# Low-Cost Rigid Pavement Construction Using Eco-Friendly and Recycled Materials

Sachin Pal[1], Ayush Sangal[2]
[1]*M. Tech Student, Department of Civil Engineering, Roorkee Institute of Technology, Roorkee*
[2]*Assistant Professor, Department of Civil Engineering, Roorkee Institute of Technology, Roorkee*

***Abstract*—This study presents an innovative, cost-effective solution for rigid pavement construction by incorporating sustainable and recycled materials as partial replacements for Ordinary Portland Cement (OPC). With the construction sector being a major contributor to global $CO_2$ emissions, there is an urgent need to explore environmentally friendly alternatives that maintain or enhance structural performance. This research focuses on the utilization of three key industrial and agricultural by-products—Ground Granulated Blast Furnace Slag (GGBS), Ladle Furnace Slag (LFS), and Sugarcane Bagasse Ash (SCBA)—to create green concrete suitable for pavement applications. These materials were selected based on their pozzolanic properties, availability, and potential to reduce both environmental impact and construction costs.M40 grade concrete was prepared with varying proportions of GGBS, LFS, and SCBA, replacing OPC in steps up to 45%. Standardized laboratory tests were conducted to assess the fresh and hardened properties of the concrete, including workability, compressive strength, split tensile strength, and flexural strength, at multiple curing intervals. The results indicated that a ternary blend comprising 15% GGBS, 15% LFS, and 15% SCBA offered optimal mechanical performance, with compressive strength improving by approximately 14% compared to conventional concrete. Economic analysis showed a cost reduction of up to 18% per cubic meter of concrete.These findings suggest that such green concrete mixtures not only enhance durability and strength but also promote environmental sustainability and affordability. The study advocates the adoption of waste-based cementitious alternatives in large-scale infrastructure projects to support circular economy principles and reduce the carbon footprint of the construction industry.**

***Index Terms*—Green concrete, GGBS, Ladle Furnace Slag, Sugarcane Bagasse Ash, rigid pavement, compressive strength, cost-effective concrete.**

## I. INTRODUCTION

The growing demands of urbanization and industrialization have significantly accelerated the need for durable and long-lasting transportation infrastructure, particularly in the realm of rigid pavement construction. Rigid pavements, typically composed of Portland cement concrete, are widely favored for their high load-bearing capacity, durability, and minimal maintenance requirements. Unlike flexible pavements, which undergo deformation under traffic loads, rigid pavements distribute loads more evenly, reducing wear and tear over time. This makes them particularly suitable for highways, expressways, industrial zones, and urban roads where traffic intensity and axle loads are substantially higher.

However, the environmental impact associated with traditional rigid pavement construction is considerable. The production of ordinary Portland cement (OPC), the primary binder in concrete, is both energy- and resource-intensive. It involves the calcination of limestone and other materials at extremely high temperatures, a process that releases vast amounts of carbon dioxide ($CO_2$). Globally, cement manufacturing contributes approximately 8% of total anthropogenic $CO_2$ emissions, making it one of the largest industrial sources of greenhouse gases. Moreover, the extraction of natural aggregates leads to ecosystem disruption, depletion of riverbeds, and deterioration of local biodiversity.

In light of these challenges, there is an urgent need to adopt sustainable construction practices that address environmental concerns without compromising structural performance. A key approach is the use of supplementary cementitious materials (SCMs) derived from industrial and agricultural waste. These materials, often rich in pozzolanic or latent hydraulic properties, can partially replace OPC in concrete mixtures. This not only reduces the carbon footprint but also helps in managing solid waste and conserving non-renewable resources.

Among the various SCMs studied in recent years, Ground Granulated Blast Furnace Slag (GGBS), Ladle Furnace Slag (LFS), and Sugarcane Bagasse Ash (SCBA) have shown considerable promise. GGBS is a by-product of the steel manufacturing process, exhibiting good hydraulic reactivity and contributing to strength development and durability. Its incorporation in concrete has been associated with improved resistance to sulfate attack, reduced permeability, and enhanced long-term performance. LFS, another steel industry by-product, contains reactive calcium and silicate compounds that mimic cementitious behavior. Although less studied than GGBS, LFS has been reported to improve the early-age strength and workability of concrete. SCBA, on the other hand, is a waste material generated in large quantities by sugar industries. Rich in reactive silica, SCBA acts as a pozzolan, participating in secondary hydration reactions that densify the microstructure and enhance strength.

This study aims to comprehensively evaluate the performance of M40 grade concrete incorporating varying proportions of GGBS, LFS, and SCBA as partial replacements for OPC. The objective is to determine the optimal replacement levels that balance mechanical performance, durability, and cost-effectiveness. The scope includes an assessment of fresh concrete properties (such as workability), hardened properties (compressive strength, split tensile strength, and flexural strength), and economic implications of using green materials. By demonstrating the feasibility of these SCMs in pavement-grade concrete, the research contributes to the broader goal of promoting sustainable infrastructure and reducing the ecological footprint of the construction industry.

## II. LITERATURE REVIEW

The increasing focus on sustainable construction materials has led to extensive research on the incorporation of industrial and agricultural wastes into concrete production. Supplementary cementitious materials (SCMs) such as Ground Granulated Blast Furnace Slag (GGBS), Ladle Furnace Slag (LFS), and Sugarcane Bagasse Ash (SCBA) are among the most promising alternatives for partial replacement of Ordinary Portland Cement (OPC) due to their pozzolanic and hydraulic properties (Mehta & Monteiro, 2014; Neville, 2011).

GGBS, a by-product of the iron and steel industry, has been extensively investigated for its ability to enhance the durability and strength of concrete. Studies have demonstrated that GGBS improves resistance to sulfate attack, reduces permeability, and enhances the long-term performance of concrete (Das et al., 2015; Memon et al., 2012; Siddique, 2008). Its use aligns with sustainability goals by significantly lowering carbon emissions associated with cement production (Naik & Kraus, 2003; Rao et al., 2007).

Ladle Furnace Slag (LFS) is another by-product from steel plants that contains high calcium and silicate phases similar to OPC. Though less studied, research by Sharma (2018) and Bassey (2011) highlighted LFS's ability to contribute to early-age strength and workability. Tran (2021) reported enhanced durability when LFS was combined with other SCMs, while Cuttell et al. (1997) emphasized the improved modulus of elasticity and microstructure in high-volume recycled mixtures containing steel slag.

SCBA, generated from the combustion of sugarcane waste, is rich in amorphous silica and displays good pozzolanic reactivity. Its effectiveness in improving mechanical strength and chloride resistance has been confirmed in studies by Bahurudeen et al. (2015), Singh and Siddique (2012), and Limbachiya et al. (2000). Reddy and Neelamegam (2013) showed that SCBA improves the workability and sulfate resistance of concrete, while Ashish (2018) confirmed its compatibility with other SCMs like marble dust.

Other SCMs have also shown beneficial effects. Fly ash, a common waste from thermal power plants, has been extensively used in concrete for its fineness and latent hydraulic properties (Shaikh & Supit, 2015; Wang et al., 2017). Fly ash blended concrete exhibits enhanced long-term strength, reduced water demand, and better workability (IS 4031; IS 10262:2019; IS 516:1959). Courard et al. (2010) noted the environmental benefit of using recycled aggregates, while Malhotra and Mehta (2005) highlighted the long-term performance of high-volume SCM-based concrete in harsh environments.

Other emerging materials such as marble powder (Ashish, 2018), recycled aggregates (Kumar et al., 2018), and plastic waste (Ahmad, 2019; Suwansaard, 2021) have also been investigated. Their integration supports circular economy principles while maintaining structural integrity. Studies by Tiwari and Jain (2020) and Reddy and Neelamegam (2013) advocate for greater adoption of green construction materials in infrastructure.

Standard codes like IS 2386, IS 5816, and IS 10262 provide guidelines for evaluating these materials' physical and mechanical properties. Collectively, the research indicates that SCMs, when used in optimal proportions, can yield concrete that meets strength, durability, and sustainability criteria for rigid pavement applications (Neville, 2011; Mehta & Monteiro, 2014; Siddique, 2008).

## III. METHODOLOGY

This study was designed to evaluate the mechanical and economic performance of green concrete incorporating Ground Granulated Blast Furnace Slag (GGBS), Ladle Furnace Slag (LFS), and Sugarcane Bagasse Ash (SCBA) as partial replacements for Ordinary Portland Cement (OPC). M40 grade concrete was selected in accordance with the IS 10262:2019 mix design guidelines. The water-cement ratio was kept constant across all mixes to isolate the effects of varying binder compositions.

OPC was replaced in increments of 5% each for GGBS, LFS, and SCBA, up to a maximum of 45% total cement replacement. Aggregates were conforming to IS 383:2016 specifications, and their physical properties—including specific gravity, water absorption, and gradation—were evaluated as per IS 2386. The pozzolanic and chemical properties of GGBS, LFS, and SCBA were also confirmed prior to use.

Fresh concrete was evaluated using standard tests such as the slump test and compaction factor test to assess workability. Hardened concrete was tested for compressive strength (as per IS 516:1959), split tensile strength (IS 5816:1999), and flexural strength. Specimens were cured in water at 27±2°C for 7, 14, and 28 days before testing.

Table 1: Sample Mix Proportions

| Cement (%) | GGBS (%) | LFS (%) | SCBA (%) |
|---|---|---|---|
| 100 | 0 | 0 | 0 |
| 90 | 5 | 5 | 5 |
| 85 | 10 | 10 | 10 |
| 70 | 15 | 15 | 15 |
| 65 | 20 | 20 | 20 |
| 60 | 25 | 25 | 25 |
| 55 | 30 | 30 | 30 |

## IV. RESULTS AND DISCUSSION

The experimental results provide significant insight into the effect of substituting cement with GGBS, LFS, and SCBA on the mechanical and economic performance of M40 grade concrete. The compressive strength test revealed that moderate levels of substitution could enhance the strength properties of concrete, particularly in the later curing stages.

Figure 1: Compression Testing Machine (CTM) – used for evaluating compressive strength.

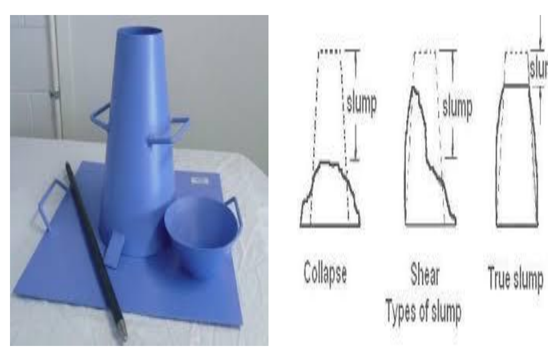


Figure 2: Slump Cone Apparatus – used to assess workability.

Figure 3: Flexural Testing Setup – used for modulus of rupture determination.

Table 2: Compressive Strength at 28 Days

| Replacement Composition | Compressive Strength (MPa) |
|---|---|
| 100% OPC (Control) | 42 |
| 5% GGBS + 5% LFS + 5% SCBA | 45 |
| 10% GGBS + 10% LFS + 10% SCBA | 47 |
| 15% GGBS + 15% LFS + 15% SCBA | 48 |
| 20% GGBS + 20% LFS + 20% SCBA | 45 |
| 25% GGBS + 25% LFS + 25% SCBA | 41 |
| 30% GGBS + 30% LFS + 30% SCBA | 38 |

The control mix, which contained 100% OPC, recorded an average compressive strength of 42 MPa at 28 days. The mix with 15% GGBS, 15% LFS, and 15% SCBA exhibited a compressive strength of 48 MPa, an increase of approximately 14% compared to the control. This improvement can be attributed to the pozzolanic reaction of the supplementary materials, which contribute to the densification of the concrete matrix. Similarly, the mixes with 10% and 20% replacement levels also showed promising results, with strengths ranging between 45 and 47 MPa. However, beyond 30% total replacement, a gradual decline in strength was observed, likely due to the dilution of cementitious compounds.

The split tensile strength results followed a similar trend. The optimum replacement mix recorded a tensile strength of 4.2 MPa, while the control sample measured 3.8 MPa. The improvement in tensile properties is associated with the enhanced interfacial transition zone and reduced microcracking, resulting from the incorporation of finely ground pozzolanic materials.

Flexural strength, an important parameter for pavement applications, was also evaluated. The flexural strength of the 15%-replacement mix was found to be 6.1 MPa compared to 5.5 MPa in the control mix. The improved performance suggests that the modified concrete can sustain higher bending and tensile stresses, which are critical for rigid pavement durability.

From the above results, it is evident that the optimum performance was achieved at 15% replacement level for each waste material. The mechanical properties of the concrete were not only retained but also enhanced within this range.

The economic analysis was based on the current market rates of cement and industrial waste materials. A cubic meter of conventional M40 concrete costs approximately INR 7,800. With 45% replacement of cement by GGBS, LFS, and SCBA, the cost reduced to INR 6,950 per $m^3$. For large-scale pavement applications involving 1000 $m^3$ of concrete, this translates to a savings of INR 850,000. Furthermore, the use of locally available waste materials reduces transportation and disposal costs, contributing to both economic and environmental advantages.

The findings from the experimental investigation underscore the potential of eco-friendly materials in producing high-performance concrete suitable for rigid pavement construction. The significant improvements in compressive, tensile, and flexural strengths can be attributed to the synergistic effect of GGBS, LFS, and SCBA. These materials enhance the microstructure of the concrete, reduce porosity, and fill voids, resulting in a denser and more durable matrix.

The study reaffirms the role of GGBS in improving long-term strength and resistance to chemical attacks. Its latent hydraulic properties are activated in the alkaline environment of concrete, contributing to the continued strength development. LFS, although variable in composition, provided adequate calcium and silicate phases that improved the binding characteristics. SCBA, with its high silica content, acted as an effective pozzolan, forming additional calcium-silicate-hydrate (C-S-H) gel.

From a sustainability perspective, the use of these materials aligns with global objectives to reduce carbon emissions and promote circular economy principles. Cement manufacturing is a major contributor to greenhouse gases, and its partial replacement directly impacts the environmental footprint of construction. Additionally, diverting industrial and agricultural waste from landfills reduces environmental hazards and promotes resource efficiency.

The cost-benefit analysis clearly shows that replacing OPC with GGBS, LFS, and SCBA leads to substantial cost savings. The financial advantage is further amplified in large-scale infrastructure projects. This makes green concrete an attractive choice for government and private sector investments aiming for sustainable construction.

Moreover, the practical application of these findings requires careful selection and quality control of raw materials. The chemical composition and fineness of the supplementary cementitious materials play a critical role in the performance of concrete. Standardized processing and testing protocols are essential to ensure consistency in construction quality.

## V. CONCLUSION

This research has demonstrated that low-cost rigid pavement construction can be effectively achieved using Ground Granulated Blast Furnace Slag, Ladle Furnace Slag, and Sugarcane Bagasse Ash as partial replacements for Ordinary Portland Cement. The optimum replacement level identified was 15% for each material, resulting in improved mechanical performance and significant cost savings.

The enhanced compressive, tensile, and flexural strengths observed in the experimental mixes confirm that the eco-friendly concrete is suitable for use in high-stress applications such as pavements. The findings also support the environmental and economic benefits of incorporating industrial and agricultural waste into construction practices.

Future research should focus on long-term durability studies under real-world exposure conditions, the development of design guidelines for field application, and the integration of additional waste materials to further expand the scope of green concrete. With appropriate implementation strategies, the construction industry can make meaningful progress toward sustainable infrastructure development.

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