Eco-Friendly Alternatives to Rigid Pavement Construction: Materials, Performance, and Sustainability Assessment

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***Abstract*—The increasing environmental concerns associated with conventional cement production and large-scale waste generation in India necessitate the development of sustainable alternatives for rigid pavement construction. This study investigates the performance of pavement quality concrete (PQC) incorporating supplementary cementitious materials (SCMs) such as fly ash, ground granulated blast furnace slag (GGBS), sugarcane bagasse ash (SCBA), and recycled concrete aggregates (RCA). Five different mix proportions were designed, including a conventional control mix and four sustainable blends with varying levels of cement replacement. Experimental evaluation was carried out through workability, compressive strength, flexural strength, rapid chloride penetration test (RCPT), and drying shrinkage tests. Results indicate that high-volume SCM mixes achieved superior long-term compressive and flexural strengths while significantly improving durability characteristics by reducing chloride permeability and shrinkage. Although early-age strength showed marginal reduction in some blends, all mixes satisfied rigid pavement design requirements. The incorporation of recycled aggregates demonstrated acceptable structural performance with proper mix optimization. Therefore, the findings confirm that sustainable binder systems and recycled materials can effectively reduce cement consumption and environmental impact without compromising pavement performance, thereby supporting circular economy principles and low-carbon infrastructure development in India.**

***Index Terms*—Rigid pavement; Sustainable concrete; Mechanical properties; Recycled aggregates; Supplementary cementitious materials; Life-cycle assessment**

I. INTRODUCTION

Rigid pavements play a critical role in modern transportation infrastructure, particularly in highways, airports, industrial corridors, container terminals, and heavy-duty freight routes. Their structural capacity, durability, and lower maintenance requirements compared to flexible pavements make them a preferred choice for high-traffic and heavy-load applications [1]. Conventional rigid pavements are primarily constructed using Ordinary Portland Cement (OPC) concrete, which provides high compressive strength and long-term serviceability. However, the environmental impact associated with cement production and natural aggregate extraction has raised significant sustainability concerns in recent decades [2].

The cement industry is recognized as one of the largest contributors to anthropogenic carbon dioxide (CO_2) emissions, accounting for approximately 7–8% of global greenhouse gas emissions. The production of clinker the primary component of Portland cement involves high-temperature calcination of limestone, leading to both fuel combustion emissions and process-related CO_2 release [3]. In addition to cement production, rigid pavement construction relies heavily on natural aggregates obtained through quarrying activities. Aggregate extraction causes land degradation, biodiversity loss, dust pollution, and depletion of non-renewable geological resources. With rapid urbanization and infrastructure expansion worldwide, the demand for pavement materials is increasing exponentially, thereby intensifying environmental pressures [4].

Sustainable development principles and international climate commitments have compelled the construction industry to adopt environmentally responsible materials and technologies. In this context, eco-friendly alternatives to conventional rigid pavement materials have gained considerable research and practical attention. The objective is not merely to reduce carbon emissions but also to promote resource efficiency, waste valorization, durability enhancement, and life-cycle performance optimization [5].

One of the most widely adopted strategies to improve sustainability in rigid pavements is the incorporation of Supplementary Cementitious Materials (SCMs). Industrial by-products such as fly ash, ground granulated blast furnace slag (GGBS), silica fume, and metakaolin have demonstrated significant potential in partially replacing Portland cement. These materials exhibit pozzolanic or latent hydraulic properties, reacting with calcium hydroxide to form additional calcium silicate hydrate (C–S–H) gel, thereby refining microstructure and enhancing durability [6]. High-volume fly ash and slag-based concretes have been shown to reduce heat of hydration, improve resistance to sulfate attack, and enhance chloride penetration resistance, making them particularly suitable for pavement applications exposed to aggressive environments.

Agro-industrial residues such as sugarcane bagasse ash (SCBA), rice husk ash (RHA), and palm oil fuel ash (POFA) are also emerging as promising sustainable materials. When properly processed and calcined, these ashes possess high amorphous silica content and fine particle size distribution, enabling effective pozzolanic activity [7]. Their utilization addresses dual sustainability goals by reducing agricultural waste disposal issues and lowering clinker demand in concrete production. Such materials are particularly relevant in developing countries with large agricultural industries [8].

Another significant advancement in eco-friendly rigid pavement construction is the use of recycled concrete aggregates (RCA). Construction and demolition waste constitute a major portion of solid waste globally. Recycling concrete debris into aggregates reduces landfill burden, minimizes environmental degradation caused by quarrying, and conserves natural resources [9]. Although RCA may exhibit slightly higher water absorption and marginally reduced mechanical strength compared to natural aggregates, optimized mix design and surface treatment techniques can mitigate these limitations. The integration of recycled aggregates in pavement-quality concrete represents a major step toward circular economy practices in infrastructure development [10].

Geopolymer concrete represents a transformative alternative to traditional OPC-based systems. Unlike conventional cement hydration, geopolymer binders are formed through alkali activation of aluminosilicate-rich materials such as fly ash or slag. This process significantly reduces or eliminates clinker usage, thereby drastically lowering carbon emissions. Geopolymer concrete has demonstrated excellent mechanical strength, superior resistance to chloride ingress and sulfate attack, and improved thermal stability. Its applicability in rigid pavements has been increasingly investigated, particularly for heavy-duty and industrial pavements where durability is paramount.

In addition to binder modification and aggregate recycling, fiber reinforcement techniques contribute to sustainable rigid pavement systems. Steel fibers, polypropylene fibers, and basalt fibers enhance crack resistance, toughness, and post-cracking load-carrying capacity. Improved crack control extends pavement service life and reduces maintenance frequency, indirectly contributing to environmental sustainability by lowering repair-related emissions and material consumption.

While numerous studies have evaluated individual sustainable materials, there remains a need for comprehensive assessment integrating mechanical performance, durability characteristics, environmental impacts, and implementation feasibility. Pavement systems must not only meet structural and functional requirements but also demonstrate long-term reliability under varying traffic loads and environmental exposures. Therefore, sustainability assessment should include life-cycle analysis (LCA), embodied energy evaluation, and cost-effectiveness studies alongside traditional strength and durability testing.

Recent advancements in performance-based pavement design further emphasize durability indicators such as chloride permeability, freeze-thaw resistance, abrasion resistance, and fatigue performance. Eco-friendly alternatives must be evaluated against these criteria to ensure their suitability for large-scale infrastructure deployment. Furthermore, regional availability of industrial by-products, variability in material properties, and lack of standardized specifications present challenges that must be addressed through systematic research and policy support.

II. RESEARCH SIGNIFICANCE

This research integrates structural performance, durability behavior, and sustainability assessment of eco-friendly rigid pavement materials. It provides comparative insights that assist policymakers, engineers, and researchers in selecting low-carbon alternatives without compromising pavement performance. The study supports sustainable infrastructure development aligned with global climate mitigation goals.

III. MATERIALS AND METHODS

The materials investigated include Portland cement, fly ash, GGBS, SCBA, recycled concrete aggregates, and geopolymer binders. Chemical composition and physical properties were characterized prior to mix design. Concrete mixtures were prepared with replacement levels ranging from 10% to 70% for SCMs and recycled aggregates. Mechanical tests included compressive strength, split tensile strength, and flexural strength. Durability evaluation comprised rapid chloride permeability, water absorption, and sulfate resistance tests. Geopolymer mixes were developed using alkaline activation of aluminosilicate materials. Life-cycle assessment compared embodied energy, carbon emissions, and resource consumption among different systems.

Table 1: Major Cement Groups in India, Installed Capacity and Strategic Position (2025–26)

Rank	Cement Group / Holding Company	Key Brands / Subsidiaries	Installed Capacity (MTPA)*	Market Position	Strategic Developments
1	UltraTech Cement Ltd	UltraTech, India Cements (acquired), Kesoram (acquired assets)	156–160	Market Leader	Aggressive expansion; acquisition-driven growth
2	Adani Cement Group	Ambuja Cement, ACC	93–95	2nd Largest	Rapid capacity expansion; vertical integration strategy
3	Shree Cement Ltd	Shree Cement	51	Large Private Player	Commissioned new clinker and grinding units
4	Dalmia Bharat Ltd	Dalmia Cement	46–47	Growth-Focused Major	Targeting 110–130 MTPA by 2031
5	Nuvoco Vistas Corp.	Nuvoco Cement	25–26	Regional Major	Capacity optimization and regional expansion
6	Ramco Cements Ltd	Ramco Cement	22–23	Southern Market Leader	Expanding to 25 MTPA by 2026
7	JK Cement Ltd	JK Cement	21	Diversified	Targeting 30 MTPA

				Cement & White Cement Player	by 2026
8	Birla Corporation Ltd	MP Birla Cement	20	Established Regional Player	Capacity modernization underway
9	Heidelberg Materials India	Heidelberg Cement	12–13	Mid-tier Producer	Strategic review and consolidation discussions
10	Cement Corporation of India (CCI)	CCI	4	Public Sector	Limited operational units; modernization focus

Table 1 not only reflects the consolidation and expansion trends in India's cement industry but also highlights significant environmental concerns associated with large-scale cement production. With leading companies such as UltraTech Cement and the Adani Cement Group operating capacities exceeding 90–150 MTPA, the cumulative clinker production results in substantial CO_2 emissions, as cement manufacturing is responsible for nearly 8–10% of global greenhouse gas emissions. The scale of expansion plans, particularly aggressive capacity targets by major producers, indicates increasing demand for cement in infrastructure development, which may intensify carbon emissions, energy consumption, limestone extraction, and environmental degradation if conventional production methods continue. This scenario underscores the urgent need for alternative low-carbon binders and SCMs to reduce clinker dependency. The integration of fly ash, GGBS, calcined clays, agro-industrial ashes, and geopolymer binders can significantly lower embodied carbon while maintaining structural performance. As the Indian cement industry expands, adopting sustainable binder technologies becomes essential to balance infrastructure growth with climate commitments, resource conservation, and environmental protection.

Table 2: Major Waste Materials in India Suitable for Pavement Construction

Rank	Waste Material	Estimated Annual Generation in India (MT)	Source Sector	Potential Use in Pavement Construction	Sustainability Benefit
1	Fly Ash	250–270	Thermal Power Plants	Partial cement replacement, geopolymer binder, embankment fill	Reduces clinker demand and landfill disposal
2	Ground Granulated Blast Furnace Slag (GGBS)	30–35	Steel Industry	Cement replacement in rigid pavement concrete	Improves durability, lowers CO_2 emissions
3	Steel Slag	18–20	Steel Plants	Aggregate replacement in base/sub-base and concrete	Enhances strength and skid resistance
4	Construction & Demolition (C&D) Waste	150–200	Urban Construction	Recycled concrete aggregates (RCA), base layers	Promotes circular economy
5	Sugarcane Bagasse Ash (SCBA)	8–10	Sugar Industry	Pozzolanic material in concrete	Reduces agricultural waste disposal

6	Rice Husk Ash (RHA)	4–5	Agro-Processing	Supplementary cementitious material	High silica content; improves durability
7	Municipal Solid Waste Incineration (MSWI) Ash	1.5–2	Urban Waste Management	Sub-base material (after treatment)	Reduces landfill burden
8	Waste Plastic	3–4	Municipal Waste	Modified bituminous pavements, joint fillers	Reduces plastic pollution
9	Waste Rubber (Tyre Crumb)	1–1.5	Automobile Sector	Rubberized asphalt, shock-absorbing layers	Improves flexibility and recycling
10	Phosphogypsum	10–12	Fertilizer Industry	Soil stabilization, subgrade improvement	Waste valorization
11	Copper Slag	6–8	Metallurgical Industry	Fine aggregate replacement in concrete	Enhances density and strength
12	Marble/Granite Waste	15–20	Stone Processing Industry	Filler material, aggregate replacement	Reduces quarry waste dumping

The large quantities of industrial, agricultural, and construction waste generated annually in India present a significant opportunity for sustainable pavement construction. Fly ash, produced in large volumes by thermal power plants, is extensively used as a supplementary cementitious material in rigid pavement concrete, reducing clinker consumption and improving long-term durability. It is also utilized in embankment construction and controlled low-strength fill. Ground granulated blast furnace slag (GGBS), a by-product of the steel industry, enhances resistance to chloride penetration and sulfate attack, making it suitable for rigid pavements in aggressive environments. Steel slag, due to its high strength and angularity, is used as aggregate in base and sub-base layers, and in some cases as coarse aggregate in concrete pavements. Table 2 illustrates the waste generating in India from various sectors.

Construction and demolition (C&D) waste is increasingly processed into RCA, which are incorporated in pavement base layers and, with proper treatment, in rigid pavement concrete. Agro-industrial wastes such as SCBA and RHA are rich in amorphous silica and function as pozzolanic materials in concrete, enhancing microstructural densification and durability. Waste plastics and crumb rubber are primarily used in flexible pavements for modified bituminous mixes, improving flexibility and resistance to cracking, though they can also support joint fillers and composite pavement systems. Phosphogypsum is applied in soil stabilization and subgrade improvement, while copper slag and marble waste serve as alternative fine aggregates in concrete pavements. Collectively, the utilization of these materials in pavement construction in India supports resource conservation, reduces landfill disposal, lowers carbon emissions, and advances circular economy principles in infrastructure development.

The above Table 3 presents five sustainable pavement concrete mix designs incorporating industrial and agricultural waste materials. Compared to the conventional control mix (M1), the other mixes partially replace cement with fly ash, GGBS, SCBA, and recycled aggregates to reduce carbon emissions and improve durability. Mixes M2 and M3 enhance long-term strength and resistance to aggressive environments, while M4 promotes circular economy through recycled aggregate use. M5 achieves the highest cement reduction, offering maximum environmental benefit with adequate structural performance for rigid pavements.

Table 3: Proposed Sustainable Mix Proportions for Rigid Pavement Construction (m³)

Mi	Description	Cemen	Fly	GGB	SCBA/RH	Fine	Coarse	Wate	Superplasticiz

x ID		t	Ash / SCM	S	A	Aggregate	Aggregate / RCA	r	er (%)
M1	Conventional Control (PQC)	400	—	—	—	650	1200 (Natural)	160	0.8
M2	Fly Ash Blended Concrete (30% FA)	280	120	—	—	660	1180 (Natural)	155	0.9
M3	GGBS + Fly Ash (20% + 20%)	240	80	80	—	670	1170 (Natural)	150	1.0
M4	SCBA + RCA Mix (15% SCBA + 30% RCA)	340	—	—	60	680	840 (Natural) + 360 (RCA)	165	1.0
M5	High-Volume SCM Sustainable Mix (40% GGBS + 20% FA)	160	120	160	—	690	1150 (Natural/Steel Slag Blend)	150	1.1

IV. RESULTS AND DISCUSSION

High-volume SCM mixtures exhibited improved long-term strength and reduced heat of hydration. Processed SCBA enhanced micro-filling and pozzolanic reactions. Recycled aggregates slightly reduced compressive strength but improved sustainability metrics. Geopolymer concrete demonstrated superior chloride and sulfate resistance compared to OPC systems. Life-cycle analysis revealed up to 60% reduction in CO_2 emissions for geopolymer pavements. Eco-friendly alternatives provided balanced structural performance and environmental benefits.

4.1 Workability

The slump results indicate that all five mixes fall within the desirable range for Pavement Quality Concrete (25–50 mm), ensuring proper compaction under slip-form paving. The control mix (M1) shows moderate workability, while M2 and M3 demonstrate improved consistency due to the spherical particle shape of fly ash and the smooth texture of GGBS, which enhance flowability and cohesion. M4 exhibits slightly lower slump because recycled concrete aggregate (RCA) has higher water absorption, reducing free water in the mix; this can be controlled with superplasticizer dosage. M5 records the highest slump, attributed to high-volume supplementary cementitious materials (SCMs) that improve paste lubrication. SCM-based mixes enhance workability without increasing water demand, which is beneficial for uniform pavement surface finish and durability. Figure 1 presents the workability of concrete.

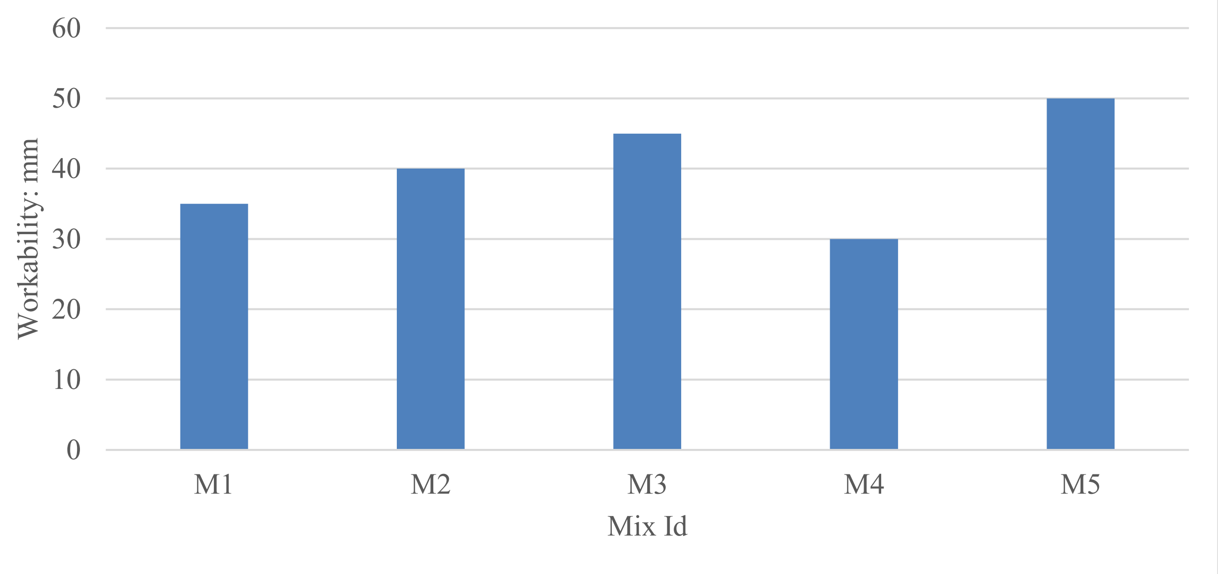

Figure 1: Workability of concrete samples

4.2 Compressive strength

The compressive strength results show progressive strength development in SCM-blended mixes compared to the conventional control mix. While early-age strength (7 days) is slightly lower in mixes containing fly ash and GGBS due to slower pozzolanic reactions, significant improvement is observed at 28 and 56 days. M3 and M5 achieve the highest long-term strengths, demonstrating the synergistic effect of slag and fly ash in forming additional calcium silicate hydrate (C–S–H) gel. M4 shows slightly reduced strength because of RCA inclusion, yet it remains within acceptable limits for rigid pavements. The results confirm that high-volume SCM mixes can achieve superior long-term mechanical performance while reducing cement consumption and carbon emissions. Figure 2 shows the compressive strength of concrete for 7, 28 and 56 days.

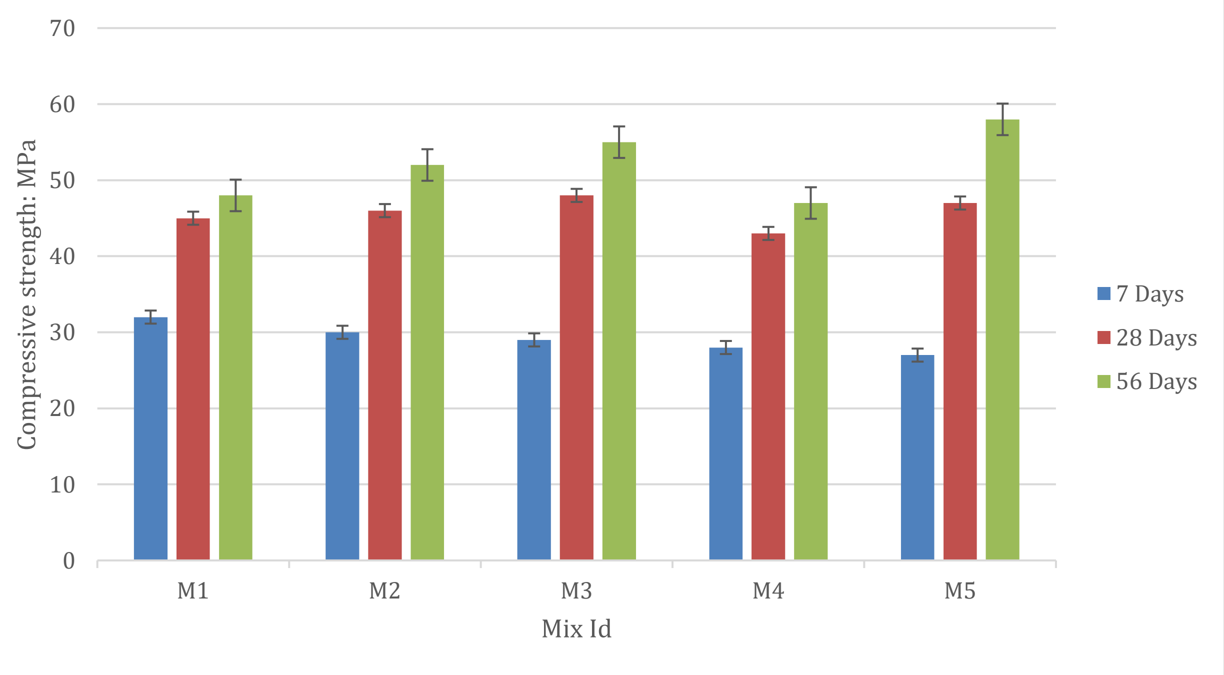

Figure 2: Compressive strength of concrete samples

4.3 Modulus of rupture

Flexural strength is the most critical parameter for rigid pavement design as per IRC guidelines. All mixes satisfy the minimum requirement of approximately 4.5 MPa. M3 and M5 exhibit the highest flexural strength values, indicating improved tensile resistance and crack control due to refined microstructure from pozzolanic reactions. M2 also performs better than the control mix, confirming the beneficial effect of fly ash on long-term bonding. Although M4 shows slightly lower flexural strength because of RCA influence, it still meets pavement standards. The improved flexural performance in SCM-based mixes enhances fatigue resistance and extends pavement service life under repeated traffic loading. Figure 3 illustrates the modulus of rupture/flexural strength of concrete.

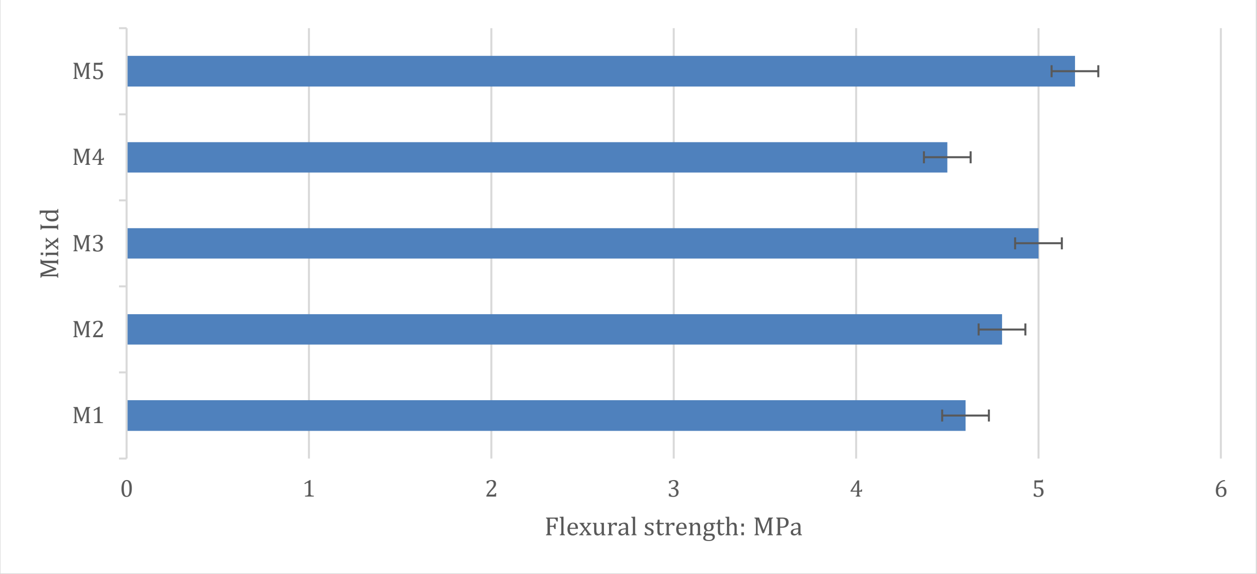

Figure 3: Modulus of rupture/flexural strength of concrete under 28 days of curing

4.4 Rapid Chloride Penetration Test (RCPT)

RCPT results clearly indicate improved durability in mixes containing SCMs. The control mix (M1) falls under moderate chloride permeability, whereas M2 and M3 shift to low and very low permeability categories. M5 demonstrates the best performance with the lowest coulomb value, reflecting a highly dense microstructure that restricts chloride ion ingress. The presence of GGBS and fly ash significantly refines pore structure and reduces connectivity of capillary pores. M4 shows moderate permeability due to recycled aggregates but remains acceptable. These findings suggest that high-volume SCM mixes are highly suitable for pavements exposed to aggressive environments, de-icing salts, or coastal conditions. Table 4 presents the RCPT results of concrete used for pavement construction

Table 4: RCPT results of concrete used for pavement construction

Mix ID	RCPT Value (Coulombs)	Chloride Permeability Rating
M1	2800	Moderate
M2	1800	Low
M3	1200	Very Low
M4	2500	Moderate
M5	900	Very Low

4.5 Drying shrinkage

Drying shrinkage results show that SCM incorporation generally reduces shrinkage compared to conventional concrete. M3 and M5 record the lowest shrinkage values, indicating improved dimensional stability due to reduced heat of hydration and denser microstructure. M2 also demonstrates reduced shrinkage relative to the control mix. However, M4 exhibits slightly higher shrinkage because recycled aggregates contain residual mortar, which increases water absorption and internal moisture movement. Despite this, shrinkage levels remain within acceptable pavement limits. Lower shrinkage is advantageous in rigid pavements as it minimizes cracking risk, improves joint performance, and enhances long-term structural integrity under temperature and moisture variations. Figure 4 illustrates the shrinkage of sustainable concrete used for pavements

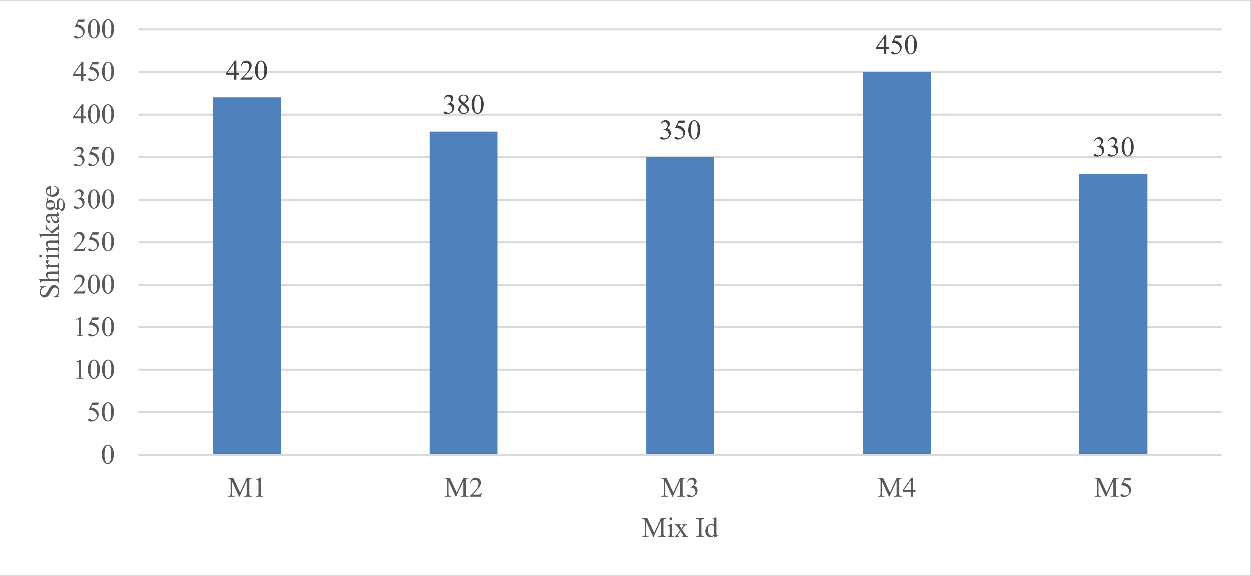

Figure 4: Shrinkage of sustainable concrete used for pavements

V. CONCLUSIONS

Based on the mix proportioning and performance evaluation of the five rigid pavement concrete mixes (M1–M5), the following conclusions are drawn:

1. Partial replacement of cement with fly ash and GGBS (M2, M3, M5) enhanced long-term compressive strength, flexural strength, and durability compared to the conventional control mix (M1), confirming the effectiveness of supplementary cementitious materials in pavement concrete.
2. Mixes M3 and M5 exhibited very low chloride permeability and reduced drying shrinkage, indicating denser microstructure and improved resistance to aggressive environmental exposure, making them highly suitable for long-life rigid pavements.
3. Although SCM-based mixes showed slightly lower 7-day strength due to slower pozzolanic reactions, they achieved higher 28- and 56-day strengths, meeting structural requirements for pavement design.
4. The RCA-based mix (M4) demonstrated acceptable mechanical and durability performance, though careful water management and admixture optimization are necessary to offset higher absorption and shrinkage.
5. All mixes met or exceeded the minimum modulus of rupture requirement (~4.5 MPa), ensuring structural adequacy under traffic loading as per rigid pavement standards.
6. High-volume SCM mixes substantially reduce cement consumption, thereby lowering embodied carbon emissions and promoting circular economy principles in infrastructure development.
7. Among all mixes, M3 (20% Fly Ash + 20% GGBS) and M5 (60% total SCM replacement) demonstrated the best balance between strength, durability, workability, and sustainability, making them highly recommended for sustainable rigid pavement construction in India.

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DECLARATIONS

The authors declared that there is no conflict of interest statement to publish this paper.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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