Strength Assessment of Flexible Pavement Incorporating Waste Plastic and Quarry Dust as Reinforcement Materials

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Abstract - The growing demand for road infrastructure has intensified the need for sustainable and resource-efficient construction practices. Conventional flexible pavements predominantly depend on non-renewable materials such as natural aggregates and bitumen, whose large-scale extraction leads to environmental degradation. At the same time, the rapid accumulation of plastic waste and quarry dust has emerged as a major ecological concern due to improper disposal practices. Addressing these dual challenges, the present study explores an innovative and environmentally responsible approach by utilizing shredded waste plastic as a partial replacement for bitumen and quarry dust as a supplementary mineral filler in bituminous mixes. The materials were selected considering their physical, chemical, and environmental attributes, along with their wide availability. A comprehensive laboratory program—including Marshall Stability, California Bearing Ratio (CBR), moisture susceptibility, and volumetric property analyses—was conducted to evaluate the performance of modified mixes with varying proportions of waste plastic and quarry dust.

The experimental results demonstrate that incorporating waste plastic significantly enhances the binding capacity, stiffness, and rutting resistance of the pavement mix, contributing to improved strength and durability. Quarry dust, when used as a filler, effectively increases mix density, reduces air voids, and enhances the overall stability of the bituminous layer. The modified mixes exhibited superior load-bearing capacity, greater resistance to moisture-induced damage, and improved structural performance compared to conventional mixes. Overall, the integration of waste plastic and quarry dust promotes sustainable pavement construction by reducing environmental pollution, minimizing reliance on natural resources, and supporting the principles of green engineering and circular economy in civil infrastructure.

Key Words: Flexible pavement, waste plastic modification, quarry dust filler, Marshall Stability, CBR, moisture susceptibility, sustainable pavement materials, bituminous mix design, rutting resistance, green engineering.

1.INTRODUCTION

The rapid expansion of industrialization, urbanization, and vehicular movement—especially in developing nations such as India—has intensified the need for durable and sustainable road infrastructure. Flexible pavements constitute nearly 90% of India's road network owing to their ease of construction, lower initial investment, and adaptability to varied environmental conditions. However, conventional flexible pavements rely predominantly on non-renewable materials such as bitumen and natural aggregates. Continuous exposure to heavy traffic loads, temperature fluctuations, and moisture leads to distresses such as rutting, cracking, and pothole formation, resulting in premature pavement failure and increased maintenance costs. These limitations highlight the need for alternative materials that can enhance pavement performance while ensuring economic and environmental sustainability.

Parallel to these infrastructural challenges, improper disposal of waste materials has emerged as a significant environmental concern. Plastic waste, generated in massive quantities from packaging, consumer products, and industrial processes, is non-biodegradable and persists in the environment for centuries. Its accumulation leads to soil contamination, drainage blockage, and severe harm to terrestrial and aquatic ecosystems. Similarly, quarry dust, a fine by-product from stone-crushing industries, is often dumped in open lands, causing air pollution, reduced soil fertility, and land degradation. Both materials, despite their hazardous environmental impact, possess valuable engineering properties that remain underutilized in large-scale applications.

In this context, the integration of waste plastic and quarry dust into flexible pavement construction presents a promising sustainable solution. Waste plastic, when shredded and incorporated into bituminous mixes, enhances the binding characteristics of bitumen, increases stiffness, and improves resistance to deformation and water ingress. Quarry dust, owing to its mineral composition and fine particle size, serves as an effective filler that increases density, reduces air voids, and strengthens the internal structure of the mix. Utilizing these materials not only improves pavement performance but also addresses critical waste management challenges.

Although pilot projects in India and other countries have demonstrated encouraging results with plastic-modified roads, the lack of standardization and comprehensive performance evaluation has limited widespread adoption. Likewise, the potential of quarry dust in flexible pavements remains underexplored despite its availability and engineering suitability. Therefore, systematic research is essential to assess the combined impact of these waste materials on the mechanical and durability characteristics of flexible pavements.

The present study aims to evaluate the performance of bituminous mixes modified with varying proportions of waste plastic and quarry dust through laboratory tests such as Marshall Stability, flow value, moisture susceptibility, and bearing capacity assessments. The objective is to determine optimum replacement levels that enhance strength, durability, and sustainability while reducing reliance on conventional materials.

1.1 Objectives of the Study

General Objective:

Specific Objectives:

- To determine the optimal percentage of waste plastic and quarry dust for reinforcement.
- To analyze the effects of these materials on the California Bearing Ratio (CBR), Unconfined Compressive Strength (UCS), and resilient modulus of pavement layers.
- To compare the performance of conventional and reinforced flexible pavements.
- To evaluate the environmental and economic benefits of using recycled materials in pavement construction.

1.2 Scope and Limitations

Scope:

- The study focuses on laboratory-scale testing of reinforced pavement materials.
- High-density polyethylene (HDPE) and low-density polyethylene (LDPE) plastic wastes are used.
- Quarry dust is sourced from local quarries.
- Tests include CBR, UCS, moisture content, and density measurements.
- Mix proportions vary from 0% to 15% reinforcement in increments of 5%.

Limitations:

- Field implementation and long-term performance are not covered.
- Only certain types of plastics and quarry dust are considered.
- Results may vary based on local material properties and environmental conditions.

2. LITERATURE REVIEW

Recent research increasingly focuses on sustainable materials for flexible pavements, driven by rising waste generation and depletion of natural resources. Studies show that waste plastic enhances bitumen's binding strength, stability, and resistance to moisture and rutting, while quarry dust improves density, reduces air voids, and strengthens the internal structure of bituminous mixes. Researchers such as Vasudevan (2006), Sharma et al. (2014), and Kumar and Rao (2015) confirm the individual benefits of these materials, whereas Patel and Shah (2020) highlight superior performance when both are combined. However, long-term field behavior and optimal proportioning remain key research gaps.

3.Materials and methodology

Table 1: Basic Properties of Bitumen

Properties	Results
Specific gravity	1.01
Penetration	67 mm
Softening point	42°C
Flash point	330°C
Fire point	350°C
Ductility	63.4 mm

3.1.1 Quarry Dust

Quarry dust is a by-product generated during the crushing of stones to produce coarse aggregates in stone quarries. Typically, this dust is disposed of as waste, leading to land and air pollution. However, due to its fine particle size, angular shape, and mineral content, quarry dust serves as a viable **filler material** in bituminous mixes.

Table 2: Basic Properties of Modifiers

Modifier used	Specific gravity
PET bottles	1.38

Table 3: Basic Properties of Coarse Aggregates

Properties	Results
Specific gravity	2.6
Water absorption	0.28%

Table 4: Basic Properties of Fine Aggregates

Properties	Results
Specific gravity	2.6
Water absorption	1.45%

In this study, quarry dust was sourced from a local quarrying plant. The material was dried and sieved through a 75-micron sieve to ensure uniformity and eliminate oversized particles. Quarry dust replaces conventional fillers like stone dust or cement and was added at 15%, 25%, and 35% by weight of the total filler component in different trial mixes.

Its high specific surface area and mineral fineness help in filling the voids between aggregate particles, thereby increasing the bulk density and reducing air voids. Additionally, the sharp edges of quarry dust particles contribute to mechanical interlocking, which enhances the strength and stability of the pavement under load. The use of quarry dust is both cost-effective and environmentally

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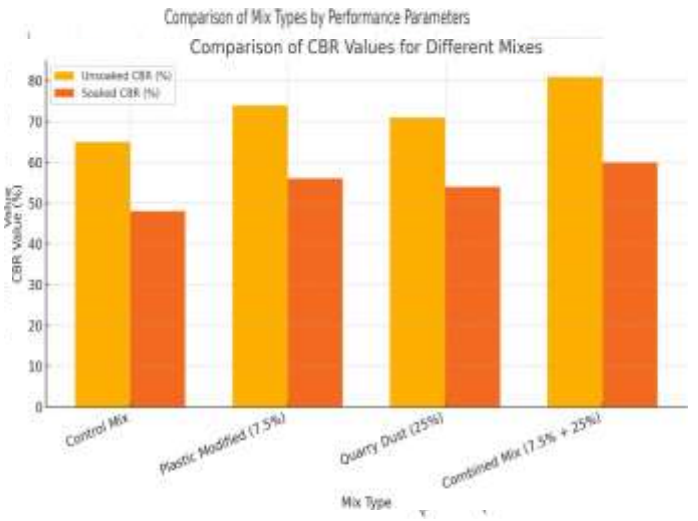
beneficial, making it an ideal secondary material in sustainable road construction

3.2 Soil

- Outskirts of Vijayawada, near Gannavaram Airport Road (area with natural clayey soil).
- About 150 kg collected for all the test samples.
- Ai r-dried, passed through 4.75 mm IS sieve, and stored in clean gunny bags before testing.
- Type: Initial soil classification → CL–ML (clayey soil with low to medium plasticity) as per IS system.

We brought brown sticky soil from near the airport road. We dried it in air, removed big stones with a sieve, and kept it in bags. This soil is not too sticky, not too sandy just medium.



Mix Type	Plastic %	Quarry Dust %	Stability (kN)	Flow (mm)	VMA (%)	Air Voids (%)	VFB (%)
Control Mix	0	0	12.5	3.6	14.8	4.2	71.6
Plastic Modified Mix	5	0	14.2	3.4	14.6	3.9	73.3
Plastic Modified Mix	7.5	0	15.1	3.3	14.4	3.7	74.3
Plastic Modified Mix	10	0	14.6	3.8	14.5	3.6	75.2
Quarry Dust Modified Mix	0	15	13.8	3.5	14.7	3.9	73.5
Quarry Dust Modified Mix	0	25	14.6	3.4	14.5	3.7	74.6
Quarry Dust Modified Mix	0	35	13.9	3.6	14.6	3.8	74.0
Combined Modified Mix	7.5	25	16.4	3.2	14.3	3.5	75.5
Combined Modified Mix	10	25	15.9	3.4	14.4	3.6	75.0

Table 3.7: Plastic and Quarry Dust Trial Mix Combinations

Mix Type	Plastic %	Quarry Dust %
Control Mix	0	0
Plastic Mix	5, 7.5, 10	0
Quarry Dust Mix	0	15, 25, 35
Combined Mix	5, 7.5, 10	15, 25, 35

4.Results and Analysis

4.1 Marshall Stability and Flow Values

The experimental analysis of the various modified bituminous mixes revealed significant performance improvements when plastic and quarry dust were incorporated, both individually and in combination. The control mix, without any additives, showed the lowest stability (12.5 kN) and higher air voids (4.2%), indicating reduced strength and inferior compaction quality. The addition of plastic alone enhanced the mechanical strength of the mix, with the 7.5% plastic-modified mix achieving a stability of 15.1 kN and a reduced air void content of 3.7%. Likewise, the use of quarry dust alone improved the mix performance, particularly at 25% quarry dust, which resulted in a stability of 14.6 kN and 3.7% air voids.

The best overall performance was obtained with the combined modified mix containing 7.5% plastic and 25% quarry dust. This mix recorded the highest stability of 16.4 kN, the lowest flow value of 3.2 mm (indicating increased stiffness), optimal air voids of 3.5%, and the highest voids filled with bitumen (VFB) at 75.5%. These values collectively demonstrate superior load-bearing capacity, improved compaction, and more effective binder utilization. In summary, the combined use of plastic and quarry dust in suitable proportions significantly enhances the durability, strength, and overall performance of the bituminous mix. Based on the test results, the mix containing 7.5% plastic and 25% quarry dust is recommended as the optimum formulation.

Figure 3: Comparative Analysis of Mix

Types Based on Stability, Flow, Air Voids, and VFB Values"

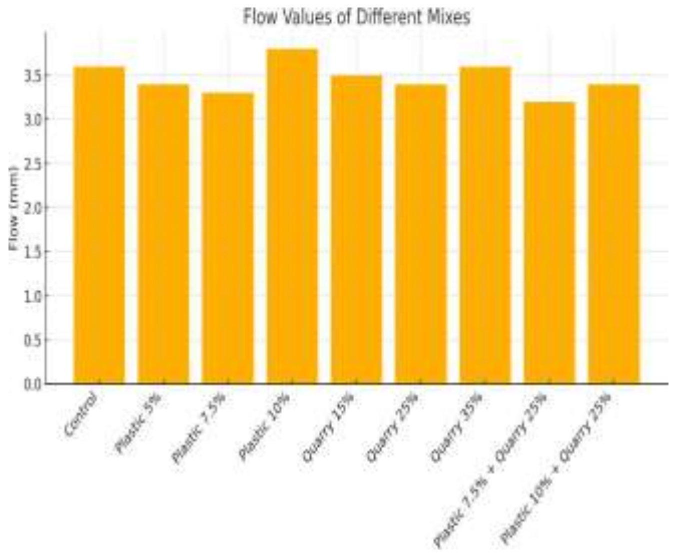


Figure 4.2: Flow Values (in mm) of Control, Plastic-Modified, Quarry Dust-Modified, and Combined Mixes"

4.2 California Bearing Ratio (CBR) Results

The California Bearing Ratio (CBR) test results are presented in Figure 4.3. The control mix exhibited 65% (unsoaked) and 48% (soaked) values. Plastic modification at 7.5% increased the soaked CBR to 56%, while quarry dust at 25% resulted in 54%. The combined mix of 7.5% plastic and 25% quarry dust achieved the highest soaked CBR of 60% and unsoaked CBR of 81%.

This indicates that the modified mixes not only enhance the load-bearing capacity but also improve water resistance, which is crucial for field performance in rainy and humid regions. These findings are consistent with previous literature emphasizing the role of plastic in improving binder adhesion and quarry dust in enhancing density (Vasudevan, 2006; Meenakshi et al., 2018).

Graph: 4.4: Comparison of Soaked and Unsoaked CBR Value Different Bituminous Mixes"

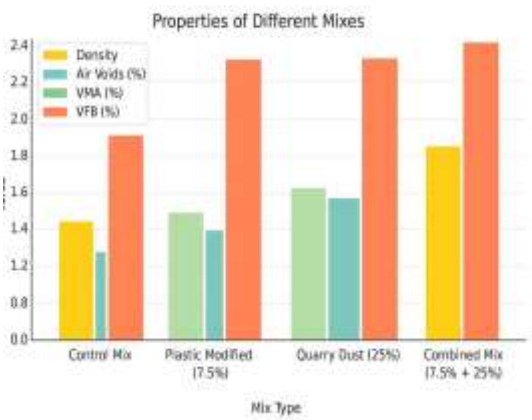


Figure 4 : Comparison of Marshall Properties (Density, Air Voids, VMA, VFB) for Different Bituminous Mixes"

5.Conclusion

This study examined the strength performance of flexible pavements modified with waste plastic and quarry dust, aiming to determine their suitability as reinforcement materials in bituminous mixes while supporting sustainable road construction. The experimental findings lead to the following conclusions:

1. The incorporation of waste plastic and quarry dust significantly enhanced the Marshall Stability values. The mix containing 7.5% plastic and 25% quarry dust registered the highest stability of 16.4 kN, substantially higher than the control mix value of 12.5 kN.
2. All modified mixes exhibited flow values within IRC's acceptable range (2–4 mm), indicating improved stiffness without losing adequate workability.
3. CBR results demonstrated increased load-bearing capacity for the modified mixes. The combined mix (7.5% plastic + 25% quarry dust) achieved the maximum soaked CBR of 60%, compared to 48% for the control mix.
4. Moisture susceptibility evaluation confirmed enhanced durability. The combined mix achieved a TSR of 80%, higher than the control mix (73%) and compliant with IRC moisture resistance requirements.
5. Volumetric assessments revealed that modified mixes were denser, exhibited lower air voids, and showed higher VFB values, indicating better compaction and reduced permeability relative to the conventional mix.
6. Environmentally, the use of plastic waste helps mitigate non-biodegradable waste accumulation, while quarry dust provides a beneficial outlet for quarrying by-products.

Overall, the study confirms that the combined use of waste plastic and quarry dust enhances the strength, durability, and sustainability of flexible pavements. The optimum mix—7.5% plastic and 25% quarry dust—can be recommended for practical implementation in pavement construction.

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