

# Utilization of Waste Materials in Concrete for the Construction of Rigid Pavement

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## Abstract:

Rapid growth in infrastructure development across the globe has led to an exponential increase in cement consumption, posing serious environmental and health concerns. The present study investigates the feasibility of partially replacing Ordinary Portland Cement (OPC) in M40-grade concrete with three industrial waste materials: Ground Granulated Blast Furnace Slag (GGBS), Ladle Furnace Slag (LFS), and Sugarcane Bagasse Ash (SCBA). Concrete specimens were prepared with varying replacement levels ranging from 5% to 50% for individual materials and in combined proportions. Compressive strength was evaluated at 7 and 28 days of curing, while split tensile strength was recorded at 28 days. Results indicate that 10% GGBS replacement yields a 12% gain in 28-day compressive strength, 15% LFS replacement achieves an optimum compressive strength of 44.89 MPa, and 15% SCBA replacement delivers the highest 28-day compressive strength of 48.67 MPa. A combination of 5% GGBS, 10% LFS, and 15% SCBA in a ternary blend exhibited a compressive strength of 46.50 MPa, demonstrating that up to 30% of cement can be substituted without compromising structural performance. Furthermore, an 18% reduction in concrete production cost was achieved through this green concrete approach. The outcomes of this research offer a sustainable, economical, and environment-friendly pathway for rigid pavement construction.

**Keywords:** Rigid Pavement, Waste Material Utilization, GGBS, Ladle Furnace Slag, Sugarcane Bagasse Ash, Green Concrete, Compressive Strength, Sustainable Construction

## I. INTRODUCTION

Infrastructure development forms the backbone of economic progress in any nation. Roads, bridges, airports, and other civil structures rely heavily on concrete as the primary construction material, with cement serving as its essential binding component. The global cement industry currently produces over four billion tonnes annually, and India alone witnesses a production range of 0.83 to 43.88 million tonnes per year from various manufacturers (Indian Bureau of Mines, 2015). India's cement consumption is growing at approximately 10% annually, making it the second-largest consumer of cement worldwide, surpassed only by water.

Despite its indispensability, cement manufacturing is associated with significant environmental hazards. The production process emits greenhouse gases such as CO<sub>2</sub>, NO<sub>2</sub>, SO<sub>2</sub>, CO, H<sub>2</sub>S, and volatile organic

compounds (VOCs), contributing to global warming, ozone depletion, acid rain, and biodiversity loss. According to the International Energy Agency, India's cement production is projected to exceed 2,000 million tonnes by 2050 if current trends continue. Cement dust also poses grave occupational health risks to factory workers and nearby residents, leading to respiratory diseases including chronic bronchitis, asthma, emphysema, lung cancer, and tuberculosis.

In parallel, construction and demolition (C&D) activities generate enormous volumes of industrial waste. India produces approximately 0.10 to 5.14 million tonnes of C&D waste annually, encompassing materials such as soil, sand, brick, concrete debris, metals, bitumen, and wood. The indiscriminate disposal of this waste compounds environmental pollution and creates public health issues.

Against this backdrop, the partial substitution of cement with industrial by-products and agricultural waste materials has emerged as a viable strategy to reduce carbon emissions, lower construction costs, and improve the mechanical performance of concrete. Materials such as GGBS, LFS, fly ash, silica fume, rice husk ash, and SCBA possess pozzolanic or cementitious properties that make them suitable candidates for cement replacement.

Rigid pavement, which utilises Portland Cement Concrete (PCC), demands high compressive and flexural strength, durability, and resistance to deformation under traffic loading. The introduction of waste-derived supplementary cementitious materials into rigid pavement concrete thus addresses both sustainability and structural objectives.

The present study focuses on evaluating the mechanical performance of concrete incorporating GGBS, LFS, and SCBA individually as well as in ternary combinations as partial cement replacements, targeting M40-grade concrete for rigid pavement applications. The study further assesses the economic implications of adopting green concrete in highway construction.

## II. LITERATURE REVIEW

A comprehensive review of published research was conducted to understand the behaviour of waste materials as cement substitutes in concrete and pavement applications.

### A. Ground Granulated Blast Furnace Slag (GGBS)

Manjunatha et al. (2014) demonstrated that replacing OPC with up to 50% GGBS in M20-grade concrete resulted in enhanced compressive strength owing to the filling of micro-voids by the finer GGBS particles. Rapid Chloride Penetration Tests (RCPT) confirmed improved durability with increasing GGBS content. Das et al. (2015) showed that GGBS-based concrete in marine environments reduced chloride permeability by 36% compared to conventional concrete. Kuo et al. (2013) reported that pozzolanic reactions in GGBS concrete lead to significant compressive strength gains in the late curing stages. Mehta and Siddique (2018) found that a combination of 85% GGBS and 15% Rice Husk Ash offered optimum compressive strength and permeability resistance.

### B. Ladle Furnace Slag (LFS)

LFS is a by-product of secondary steel refining processes in ladle furnaces. Marinho et al. (2017) reported that LFS contains approximately 88% calcium oxide and calcium magnesium silicates by total mass, making it chemically analogous to cement clinker. Manso et al. (2005) validated the use of LFS in soil-cement mixtures for road paving, citing its time-dependent load-bearing and resilient properties as additional benefits. Raženovic et al. (2011) confirmed through chemical analysis that calcium, silicon,

magnesium, and aluminium oxides constitute more than 92% of LFS, establishing its cementitious suitability.

### C. Sugarcane Bagasse Ash (SCBA)

Amin (2011) established that 20% replacement of OPC with SCBA is optimum, delivering comparable compressive strength, workability, and chloride resistivity. Bahurudeen et al. (2015) attributed SCBA's cementitious activity to the high silica ( $\text{SiO}_2$ ) content, which reacts with calcium hydroxide in cement to form additional calcium silicate hydrate (C-S-H) gel, thereby improving density and durability. Cordeiro et al. (2009) demonstrated that ultrafine grinding of bagasse ash to below 60  $\mu\text{m}$  particle size enables 20% cement replacement without any compromise in compressive strength. Mangi et al. (2017) reported a 12% increase in compressive strength at a 5% SCBA replacement level compared to conventional M20 concrete.

### D. Other Relevant Waste Materials

Mohammadinia et al. (2017) showed that fly ash at 15% improves the strength and stability of reclaimed asphalt pavement and crushed brick aggregates used in flexible pavement bases. Jassim (2017) successfully replaced up to 35% of cement with polyethylene waste. Maddalena et al. (2018) confirmed that silica fume-based concrete achieves 80% of OPC strength while reducing the carbon footprint by 23–55%. Wagih et al. (2012) noted that recycled concrete aggregate (RCA) at 50% replacement exhibits comparable strength to natural aggregate, while complete replacement at 100% results in approximately 18% strength reduction.

## III. MATERIALS AND METHODS

### A. Materials

The study employed the following primary materials:

- 1) Ordinary Portland Cement (OPC):** 53-grade OPC conforming to IS 12269-2013 was used as the base binder material. Normal consistency was determined to be 27%, with initial and final setting times of 27 minutes and 7 hours respectively. Specific gravity was 3.12, and 28-day compressive strength was 42 N/mm<sup>2</sup>.
- 2) Fine Aggregate:** Crushed stone dust conforming to Zone II grading per IS 383:1970 was used in place of river sand, with a specific gravity of 2.74.
- 3) Coarse Aggregate:** Recycled concrete aggregate of maximum size 20 mm was used, with a specific gravity of 2.67, conforming to IS 2386:1963.
- 4) Ground Granulated Blast Furnace Slag (GGBS):** GGBS sourced from the steel industry was used with a chemical composition including 35%  $\text{SiO}_2$ , 13%  $\text{Al}_2\text{O}_3$ , 40%  $\text{CaO}$ , and 8%  $\text{MgO}$ . Its higher  $\text{CaO}$  and  $\text{SiO}_2$  content compared to OPC contributes to secondary pozzolanic reactions.
- 5) Ladle Furnace Slag (LFS):** LFS obtained from secondary steel refining contains 48.37%  $\text{CaO}$ , 15.25%  $\text{MgO}$ , 15%  $\text{SiO}_2$ , and 14.30%  $\text{Al}_2\text{O}_3$ . Its fine particle distribution (20–35% below 75  $\mu\text{m}$ ) enhances its reactivity as a cementitious supplement.
- 6) Sugarcane Bagasse Ash (SCBA):** Agricultural waste ash rich in silica (78.34%  $\text{SiO}_2$ ) with  $\text{Al}_2\text{O}_3$  (8.55%),  $\text{Fe}_2\text{O}_3$  (3.61%), and  $\text{CaO}$  (2.15%) was used. The high  $\text{SiO}_2$  content promotes C-S-H gel formation critical for strength development.

**7) Chemical Admixture:** A superplasticiser was incorporated at 7 kg/m<sup>3</sup> to maintain workability in low water-cement ratio mixes.

### B. Mix Design

Concrete mix design for M40 grade was carried out in accordance with IS 10262:2009 and IS 456:2000. The mix proportions per cubic metre are summarised in Table 1.

**Table 1: Mix Proportions for M40 Grade Concrete (per m<sup>3</sup>)**

Material	Quantity (kg/m <sup>3</sup> )
Ordinary Portland Cement	350
Water	140
Fine Aggregate (Stone Dust)	896
Coarse Aggregate (Recycled)	1140
Chemical Admixture	7

Cement was partially replaced with GGBS, LFS, and SCBA individually at 0%, 5%, 10%, 15%, 20%, 25%, 30%, and 35% for 7-day tests, and extended up to 50% for 28-day evaluation. Ternary combinations were also prepared at cumulative replacement levels of 15% to 30% using combinations such as 5G5L5S (5% GGBS, 5% LFS, 5% SCBA) and 5G10L15S (5% GGBS, 10% LFS, 15% SCBA) for mixed-material optimization.

### C. Specimen Preparation and Testing

Cube specimens of 150 mm × 150 mm × 150 mm were cast for compressive strength testing following IS 516:1959. Cylindrical specimens of 150 mm diameter × 300 mm height were cast for split tensile strength evaluation. All specimens were demoulded after 24 hours and subsequently cured in a water tank at 27 ± 2°C. The Compression Testing Machine (CTM) was used for compressive strength at 7 and 28 days of curing, while the Universal Testing Machine (UTM) was employed for split tensile strength at 28 days. A minimum of three specimens per proportion were tested, and average values were reported.

The following tests on base materials were conducted prior to mix design:

**Normal consistency:** Vicat's apparatus (IS 4031 – Part 4:1988)

**Setting time:** Vicat's needle (IS 4031 – Part 5:1988)

**Specific gravity:** Density bottle method for cement; pycnometer for fine aggregate; wire basket method for coarse aggregate (IS 2386 – Part 3:1963)

**Compressive strength of cement mortar:** 70 mm × 70 mm × 70 mm cubes cured for 3, 7, and 28 days.

#### IV. RESULTS AND ANALYSIS

##### A. Material Properties

The results of material characterisation tests on OPC, fine aggregate, and coarse aggregate are presented in Table 2. All values fall within the permissible limits of relevant Indian Standards, confirming suitability for M40-grade concrete production.

**Table 2: Characterisation of Base Materials**

Property	Result
Normal Consistency of Cement	27%
Initial Setting Time	27 minutes
Final Setting Time	7 hours
Compressive Strength (3 days)	21 N/mm <sup>2</sup>
Compressive Strength (7 days)	30 N/mm <sup>2</sup>
Compressive Strength (28 days)	42 N/mm <sup>2</sup>
Tensile Strength of Cement (3 days)	22 kg/cm <sup>2</sup>
Tensile Strength of Cement (7 days)	27 kg/cm <sup>2</sup>
Specific Gravity – Cement	3.12
Specific Gravity – Fine Aggregate	2.74
Specific Gravity – Coarse Aggregate	2.67

##### B. Compressive Strength – GGBS

Table 3 presents the 28-day average compressive strength of concrete with varying GGBS replacement levels. At 10% replacement, the compressive strength increased by approximately 12% over the control mix (41.56 MPa), reaching 45.29 MPa. The strength gradually declined at higher replacement percentages. A 50% GGBS replacement still retained a compressive strength of 27.97 MPa, which exceeds the minimum threshold for M30 grade concrete, suggesting extended applicability.

**Table 3: 28-Day Compressive Strength – GGBS Replacement**

GGBS %	Cast I (MPa)	Cast II (MPa)	Cast III (MPa)	Average (MPa)
0%	40.65	42.17	41.87	41.56
5%	42.77	44.09	46.52	44.46
10%	43.12	45.90	46.86	45.29
15%	42.57	40.66	40.73	41.32
20%	39.17	40.34	40.18	39.89

25%	38.97	38.15	38.74	38.62
30%	37.41	35.80	36.85	36.68
35%	34.00	35.80	30.50	33.43
40%	31.67	33.39	32.80	32.62
45%	32.45	30.22	30.54	31.07
50%	29.41	28.32	26.19	27.97

### C. Compressive Strength – LFS

Table 4 presents the 28-day compressive strength results for LFS replacement. A peak compressive strength of 44.89 MPa was recorded at 15% LFS substitution. The strength remained above the control value (41.56 MPa) up to 20% replacement, beyond which it declined steadily. At 50% LFS replacement, the compressive strength fell to 26.60 MPa, marking the lower boundary of structural usability for highway pavements.

**Table 4: 28-Day Compressive Strength – LFS Replacement**

LFS %	Cast I (MPa)	Cast II (MPa)	Cast III (MPa)	Average (MPa)
0%	40.65	42.17	41.87	41.56
5%	43.15	40.97	42.65	42.25
10%	42.55	44.73	45.34	44.20
15%	46.87	44.17	43.65	44.89
20%	42.96	40.19	40.74	41.29
25%	39.18	39.52	38.15	38.95
30%	37.50	37.70	36.24	37.14
35%	35.14	33.46	32.71	33.77
40%	31.74	34.83	30.27	32.28
45%	29.85	28.21	26.91	28.32
50%	27.77	25.34	26.69	26.60

### D. Compressive Strength – SCBA

Among the three materials evaluated individually, SCBA at 15% replacement yielded the highest 28-day compressive strength of 48.67 MPa, representing a 17.1% improvement over the control mix. This enhancement is attributed to the high reactive silica content (78.34%) in SCBA, which accelerates secondary pozzolanic reactions and produces additional C-S-H gel, densifying the concrete

microstructure. Strength remained above the control value up to 20% replacement (42.10 MPa). Table 5 summarises these findings.

**Table 5: 28-Day Compressive Strength – SCBA Replacement**

SCBA %	Cast I (MPa)	Cast II (MPa)	Cast III (MPa)	Average (MPa)
0%	40.65	42.17	41.87	41.56
5%	45.91	43.56	45.44	44.97
10%	47.61	46.43	46.59	46.87
15%	48.43	49.77	47.83	48.67
20%	43.23	42.48	40.59	42.10
25%	38.18	39.11	38.57	38.62
30%	36.59	37.85	36.74	37.06
35%	35.48	35.49	34.79	35.08
40%	33.83	34.83	34.28	34.31
45%	30.85	32.28	31.92	31.68
50%	30.65	30.11	30.44	30.40

**E. Split Tensile Strength – 28 Days**

Table 6 summarises the 28-day split tensile strength of concrete with GGBS, LFS, and SCBA replacements. For GGBS, peak split tensile strength of 3.37 MPa was achieved at 15% replacement, representing an 11.5% gain over the reference concrete (3.02 MPa). LFS exhibited the highest split tensile improvement, reaching 4.06 MPa at 15% replacement, a 34.4% increase over control. SCBA at 10% replacement delivered 3.41 MPa, an improvement of 12.9%. Across all three waste materials, split tensile strength remained higher than or comparable to the control mix for all replacement levels tested, confirming no adverse effect on tensile performance.

**Table 6: 28-Day Split Tensile Strength Comparison**

Replacement %	GGBS (MPa)	LFS (MPa)	SCBA (MPa)
0% (Control)	3.02	3.02	3.02
5%	3.21	3.43	3.16
10%	3.29	3.81	3.41
15%	3.37	4.06	3.38
20%	3.29	3.98	3.29
25%	3.22	3.83	3.26

30%	3.14	3.72	3.21
35%	3.08	3.62	3.10

### F. Ternary Combination Results

Ternary blends using simultaneous partial replacement with GGBS, LFS, and SCBA were evaluated at cumulative replacement levels of 15%, 20%, 25%, and 30%. Table 7 presents selected combination results. The combination designated 5G10L15S (5% GGBS + 10% LFS + 15% SCBA, total 30% replacement) achieved the highest average compressive strength of 46.50 MPa among all ternary blends. Notably, up to 30% cumulative replacement of cement consistently produced compressive strengths above 40 MPa, satisfying M40 grade requirements. This demonstrates excellent synergy between the three materials, wherein GGBS provides micro-void filling, LFS contributes cementitious binding, and SCBA accelerates pozzolanic gel formation.

**Table 7: Compressive Strength of Selected Ternary Combinations (28 days)**

Combination	Description	Average Strength (MPa)
5G5L5S	5% GGBS + 5% LFS + 5% SCBA	44.71
5G5L10S	5% GGBS + 5% LFS + 10% SCBA	45.76
5G10L15S	5% GGBS + 10% LFS + 15% SCBA	46.50
5G15L5S	5% GGBS + 15% LFS + 5% SCBA	44.58
10G10L10S	10% GGBS + 10% LFS + 10% SCBA	43.40
10G15L5S	10% GGBS + 15% LFS + 5% SCBA	42.92
15G5L5S	15% GGBS + 5% LFS + 5% SCBA	41.75

### G. Cost Analysis

An economic analysis was performed comparing conventional concrete with the proposed green concrete mix for 1000 m<sup>3</sup> of pavement construction. The results are presented in Table 8. Since GGBS, LFS, and SCBA are industrial and agricultural by-products generally available at negligible or low procurement cost, replacing 30% of OPC (priced at approximately ₹410 per bag of 50 kg) results in substantial cost savings. The total concrete production cost is reduced from ₹4,960,223 to ₹4,099,223 for 1000 m<sup>3</sup>, representing an 18% cost reduction while maintaining M40 structural performance standards.

**Table 8: Cost Comparison – Conventional vs. Green Concrete (per 1000 m<sup>3</sup>)**

Material	Conventional Cost (₹)	Green Concrete Cost (₹)
Cement	28,70,000	20,09,000
Stone Dust	6,96,889	6,96,889
Coarse Aggregate	13,93,334	13,93,334

GGBS / LFS / SCBA	—	Negligible
Total	49,60,223	40,99,223

## V. DISCUSSION

The experimental outcomes of this study reveal several important trends that merit detailed discussion.

**Effect of GGBS:** The compressive strength enhancement at 5–10% GGBS replacement can be attributed to the latent hydraulic property of GGBS, wherein calcium hydroxide released during cement hydration reacts with GGBS to form additional C-S-H gel. At higher replacement levels (above 15%), the reduced OPC content limits the available calcium hydroxide, slowing secondary hydration and reducing compressive strength. The 50% GGBS replacement still yielded 27.97 MPa, which, while below M40 specifications, satisfies M25 grade requirements and may find application in sub-base concrete layers of pavement systems.

**Effect of LFS:** LFS yielded a maximum split tensile strength improvement of 34.4% at 15% replacement, the highest tensile gain among the three materials. This behaviour is explained by LFS's high CaO content (48.37%), which enables direct cementitious hydration reactions independent of OPC's calcium hydroxide. However, the presence of free CaO and MgO in LFS can cause expansive reactions at high replacement levels, leading to micro-cracking and strength reduction beyond 20% substitution. The use of aged or autoclave-treated LFS could potentially mitigate this concern in future studies.

**Effect of SCBA:** SCBA demonstrated the most significant compressive strength improvement (48.67 MPa at 15%), primarily due to its exceptionally high reactive silica content (78.34%). The fine amorphous SiO<sub>2</sub> particles react rapidly with calcium hydroxide to generate dense C-S-H gel networks, refining pore structures and reducing permeability. The strength decrease at 20% SCBA replacement indicates a dilution effect where excess SCBA displaces too much OPC, limiting calcium hydroxide availability for pozzolanic reactions. The results align closely with findings by Bahurudeen et al. (2015) and Amin (2011).

**Ternary Combination Effect:** The synergistic action of GGBS (pore-filling), LFS (cementitious binding), and SCBA (pozzolanic reaction) in ternary blends produced compressive strengths consistently above 40 MPa at cumulative replacement levels up to 30%. The combination 5G10L15S at 46.50 MPa outperformed single-material replacements at equivalent replacement levels, confirming that ternary blending enhances microstructural densification more effectively than binary or single-material systems. This finding has significant practical implications for the design of sustainable rigid pavement mixes.

**Environmental Implications:** A 30% reduction in cement usage across 1000 m<sup>3</sup> of concrete translates to approximately 105 tonnes of cement saved, corresponding to a reduction of approximately 90–98 tonnes of CO<sub>2</sub> emissions (based on 0.85–0.93 tonne CO<sub>2</sub> per tonne of cement produced). This quantifies the direct environmental benefit of the proposed green concrete approach and aligns with national sustainability objectives under India's environmental regulations.

## VI. CONCLUSION

This study investigated the mechanical performance and economic viability of M40-grade green concrete incorporating GGBS, LFS, and SCBA as partial cement replacements for rigid pavement construction. The following conclusions are drawn:

1. GGBS at 10% replacement increased 28-day compressive strength by 12% (45.29 MPa) compared to the control mix (41.56 MPa), and the optimum individual replacement level is 10–15%.
2. LFS at 15% replacement yielded the optimum 28-day compressive strength of 44.89 MPa, while achieving the highest split tensile improvement (4.06 MPa, a 34.4% gain over control) at the same replacement level.
3. SCBA at 15% replacement delivered the highest compressive strength (48.67 MPa) among all individual materials tested, representing a 17.1% improvement over the control concrete.
4. A ternary combination of 5% GGBS, 10% LFS, and 15% SCBA (total 30% cement replacement) produced an average compressive strength of 46.50 MPa, satisfying M40 grade requirements while maximizing waste material utilization.
5. Split tensile strength remained higher than or comparable to the control concrete across all individual and combined replacement levels tested, confirming no adverse effect on tensile performance.
6. The adoption of green concrete mixes incorporating these waste materials reduces total concrete production cost by approximately 18%, translating to substantial savings in large-scale highway construction projects.
7. A 30% cement reduction in 1000 m<sup>3</sup> of concrete saves approximately 105 tonnes of cement and prevents emission of 90–98 tonnes of CO<sub>2</sub>, contributing meaningfully to environmental sustainability.

## VII. FUTURE SCOPE

Future research may extend this work in several directions. The long-term durability of GGBS–LFS–SCBA green concrete under freeze–thaw cycles, wet–dry exposure, and sulphate attack should be investigated to confirm pavement serviceability in diverse climates. Field trials on actual rigid pavement sections are recommended to validate laboratory findings under realistic traffic and environmental loading conditions. The replacement percentage of waste materials may be pushed toward 80–100% by designing geopolymer or alkali-activated binder systems using these materials. The incorporation of reinforcement in rigid pavement slabs and the evaluation of flexural strength and modulus of rupture are critical additional parameters for full-scale design validation. Additionally, Life Cycle Assessment (LCA) studies quantifying the total environmental and economic impact from raw material extraction through pavement demolition would provide a holistic view of the sustainability gains achieved.

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