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Comprehensive Review on Enhancing Strength and Fatigue Resistance of Bituminous Pavements Using PET Plastics and Polypropylene Fibers

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A B S T R A C T

This comprehensive review evaluates the role of Polyethylene Terephthalate (PET) waste plastics and Polypropylene Fibers (PPF) in enhancing the structural performance, strength, durability, and fatigue resistance of bituminous pavements. With increasing traffic loads, temperature fluctuations, and environmental distress, conventional bitumen often experiences premature failures such as rutting, cracking, moisture damage, and fatigue-related deterioration. PET plastics improve stiffness, interlocking, and tensile strength, while polypropylene fibers enhance ductility and crack resistance. Together, these materials provide a synergistic effect that significantly improves pavement life. This review consolidates methodologies, material properties, experimental findings, performance outcomes, advantages, constraints, and future research potential across multiple international studies. The paper concludes that PET content between 6–10% and PPF around 0.2–0.5% are optimal for achieving superior performance in flexible pavements.

Keywords: Bituminous pavement, PET plastic, Polypropylene fibers, Fatigue resistance, Modified bitumen

Introduction

Bituminous pavements constitute a major share of roadway infrastructure in India and across the globe. Increasing axle loads, rising temperature variations, environmental degradation, and heavy traffic volumes lead to pavement failures such as rutting, fatigue cracking, raveling, stripping, and thermal cracking. Traditional bitumen alone cannot withstand harsh climatic and traffic conditions over long periods. This has led researchers to develop modified asphalt mixes using additives such as polymers, fibers, rubber particles, and waste plastics.

Among these, Polyethylene Terephthalate (PET) waste plastics—largely sourced from discarded bottles—are abundant and environmentally harmful unless recycled. Polypropylene fibers (PPF), known for their tensile strength and ductility, complement PET's stiffness by providing resistance against cracks and improving fatigue life. This makes PET–PPF reinforced bitumen a highly promising material for sustainable, long-lasting pavement construction.

Need for bitumen modification

Conventional bitumen suffers from several shortcomings when exposed to varying climatic and traffic conditions. It softens excessively during high temperatures, resulting in rutting and deformation in wheel paths. At low temperatures, it becomes brittle, leading to cracking and material disintegration. Furthermore, cyclic loading from heavy vehicles causes fatigue damage over time. These issues demand modification to improve the performance characteristics of asphalt mixes. PET plastics exhibit high melting temperatures, good stiffness, and chemical resistance, making them suitable for reinforcing the bitumen–aggregate matrix. On the other hand, polypropylene fibers enhance tensile strength and help control micro-cracking by distributing stresses more uniformly throughout the mix. Together, PET and PPF enhance the mechanical integrity of the pavement and reduce the need for frequent maintenance. Additionally, using waste plastic in bitumen supports sustainable development by reducing environmental pollution.

Properties of PET Plastics and Polypropylene Fibers

PET Plastics:

Polyethylene Terephthalate (PET) plastics possess several engineering properties that make them suitable for bitumen modification. PET has high tensile strength, good 9999of 150–160°C in the dry process. When PET is added to heated aggregates, it melts and forms a thin uniform coating around the aggregate particles. This coating improves interlocking, reduces permeability, and increases stiffness of the mix, resulting in higher Marshall stability and better load distribution. PET also exhibits strong chemical resistance, which prevents degradation under vehicular and environmental stresses. Because of its availability as waste bottles, PET also contributes to sustainability while delivering significant structural benefits.

Polypropylene fibers (PPF):

Polypropylene fibers (PPF), unlike PET, act as micro-reinforcement elements that increase the ductility and toughness of the bituminous mix. PPF has excellent flexibility, low density, and high elongation properties, which help in absorbing tensile stresses and delaying crack formation. When subjected to repeated traffic loading, these fibers bridge micro-cracks and distribute stresses more evenly across the pavement structure. This reinforcement mechanism improves fatigue life, reduces thermal cracking, and increases the resistance of the pavement to deformation. Because PPF balances the brittleness introduced by PET, the combination of both materials produces a more durable and resilient bituminous mix.

Literature Review

Researchers worldwide have studied the integration of PET and PPF in bituminous mixes. Major findings include:

A wide range of studies has been conducted globally on the use of PET plastics in asphalt mixes. Most researchers agree that PET content between 5–10% by weight of bitumen results in significant improvements in Marshall stability, stiffness, and rutting resistance. PET-modified mixes exhibit a stronger aggregate–binder bond, better load distribution, and reduced deformation under heavy traffic. However, several studies also reported that mixes containing PET alone tend to become stiff and brittle, resulting in reduced flow values and higher chances of cracking, especially at lower temperatures. These disadvantages highlight the need to combine PET with a flexible modifier such as PPF.

In parallel, studies on polypropylene fibers demonstrate that they enhance the fatigue resistance, ductility, and crack control ability of bituminous mixes. When PPF is added in small percentages (0.2–0.5%), the fibers merge with the bitumen matrix and act as reinforcement during cyclic loading. They effectively bridge micro-cracks, prevent sudden failure, and increase the pavement’s ability to withstand temperature variations. Literature combining PET and PPF shows that the synergy of stiffness (from PET) and flexibility (from PPF) leads to a more balanced and durable asphalt mix. Field applications reported longer pavement life, reduced rutting, and improved performance in various climatic conditions.

These findings strongly support the inclusion of composite waste plastic–fiber reinforcement in pavement surface layers.

Materials and Mix Design Methodology

PET-modified bituminous mixes generally use aggregates conforming to IS 383 specifications and VG-30 grade paving bitumen. PET flakes of about 10–12 mm and polypropylene fibers of around 12 mm are used in the mix. The dry process is commonly preferred, where PET is added to hot aggregates at temperatures between 150–160°C, allowing it to melt and coat the aggregate particles. Bitumen is then added to complete the mixing process. The Marshall Method is widely used to evaluate the stability, flow value, air voids, VMA, and density of different mix proportions. Researchers typically experiment with PET dosages ranging from 6% to 10% and maintain PPF at 0.2% to 0.5% to determine the optimum mix. The selection of optimum binder content is based on maximizing stability and ensuring acceptable flow values. This methodology helps determine the ideal blend that offers superior performance in terms of strength and fatigue resistance.

Performance Evaluation Based on Experimental Studies

Experimental studies consistently show that the addition of PET significantly increases the Marshall stability of bitumen mixes. Stability values often increase by 20–35%, which indicates a higher resistance to deformation under heavy loads. PET also reduces air voids and increases density, resulting in a structurally stronger mix. However, PET alone tends to decrease the flow value, causing the pavement to become brittle. This disadvantage is addressed by adding polypropylene fibers, which help restore ductility and ensure that the mix can accommodate strain without cracking. The combined effect of PET and PPF offers a balanced mixture with improved strength and flexibility.

Fatigue performance also improves considerably when PPF is added, as the fibers bridge micro-cracks and delay their propagation under repetitive stresses. PET enhances rutting resistance because of its stiffness, reducing permanent deformation in wheel paths. Some studies indicate improvements in moisture resistance as well, though additional research is necessary for validation. The overall mechanical, structural, and durability enhancements provided by PET–PPF reinforcement have been shown to outperform conventional mixes consistently. This makes them suitable for high-traffic roads, highways, and regions subjected to extreme temperature variations.

Environmental and Economic Benefits

The inclusion of PET plastics and polypropylene fibers in asphalt mixes offers both environmental and financial advantages. Using PET helps reduce plastic waste disposal in landfills and minimizes environmental pollution. It promotes recycling and supports sustainable construction practices. Economically, PET and PPF reduce maintenance costs because the modified pavements last longer and resist damage more effectively. Extended pavement life translates into fewer repairs and reduced lifecycle costs. Additionally, the overall production cost of modified bitumen is often lower than using imported polymer modifiers, making PET-PPF reinforced asphalt a cost-effective solution for road construction.

Limitations of Existing Studies

Despite the numerous benefits, some limitations exist in current research. Long-term field studies on PET–PPF modified pavements are limited, making it difficult to fully understand their performance over several years. Moisture susceptibility and aging behavior of PET-modified asphalt need further investigation. PET requires high temperatures for melting, which may increase energy consumption during production. Uniform dispersion of polypropylene fibers can sometimes be challenging, affecting consistency. Standardized guidelines for the use of PET and PPF in bitumen are still lacking, creating variation in mix proportions and performance outcomes across different studies.

Future Scope of Research

Although PET and PPF modified mixes have shown promising results in laboratory conditions, further research is needed to understand their long-term field performance. Long-duration studies on national highways and high-traffic routes will help determine how the mix behaves under real-world environmental and loading conditions. Advanced test methods such as wheel tracking, dynamic modulus, indirect tensile strength, and freeze–thaw testing should be conducted to evaluate rutting resistance, stiffness variation, and moisture susceptibility more accurately. Additionally, the aging behavior of PET-modified asphalt needs to be studied to ensure long-term durability.

There is also significant scope for exploring combinations of PET and PPF with other admixtures such as nano-materials, crumb rubber, and polymer additives to further enhance performance. Research on optimizing fiber dispersion, mixing temperatures, and PET flake size could improve consistency during production. Life-cycle assessment (LCA) and cost–benefit analysis would provide a clearer understanding of economic and environmental impacts. Finally, developing national-level guidelines and standard specifications for PET–PPF modified mixes will help promote large-scale adoption and ensure uniformity across road construction projects.

Conclusion

This review concludes that the integration of PET plastic waste and polypropylene fibers significantly enhances the mechanical, structural, and fatigue performance of bituminous pavements. PET improves stiffness, stability, and load-bearing capacity, while PPF enhances ductility, flexibility, and fatigue resistance. When used together, they create a balanced composite system that provides superior performance compared to conventional bitumen mixes. Optimal results are reported at approximately 8% PET and 0.2–0.5% PPF. This modification is not only technically effective but also environmentally beneficial, offering a sustainable solution for modern road construction.

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