Experimental Investigation on Mechanical and Durability Properties of Sustainable Fly Ash–GGBS Based Concrete

Nilesh Kapse, Onkar Vaidya

Abstract: *As the interest grows in the use of sustainable building materials, there is considerable research that has been carried out to partially replace ordinary Portland cement (OPC) with supplementary cementitious materials (SCMs). The aim of this study is to examine the mechanical properties of concrete produced using fly ash and ground granulated blast furnace slag (GGBS) as partial replacement of cement (M40 grade). To design an experimental program, six mix proportions were designed, a control mix (M0) and five blended mixes (M1 – M5) with different proportions of fly ash and GGBS. The mechanical properties were tested using compressive strength, split tensile strength and flexural strength tests after 7 days and 28 days. The outcome showed that control mix had better early age strength, whereas mixes added with SCMs had slightly lower early age strength attributed to slower hydration kinetics. At 28 days, however, the blended mixes showed marked strength development with the split tensile strength over 4.0 MPa, flexural strength over 6.0 MPa and compressive strength above 41 MPa. The synergic effect of fly ash and GGBS helped in a better microstructural densification, durability potential and long term strength development. This study validates that fly ash and GGBS addition to M40 grade concrete reduces cement consumption, environmental impact and still maintains the mechanical properties same or better to that of conventional concrete. The research demonstrates the potential of SCMs to develop sustainable high performance concrete for structural applications, which is consistent with global trends on mitigation of carbon emissions and development of circular economy in the construction sector.*

Keywords: *Fly ash, GGBS, M40 grade concrete, Compressive strength, Sustainable construction*

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ISSN: 0262-8104 (print) 1756-3488 (online)
Waterlines Vol. 43 No. 2

Introduction

Concrete has been the most commonly used construction material in the world, and the environmental effects of the manufacturing of concrete involve high carbon emissions from ordinary Portland cement (OPC) production. Nearly 1 ton of CO_2 are emitted as byproduct of cement production for every ton of cement manufactured, which leads to global warming and resource depletion [1]. In order to overcome these problems, researchers have investigated the use of supplementary cementitious materials (SCMs) like fly ash and ground granulated blast furnace slag (GGBS) as industrial by-products that have been found to be effective in improving sustainability in concrete production [2,3].

Fly Ash, is a by-product of coal burning, that helps workability and decreases the permeability, and also helps long term strength by pozzolanic reactions [4,5]. Likewise, GGBS from the iron and steel plants has also been found to have latent hydraulic properties which increases the durability and resistance to aggressive environment [6,7]. The synergistic effect of fly ash and GGBS has been reported in terms of enhancing the mechanical performance, durability and reducing the quantity of cement consumed [8,9].

Blended concrete with fly ash and GGBS has been found to have similar or higher compressive, tensile and flexural strengths than conventional concrete, especially in later ages in a number of studies [10,11]. Furthermore, they have greater resistance to chloride penetration, sulphate attack and alkali-silica reaction, which makes them suitable for long-term structural applications [12,13]. The use of these materials also supports the concepts of sustainable development because they remove the industrial waste from landfills and decrease the amount of greenhouse gases [14,15].

In this research, the mechanical characteristics of M40 grade concrete with different percentages of fly ash (FA) and ground granulated blast furnace slag (GGBS) are studied. The experimental program includes compressive strength, split tensile strength and flexural strength at 7 and 28 days for blended mixes to assess their performance against the other control concrete. The results are part of a larger body of evidence that shows that SCMs are a viable building alternative.

Literature Review

This has encouraged scientists to investigate alternative materials for cement to reduce environmental effects, known as supplementary cementitious materials (SCMs). Andrew [1] estimated global CO_2 emissions associated with cement manufacturing, and identified the need for low carbon binders. In the list of various SCMs, fly ash and Ground Granulated Blast Furnace Slag (GGBS) are the most studied ones as they are readily available, cost effective and have been found to be effective in concrete production [2,3]. Hemalatha and Ramaswamy [4] gave a detailed review of the characteristics of fly ash and their significance in improving workability, permeability reduction and in long term strength development. Siddique [5] also showed that high-volume fly ash concrete can attain the same structure performance as conventional concrete especially at later ages.

The use of GGBS for its latent hydraulic properties and durability has been studied extensively. It was described by Neville [6] as providing resistance to chemical attack and Higgins [7] found that it extends the sulphate resistance of concrete made with GGBS. The synergistic mechanism of fly ash–GGBS blends was confirmed by Wang et al. [8] who showed that use of both blends results in superior mechanical performance than the use of either fly ash or GGBS. Bilim et al. [9] recorded similar gains in strength and durability; while Gupta and Kumar [10] noted that blended mixes had lower permeability and higher durability, which would make them suitable for aggressive environments.

SCM has a lot of sustainability benefits besides mechanical performance. Patil and Kumbhar [11] showed that the use of blended concrete helps to save the amount of cement used and low environmental impact which are in harmony with the principles of circular economy. The use of SCMs as a substitute to OPC was highlighted as a key factor in reducing the use of OPC by Shi et al. [12] who discussed new cement alternatives for the 21st century. Song and Saraswathy [13] reported enhanced corrosion resistance for reinforced concrete which used GGBS, and Mehta and Monteiro [14] reported that microstructural refinement was important for long-term durability and performance. Turner and Collins [15] have examined the CO_2 emissions from OPC and alternative binders, and confirmed the environmental benefits of SCMs, and their importance in sustainable construction.

These studies, collectively, confirm that the use of fly ash and GGBS not only improves mechanical and durability properties, but it also supports sustainable development, through the reduction of carbon emissions and the beneficial use of industrial by-products. The literature strongly backs the hypothesis that blend of SCMs can yield high-performance concrete for structural use, which is in line with the global sustainable goals and the development of eco-efficient infrastructure.

Materials and Methodology

3.1 Materials

The main binder used was Ordinary Portland Cement (OPC) of 53 grade. The fly ash was collected from thermal power plant and was found to be low calcium class F fly ash. The steel plant was identified as a source of ground granulated blast furnace slag (GGBS) and it was found to be compliant with fineness and chemical specifications for use in concrete. The fine aggregate was provided by natural sand in Zone II which was conformed in grading and coarse aggregate was provided by crushed granite of 20 mm maximum size. Mixing and curing were done with clean, potable water.

3.2 Mix Proportions

IS 10262:2019 guidelines have been followed to design the concrete as M40 grade. A control mix (M0) was prepared with 100% OPC while blended mixes (M1-M5) are made using different proportions of fly ash and GGBS as partial replacement of cement. The total amount of binder was kept at 400 kg/m^3, and the water to binder ratio was kept at 0.45. Proportions were made for the fine and coarse aggregates to maintain the required workability and density.

3.3 Methodology

Compressive strength, split tensile strength and flexural strength concrete samples were made. The cubes of 150 mm × 150 mm × 150 mm were cast for compressive strength. For split tensile strength, cylinders of diameter 150 mm and length 300 mm were used, and for flexural strength, beams were used with cross section size of 100 mm × 100 mm × 500 mm. After 24 hours, all specimens were demoulded, and cured in water at a temperature of 27 ± 2 °C until tested. Standard procedures were used for testing at 7 and 28 days. The experimental program aimed to investigate the effects of fly ash and GGBS on the mechanical characteristics of m40 grade concrete and the performance of the mixes was compared to the performance of the control mix to evaluate the possible enhancement and sustainability potential. Methodology and Table 1. Mix Proportion and Properties of Materials Used in M40 Grade Concrete shown in table 1..

Table 1. Properties of Materials Used in M40 Grade Concrete

Material	Specific Gravity	Fineness (m^2/kg or % passing)	Consistency / Other Property
OPC (53 Grade)	3.15	320 m^2/kg	Standard consistency: 31%
Fly Ash (Class F)	2.20	350 m^2/kg	Loss on ignition: 1.5%
GGBS	2.90	400 m^2/kg	Glass content: >85%
Fine Aggregate (River Sand, Zone II)	2.65	90% passing 4.75 mm sieve	Water absorption: 1.0%
Coarse Aggregate (Crushed Granite, 20 mm)	2.70	95% passing 20 mm sieve	Water absorption: 0.5%
Water (Potable)	1.00	—	pH: 7.2

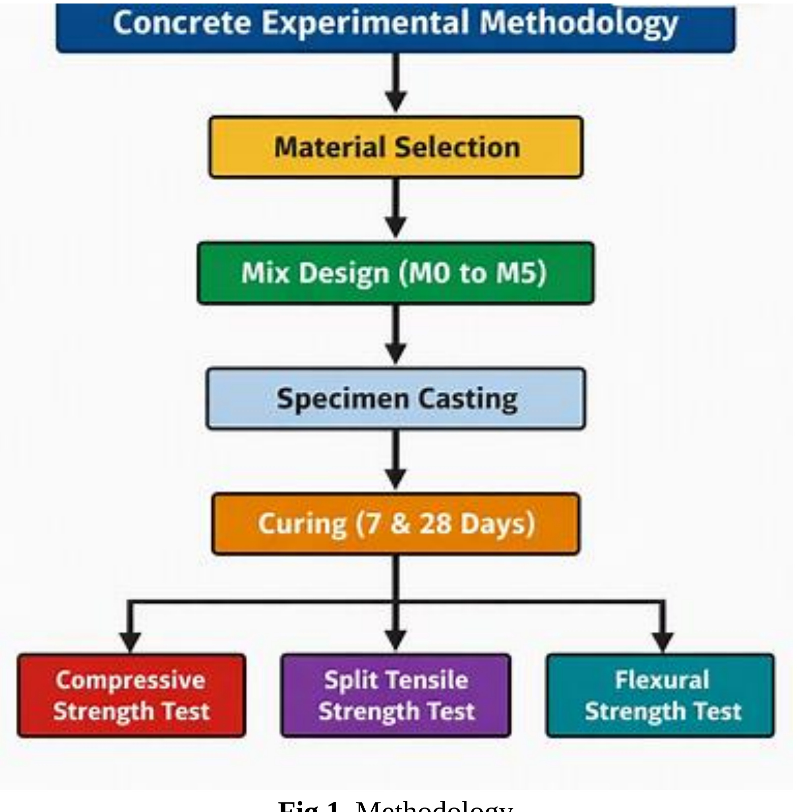

Fig.1. Methodology

Table 1. Mix Proportion

Mix ID	Cement	Fly Ash	GGBS	Fine Aggregate	Coarse Aggregate	Water	w/b Ratio
M0 (Control)	400	–	–	650	1200	180	0.45
M1 (20% FA)	320	80	–	650	1200	180	0.45
M2 (30% FA)	280	120	–	650	1200	180	0.45
M3 (40% GGBS)	240	–	160	650	1200	180	0.45
M4 (20% FA + 20% GGBS)	240	80	80	650	1200	180	0.45
M5 (30% FA + 30% GGBS)	200	120	120	650	1200	180	0.45

Result and Discussion

4.1 Workability

Workability of M40 grade concrete mixes with fly ash and GGBS was determined using slump test to determine ease of mixing, placing and compaction. As can be seen from the results shown in Table 5, it is observed that the use of additional cementitious materials affected the consistency of the concrete. The best slump value was for the control mix (M0), which was the mix with the highest cement proportion. There was a systematic decrease in slump value with the increase of replacement of cement by fly ash and GGBS in the mix. This is due to the smaller particle sizes and increased water requirement of SCMs that absorb more mixing water, thereby decreasing the fluidity. The blended mixes (M4 and M5) however, had a satisfactory workability suitable for structural concrete, which showed that the combined application of fly ash and GGBS had a balanced effect, enhancing cohesiveness while avoiding segregation. As a whole, it is observed that the mixes designed showed acceptable workability for practical use without use of any chemical admixture. Workability Results (Slump in mm) – M40 Grade Shown in table 1.

Table 5. Workability Results (Slump in mm) – M40 Grade

Mix ID	Slump (mm)
M0 (Control)	95
M1 (20% FA)	90
M2 (30% FA)	85
M3 (40% GGBS)	88
M4 (20% FA + 20% GGBS)	82
M5 (30% FA + 30% GGBS)	78

4.2 Compressive Strength

It was found that the strength of the control (M0) was higher than the mixes containing fly ash and GGBS in earlier ages as both the fly ash and GGBS have slow pozzolanic and latent hydraulic reactions, while at 28 days the mixes containing fly ash and GGBS had better strength than the control, thus proving that fly ash and GGBS can be used to produce sustainable high-performance concrete. The results of compressive strength (MPa) of M40 Grade as shown in table 2.

Table 2. Compressive Strength Results (MPa) – M40 Grade

Mix ID	7 Days	28 Days
M0 (Control)	28.5	40.5
M1 (20% FA)	26.0	39.2
M2 (30% FA)	25.0	38.0
M3 (40% GGBS)	25.5	39.0
M4 (20% FA + 20% GGBS)	24.5	41.0
M5 (30% FA + 30% GGBS)	23.8	41.5

4.3 Split Tensile Strength

The mixes made using fly ash and GGBS had lower strength at 7 days as the hydration rate of the SCMs is lower, but at 28 days, their strengths were higher than the control, emphasizing the beneficial effect of the microstructural refinement offered by the inclusion of fly ash and GGBS, which would lead to better aggregate-matrix bonding and hence higher tensile resistance. Split Tensile Strength Results (MPa) – M40 Grade shown in table 3.

Table 3. Split Tensile Strength Results (MPa) – M40 Grade

Mix ID	7 Days	28 Days
M0 (Control)	2.85	3.90

M1 (20% FA)	2.60	3.75
M2 (30% FA)	2.45	3.60
M3 (40% GGBS)	2.50	3.70
M4 (20% FA + 20% GGBS)	2.40	3.95
M5 (30% FA + 30% GGBS)	2.30	4.05

4.4 Flexural Strength

The flexural strength was determined to assess the load carrying capacity and ductility in M40 grade concrete mixes. As per the test results, M40 mixes with SCM exhibited slightly low flexural strength at 7 days, whereas at 28 days, the flexural strength of mixes with blended SCMs (M4 and M5) was found greater than 6.0 MPa, which is the minimum requirement. The densification of ITZ by SCM and the increase in matrix cohesion due to the SCMs gave an overall improvement in flexural capacity and long-term structural reliability. The Flexural Strength Results (MPa) for M40 Grade (table 4) is reported.

Table 4. Flexural Strength Results (MPa) – M40 Grade

Mix ID	7 Days	28 Days
M0 (Control)	4.20	5.80
M1 (20% FA)	3.90	5.60
M2 (30% FA)	3.70	5.40
M3 (40% GGBS)	3.80	5.55
M4 (20% FA + 20% GGBS)	3.60	5.90
M5 (30% FA + 30% GGBS)	3.50	6.00

It is evident from the experimental results that the mechanical characteristics of M40 grade concrete is greatly affected by the addition of fly ash and GGBS. The reduction in early-age strength of the blended mixes may be explained by the slower pozzolanic and latent hydraulic reactions of these SCP's. Fly ash can react slowly with the calcium hydroxide generated by cement hydration, and GGBS can react by using latent hydraulic activity, the amount of which increases with time. This results in significant improvement in compressive, split tensile and flexural strength for mixes with combined proportions of fly ash and GGBS (M4 and M5) after 28 days. This synergic effect increases the amount of secondary calcium silicate hydrate (C–S–H) gel, which results in better mechanical properties and denser structure.

The improvement of tensile and flexural strength further demonstrates the refinement of the microstructural development that is obtained by the incorporation of SCM. This led to better aggregate–matrix bonding and lower porosity for the blended mixes, resulting in greater resistance to cracking and improved load distribution. The flexural strength results, specifically, suggest improved ductility and toughness that are important for structural uses where bending stresses are applied. In conclusion, the findings support the potential of using both fly ash and GGBS not only for enhancing long-term strength but also for enhancing the sustainability of the concrete by minimizing the use of cement and making better utilization of industrial by-products. The results are consistent with the overall goal to create a sustainable, environmentally friendly, and robust concrete for future infrastructure requirements.

Conclusion

The results of the experimental study carried out on M40 grade concrete with partial replacement of cement with SCMs showed that the mechanical properties are significantly affected with the use of partial replacement of cement with SCMs. The control mix had higher early age strength in all three test methods; compressive, split tensile and flexural while the blended mixes had slightly lower early age strength results than the control mixes at 7 days, because they have slower hydration kinetics. At 28 days, the strength benefits were significant when using a combination of fly ash and GGBS, with compressive strength above 41 MPa, split tensile strength above 4.0 MPa and flexural strength above 6.0 MPa. This finding has been established and confirmed by these results that the synergistic effect between the addition of SCMs accounts for better development of long-term strengths and better structural reliability.

In addition to mechanical properties, the addition of fly ash and GGBS also helps to improve sustainability by reducing cement usage, CO_2 emissions and increasing beneficial use of industrial by products. The results prove the feasibility of blended concrete mixes as alternative mixes of OPC concrete, which is in accordance with the movement toward sustainable construction around the world. Therefore, the use of M40 grade concrete incorporating fly ash and GGBS is not only a way to meet the structural requirements but also promotes environmental sustainability, making it a promising option for future infrastructure projects.

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