Experimental Investigation on Concrete Beam Using Gfrp Bars with Partial Replacement of Coarse Aggregate with Stainless Steel Slag

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***Abstract*—The increasing demand for sustainable construction materials has encouraged the use of industrial by-products and alternative reinforcement in concrete. This study investigates the mechanical and structural performance of concrete incorporating stainless steel slag (SSS) as a partial replacement for coarse aggregate and Glass Fiber Reinforced Polymer (GFRP) bars as an alternative to conventional steel reinforcement. In Phase 1, coarse aggregate was replaced with stainless steel slag at proportions of 20%, 30%, and 40% by weight, and the fresh and hardened properties of concrete such as workability, compressive strength, split tensile strength, and flexural strength were evaluated. The results indicated that the inclusion of stainless-steel slag improved the strength characteristics of concrete up to an optimum replacement level of 30%. Based on the optimum mix, Phase 2 focused on the flexural behavior of reinforced concrete beams. Four reinforced concrete beams of size 150 mm × 150 mm × 1300 mm were cast: (i) conventional concrete with steel reinforcement, (ii) conventional concrete with GFRP bars, (iii) concrete with 30% stainless steel slag and steel reinforcement, and (iv) 30% stainless steel slag concrete with GFRP bars. The beams were tested under flexural loading to evaluate their load–deflection behavior, cracking characteristics, and ultimate load capacity. The study aims to determine the effectiveness of stainless-steel slag as a sustainable aggregate replacement and assess the structural performance of GFRP-reinforced concrete beams. The results contribute to the development of durable, corrosion-resistant, and environmentally sustainable concrete structures.**

***Index Terms*—Beam, Stainless steel slag, GFRP bars, Compressive Strength, Two-point load, Crack pattern.**

I. INTRODUCTION

Global warming has emerged as one of the most critical environmental challenges of the 21st century. Among the major contributors to anthropogenic greenhouse gas emissions is the cement industry, which is responsible for approximately 8% of global carbon dioxide (CO2) emissions. In response to growing environmental concerns and the global push toward sustainable development, there is an increasing focus on identifying and incorporating alternative materials that can partially or wholly replace conventional cement in construction. Sustainable construction practices are guided by three primary pillars: environmental sustainability, economic feasibility, and social responsibility. Within this context, the present study investigates the partial replacement of coarse aggregate with stainless steel slag, a biomass-derived waste material, and the incorporation of Glass Fiber Reinforced Polymer (GFRP) as a reinforcing agent in concrete.

The increasing demand for sustainable and durable construction materials has led to the exploration of alternative resources and reinforcement systems in concrete structures. This study focuses on the combined use of stainless-steel slag as a partial replacement for coarse aggregate and Glass Fiber Reinforced Polymer (GFRP) bars as a substitute for traditional steel reinforcement in reinforced concrete beams. The objective is to evaluate the feasibility of using industrial waste materials and corrosion-resistant reinforcement to enhance structural performance while reducing environmental impact. Concrete beam specimens are cast with varying proportions of steel slag and reinforced with GFRP bars, and are assessed for their mechanical properties, including strength and workability. The research aims to promote the use of eco-friendly materials in structural applications, contributing to the development of more sustainable construction practices.

II. LITERATURE REVIEW

1. Zulmahdi Darwis et al., (2023): The study investigates the effect of substituting steel slag for coarse aggregate on the compressive strength of concrete and determines the optimal steel slag to normal concrete ratio. Concrete samples aged for three, seven, and 28 days were prepared using SNI 7656:2012, incorporating different proportions of steel slag as a substitute for coarse aggregate. Results indicate that variations of 20%, 40%, and 60% show improvements in comparison to normal concrete after three and seven days of curing. However, the variations of 80% and 100% are less commonly used than standard concrete. The increase in compressive strength of steel slag concrete aged 28 days, compared to normal concrete, for variations of 20%, 40%, and 60% is 1.54%, 3.00%, and 6.57%, respectively, while the reduction for variations of 80% and 100% is 7.93% and 18.80%. Based on the results, steel slag concrete with a 60% substitution of coarse aggregate exhibits the optimal compressive strength ratio in the mixture.

2. M.D. Rubio-Cintas, et al., (2019): This paper analyzes the mechanical behavior of concrete samples with the addition of an industrial waste, such as ferritic fume dust produced by electric arc furnaces (EAF) when the materials are melted and makes a comparison using other types of additions of concrete such us silica fume. At the same time this paper studies the capacity of the matrix to encapsulate this residue that eventually ends up deposited in a landfill. The results show that, besides giving the concrete a greater resistance as it happens with silica fume, the use of this type of waste as an addition to concrete is suitable since the material remains encapsulated in the concrete matrix, thus not producing leaching of heavy metals which can be harmful to the environment and therefore to the health of the human being.

3. Julia Rosales et.al.,(2020): This work shows the feasibility of using stainless steel slag as a substitute for limestone filler in the manufacture of self-compacting concrete. The influence of different treatments applied to slags on physical and chemical properties was studied. On the other hand, the mechanical behaviour, as well as the durability acquired in self-compacting concrete, has been analysed. Very encouraging results were obtained, since this research demonstrates the possible application of this stainless-steel slag as a construction material, improving sustainability and promoting circular economy processes, which are achieved through the minimization of the waste disposal and accumulation.

4. Khaled Mohamed,et al., (2017): This study uses nonlinear finite-element analysis (FEA) to perform an in-depth investigation. FEA response was compared against the experimental results in terms of crack patterns, failure modes, strains in reinforcement and concrete, and load–deflection relationships. The results show that the simulation procedures employed were stable and compliant, and that they provided reasonably accurate simulations of the behavior. FEA was used to confirm some hypotheses associated with the experimental investigations. A comprehensive parametric study was conducted to investigate the effect of web reinforcement and loading-plate size on the strut efficiency factor. It was shown that vertical web reinforcement has no clear effect on the strength, but it is required for crack control. On the other hand, horizontal web reinforcement should be accompanied with vertical reinforcement. Loading-plate size showed a clear effect on the deep-beam strength. Based on the numerical simulation results, a modification to a recently proposed STM is suggested. The modified STM was compared to available STMs in design codes and provisions, yielding better correlation with experimental results.

5. Anjali Kumari Pravin Kumar Pandey et al., (2024): This paper aims to provide insights into the structural characteristics of concrete columns reinforced with Fiber Reinforced Polymer (FRP) rebars, specifically GFRP bars, as alternatives to steel bars. It examines the influence of parameters such as aspect ratio, concrete type and grade, slenderness ratio, and reinforcement percentage on the strength and

ductility of GFRP RCC columns under axial and eccentric loads. Design equations and numerical methods for predicting load-carrying capacity are summarized. The literature review reveals that GFRP RCC columns have 80–100% of the strength of steel RCC columns under concentric loading and 60–103% under eccentric loading, with a higher ductility index than steel RCC columns by an average of 17.4%. For NSC and HSC columns, GFRP bars contribute about 50% of the axial load-carrying capacity compared to steel bars. From the literature review in predicting the design load-bearing capacity of GFRP-RCC columns.

III. STAINLESS STEEL SLAG WITH GFRP BARS AND CONVENTIONAL CUBE

Stainless steel slag is a by-product formed during the production and refining of stainless steel, typically in Electric Arc Furnaces (EAF) and Argon Oxygen Decarburization (AOD) units. During this process, impurities in the steel (such as sulfur, silicon, phosphorus) are oxidized and combine with fluxes like lime (CaO) and dolomite ($CaMg(CO_3)_2$) to form slag.Stainless steel slag (SSS), a byproduct of stainless-steel production, shows significant potential for sustainable use in construction. It can be effectively utilized as a partial replacement for coarse aggregates in concrete, enhancing strength and durability while reducing reliance on natural resources.

Glass Fiber Reinforced Polymer (GFRP) bars are composite reinforcement materials made by combining glass fibers with a polymer resin matrix. These bars serve as an alternative to traditional steel reinforcement in concrete structures and are particularly valued for their high strength-to-weight ratio, corrosion resistance, and durability in aggressive environments.

A conventional cube is a fundamental structural element used extensively in construction and engineering to support loads and resist bending. Typically horizontal, conventional beams transfer applied loads primarily through bending moments and shear forces to supporting structures such as columns or walls. These beams are designed using classical beam theory, which assumes that the material behaves elastically under loading conditions. They are designed based on our requirement such as size, shape etc. Common materials used in conventional beams include reinforced concrete, steel, and wood, depending on the application and load requirements. They are classified based on their support conditions (simply supported, cantilever, fixed, continuous), cross sectional shapes (rectangular, I-beam, T-beam), and materials.

IV. DIMENSIONS

For the experimental investigation, reinforced concrete beam specimens were cast with standard dimensions of 150 mm × 150 mm × 1300 mm to evaluate their structural behaviour under flexural loading conditions. The beam specimens consisted of both conventional and SSS concrete beams. These beams were tested under two-point loading to study their load–deflection behaviour, ultimate load carrying capacity, and crack propagation patterns. The adoption of uniform beam dimensions ensured consistency in the experimental program and enabled accurate comparison between the conventional and SSS beam specimens

V. EXPERIMENTAL INVESTIGATION

The experimental investigation comprised the collection of materials required for the preparation of both conventional concrete and Stainless-steel slag mixes. Material characterization tests were conducted for conventional and SSS constituents to evaluate their fundamental properties, and the obtained results were systematically compared. In addition, standard tests were performed on fine and coarse aggregates to assess their physical and mechanical characteristics, ensuring their suitability for concrete production. The outcomes of these material tests formed the basis for understanding the performance differences between conventional concrete and SSS in the subsequent experimental program. An M30 grade concrete mix was designed and adopted as the control mix for conventional concrete. The same mix proportions were maintained for all mixes to ensure consistency, and cement was partially replaced with SSS at levels of 20%, 30%, and 40% by weight of cement. Based on these mix designs, concrete specimens were cast in the form of beam. A total of four RC beam specimens with dimensions of 150 mm × 150 mm × 1300 mm were cast, consisting of one conventional and three various mix beams. The specimens were prepared following standard casting procedures. The cured beam specimens were initially tested under two-point loading conditions to evaluate their load–deflection behavior, crack propagation patterns

VI. RESULTS

The results section presents the experimental outcomes obtained from the testing of RC beam specimens. The beam specimens were evaluated under two-point loading conditions to study their structural behavior, including load–deflection, ultimate load carrying capacity, and crack patterns. The results obtained for conventional and SSS beams were compared. The measured strength values obtained for conventional concrete and SSS-modified concrete at different replacement levels are reported and compared. These results provide a clear understanding of the influence of SSS incorporation on the strength performance of concrete

TAB:1 RESULT OF CONVENTIONAL BEAM (B1)

Load (kN)	Deflection at l/2 (mm)	Deflection at l/3 (mm)	Remarks
0	0	0	
5	0	0	
13	1.3	0.8	
15	1.4	0.8	First Crack
16	1.5	1	
20	2	1.2	
23	2.3	1.3	
27	2.8	1.4	
31	3.2	1.5	
34	3.7	1.9	
38	4.1	2.2	
39	4.3	2.7	
40	6.6	3	
41	7.1	3.2	
42	7.9	3.7	
43	9.7	4.5	
45	10.1	4.9	Ultimate Load

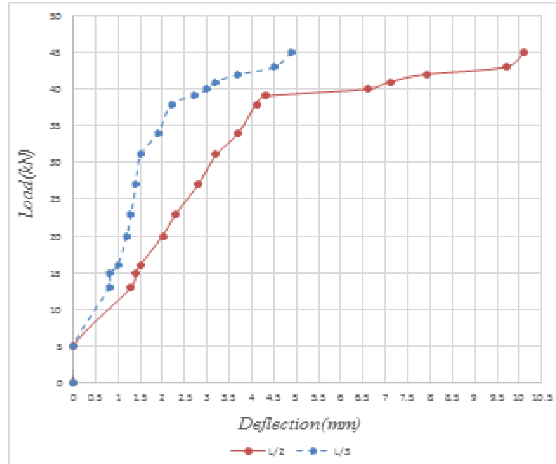

Fig 1 Graph for conventional beam (B1)

The above graph represents the load–deflection behavior of the conventional concrete beam under two-point loading conditions.

TAB:2 RESULT OF CC+30% SSS BEAM (B2)

Load (kN)	Deflection at l/2 (mm)	Deflection at l/3 (mm)	Remarks
0	0	0	
1.8	0	0	
5.1	0.2	0.2	
5.4	0.4	0.6	
7.4	1.8	1.2	
13.2	2.4	1.6	
16.2	3.2	2	
17.9	3.8	2.5	
19.1	4.9	3.1	
20.1	5.5	3.6	First Crack
23.2	6.4	4.4	
29.1	9	5	
30.8	9.7	6.7	
34.2	11.3	7.4	
37.1	12.3	8	
40.3	13.6	8.3	
42.9	15.1	9.3	
45.8	18	10.8	
51.3	20.5	12	
53.6	22.5	12.9	
55	24	13.2	Ultimate Load

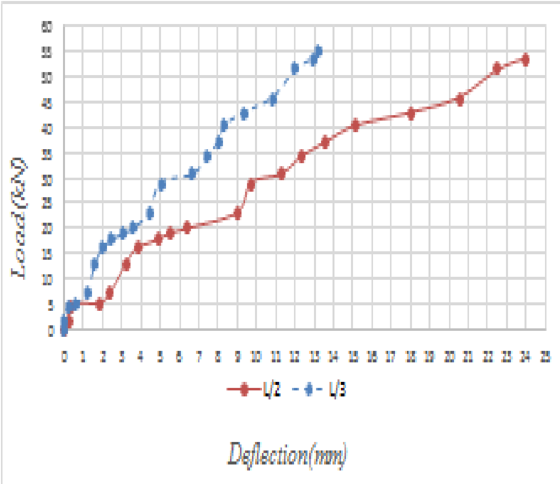

Fig 2 Graph for CC+30% SSS beam (B2)

The above graph represents the load–deflection behavior of the conventional concrete beam + 30% SSS under two-point loading conditions.

TAB:3 RESULT OF CC+GFRP BEAM (B3)

Load (kN)	Deflection at l/2 (mm)	Deflection at l/3 (mm)	Remarks
0	0	0	
3.2	0.1	0.2	
4.2	0.3	0.3	
7.5	0.8	0.4	
8.5	0.9	0.5	
10.5	1.4	0.8	
12.5	2.3	1.3	
14.2	2.8	1.4	
14.8	3.4	1.7	
17.3	4.3	1.9	First Crack
19.1	5	2.4	
22.2	6.3	3	
24	7	3.5	
24.8	7.5	4.1	
27.9	8.4	4.4	
30.1	9.4	4.8	
33.9	11.4	6.2	
37.1	12.9	7.1	
38.9	14	7.7	
41.8	15.5	8.6	
44.4	16.6	9.1	
47.1	18.7	10.4	
48.7	23.9	13.1	
49	24.5	13.4	Ultimate Load

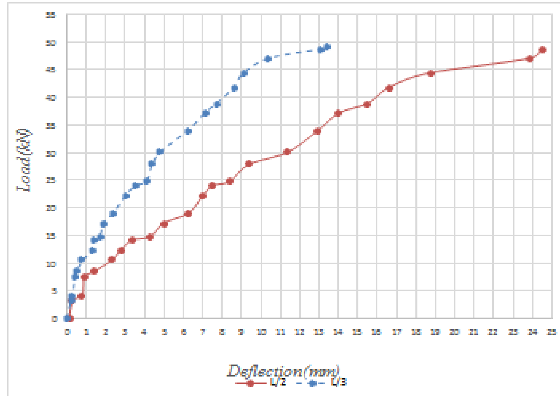

Fig 3 Graph for CC+GFRP beam (B3)

The above graph represents the load–deflection behavior of the conventional concrete beam + GFRP BARS under two-point loading conditions.

TAB:4 RESULT OF 30% SSS+GFRP BEAM (B4)

Load (kN)	Deflection at l/2 (mm)	Deflection at l/3 (mm)	Remarks
0	0	0	
9.1	0.5	0.9	
18	1.5	1.8	
39.5	4.3	2.5	
41.1	4.4	2.5	
43.8	4.7	2.7	
45.1	4.9	2.8	
46.5	5.1	3.1	
47.1	5.2	3.1	First Crack
48	5.4	3.2	
49.7	5.6	3.3	
50.5	5.7	3.4	
51.2	5.9	3.5	
52	6.1	3.6	
53.3	7	4	
54.1	7.4	4.2	
55	7.8	4.3	
56.2	8.2	4.5	
59	10.4	5.6	
60.2	11.5	5.8	
62.4	13.1	7.1	
64.8	17.8	8.3	Ultimate Load

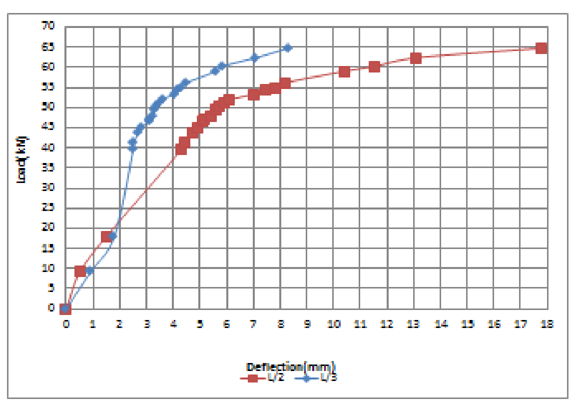

Fig 4 Graph for 30% SSS+GFRP beam (B4)

The above graph represents the load–deflection behavior of the conventional concrete beam + 30% SSS + GFRP BARS under two-point loading conditions.

CRACK PATTERN AND FAILURE MODE

Crack pattern refers to the distribution, direction, shape, and location of cracks that develop in a structural member when it is subjected to loading. It helps in identifying the type of stresses acting on the structure, such as flexural, shear, or torsional stresses. The observed crack is identified as a shear crack due to its diagonal orientation across the beam. Shear cracks typically occur when the shear stress exceeds the shear capacity of concrete, resulting in inclined cracks at about 30°–45° to the beam axis.

Fig 5 Crack pattern of Beams

VII. CONCLUSION

The replacement of coarse aggregate with stainless steel slag significantly influences the mechanical properties of concrete such as compressive strength, split tensile strength, and flexural strength. Among all mixes, the concrete with 30% replacement of coarse aggregate with SSS showed the maximum strength values in all tests: Compressive strength: 39.67 N/mm² at 28 days.

Split tensile strength: 4.21 N/mm² at 28 days

Flexural strength: 5.32 N/mm² at 28 days

Maximum compressive strength increase: 28.75% at 30% SSS

Maximum split tensile strength increase: 8.23% at 30% SSS

Maximum flexural strength increase: 12.24% at 30% SSS

Beyond 30% replacement (i.e., at 40%), a reduction in strength was observed, likely due to excess slag particles affecting workability and proper compaction. Hence, it can be concluded that 30% replacement of coarse aggregate with stainless steel slag gives optimum results and can be effectively used in concrete production to improve strength characteristics and promote sustainable use of industrial waste materials. This project effectively demonstrates the potential of incorporating Stainless steel slag and GFRP into concrete to enhance both environmental sustainability and structural performance. Excessive replacement can weaken the bond between the cement paste and aggregates, decreasing the overall bonding strength and reducing the effectiveness of the pozzolanic activity. Overall, this study confirms that the combined use of Stainless steel slag and GFRP Bars in concrete offers an eco-friendly, cost-effective, and structurally superior alternative for modern construction needs. The combination of 30% Stainless Steel Slag and GFRP (Glass Fiber Reinforced Polymer) bars yielded the highest load capacity at 64.8 kN. This represents a 44% increase in strength compared to conventional concrete with steel rebar (45 kN). This suggests a strong synergistic effect between the slag aggregate and the composite reinforcement. Replacing a portion of the aggregate with stainless steel slag significantly enhances the ultimate load. When looking at the steel rebar samples, adding slag increased the load from 45 kN to 55 kN. The slag likely provides a denser matrix or better interfacial transition zone (ITZ) bonding, which improves the overall structural integrity. GFRP Behavior: Conventional concrete with GFRP bars showed the highest mid-span deflection (24.5 mm), which is typical for GFRP due to its lower modulus of elasticity compared to steel. Improved Stiffness with Slag: Interestingly, when 30% Slag was added to the GFRP mix, the deflection decreased from 24.5 mm to 17.8 mm despite carrying a much higher load. This indicates that the slag addition increases the stiffness of the concrete member, helping to control the large deformations usually associated with GFRP reinforcement. The CC + 30% Stainless Steel Slag + GFRP bars mix is the optimal configuration among those tested. It provides the best balance of high ultimate strength and controlled deflection. This combination appears to be a viable sustainable alternative to traditional steel-reinforced concrete, offering better corrosion resistance using GFRP and waste material utilization Stainless steel slag.

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