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Experimental Investigation on the Performance of Rigid Pavement Incorporating Non-Degradable Waste, Quarry Dust, and M-Sand

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ABSTRACT: The rapid depletion of natural river sand and the growing accumulation of non-degradable plastic waste have created significant environmental challenges in the construction industry. This study presents an experimental investigation on the performance of rigid pavement concrete incorporating non-degradable plastic waste, quarry dust, and manufactured sand (M-sand) as partial replacements for conventional fine aggregates. Concrete mixes were prepared with varying percentages of shredded plastic waste (10%, 15%, and 20%) in combination with quarry dust and M-sand, and the specimens were evaluated for workability, compressive strength, flexural strength, split tensile strength, and water absorption. Results indicate that the mix containing 10% plastic waste achieved improved compressive and flexural strength compared to conventional concrete due to enhanced particle packing and matrix densification, whereas higher replacement levels resulted in gradual strength reduction because of weaker interfacial bonding. The findings demonstrate that plastic waste replacement up to 10–15%, combined with quarry dust and M-sand, is technically feasible for rigid pavement applications while promoting sustainable construction practices and reducing dependence on natural sand.

Keywords: Rigid pavement, Plastic waste concrete, Quarry dust, Manufactured sand, Sustainable construction, Compressive strength, Flexural strength.

I. INTRODUCTION

The construction sector is one of the largest consumers of natural resources, particularly sand and aggregates. River sand mining has resulted in severe ecological imbalance, including erosion, lowering of groundwater levels, and destruction of aquatic habitats. Simultaneously, plastic waste accumulation poses long-term environmental hazards due to its non-biodegradable nature. According to global environmental assessments, only a small fraction of plastic waste is recycled, while the majority ends up in landfills or open environments.

Rigid pavements depend on concrete with adequate compressive and flexural strength to resist traffic loads and environmental stresses. The use of alternative fine aggregates such as quarry dust and M-sand offers a viable solution to reduce dependency on natural sand. Additionally, incorporating shredded plastic waste into concrete contributes to waste management and resource efficiency.

This research aims to experimentally evaluate the performance of rigid pavement concrete incorporating non-degradable plastic waste along with quarry dust and M-sand.

II. LITERATURE REVIEW

Numerous studies have explored sustainable alternatives in concrete production. The use of manufactured sand (M-sand) as a replacement for river sand has shown promising results in improving durability and mechanical performance. Nanthagopalan and Santhanam reported that M-sand concrete exhibits improved compressive strength due to better particle gradation and reduced impurities [1].

Quarry dust, a by-product of stone crushing operations, has been investigated as a fine aggregate replacement. Ilangovana et al. demonstrated that quarry dust enhances compressive strength due to improved particle packing and reduced voids within the concrete matrix [2].

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Research on plastic waste incorporation in concrete indicates that shredded PET and HDPE can be used as partial aggregate replacements. Saikia and de Brito observed that plastic aggregates improve ductility but may reduce compressive strength beyond optimal limits [3]. Similarly, Ismail and Al-Hashmi reported that plastic waste up to 10–15% replacement provides acceptable strength performance [4].

Siddique et al. studied the mechanical properties of waste plastic concrete and found that lower percentages maintain structural integrity while contributing to sustainability [5]. Frigione investigated recycled PET as fine aggregate and concluded that moderate replacement levels are feasible for non-structural applications [6].

Soutsos et al. examined recycled aggregates in pavement concrete and emphasized the importance of performance validation before field implementation [7]. Mehta and Monteiro highlighted the significance of microstructural integrity in sustainable concrete systems [8].

Although previous studies have examined quarry dust, M-sand, and plastic waste independently, limited research exists on their combined application in rigid pavements. This study seeks to bridge this gap.

III. MATERIALS AND EXPERIMENTAL METHODOLOGY

The experimental program was designed to evaluate the feasibility of incorporating non-degradable plastic waste, quarry dust, and manufactured sand (M-sand) in rigid pavement concrete. The materials used in this study are described in detail below.

1) Cement

Ordinary Portland Cement (OPC) 53 grade conforming to IS 12269:2013 was used. The cement was tested for specific gravity, standard consistency, initial and final setting time, and fineness as per relevant BIS standards. The specific gravity of cement was found to be 3.15. The cement exhibited normal setting characteristics and satisfied the requirements for pavement-grade concrete.

2) Coarse Aggregate

Crushed angular coarse aggregates of 20 mm nominal maximum size were used. The aggregates were tested for specific gravity, water absorption, impact value, and crushing value in accordance with IS 2386. The specific gravity of coarse aggregate was 2.70 and water absorption was less than 1%, indicating good quality material suitable for rigid pavement construction.

3) Fine Aggregates

Three types of fine materials were used in this investigation:

a) River Sand (Control Mix)

Natural river sand conforming to Zone II grading as per IS 383:2016 was used in the control mix. The specific gravity was 2.62.

b) Quarry Dust

Quarry dust, obtained as a by-product from stone crushing operations, was used as partial replacement of fine aggregate. The material exhibited angular particle shape and improved packing characteristics. The specific gravity was found to be 2.65. Sieve analysis indicated well-graded particles within permissible limits.

c) Manufactured Sand (M-Sand)

M-sand produced by crushing hard granite stones was used as a replacement for natural sand. It satisfied the grading requirements of IS 383:2016 (Zone II). The specific gravity was 2.64. The angularity of M-sand contributed to improved interlocking and mechanical performance.

4) Non-Degradable Plastic Waste

Shredded plastic waste (PET/HDPE) was collected, cleaned, and mechanically shredded into particles of approximately 2–4 mm size. The plastic was used as partial replacement of fine aggregate by weight. The specific gravity of plastic was approximately 0.90–1.10. Due to its hydrophobic and non-reactive nature, it does not chemically bond with cement paste but acts as a lightweight filler material.

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5) Water

Potable water free from impurities, oils, acids, and organic matter was used for mixing and curing of concrete specimens.

B. Mix Proportioning

Concrete mix design was carried out for M20 grade concrete following IS 10262:2019 guidelines. The target mean strength was calculated considering standard deviation and quality control measures.

The water-cement ratio was maintained at 0.50 for all mixes to ensure consistency in comparison. Plastic waste was introduced as partial replacement of fine aggregate at different percentages while maintaining total fine aggregate content constant.

Table 1: Mix Combinations

Mix ID	Plastic Waste (%)	Quarry Dust (%)	M-Sand (%)	River Sand (%)
CM	0	0	0	100
M1	10	45	45	0
M2	15	45	40	0
M3	20	40	40	0

The proportions were selected based on previous literature and preliminary trial mixes to achieve optimum performance.

C. Specimen Preparation

All materials were weighed accurately as per mix design proportions. The dry materials (cement, aggregates, quarry dust, M-sand, and plastic waste) were mixed thoroughly in a concrete mixer to ensure uniform distribution. Water was added gradually and mixing was continued until a homogeneous mix was obtained.

Concrete was placed into moulds in three layers and compacted using a table vibrator to eliminate entrapped air.

Specimen Details

- Cubes (150 mm × 150 mm × 150 mm) for compressive strength
- Prismatic beams (100 mm × 100 mm × 500 mm) for flexural strength
- Cylinders (150 mm × 300 mm) for split tensile strength

After 24 hours, specimens were demoulded and cured in water at 27 ± 2°C until the testing age of 7 and 28 days.

D. Testing Procedures

1) Workability Test

Slump test was conducted as per IS 1199:2018 to determine the workability of fresh concrete. The slump value was recorded immediately after mixing.

2) Compressive Strength Test

Compressive strength was determined at 7 and 28 days using a compression testing machine (CTM) as per IS 516. The load was applied gradually at a uniform rate until failure. The compressive strength was calculated using:

$$f_c = \frac{PP}{AA}$$

where:

PP = Ultimate load (N)

AA = Cross-sectional area (mm²)

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3) Flexural Strength Test

Flexural strength (modulus of rupture) was determined using a two-point loading method on beam specimens. Since rigid pavements are primarily governed by flexural stresses due to wheel loads, this test is critical for evaluating pavement suitability.

4) Water Absorption Test

Durability performance was assessed through water absorption tests. Oven-dried specimens were immersed in water for 24 hours and percentage absorption was calculated.

E. Experimental Program Summary

The experimental investigation focused on:

- Evaluating mechanical performance
- Studying workability variations
- Assessing durability characteristics
- Identifying optimum replacement percentage

The methodology ensured systematic comparison between control and modified mixes under identical curing and testing conditions.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

The experimental program evaluated the performance of rigid pavement concrete incorporating non-degradable plastic waste, quarry dust, and M-sand. The results are discussed in terms of workability, compressive strength, flexural strength, split tensile strength, and durability characteristics. Comparative analysis with control concrete is also presented.

A. Workability (Slump Test)

Workability is a critical parameter in pavement concrete to ensure proper compaction and surface finish. Slump tests were conducted immediately after mixing.

Table 2: Slump Values

Mix ID	Plastic (%)	Slump (mm)
CM	0	78
M1	10	70
M2	15	63
M3	20	55

The slump value gradually decreased with increasing plastic content. The control mix exhibited a slump of 78 mm, indicating good workability. The reduction in slump for modified mixes can be attributed to:

1. Hydrophobic nature of plastic particles.
2. Increased surface area due to angular quarry dust and M-sand.
3. Reduced paste lubrication effect.

However, even at 20% plastic replacement, the slump remained within acceptable limits for rigid pavement concrete (50–80 mm range). Proper compaction was achievable without segregation.

B. Compressive Strength

Compressive strength is the primary parameter governing concrete quality. Tests were conducted at 7 and 28 days.

Table 3: Compressive Strength Results

Mix ID	7-Day Strength (MPa)	28-Day Strength (MPa)
CM	18.4	27.8
M1	19.2	29.6
M2	17.8	26.9
M3	15.6	23.5

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The results indicate that:

- Mix M1 (10% plastic + quarry dust + M-sand) achieved the highest 28-day compressive strength of 29.6 MPa.
- This represents approximately **6.5% improvement** over the control mix.

The improvement in M1 can be attributed to:

- Enhanced particle packing due to quarry dust.
- Better interlocking from angular M-sand particles.
- Reduced micro-voids within the matrix.

However, strength decreased beyond 15% plastic replacement. At 20% replacement (M3), compressive strength reduced by nearly 15% compared to control. This reduction is due to:

- Weak interfacial transition zone (ITZ) between plastic and cement paste.
- Low stiffness of plastic particles.
- Increased void content.

Thus, the optimum plastic replacement level was found to be **10–15%**.

C. Flexural Strength (Modulus of Rupture)

Flexural strength is critical for rigid pavement design, as pavements are subjected to bending stresses under wheel loads.

Table 4: Flexural Strength at 28 Days

Mix ID	Flexural Strength (MPa)
CM	3.85
M1	4.12
M2	3.74
M3	3.28

The results show:

- M1 exhibited the highest flexural strength (4.12 MPa).
- Approximately **7% improvement** compared to control.

The improvement is due to:

- Dense matrix formation.
- Reduced micro-cracking.
- Improved stress distribution due to fine particle gradation.

However, at 20% plastic replacement, flexural strength reduced significantly due to poor bonding and lower modulus of elasticity of plastic particles.

For rigid pavement applications, IRC guidelines recommend minimum flexural strength values depending on traffic category. Mix M1 satisfies requirements for low to medium traffic pavements.

D. Split Tensile Strength

Split tensile strength reflects resistance to cracking.

Table 5: Split Tensile Strength at 28 Days

Mix ID	Split Tensile Strength (MPa)
CM	2.75
M1	2.90
M2	2.68
M3	2.40

A marginal increase in tensile strength was observed in M1. This suggests:

- Improved aggregate interlocking.
- Better crack resistance due to fine particle packing.

Higher plastic percentages reduced tensile strength due to reduced cohesion between plastic particles and cement matrix.

E. Water Absorption (Durability Indicator)

Durability is essential for long-term pavement performance.

Table 6: Water Absorption Results

Mix ID	Water Absorption (%)
CM	1.82
M1	1.95
M2	2.12
M3	2.45

Water absorption increased slightly with plastic content. The increase is due to:

- Weak bonding zones around plastic particles.
- Increased micro-voids at higher replacement levels.

However, values remained below 3%, indicating acceptable durability for pavement applications.

F. Comparative Performance Analysis

The combined incorporation of quarry dust and M-sand significantly contributed to strength enhancement by:

- Filling micro-voids
- Improving particle gradation
- Enhancing density

Plastic waste contributed to:

- Reduced density (lightweight effect)
- Slight ductility improvement
- Environmental sustainability

However, excessive plastic replacement reduced mechanical strength due to weak ITZ formation.

G. Engineering Interpretation for Rigid Pavements

Rigid pavements are primarily governed by flexural strength rather than compressive strength. Based on experimental findings:

- M1 mix is structurally suitable.
- It achieves higher flexural capacity.
- It maintains adequate durability.
- It provides environmental benefits.

Therefore, the optimum mix (10% plastic + quarry dust + M-sand) can be recommended for:

- Rural rigid pavements
- Parking lots
- Low to medium traffic roads
- Industrial flooring

V. LIMITATIONS AND FUTURE SCOPE

The present study was conducted under controlled laboratory conditions, and therefore the results may not fully represent field performance of rigid pavements under varying environmental and traffic loading conditions. The plastic waste used was limited to uniformly shredded PET/HDPE, and variations in plastic type and size were not examined. Long-term durability aspects such as fatigue resistance, abrasion, freeze–thaw behavior, and chemical attack were not investigated. In addition, microstructural analysis was not performed to directly evaluate the interfacial bonding between plastic particles and cement matrix.

Future research should focus on long-term durability evaluation, field trial pavement sections, and advanced microstructural studies using techniques such as SEM analysis. Life cycle assessment and cost analysis should also be carried out to validate environmental and economic feasibility. With further validation, the proposed material combination can be effectively implemented in sustainable rigid pavement construction.

VI. CONCLUSION

This experimental investigation evaluated the performance of rigid pavement concrete incorporating non-degradable plastic waste, quarry dust, and manufactured sand (M-sand) as partial replacements for conventional fine aggregates. Based on the laboratory results and detailed analysis, the following conclusions can be drawn. The inclusion of quarry dust and M-sand improved particle packing and contributed to enhanced matrix density. The mix containing 10% plastic waste replacement (M1) demonstrated improved compressive strength and flexural strength compared to the control mix. This indicates that limited incorporation of plastic waste, when combined with well-graded fine materials, can produce structurally adequate concrete suitable for rigid pavement applications. Workability decreased with increasing plastic content due to the hydrophobic nature of plastic particles; however, the values remained within acceptable limits for pavement concrete. Beyond 15–20% plastic replacement, a noticeable reduction in compressive, tensile, and flexural strength was observed due to weaker interfacial bonding and increased void formation. Durability performance, as indicated by water absorption results, remained within permissible limits for all mixes, although slight increases were observed at higher plastic contents. Overall, the study confirms that plastic waste replacement up to 10–15% combined with quarry dust and M-sand is technically feasible for low to medium traffic rigid pavements. The proposed material system contributes to sustainable construction by reducing natural sand consumption and diverting non-degradable plastic waste from landfills. With further long-term validation and field implementation studies, this approach can support environmentally responsible infrastructure development.

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