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Sustainable Rigid Pavement Concrete Using Reclaimed Asphalt Pavement, ZSF, and Steel Slag: A Multi-Parameter Evaluation

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Abstract—**The depletion of natural aggregates and the resulting cost escalation have driven the need for sustainable alternatives in pavement construction. Reclaimed Asphalt Pavement (RAP)presents a viable solution for use in rigid concrete pavements. This study investigates the fresh,mechanical, durability, and microstructural properties of RAP-incorporated concrete. It emphasizes the importance of compaction parameters such as Maximum Dry Density (MDD)and Optimum Moisture Content (OMC) in optimizing mix design. Results indicate that while RAP inclusion generally reduces compressive, flexural, and tensile strengths, mixes with up to 40–50% RAP content maintain acceptable performance, making them suitable for pavement applications.The research further evaluates the role of Washed RAP (WRAP) and Dirty RAP (DRAP), along with Zirconia Silica Fumes (ZSF), in enhancing concrete performance. The addition of 10%ZSF improves compressive and tensile strengths and mitigates the adverse effects of RAP,particularly up to 40% replacement levels. Durability properties such as water absorption and sorptivity show significant improvement, especially with WRAP aggregates. Microstructural analysis reveals that mineral admixtures enhance the Interfacial Transition Zone (ITZ), reduce porosity, and promote the formation of C–S–H gel, thereby strengthening the concrete matrix. However, proper treatment of RAP, especially removal of asphalt coating, is essential for improved bonding.Additionally, the incorporation of Steel Slag (SS) alongside RAP and ZSF enhances durability characteristics, including resistance to abrasion, chloride penetration, and sulfate attack. Tests such as Cantabro loss, carbonation, and ion penetration confirm the suitability of RAP-based mixes for harsh environmental conditions. Microstructural studies using FE-SEM and XRD highlight the interaction between RAP aggregates and cementitious materials, though a relatively weaker ITZ remains a concern. Overall, this study demonstrates that optimized combinations of RAP, ZSF, and SS can produce sustainable, durable, and cost-effective rigid pavements, while recommending further research on long-term performance and compaction behavior.**

Index Terms—**Reclaimed asphalt pavement, Steel slag, Zirconia silica fumes, Sustainable concrete, Rigid pavement, Recycled aggregates, Durability analysis, Interfacial Transition Zone, Pozzolanic materials, Green construction.**

I. INTRODUCTION

The rapid expansion of transportation infrastructure and increasing demand for construction materials have resulted in the excessive consumption of natural aggregates in rigid pavement construction. Simultaneously, the accumulation of construction and demolition waste, particularly Reclaimed Asphalt Pavement (RAP), has become a significant environmental concern worldwide. RAP generated from rehabilitation and maintenance of flexible pavements contains valuable aggregates coated with aged bitumen, which can potentially be reused in concrete pavement applications. The incorporation of RAP in rigid pavement concrete not only reduces dependency on virgin aggregates but also minimizes landfill disposal and conserves natural resources. However, RAP aggregates generally exhibit lower strength, higher porosity, and weaker bonding characteristics because of the presence of asphalt coating, which adversely affects the mechanical and durability performance of concrete. Previous studies reported that controlled RAP replacement levels can produce sustainable concrete suitable for pavement applications, provided that proper mix optimization and supplementary cementitious materials are employed (Huang et al., 2005; Brand and Roesler, 2015).

In recent years, researchers have explored the combined use of RAP with mineral admixtures such as silica fume and industrial by products including steel slag to improve the performance of sustainable pavement concrete. Zirconia Silica Fumes (ZSF) possess extremely fine particles and high pozzolanic reactivity, which contribute to pore refinement, enhanced hydration, and improved Interfacial Transition Zone (ITZ) characteristics. Similarly, steel slag exhibits excellent mechanical strength, abrasion resistance, and angularity, making it suitable for rigid pavement applications subjected to heavy traffic loads. The use of Washed RAP (WRAP) has also shown promising results because removal of asphalt coating improves aggregate bonding with the cement matrix. Durability issues such as chloride penetration, sulfate attack, carbonation, and sorptivity remain critical concerns for RAP based concrete, especially under aggressive environmental conditions. Therefore, the present study investigates the combined influence of RAP, ZSF, and steel slag on the fresh, mechanical, durability, and microstructural properties of rigid pavement concrete with emphasis on compaction characteristics including Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) (Medina et al., 2012; Pasetto and Baldo, 2011; Limbachiya et al., 2004).

II. MATERIALS AND METHODS

Ordinary Portland Cement of 53 grade conforming to IS 12269 was used as the primary binder material. Natural river sand and crushed granite aggregates served as fine and coarse aggregates, respectively. Reclaimed Asphalt Pavement aggregates were collected from milled asphalt pavement layers and classified into Washed RAP (WRAP) and Dirty RAP (DRAP) categories. The WRAP aggregates were treated to remove loose asphalt coatings and dust particles before use. Steel slag obtained from a local steel manufacturing industry was used as partial coarse aggregate replacement, while Zirconia Silica Fumes were incorporated as a mineral admixture at 10% replacement of cement by weight. RAP aggregates replaced natural coarse aggregates at proportions of 0%, 20%, 40%, 50%, and 60%. Concrete mixes were designed according to IS 10262 provisions with a constant water cement ratio of 0.42.

Laboratory investigations were conducted to evaluate fresh properties, compaction characteristics, mechanical strength, durability, and microstructural behavior. Maximum Dry Density and Optimum Moisture Content were determined through modified compaction tests to optimize the mix proportions. Mechanical tests including compressive strength, split tensile strength, and flexural strength were conducted at 7, 28, and 56 days of curing. Durability performance was assessed using water absorption, sorptivity, chloride ion penetration, sulfate resistance, Cantabro abrasion loss, and carbonation depth tests. Microstructural investigations were performed using Field Emission Scanning Electron Microscopy (FE SEM) and X Ray Diffraction (XRD) analysis to evaluate the Interfacial Transition Zone and hydration products within the concrete matrix.

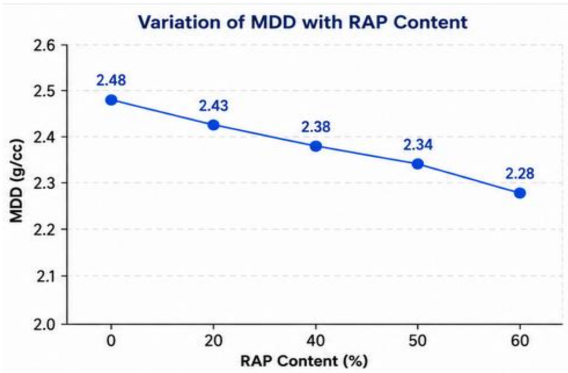
III. RESULTS AND DISCUSSION

The incorporation of RAP aggregates influenced both the compaction and strength characteristics of concrete. Increasing RAP content reduced Maximum Dry Density because of the lower specific gravity and higher asphalt content associated with RAP aggregates. Simultaneously, Optimum Moisture Content increased slightly because of the porous nature of RAP particles. However, the inclusion of steel slag improved density characteristics because of its higher unit weight and angular particle geometry. Concrete mixes containing up to 40% RAP exhibited satisfactory workability and compaction behavior suitable for rigid pavement applications.

Table 1. Compaction Characteristics of RAP Concrete Mixes

RAP Content (%)	MDD (g/cc)	OMC (%)
0	2.48	5.8
20	2.43	6.1
40	2.38	6.4
50	2.34	6.7
60	2.28	7.0

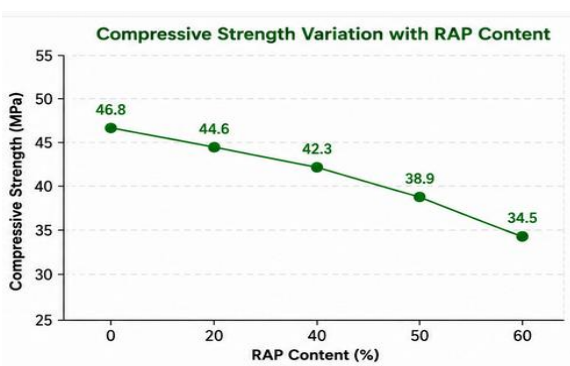
The reduction in MDD and increase in OMC can be attributed to the porous and absorptive nature of RAP aggregates. Nevertheless, WRAP aggregates showed better compaction efficiency compared to DRAP because removal of loose asphalt coating enhanced particle interaction and reduced void content.



Mechanical strength results indicated that increasing RAP replacement reduced compressive, tensile, and flexural strengths because of weaker aggregate bonding and softer asphalt coated surfaces. However, the addition of 10% ZSF significantly mitigated the strength reduction by improving particle packing and promoting pozzolanic reactions. Concrete containing 40% WRAP and 10% ZSF achieved compressive strength values comparable to control concrete, demonstrating the beneficial role of mineral admixtures in sustainable pavement systems.

Table 2. Mechanical Properties of RAP and ZSF Modified Concrete

RAP Content (%)	Compressive Strength (MPa)	Split Tensile Strength (MPa)	Flexural Strength (MPa)
0	46.8	4.32	5.84
20	44.6	4.18	5.61
40	42.3	4.05	5.28
50	38.9	3.74	4.82
60	34.5	3.28	4.16

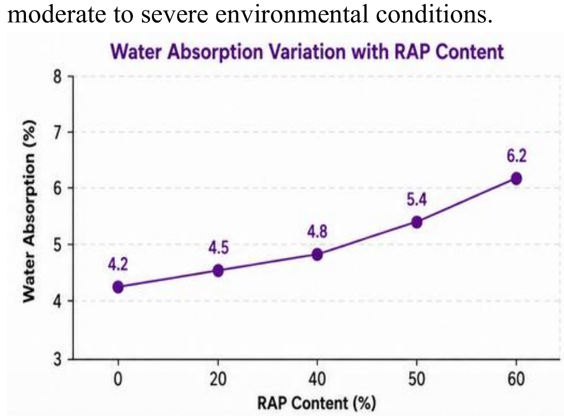


Durability performance improved considerably with the incorporation of ZSF and steel slag. Water absorption and sorptivity values decreased because of pore refinement and improved packing density. Steel slag enhanced abrasion resistance and reduced Cantabro loss because of its superior hardness and angularity. Chloride penetration and sulfate attack resistance also improved because of the denser microstructure generated by pozzolanic reactions. Carbonation depth remained relatively low for WRAP based mixes containing ZSF, indicating better long term durability under aggressive exposure conditions.

Table 3. Durability Properties of RAP Based Concrete

RAP Content (%)	Water Absorption (%)	Sorptivity (mm/min½)	Cantabro Loss (%)	Chloride Penetration (Coulombs)
0	4.2	0.115	8.4	1480
20	4.5	0.122	8.8	1560
40	4.8	0.130	9.6	1655
50	5.4	0.148	11.2	1840
60	6.2	0.169	13.6	2135

Microstructural investigations using FE SEM and XRD confirmed the formation of dense calcium silicate hydrate gel and improved aggregate paste bonding in mixes containing ZSF and steel slag. However, relatively weaker ITZ regions persisted around untreated RAP aggregates because of residual asphalt films. The combined use of WRAP, ZSF, and steel slag effectively minimized porosity and improved durability performance, making the concrete suitable for rigid pavement applications under moderate to severe environmental conditions.



IV. CONCLUSION

The present study demonstrates that Reclaimed Asphalt Pavement can be effectively utilized in rigid pavement concrete when combined with Zirconia Silica Fumes and steel slag. Increasing RAP content reduced density and mechanical strength because of weaker aggregate bonding and higher porosity; however, mixes containing up to 40% RAP maintained satisfactory performance for pavement applications. The incorporation of 10% ZSF significantly improved compressive, tensile, and flexural strengths by enhancing hydration and refining the pore structure. Washed RAP aggregates exhibited superior bonding characteristics and durability performance compared to Dirty RAP aggregates because of reduced asphalt coating interference. Steel slag further enhanced abrasion resistance, chloride penetration resistance, and sulfate durability because of its high hardness and angularity. Microstructural analysis confirmed improved Interfacial Transition Zone characteristics and increased formation of calcium silicate hydrate gel in optimized mixes. Overall, the combined utilization of RAP, ZSF, and steel slag provides a sustainable, durable, and economically viable solution for rigid pavement construction while reducing dependence on natural aggregates and minimizing environmental impacts.

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