An Experimental Study on Sustainable Concrete with Partial Replacement of Fine and Coarse Aggregates using Steel Industry By – Products

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***Abstract*—The rapid depletion of natural aggregates and the growing environmental impact of industrial waste disposal have necessitated the development of sustainable alternatives in concrete production. This study investigates the feasibility of utilizing steel industry by-products—Coal Bottom Ash (CBA) as a partial replacement for fine aggregates and Blast Furnace Slag (BFS) as a partial replacement for coarse aggregates—in M25 grade concrete. Five trial mix proportions were developed, incorporating varying replacement levels of CBA and BFS (10%, 20%, 25% and 40%) and compared against a conventional control mix. Comprehensive experimental investigations were conducted on fresh and hardened properties, including workability, compressive strength, split tensile strength, flexural strength and durability characteristics in accordance with IS standards. The results indicate that optimum replacement levels improve workability and enhance long-term strength due to the porous texture of CBA and the dense, durable nature of BFS. Moderate replacement levels (20–25%) demonstrated the best balance between strength and sustainability, with strength values comparable to or exceeding the control mix. The study confirms that significant portions of natural aggregates can be substituted with steel industry by-products without compromising structural performance. This approach promotes resource conservation, reduces environmental pollution and contributes to the development of eco-friendly concrete suitable for sustainable construction applications.**

***Index Terms*—Sustainable Concrete, Coal Bottom Ash (CBA), Blast Furnace Slag (BFS), Industrial By-Products, Eco-Friendly Construction Materials.**

I. INTRODUCTION

Concrete remains the most widely utilized construction material globally due to its versatility, durability and structural efficiency. However, its conventional production relies heavily on natural river sand and crushed stone, leading to rapid depletion of natural resources, environmental degradation and increased carbon emissions associated with material extraction and manufacturing. In parallel, the steel and thermal power industries generate large quantities of by-products such as Coal Bottom Ash (CBA) and Blast Furnace Slag (BFS), which pose significant challenges in terms of disposal, land occupation and potential environmental pollution.

Recent advancements in sustainable construction materials have emphasized the use of industrial by-products as partial replacements for traditional concrete ingredients. CBA, a granular residue from coal combustion, possesses low specific gravity and a porous texture, making it a potential alternative to natural fine aggregates. Similarly, BFS, a non-metallic by-product from iron manufacturing, exhibits desirable mechanical and durability characteristics that can complement or replace conventional coarse aggregates. Incorporating these materials not only reduces dependence on natural aggregates but also promotes waste valorization, aligning with global sustainability goals and circular economy principles.

This study investigates the combined utilization of CBA and BFS as partial replacements for fine and coarse aggregates in M25 grade concrete. The research examines their influence on fresh concrete behaviour, mechanical performance and durability characteristics through systematic laboratory experimentation. By identifying optimal replacement levels that balance strength, workability and sustainability, this study aims to contribute to the development of eco-friendly, resource-efficient concrete for modern construction applications.

II. LITERATURE REVIEW

Previous studies show that industrial by-products such as fly ash, GGBS, steel slag and coal bottom ash (CBA) can effectively replace conventional materials in concrete. Researchers have reported improvements in strength, durability and microstructure when these materials are used in optimum proportions. CBA has been identified as a viable replacement for fine aggregates due to its granular nature, while blast furnace slag (BFS) and steel slag have shown good potential as substitutes for coarse aggregates, offering enhanced mechanical properties and improved sustainability.

However, most existing research focuses on using these materials individually and very few studies have examined the combined effects of replacing both fine and coarse aggregates simultaneously. There is also limited data on long-term durability, optimized replacement levels and sustainability benefits when these industrial by-products are used together in concrete. This gap justifies the need for the present study, which aims to explore the combined performance of CBA and BFS in producing eco-friendly and structurally reliable concrete.

III. OBJECTIVES

a. To evaluate the physical and chemical of Coal Bottom Ash (CBA) and Blast Furnace Slag (BFS) to determine their suitability as alternative fine and coarse aggregates in concrete.
b. To develop and optimize concrete mix proportions incorporating varying replacement levels of CBA and BFS and to identify the most effective combination for achieving desired workability and strength.
c. To assess the impact of CBA and BFS on the fresh and hardened properties of M25 grade concrete, including workability, compressive strength, split tensile strength and flexural strength.
d. To investigate the durability performance of concrete containing these steel industry by-products through tests such as water absorption, acid resistance and sulphate/chloride attack.
e. To promote sustainable construction practices by quantifying the environmental benefits of replacing natural aggregates with industrial by-products, thereby reducing resource consumption and waste disposal burdens.

IV. METHODOLOGY

The experimental program was carried out in several systematic stages to assess the suitability of Coal Bottom Ash (CBA) and Blast Furnace Slag (BFS) as partial replacements for fine and coarse aggregates in M25 grade concrete. All materials—cement, manufactured sand, crushed granite, CBA, and BFS—were procured from reliable local sources and tested as per IS standards. Preliminary characterization tests such as sieve analysis, specific gravity, water absorption, bulk density, and chemical composition (where applicable) were performed in accordance with IS 2386 and IS 4031 to ensure conformity with concrete requirements.

Concrete mix design was prepared as per IS 10262:2019 and IS 456:2000. A control mix (0% replacement) was developed first, followed by four trial mixes incorporating varying percentages of CBA and BFS (10%, 20%, 25%, and 40%). Each mix was proportioned by adjusting fine and coarse aggregates based on the designated replacement ratio while keeping cement content and water–cement ratio constant. Fresh concrete properties were evaluated using the slump test and compaction factor test in accordance with IS 1199.

Standard concrete specimens (cubes, cylinders, and prisms) were cast for all mixes and compacted using a vibrating table. After 24 hours, specimens were demolded and transferred to a curing tank maintained at 27 ± 2°C as per IS 516. Mechanical tests—including compressive strength, split tensile strength, and flexural strength—were conducted at 7, 14, and 28 days. Durability-related tests such as water absorption, acid resistance, sulphate resistance, and chloride penetration were also performed following relevant IS codes to assess long-term performance. All test results were compared against the control mix to determine the effect of increasing replacement levels and to identify the optimum sustainable mix.

4.1 MATERIALS USED

- Cement: Ordinary Portland Cement (OPC) of 53 grade was used throughout the study. The cement conformed to IS 12269 specifications and was tested for consistency, fineness, initial and final setting time, and compressive strength to ensure its suitability for concrete production.
- Fine Aggregates: Manufactured Sand (M-Sand) was used as the primary fine aggregate. It was clean, angular, well-graded, and free from harmful impurities. Sieve analysis, specific gravity, and water absorption tests were performed as per IS 2386 to confirm grading requirements.
- Coal Bottom Ash (CBA): CBA obtained from a thermal power plant was used as a partial replacement for fine aggregates. The material was granular, porous, and lightweight. It was tested for particle size distribution, specific gravity, water absorption, and chemical composition to ensure compatibility with concrete.
- Coarse Aggregates: Crushed granite aggregates of 20 mm and 12.5 mm nominal sizes were used. The aggregates were tested for impact value, crushing value, specific gravity, flakiness index, and water absorption in accordance with IS 2386 to meet concrete quality standards.
- Blast Furnace Slag (BFS): Air-cooled Blast Furnace Slag sourced from a steel plant was used as a partial replacement for coarse aggregates. Its physical properties such as hardness, specific gravity, and water absorption were evaluated to ensure its performance in concrete mixes.
- Water: Clean potable water free from oils, acids, organic matter, or salts was used for both mixing and curing. The water met the requirements specified in IS 456:2000.

4.2 TRIAL MIXES

Trial Mix	Description	Cement	Fine Aggregates		Coarse Aggregates	
			Sand	CBA	Crushed Stone	BFS
M1	Conventional Concrete Mix	100%	100 %	00 %	100%	00 %
M2	Optimized Mix based On Literature	100%	75%	25 %	75%	25 %
M3	Low Replacement Mix	100%	90%	10 %	90%	10 %
M4	Moderate Replacement Mix	100%	80%	20 %	80%	20 %
M5	High Replacement Mix	100%	60%	40 %	60%	40 %

V. RESULTS AND DISCUSSIONS

5.1 COMPRESSIVE STRENGTH TEST RESULTS

5.1.1 7 - Day Compressive Strength for Trial Mixes with Partial Replacement of Fine and Coarse Aggregates.

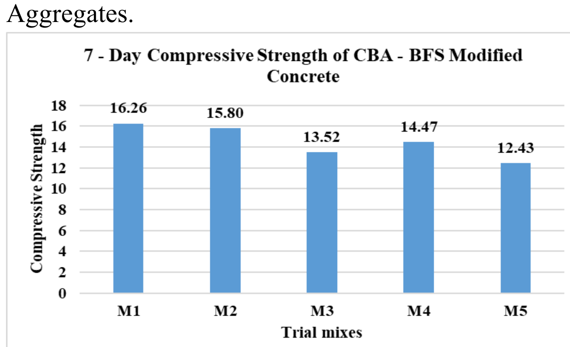

Fig 1: 7 - Day Compressive Strength of CBA - BFS Modified Concrete

The graph shows the 7-day compressive strength of concrete for different trial mixes with partial replacement of fine and coarse aggregates using CBA and BFS. The control mix (M1) achieved the highest early strength, while M2 also performed well with only a slight reduction, indicating that 25% replacement is still effective. Mixes M3 and M4 showed moderate strengths, reflecting the influence of lower and medium replacement levels. The strength decreased further for M5, which had the highest replacement (40%). Overall, the results show that lower to moderate replacement levels provide acceptable early-age strength, while higher replacements reduce performance.

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5.1.2 14 - Day Compressive Strength for Trial Mixes with Partial Replacement of Fine and Coarse Aggregates.

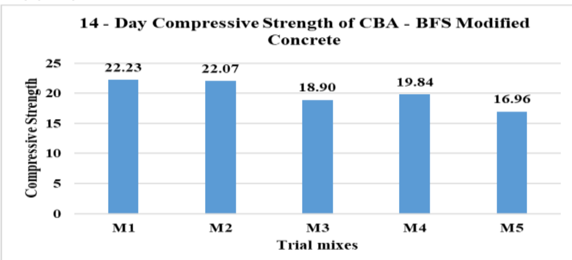

Fig 2: 14 - Day Compressive Strength of CBA - BFS Modified Concrete

The 14-day compressive strength results show a trend similar to the 7-day performance. The control mix (M1) recorded the highest strength, while M2 closely followed with a value almost equal to the conventional mix, indicating that a 25% replacement level still provides good strength gain. Mixes M3 and M4 exhibited moderate strengths, reflecting the effect of lower and medium replacement percentages. The strength reduction was more noticeable in M5 due to the high (40%) replacement of aggregates. Overall, the results indicate that low to moderate replacement levels support satisfactory strength development up to 14 days.

5.1.3 28 - Day Compressive Strength for Trial Mixes with Partial Replacement of Fine and Coarse Aggregates.

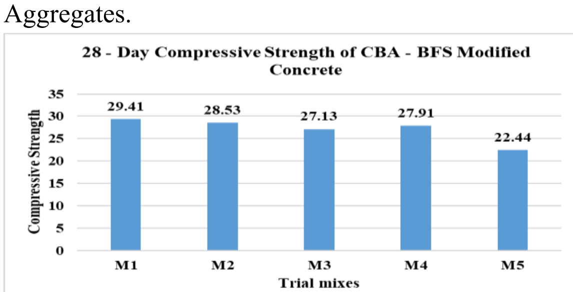

Fig 3: 28 - Day Compressive Strength of CBA - BFS Modified Concrete

The 28-day compressive strength results show that all mixes exhibited significant strength gain with curing age. The control mix (M1) achieved the highest strength, while M2 followed closely, indicating that a 25% replacement of aggregates with CBA and BFS still maintains good long-term performance. Mixes M3 and M4 also recorded satisfactory strengths, remaining close to the conventional mix despite the increased replacement levels. The strength of M5 was the lowest due to the high (40%) replacement percentage, which affects the overall density and bonding of the concrete. Overall, the results confirm that low to moderate replacement levels (10–25%) provide acceptable 28-day strength, while higher replacements reduce performance.

5.2 SPLIT TENSILE STRENGTH TEST RESULTS

5.2.1 7 - Day Split Tensile Strength for Trial Mixes with Partial Replacement of Fine and Coarse Aggregates.

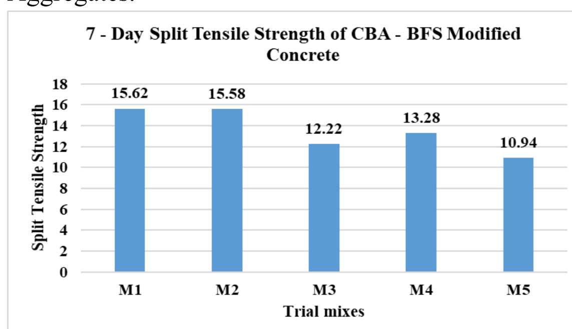

Fig 4: 7 - Day Split Tensile Strength of CBA - BFS Modified Concrete

The 7-day split tensile strength results show that the control mix (M1) achieved the highest value, with M2 closely matching it, indicating that a 25% replacement of aggregates with CBA and BFS does not significantly reduce early tensile strength. Mixes M3 and M4 showed moderate strength values, reflecting the influence of 10% and 20% replacement levels. The lowest strength was recorded for M5, which contained the highest replacement (40%), resulting in reduced bonding and tensile resistance. Overall, lower to moderate replacement levels provide acceptable early-age tensile strength, while higher replacements lead to noticeable reductions.

5.2.2 14 - Day Split Tensile Strength for Trial Mixes with Partial Replacement of Fine and Coarse Aggregates.

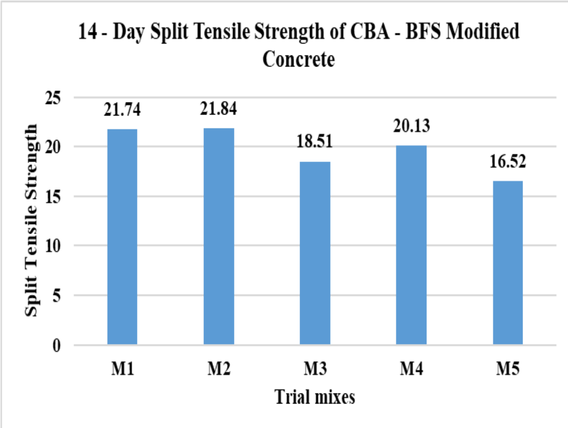

Fig 5: 14 - Day Split Tensile Strength of CBA - BFS Modified Concrete

The 14-day split tensile strength results show that M1 and M2 recorded the highest values, indicating that a 25% replacement of aggregates with CBA and BFS still provides tensile strength comparable to the control mix. Mix M3 and M4 showed moderate strength development, demonstrating that 10–20% replacement levels maintain acceptable performance. The lowest strength was observed in M5 due to the higher 40% replacement, which affects the internal bonding of the concrete. Overall, the results confirm that low to moderate replacement levels support good tensile strength gain up to 14 days, while higher replacements reduce performance.

5.2.3 28 - Day Split Tensile Strength for Trial Mixes with Partial Replacement of Fine and Coarse Aggregates.

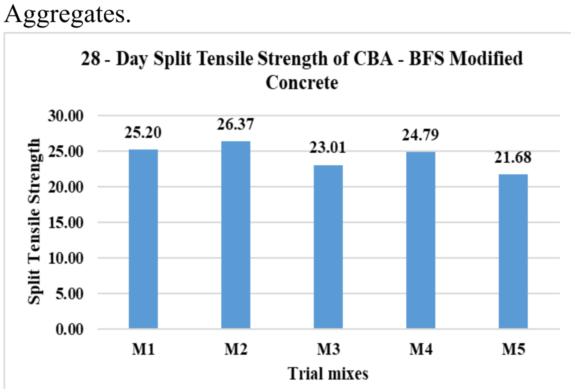

Fig 6: 28 - Day Split Tensile Strength of CBA - BFS Modified Concrete

The 28-day split tensile strength results show that M2 achieved the highest value among all mixes, indicating that a 25% replacement of aggregates with CBA and BFS performs even better than the control mix at later ages. M1 also shows strong performance, while M3 and M4 recorded moderate strengths, demonstrating that 10–20% replacements still maintain good tensile capacity. Mix M5 showed the lowest strength due to the higher 40% replacement, which affects overall bonding and matrix density. Overall, the results confirm that moderate replacement levels (especially 25%) support strong long-term tensile performance, whereas higher levels reduce strength.

5.3 FLEXURAL STRENGTH TEST RESULTS

5.3.1 14 - Day Flexural Strength for Trial Mixes with Partial Replacement of Fine and Coarse Aggregates.

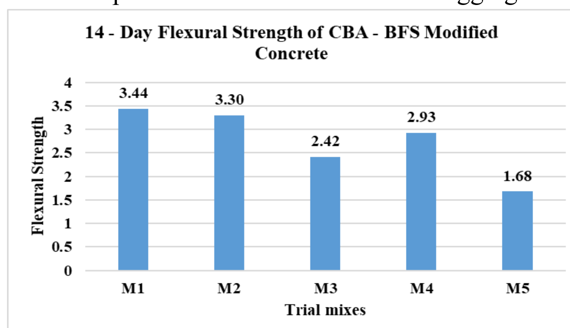

Fig 7: 14 - Day Flexural Strength of CBA - BFS Modified Concrete

The 14-day flexural strength results show that the control mix (M1) achieved the highest value, followed closely by M2, indicating that a 25% replacement of aggregates with CBA and BFS still provides strong flexural performance. Mixes M3 and M4 recorded moderate strengths, showing that 10–20% replacement levels maintain acceptable bending resistance. The lowest flexural strength was seen in M5 due to the high 40% replacement, which reduces the overall stiffness and bonding of the concrete. Overall, the results suggest that lower to moderate replacement levels support good flexural Behaviour, while higher replacements lead to significant strength reduction.

4.3.2 28 - Day Flexural Strength for Trial Mixes with Partial Replacement of Fine and Coarse Aggregates.

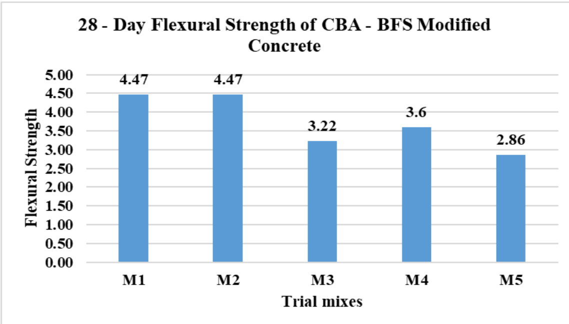

Fig 8: 28 - Day Flexural Strength of CBA - BFS Modified Concrete

The 28-day flexural strength results show that both M1 (control mix) and M2 achieved the highest and equal strength values, indicating that a 25% replacement of aggregates with CBA and BFS performs on par with conventional concrete at later ages. Mix M3 and M4 recorded moderate strengths, showing that 10–20% replacement levels still support good flexural behavior. The lowest strength was observed in M5 due to the high 40% replacement, which affects the stiffness and bending resistance of the concrete. Overall, the results confirm that moderate replacement levels maintain strong flexural performance, while higher replacements lead to reduced strength.

5.4 ACID ATTACK TEST RESULTS

5.4.1 28 - Day Acid Attack Test Results for Trial Mixes with Partial Replacement of Fine and Coarse Aggregates.

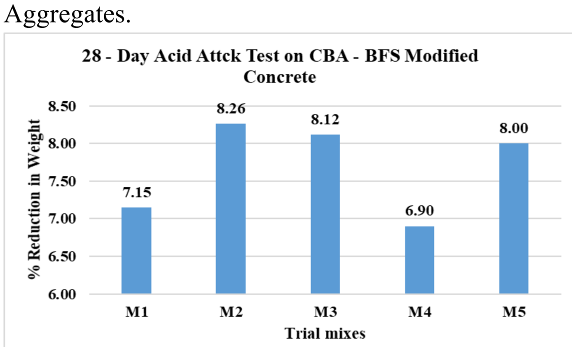

Fig 9: 28 - Day Acid Attack Test on CBA - BFS Modified Concrete

The 28-day acid attack results show that all mixes experienced a reduction in weight after immersion, indicating the effect of acidic exposure on the concrete matrix. M4 recorded the lowest weight reduction (6.90%), suggesting better resistance compared to the other mixes. M1 also performed moderately well with a 7.15% reduction. Mixes M2, M3, and M5 exhibited higher weight losses between 8.00% and 8.26%, showing greater deterioration under acidic conditions. Overall, the results indicate that moderate replacement levels offer slightly better acid resistance, while higher replacement percentages tend to reduce durability.

5.5 WATER ABSORPTION TEST RESULTS

5.5.1 28 - Day Water Absorption Test Results for Trial Mixes with Partial Replacement of Fine and Coarse Aggregates.

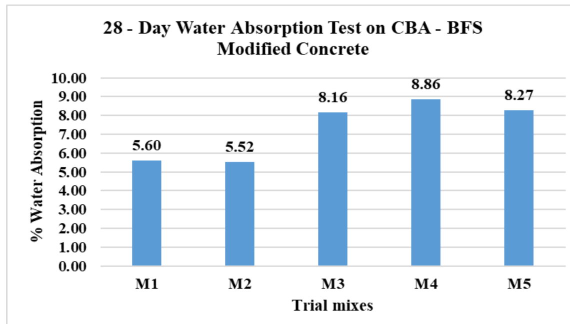

Fig 9: 28 - Day Water Absorption Test on CBA - BFS Modified Concrete

The 28-day water absorption results show that the control mix (M1) and M2 recorded the lowest absorption values, indicating a denser concrete matrix with fewer interconnected pores. Mixes M3, M4, and M5 exhibited higher absorption levels, ranging from 8.16% to 8.86%, which reflects increased porosity due to the higher replacement of aggregates with CBA and BFS. The highest absorption was observed in M4, suggesting greater water ingress compared to other mixes. Overall, the results indicate that lower replacement levels (up to 25%) maintain better resistance to water penetration, while higher replacements lead to increased absorption and reduced durability.

VI. CONCLUSIONS

This study evaluated the performance of concrete incorporating Coal Bottom Ash (CBA) as a partial replacement for fine aggregates and Blast Furnace Slag (BFS) as a partial replacement for coarse aggregates. Based on the experimental results, the control mix (M1) consistently achieved the highest mechanical strengths, while the mix containing 25% replacement of both fine and coarse aggregates (M2) performed closest to the conventional concrete across all tests. The 10% and 20% replacement mixes (M3 and M4) also exhibited satisfactory compressive, split tensile, and flexural strengths, confirming that low to moderate replacement levels do not significantly compromise structural performance. However, higher replacement levels (M5: 40%) resulted in noticeable reductions in strength due to increased porosity and weaker aggregate bonding.

Durability results showed that mixes with lower to moderate replacements demonstrated better resistance to acid attack and lower water absorption compared to higher replacement levels. M2 and M4, in particular, exhibited balanced behavior, indicating improved microstructural stability while still achieving material savings. The higher absorption and weight loss seen in M5 further confirm the limitations of excessive replacement.

Overall, the findings indicate that partial replacement of natural aggregates with CBA and BFS up to 25% is feasible for producing sustainable concrete with acceptable mechanical and durability performance. This approach contributes to waste utilization, conservation of natural resources, and improved environmental sustainability, meeting the core objectives of the study. Further research involving microstructural analysis and long-term durability evaluation is recommended to strengthen the practical application of these materials.

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