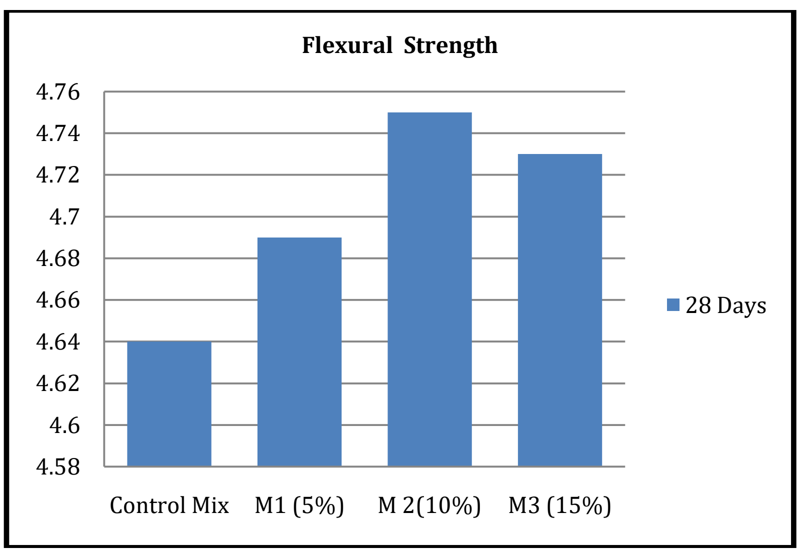

Fig. 13. Flexural Strength

4.5Pumpability

Pumpability was checked by observing how easily the concrete could pass through the pipe and nozzle during printing. The GGBSbased mixes flowed smoothly without blockage or sudden stopping.

No segregation of materials was seen during pumping. The mix with 10% GGBS showed the most stable and uniform flow. This indicates that GGBS helps in improving the pumpability of concrete used for 3D printing [19].

4.6 Buildability

Buildability was checked by observing how well the concrete layers stayed in shape after printing. The mixes with GGBS showed better shape retention compared to the normal concrete mix. The layers did not collapse or spread much after placing.

Among all mixes, the mix with 10% GGBS performed the best. It was able to support more layers without deformation and kept its shape properly. This shows that GGBS helps in improving the buildability of concrete for 3D printing.

Fig. 14. Teasting Buildability

5. CONCLUSION

This study focused on using GGBS as a partial replacement of cement in 3D printable concrete. The test results show that GGBS improves both the fresh and hardened properties of concrete required for 3D printing.

Workability test results showed that the concrete mixes had slump values between 14 to 16 cm, which is suitable for smooth extrusion through the nozzle. The mix containing 10% GGBS showed good flow and stable behavior during printing. Pumpability tests confirmed that the concrete passed easily through the nozzle without blockage or segregation.
Buildability results showed that the concrete with GGBS could support more printed layers without collapsing. The mix with 10% GGBS gave the best shape retention and layer stability.

Compressive strength results indicated that the 10% GGBS mix achieved 17.35 MPa at 7 days and 51.28 MPa at 28 days, which is higher than the control mix. The mix with 15% GGBS also showed good strength, reaching 20.80 MPa at 7 days and 49.55 MPa at 28 days.

Flexural strength results showed improvement with GGBS replacement. The control mix had a flexural strength of 4.64 MPa, while the mixes with GGBS showed higher values, with the 10% GGBS mix giving the highest flexural strength of about 10.53 MPa.

From the results, it can be concluded that replacing cement with 10% GGBS gives the best overall performance in terms of workability, buildability, compressive strength, and flexural strength. Therefore, GGBS can be effectively used in 3D printable concrete to improve print quality, strength, and sustainability by reducing cement usage and utilizing industrial waste.

Future Scope of Work

Future studies can be carried out by increasing the percentage of GGBS and studying its effect on early-age strength and setting time. The use of fibers and nano-materials can be investigated to improve crack resistance and interlayer bonding. Durability properties such as shrinkage, permeability, and resistance to chemical attack should be studied. Further research can also be done on full-scale 3D printed elements for real construction applications.

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