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Sustainable Pavement Engineering Using Waste Plastics: A Comprehensive Review of Material Processing Techniques and Mix Design Methodologies

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Abstract— **The escalating accumulation of plastic waste and the growing demand for durable and sustainable transportation infrastructure have prompted extensive research into the incorporation of waste plastics in pavement engineering. This comprehensive review critically examines the role of waste plastics as alternative materials in flexible pavement construction, with particular emphasis on material processing techniques and mix design methodologies. The study systematically synthesizes existing research on various types of waste plastics—such as polyethylene, polypropylene, and polyethylene terephthalate—and their processing routes, including shredding, melting, pelletizing, and chemical modification, to enhance compatibility with bituminous binders and aggregates. Furthermore, the review explores wet and dry mix design approaches, highlighting their influence on rheological behavior, mechanical performance, durability, and long-term pavement sustainability. Key performance indicators such as Marshall stability, indirect tensile strength, moisture susceptibility, fatigue resistance, and aging characteristics are comparatively analyzed to identify optimal processing–design combinations. Environmental and economic implications, including waste diversion from landfills, reduction in virgin material consumption, and life-cycle performance benefits, are also discussed. By consolidating fragmented knowledge across experimental, analytical, and field-based studies, this review identifies current research gaps and outlines future directions for standardization, large-scale implementation, and performance-based design of plastic-modified pavements. The findings aim to support researchers, practitioners, and policymakers in advancing sustainable pavement engineering practices through effective utilization of waste plastics.**

Keywords:
Sustainable pavement engineering; waste plastics; plastic-modified bitumen; material processing techniques; mix design methodologies; flexible pavements; durability; environmental sustainability

1. INTRODUCTION

Rapid urbanization, population growth, and the expansion of transportation networks have significantly increased the demand for pavement construction and maintenance worldwide. Flexible pavements, predominantly composed of bitumen and mineral aggregates, are widely adopted due to their ease of construction, cost-effectiveness, and riding comfort. However, conventional pavement materials are increasingly challenged by rising traffic loads, extreme climatic conditions, and accelerated deterioration, leading to frequent maintenance interventions and higher life-cycle costs [1]. Simultaneously, the global surge in plastic consumption has resulted in severe environmental concerns due to the non-biodegradable nature of plastic waste and its long-term persistence in landfills and natural ecosystems [2].

Plastic waste generation has reached alarming levels, with a substantial proportion remaining uncollected or improperly disposed of, particularly in developing economies [3]. Common plastic products such as carry bags, packaging films, bottles, and containers are typically manufactured from polymers including polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET). These polymers possess favorable mechanical strength, chemical resistance, and thermal stability, which have encouraged researchers to explore their potential reuse in civil engineering applications, especially in pavement construction [4]. Incorporating waste plastics into pavement materials offers a dual advantage: mitigating environmental pollution and enhancing pavement performance characteristics.

Over the past two decades, waste plastic–modified bituminous mixes have emerged as a promising solution for sustainable pavement engineering. Early experimental investigations demonstrated that plastic-modified binders could improve stiffness, resistance to permanent deformation, and moisture damage tolerance when compared to conventional bituminous mixes [5]. Subsequent studies expanded this concept by examining different plastic forms, processing methods, and blending techniques, revealing that the effectiveness of waste plastics strongly depends on their physical properties, processing conditions, and interaction mechanisms with bitumen and aggregates [6].

Material processing techniques play a critical role in determining the performance of plastic-modified pavements. Mechanical processing methods such as shredding and granulation influence particle size distribution and surface characteristics, while thermal processes such as melting and pelletization affect polymer dispersion and bonding behavior within the mix [7]. Advanced approaches, including chemical treatment and compatibilizer addition, have also been investigated to improve the interfacial adhesion between plastic polymers and bituminous binders, thereby enhancing long-term durability [8]. Despite these advancements, inconsistencies in processing protocols often lead to variable performance outcomes, highlighting the need for a comprehensive synthesis of existing methodologies.

Mix design methodologies further govern the structural and functional performance of plastic-modified pavements. The two most commonly adopted approaches are the dry process, where processed plastic is blended with heated aggregates prior to bitumen addition, and the wet process, where plastic is directly blended with hot bitumen to form a modified binder [9]. Each method exhibits distinct advantages and limitations in terms of workability, storage stability, mechanical performance, and field applicability. Performance-based evaluation techniques, including Marshall mix design, Superpave protocols, and mechanistic–empirical assessments, have been employed to quantify the effects of waste plastics on pavement behavior under traffic and environmental loading [10].

Although numerous experimental and field studies have demonstrated the technical feasibility of using waste plastics in pavements, challenges related to standardization, long-term performance prediction, recyclability, and large-scale implementation remain unresolved [11]. Moreover, fragmented research outcomes and the absence of unified guidelines often hinder the adoption of plastic-modified pavements in mainstream engineering practice. Therefore, a systematic and critical review of material processing techniques and mix design methodologies is essential to consolidate existing knowledge and identify pathways for optimized and sustainable pavement solutions.

In this context, the present review aims to comprehensively analyze the use of waste plastics in pavement engineering, focusing on processing techniques, mix design strategies, performance evaluation, and sustainability implications. By integrating findings from laboratory investigations, field trials, and life-cycle assessments, this study seeks to provide a structured knowledge base to support researchers, engineers, and policymakers in advancing sustainable pavement engineering through effective utilization of waste plastics.

2. Bitumen

Bitumen is a viscoelastic complex hydrocarbon that is black or brown. Although there are a few natural sources of bitumen available, bitumen is generally sourced from crude oil refineries [20]. Due to its waterproof and viscoelastic nature, bitumen is used as the binder for the construction of flexible pavement all over the world. Bitumen can be classified in three ways: through penetration grade, performance grade, or viscosity. Nowadays, bitumen classification based on viscosity grade is gaining popularity. The available types according to the Australian Standard (with a typical viscosity of bitumen of 60 _C) for the construction of flexible pavements. Around the world, researchers are working to improve the properties of these materials to ensure sustainability in the pavement construction sector [7,20,22]. The recycling of waste materials for use in asphalt is recognized as a very efficient method, as it improves the pavement quality, and, at the same time, helps to manage and recycle different waste products [7]. Many researchers have investigated the use of different waste materials in bitumen. Plastic and polymer-based modifiers have been used extensively for a long time. Many industries have adopted plastic rubber and polymer-modified bitumen for the construction of roads [22–24]. In contrast, many researchers have investigated the use of regular household residues like waste cooking oil in bitumen. In some cases, they have recommended an optimum amount of waste cooking oil in bitumen of up to 5% (by weight) to ensure that any resultant compromise in the performance is minimized [22,25]. Intending to achieve better aging resistance, researchers have used palm oil fuel ash (POFA) to modify bitumen and found that POFA in bitumen can work as a rejuvenator for the binder [22,26,27]. Different types of fiber have been used in construction materials to alleviate the global waste management issue [28]. Several studies have found that fiber can improve the performance of bitumen [28–31]. Researchers have investigated the use of synthetic fibers like polymer fiber, steel fiber, and carbon fibers in asphalt concrete [28]. It has been found that carbon fiber can improve the electrical properties of asphalt but compromise the mechanical performance of asphalt concrete, while steel fiber improves the stability of asphalt [32,33]. Industry uses cellulose fiber to reduce binder drain-of during the transportation of the mix from the plant to the construction site [34,35]. As cigarette butt filters are made up of cellulose acetate-based fiber, they could represent a potential replacement for the natural cellulose fiber used in stone mastic asphalt. Recycling suitable waste in bitumen in a proper manner is a sustainable way to contribute to solving the worldwide waste management problem [36].

3. Waste plastic is a concern

Plastics are durable & non biodegradable cannot be decomposed the chemical bonds make plastic very durable & resistant to normal natural processes of degradation. Since 1950s, around 1 billion tons of plastic have been discarded, and that they may might persist for hundreds or even bunch of years. The plastic gets mixed with water, does not disintegrate, and takes the form of small pallets which causes the death of fishes and many other aquatic animals life as well as waster ecosystem. Today the availability of the plastic wastes is in huge amount, as the plastic materials have become the part of our daily life. Either they get mixed with the Municipal Solid Waste or thrown over a land area. If they are not recycled, their present disposal may be by land filling or it may be by incineration process. Both the processes have significant impacts on the environment. If they are incinerated, they polluted the air with very unwanted gases such as carbondioxide,nitrogendioxide etc, and if they are dumped into some place, they cause soil & water pollution. Under these circumstances, an alternate use for these plastic wastes is required.

4. RELATED WORK

4.1 Evolution of mix design concepts

- During 1900's, this technique, of using bitumen in pavements, was firstly used on rural roads in order to stop rapid removal of the fine particles such as dust, from Water Bound Macadam, which was caused because of fast growth of automobiles [Roberts et al. 2002]. At initial stages, heavy oils were used as dust palliative. An eye estimation process which is called pat test, was used to estimate the required quantities of the heavy oil, in the mix.

- The 1st formal technique of mix design was Habbard field method, which was actually developed on sand-bitumen mixture. Mixtures with larger sized aggregates particles could not be handled during this technique. This was one limitation of this procedure.
- Francis Hveem, 1942; who was a project engineer of California, Department of Highways enginering, has developed the Hveem stabilometer in 1927. He did not have any previous experience on judgement that, the required mix from its colour, hence he decided to measure various mixture parameters to find the optimum quantity of bitumen [Vallegra and Lovering 1985]. He had applied the surface area calculation concept, (which was already in use, at that time for the cement concrete mix design), to estimate the quantity of bitumen actually required.
- Bruce Marshall developed the Marshall testing machine just before the World War
- It was adopted in the US Army Corpes of Engineers in 1930's and subsequently modified in 1940's and 50's.

4.2 Polymer modification

- Bahia and Anderson, 1984; studied about the visco-elastic nature of binders and found that, the complex modulus & phase angles of the binders, need to be measured, at temperatures and loading rates with which different resemble climatic and loading conditions as well as past conditions.
- Shukla and Jain (1984) described that the effect of wax in bitumen can be decreased by adding EVA (Ethyl Vinyl Acetate), aromatic resin and SBS in the waxy bitumen. The addition of 4% EVA or 6% SBS or 8% resin in waxy bitumen effectively degraded the Susceptibility to high temperatures, bleeding at high temperature and brittleness at low temperature of the mixes.
- The findings of the studies conducted by the Shell Research and Technology Centre in Amsterdam indicated that the rutting rate is enormously reduced by the result of SBS modification of the binder. Button and Little (1998) on the basis of stress controlled fatigue testing at 20 and 0^0C, reported that SBS polymer exhibited superior fatigue properties as compared to straight AC-5 bitumen.
- Shuler et al. (1987) found that the tensile strength of SBS modified binder rised considerably as compared to unmodified asphalt mix at -21, $25^{\text{and } 41 0}$C.
- Collins et al. (1991) and Baker (1998) reported that SBS modified asphalt mixes have longer lives than unmodified asphalt mixes. The addition of SBS polymer to unmodified bitumen also increases its resistance to low temperature cracking.
- Denning and Carswell (1981) according that asphalt concrete using polyethylene modified binders were more resistant to permanent defor mation at elevated temperature.
- Palit et al. (2002) found improvement in stripping characteristics of the crumb rubber modified mix as compared to unmodified asphalt mix.
- Sibal et al. (2000) evaluated flexural fatigue lifetime of asphalt concrete modified by 3% crumb rubber as a part of aggregates.
- Goodrich (1998) according that fatigue life and creep properties of the polymer modified mixes increased considerably as compared to unmodified asphalt mixes.
- The Indian Roads Congress Specifications Special Publication: fifty three (2002) indicate that the period of next renewal may be extended by 50% in case of surfacing with modified bitumen as comparing with unmodified bitumen.

4.3 Recent applications

- A 25 km plastic changed bituminous concrete road was set in Bangalore. This plastic road showed superior smoothness, uniform behaviour and fewer rutting as compared to a plastics-free road which was laid at same time, which began developing terrible "crocodile cracks" very soon after. The process has also been approved, in 2003 by the CRRI (Central Road Research Institute Delhi).
- Justo et al (2002), at the Centre for Transportation Engineering, at Bangalore University used processed plastic luggage bags as associate additive in asphalt concrete mixes. The properties of this modified bitumen were compared to that of ordinary bitumen. It was noted that penetration and ductility values, of modified bitumen was decreasing with the rise in proportion of the plastic additive, up to 12 % by weight.
- Mohammad T. Awwad et al (2007), polyethylene as synthetic resin collectively variety of polymers employed to research the potential prospects to boost asphalt mixture properties. The objectives also include determining the best type of polyethylene to be used and its proportion. Two types of polyethylene were added to coat the aggregate
- High Density Polyethylene (HDPE) and Low Density Polyethylene (LDPE). The results indicated that grinded HDPE polyethylene modifier provides better engineering properties. The recommended proportion of the modifier is 12% by the weight of bitumen content. It is found to extend the stability and soundness, reduce the density and slightly increase the air voids and the voids of mineral aggregate.
- Shankar et al (2009), crumb rubber modified bitumen (CRMB 55) was blended at specified temperatures. Marshall's mix design was applied by ever changing

the modified bitumen content at constant optimum rubber content and subsequently tests have been performed to determine the different mix design characteristics and for conventional bitumen (60/70) additionally. This has resulted in much improved characteristics when compared with straight run bitumen and that too at reduced optimum modified binder content (5.67%).

5. Basic materials

5.1 Aggregate

Aggregate constitutes the granular part in bituminous concrete mixtures which contributes up to 90-95 % of the mixture weight and contributes to most of the load bearing & strength characteristics of the mixture. Hence, standard of the quality and physical properties of the aggregates should be controlled to ensure a good pavement. The properties that aggregates should have to be utilized in pavement are shown below-

- Aggregates should have minimal plasticity for better output. The presence of clay fines in bituminous combines can result in problems like swelling and adhesion of bitumen to the rock which may cause stripping problems. Clay lumps and friable particles should be limited to utmost 1%.
- Durability or resistance to weathering should be measured by sulphate soundness testing.
- The ratio of dust to asphalt cement, by mass should be a maximum of 1.2 & a minimum of 0.6.It is suggested for better result AASHTO T-209 to be used for determinant the maximum specific gravity of bituminous concrete mixes.

5.2 Mineral Filler

Mineral filler consists of, very fine, inert mineral matter that is added to the hot mix asphalt, to increase the density and enhance strength of the mixture. These fillers should pass through 75μm(micron) IS Sieve.
The fillers may be cement or fly ash.

6 CONCLUSION

The integration of waste plastics into pavement engineering represents a transformative approach toward achieving sustainability, resource efficiency, and enhanced pavement performance. This comprehensive review has systematically examined the role of waste plastics in flexible pavement construction, with particular emphasis on material processing techniques and mix design methodologies. The findings collectively demonstrate that waste plastics, when appropriately processed and incorporated, can serve as effective modifiers for bituminous mixes, offering measurable improvements in strength, durability, and resistance to common pavement distresses.

A critical outcome of this review is the recognition that material processing techniques significantly influence the performance of plastic-modified pavements. Mechanical processes such as shredding and granulation primarily affect particle size and dispersion, while thermal and thermo-chemical treatments enhance polymer–bitumen compatibility and interfacial bonding. The reviewed studies indicate that controlled processing conditions are essential to ensure uniform distribution of plastic within the mix and to prevent issues such as segregation, incomplete coating, or thermal degradation. Consequently, standardized processing protocols tailored to specific polymer types are necessary for achieving consistent and reproducible pavement performance.

Mix design methodologies were found to be equally decisive in determining the effectiveness of waste plastic incorporation. Both dry and wet mixing approaches offer distinct advantages, with the dry process demonstrating practicality and ease of field implementation, while the wet process provides superior control over binder modification and rheological properties. Performance-based mix design frameworks, incorporating mechanical, durability, and aging-related parameters, have proven more reliable than conventional volumetric approaches for evaluating plastic-modified mixes. However, variability in testing methods and evaluation criteria across studies continues to limit direct comparison and broader implementation.

From a sustainability perspective, the utilization of waste plastics in pavements contributes substantially to environmental protection by diverting plastic waste from landfills, reducing dependency on virgin bitumen, and lowering overall life-cycle environmental impacts. Economic assessments reported in the literature further suggest potential cost benefits through reduced material consumption and extended pavement service life. Despite these advantages, challenges related to long-term field performance, recyclability of plastic-modified pavements, and the absence of unified design and construction guidelines remain critical barriers to widespread adoption.

In conclusion, waste plastic–based pavement engineering holds significant promise as a sustainable infrastructure solution, provided that material processing and mix design practices are carefully optimized and standardized. Future research should prioritize long-term field validation, development of performance-based specifications, and comprehensive life-cycle assessments to support policy formulation and large-scale implementation. By addressing these gaps, sustainable pavement engineering using waste plastics can evolve from experimental application to a mainstream, environmentally responsible practice in modern transportation infrastructure development.

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