EXPERIMENTAL INVESTIGATION ON BUCKLING BEHAVIOUR OF RECTANGULAR STEEL TUBE COLUMNS INFILLED WITH BLAST FURNACE SLAG AGGREGATE CONCRETE INCORPORATING GGBS AND SILICA FUME CONCRETE

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Abstract: The increasing demand for sustainable construction materials has encouraged the utilization of industrial by-products in structural concrete applications. This study investigates the axial compression and buckling behaviour of rectangular Concrete Filled Steel Tube (CFST) columns infilled with concrete containing Ground Granulated Blast Furnace Slag (GGBS), Silica Fume (SF), and Blast Furnace Slag Aggregate (BFSA). M30 grade concrete was designed with varying percentages of GGBS replacement (25%, 40%, 50%, 60%, and 75%) and BFSA replacement (20%, 40%, 60%, and 80%). Based on compressive strength results, the optimum mix consisted of 50% GGBS, 10% Silica Fume, and 40% BFSA. Concrete cube specimens were tested at 7, 28, and 56 days, while rectangular CFST columns of dimensions 100 mm × 50 mm × 1000 mm and 100 mm × 50 mm × 1500 mm were subjected to axial compression testing. Results indicated that the optimized concrete achieved a maximum 56-day compressive strength of 39.46 MPa and enhanced the ultimate load carrying capacity of CFST columns by approximately 8.95% compared with conventional concrete columns. The study demonstrates that industrial by-products can effectively improve structural performance while contributing to sustainable construction practices.

Keywords: Concrete Filled Steel Tube, Ground Granulated Blast Furnace Slag, Silica Fume, Blast Furnace Slag Aggregate, Sustainable Concrete, Axial Compression, Buckling Behaviour.

1. INTRODUCTION

The growing demand for sustainable and high-performance construction materials has encouraged researchers to explore alternative constituents in concrete technology. Industrial by-products such as Ground Granulated Blast Furnace Slag (GGBS), Silica Fume, and Blast Furnace Slag Aggregate (BFSA) have gained attention due to their ability to improve concrete properties while reducing environmental impact. These materials help in minimizing cement consumption and natural resource depletion, thereby supporting eco-friendly construction practices.

Concrete Filled Steel Tube (CFST) columns represent an efficient composite structural system that combines the compressive strength of concrete with the tensile strength and confinement provided by steel tubes. This interaction results in improved load-bearing capacity, enhanced ductility, and better resistance to buckling when compared to conventional structural members. Rectangular CFST columns are widely used in modern infrastructure due to their ease of construction and favorable structural performance.

Despite extensive research on CFST systems and supplementary cementitious materials individually, limited studies have been conducted on CFST columns incorporating a combination of GGBS, Silica Fume, and BFSA. In particular, the axial compression behavior and buckling performance of such sustainable composite columns require further investigation. Additionally, the effect of slenderness ratio on the structural response of these columns remains insufficiently explored.

In this context, the present study focuses on developing sustainable M30 grade concrete using industrial by-products and evaluating its performance in rectangular CFST columns under axial loading conditions.

2. LITERATURE REVIEW

2.1 General

A comprehensive review of existing literature provides a clear understanding of the developments in the field of composite columns and sustainable concrete materials. It helps to identify research trends, material advancements, and existing limitations in the performance of Concrete Filled Steel Tube (CFST) columns incorporating industrial by-products.

2.2 Review of Literature

Several researchers have investigated the use of supplementary cementitious materials and industrial by-products to enhance concrete performance.

Anil Singh (2016) studied the effect of silica fume as a partial replacement of cement and reported significant improvement in compressive strength and durability of concrete. The study concluded that an optimum replacement level of around 10% provides better performance characteristics.

Ganesamoorthy R M (2017) examined composite columns and highlighted the advantages of combining steel and concrete. The study showed that composite action improves load-carrying capacity and reduces buckling risk, making it suitable for high-rise structures and seismic applications.

Yang Zhang (2020) investigated steel slag aggregate concrete-filled steel tubular columns under axial compression. The results indicated that mechanical performance depends on loading conditions, diameter-to-thickness ratio, and expansion characteristics of steel slag concrete.

Feng Yu (2020) studied bond-slip effects in steel slag aggregate CFST columns and observed that bond deterioration significantly affects stiffness and load-carrying capacity. However, higher expansion ratios improve structural performance.

Donia Salman (2022) focused on the interfacial bond behavior in CFST columns using waste steel slag aggregates. The study reported improved bond strength at early ages and highlighted the influence of age and replacement levels on long-term performance.

A. J. Najia (2022) investigated steel fiber-reinforced CFST columns and found that steel fibers significantly enhance axial load capacity and ductility, improving overall structural performance.

Said Ikram Sadat (2024) developed a finite element model for CFST columns with dune sand concrete and reported reduced capacity with increased replacement levels due to weaker confinement effects.

Ganga V (2024) studied self-compacting concrete in CFST columns and highlighted the importance of proper compaction and material selection. The study also identified a research gap in rectangular CFST column behavior compared to circular sections.

2.3 Summary of Literature Review

From the reviewed studies, the following key points are observed:

- CFST columns exhibit superior load-carrying capacity due to composite action between steel and concrete.
- Supplementary cementitious materials such as silica fume and GGBS significantly improve concrete strength and durability.
- Steel slag and industrial by-products enhance sustainability but require proper proportioning for optimum performance.
- Buckling behavior is strongly influenced by slenderness ratio and column geometry.
- Limited research is available on combined use of GGBS, silica fume, and BFSA in rectangular CFST columns under axial loading.

RESEARCH GAP AND OBJECTIVES

3.1 Research Gap

Concrete Filled Steel Tube (CFST) columns have gained significant attention in structural engineering due to their superior load-carrying capacity, ductility, and resistance to buckling. At the same time, sustainable construction materials such as Ground Granulated Blast Furnace Slag (GGBS), Silica Fume, and Blast Furnace Slag Aggregate (BFSA) have been widely studied as partial replacements for cement and natural aggregates.

Although individual studies exist on GGBS, Silica Fume, and BFSA, most research has focused on their separate applications in concrete. Very limited experimental work has been carried out on the combined use of these materials in M30 grade concrete for structural applications. In particular, the behavior of CFST columns filled with such sustainable concrete under axial loading has not been sufficiently explored.

Furthermore, the influence of slenderness ratio on rectangular CFST columns filled with industrial by-product-based concrete is not well established. This creates a research gap in understanding the axial compression behavior, deformation characteristics, and buckling response of such composite columns.

Hence, there is a need to experimentally investigate CFST columns using sustainable concrete mixes incorporating GGBS, Silica Fume, and BFSA.

3.2 Objectives of the Study

The objectives of the present study are as follows:

- To determine the optimum percentage replacement of cement with Ground Granulated Blast Furnace Slag (GGBS).
- To determine the optimum percentage replacement of coarse aggregate with Blast Furnace Slag Aggregate (BFSA).
- To evaluate the compressive strength of M30 grade sustainable concrete incorporating GGBS and Silica Fume.
- To investigate the axial compression behaviour of rectangular CFST columns filled with conventional and modified concrete.

- To study the influence of slenderness ratio on load-carrying capacity and deformation characteristics of CFST columns.

4. MATERIALS AND METHODOLOGY

4.1 General

This study focuses on the development of sustainable M30 grade concrete using industrial by-products such as Ground Granulated Blast Furnace Slag (GGBS), Silica Fume, and Blast Furnace Slag Aggregate (BFSA). The experimental program includes material testing, mix design, casting of specimens, and evaluation of compressive strength and axial behaviour of Concrete Filled Steel Tube (CFST) columns.

4.2 Materials Used

4.2.1 Cement

Ordinary Portland Cement (OPC) 53 grade was used in this study. It provides high early strength and is suitable for structural applications requiring high load-bearing capacity.

4.2.2 Fine Aggregate

Manufactured sand (M-sand) passing through 4.75 mm sieve was used as fine aggregate. It improves workability and ensures proper particle packing in concrete.

4.2.3 Coarse Aggregate

Crushed stone aggregate of 20 mm size was used. It contributes to strength and structural stability of concrete.

4.2.4 Ground Granulated Blast Furnace Slag (GGBS)

GGBS is a supplementary cementitious material obtained from iron manufacturing waste. It improves durability, reduces permeability, and enhances long-term strength.

4.2.5 Silica Fume

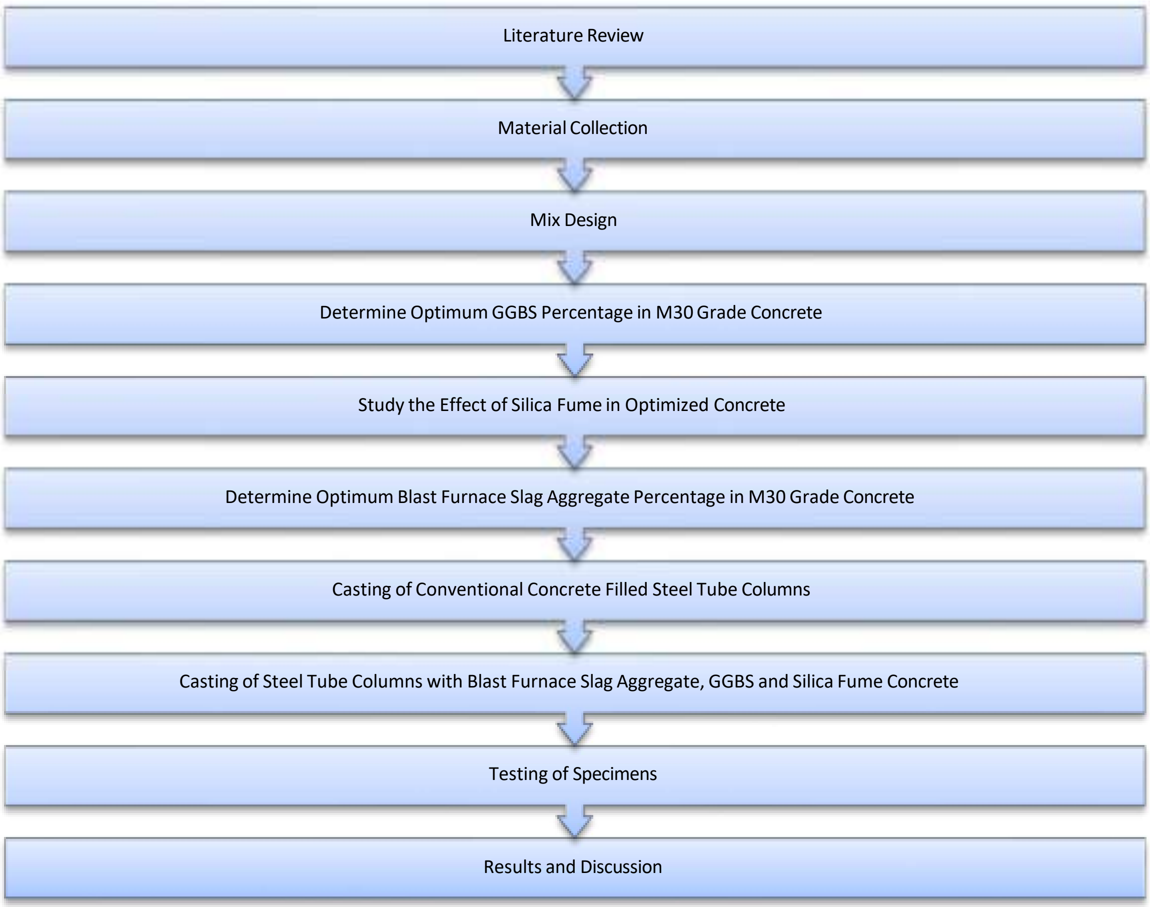
Silica fume is an ultra-fine pozzolanic material that increases compressive strength, reduces voids, and enhances durability of concrete.

4.2.6 Blast Furnace Slag Aggregate (BFSA)

BFSA is used as a partial replacement for natural coarse aggregate. It improves sustainability and mechanical performance of concrete.

4.3 Methodology

The methodology followed in this study is shown in the flow of experimental work:



4.4 Mix Design

4.4.1 General

This chapter presents the experimental investigation carried out in the present study. Preliminary tests were conducted to determine the physical properties of the constituent materials used in concrete production. M30 grade concrete was designed as per IS 10262:2019. Different percentages of GGBS, Silica Fume and Blast Furnace Slag Aggregate (BFSA) were incorporated as partial replacements for cement and coarse aggregate. Concrete cubes were cast and tested to determine compressive strength. Based on the optimum mix obtained from the cube test results, CFST column specimens were cast and tested.

4.4.2 Properties of Materials

The physical properties of cement, fine aggregate, coarse aggregate, GGBS and silica fume were determined in accordance with relevant Indian Standard specifications. The test results are presented in Table 4.1.

Table 4.1 Physical Properties of Materials

Material	Property	Value
OPC 53 Grade Cement	Specific Gravity	3.15
	Fineness	7.4%
	Standard Consistency	32%
	Initial Setting Time	31 min
	Final Setting Time	286 min
Fine Aggregate (M-Sand)	Specific Gravity	2.45
	Fineness Modulus	2.56
Coarse Aggregate (20 mm)	Specific Gravity	2.74
	Fineness Modulus	6.60
GGBS	Specific Gravity	2.80
	Fineness	8%
Silica Fume	Specific Gravity	2.25
	Fineness	2.3%

The test results confirm that all materials satisfy the requirements of the relevant IS codes and are suitable for concrete production.

4.4.3 Mix Design of Concrete

Concrete mixes were designed for M30 grade concrete in accordance with IS 10262:2019. Different percentages of GGBS, Silica Fume and BFSA were incorporated to study their influence on concrete performance.

4.4.3.1 Conventional Concrete Mix

Table 4.2 Conventional M30 Concrete Mix

Material	Quantity (kg/m³)
Cement	394
Fine Aggregate	841
Coarse Aggregate	1095
Water	157.6

Mix Ratio = 1 : 2.13 : 2.78 : 0.40

4.4.3.2 Concrete with GGBS and Silica Fume

Silica fume content was maintained at 10% of the binder content, while cement was partially replaced by GGBS at various percentages.

Table 4.3 Mix Proportions with GGBS and Silica Fume

Mix ID	GGBS (%)	Cement (kg/m³)	GGBS (kg/m³)	Silica Fume (kg/m³)
GS25	25	256.1	98.5	39.4
GS40	40	197.0	157.6	39.4
GS50	50	157.6	197.0	39.4
GS60	60	118.2	236.4	39.4
GS75	75	59.1	295.5	39.4

Fine aggregate = 841 kg/m³, Coarse aggregate = 1095 kg/m³, Water = 157.6 kg/m³.

4.4.3.3 Concrete with GGBS (Without Silica Fume)

Table 4.4 Mix Proportions with GGBS Alone

Mix ID	GGBS (%)	Cement (kg/m³)	GGBS (kg/m³)
G25	25	295.5	98.5
G40	40	236.4	157.6
G50	50	197.0	197.0
G60	60	157.6	236.4
G75	75	98.5	295.5

Fine aggregate = 841 kg/m³, Coarse aggregate = 1095 kg/m³, Water = 157.6 kg/m³.

4.4.3.4 Concrete with GGBS, Silica Fume and BFSA

To achieve sustainable concrete production, coarse aggregate was partially replaced by BFSA at different percentages.

Table 4.5 Mix Proportions with BFSA

Mix ID	BFSA (%)	Coarse Aggregate (kg/m³)	BFSA (kg/m³)
BF20	20	876	219
BF40	40	657	438
BF60	60	438	657
BF80	80	219	876

4.4.3.5 Mix Selected for CFST Column

Based on the experimental programme, the BF40 mix was selected for CFST column casting.

Table 4.6 Mix Proportions for CFST Column

Material	Quantity (kg/m³)
Cement	197
GGBS	157.6
Silica Fume	39.4
Fine Aggregate	841
Coarse Aggregate	657
BFSA	438
Water	157.6

4.4 Summary

1. Preliminary tests were conducted on cement, aggregates, GGBS and silica fume.
2. M30 concrete was designed as per IS 10262:2019.
3. GGBS replacement levels of 25%, 40%, 50%, 60% and 75% were adopted.
4. Silica fume was maintained at 10% replacement level.
5. BFSA replacement levels of 20%, 40%, 60% and 80% were considered.
6. The selected mix was used for casting CFST columns and cube specimens for further testing.
7.

4.5 CASTING

Based on the above mix proportions the concrete cubes were casted. The concrete cubes are of size 150mm×150mm×150mm. For conventional concrete totally 9 cubes were casted. For finding the optimum proportion of GGBS totally 45 cubes were casted and for each proportion nine cubes were casted. For finding the effect of silica fume in concrete the concrete cubes were casted without using Silica Fume on varying percentages of GGBS and totally 45 cubes were casted and for each proportion nine cubes were casted. With the optimized proportion of GGBS the proportion of BFS aggregate were varied to find the optimum proportion of BFS aggregate and totally 36 cubes were casted. After finding the optimized proportion of GGBS, Silica Fume and BFS aggregate the CFST columns of dimensions 100mm×50mm×1000mm and 100mm×50mm×1500mm were casted. Similarly for conventional M30 grade of concrete the CFST columns of dimensions 100mm×50mm×1000mm and 100mm×50mm×1500mm were casted.

Fig.4.1 Concrete Cube Specimen (150mm×150mm×150mm)

Fig.4.2 CFST Column Specimen (100mm×50mm×1000mm and 100mm×50mm×1500mm)

4.6 TESTING

After the cubes have been cured, they are taken out from the Curing tank, cleaned up, and then put into the Compression Testing Machine. The load was applied gradually onto the top surface of the cube until failure of its structure occurs. The ultimate load the cube can take before fracture was carefully noted. The compressive strength was obtained by dividing the peak load by the face area of the cube. Compressive strength for M30-grade concrete should be more than or equal to 30 MPa at the age of 28 days. Concrete is said to achieve structural strength if it achieves that strength in test results or more. Similarly the testing of Concrete cube specimens were done. The CFST columns were casted and tested on Column Testing Frame machine.

Fig.4.3 Testing of Concrete Cube Specimen

5. RESULTS AND DISCUSSION

5.1 Compressive Strength of Concrete Cubes

The compressive strength results obtained for conventional concrete and concrete containing GGBS, silica fume and BFSA are presented in Table 3. The strength development was evaluated at 7, 28 and 56 days.

Table 5.1 Compressive Strength of Concrete Mixes

Mix ID	7 Days (MPa)	28 Days (MPa)	56 Days (MPa)
CC	24.80	35.40	36.22
GS25	13.20	23.08	24.06
GS40	15.10	24.86	28.91
GS50	21.90	35.23	38.20
GS60	9.17	15.13	17.42
GS75	12.40	19.91	22.98

The incorporation of GGBS and silica fume significantly influenced the compressive strength of concrete. Among all the mixes, GS50 exhibited the highest 56-day compressive strength of 38.20 MPa, which was approximately 5.5% higher than that of conventional concrete. The improvement can be attributed to the pozzolanic reaction of silica fume and the latent hydraulic properties of GGBS, resulting in a denser microstructure.

Concrete mixtures without silica fume exhibited lower compressive strength at all curing ages. The maximum 56-day strength achieved without silica fume was 32.16 MPa for the 50% GGBS replacement level, indicating the beneficial contribution of silica fume to strength enhancement.

Similarly, the use of BFSA as coarse aggregate replacement improved the compressive strength up to an optimum replacement level of 40%. The BF40 mix achieved a maximum 56-day compressive strength of 39.46 MPa, representing the best overall performance among all concrete mixtures investigated.

5.2 Axial Load Capacity of CFST Columns

The ultimate load capacities of the CFST columns are summarized in Table 4.

Table 5.2 Ultimate Load Capacity of CFST Columns

Specimen	Ultimate Load (kN)
A-30-1	183.50
A-30-1.5	164.70
B-30-1	201.56
B-30-1.5	178.41
A-40-1	226.10
A-40-1.5	192.51
B-40-1	244.75
B-40-1.5	214.62

The optimized concrete-filled steel tubular columns demonstrated superior load-carrying capacity compared with conventional CFST columns. The maximum ultimate load of 244.75 kN was recorded for specimen B-40-1, whereas the corresponding conventional specimen A-40-1 carried 226.10 kN. This corresponds to an increase of approximately 8.2%.

The improvement in structural performance is attributed to the enhanced compressive strength of the optimized concrete mix containing GGBS, silica fume and BFSA. The combined action of the steel tube confinement and improved concrete core resulted in higher load resistance and delayed failure.

6. CONCLUSION

This study investigated the structural performance of rectangular Concrete-Filled Steel Tube (CFST) columns incorporating Blast Furnace Slag Aggregate (BFSA), Ground Granulated Blast Furnace Slag (GGBS), and Silica Fume as sustainable replacement materials. Based on the experimental investigation, the following conclusions were drawn:

1. The optimum replacement levels were identified as 50% GGBS, 40% BFSA, and 10% Silica Fume, which provided the best overall mechanical performance.

2. The conventional M30 concrete achieved compressive strengths of 24.8 MPa, 35.4 MPa, and 36.22 MPa at 7, 28, and 56 days, respectively.

3. For M30 grade rectangular CFST columns (100 mm × 50 mm), the ultimate compressive load capacities of conventional concrete-filled specimens were 183.5 kN and 164.7 kN for column lengths of 1000 mm and 1500 mm, respectively.

4. The optimized BFSA-GGBS-Silica Fume concrete-filled CFST columns exhibited higher load-carrying capacities of

201.56 kN and 178.41 kN for 1000 mm and 1500 mm column lengths, respectively.

5. For M40 grade concrete, the conventional CFST columns achieved ultimate loads of 226.1 kN and 192.51 kN for column lengths of 1000 mm and 1500 mm, respectively.

6. The optimized BFSA-GGBS-Silica Fume concrete-filled CFST columns achieved improved ultimate loads of 244.75 kN and 214.62 kN for 1000 mm and 1500 mm column lengths, respectively.

7. The incorporation of BFSA, GGBS, and Silica Fume enhanced the compressive performance of CFST columns, resulting in an average strength improvement of approximately 8.95% compared with conventional concrete-filled specimens.

8. The buckling behavior of longer CFST columns was found to be more uniform than that of shorter columns, indicating improved structural stability with increasing slenderness.

9. The experimental results demonstrate that the combined utilization of BFSA, GGBS, and Silica Fume can produce sustainable and structurally efficient CFST columns while reducing dependence on natural aggregates and conventional cementitious materials.

Overall, the proposed sustainable concrete mix exhibited superior load-carrying capacity and satisfactory buckling performance, making it a promising alternative for structural application

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