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Recycling Waste Plastics In Pavement Engineering: Advances, Performance Enhancement, And Circular Economy Perspectives

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Abstract
Global accumulation of plastic waste has surpassed 400 million tons within a single year and only 9% of it is recycled which causes huge challenges to the environment and resources. One of the sustainable and scalable solutions to efficiently manage plastic waste is Avenue to Pavement. The most recent advancements and their recycling techniques are summarized in this review with special focus to aggregate, fiber, and filler usage in concrete, as well as dry and wet asphalt processes. The asphalt industry benefits from the addition of recycled plastic as it decreases the use of virgin plastics and improves the rutting resistance, fatigue life, moisture sustainability, and ageing durability. The addition of plastics to concrete lowers the density, enhances ductility, improves impact resistance and counteracts strength reduction through surface modification and hybrid composites. Recycled plastics geosynthetics, modular systems, and insulation frameworks offer long-lasting low-maintenance solutions. Issues pertaining to contamination, incompatible polymers, waste streams, microplastic emissions, and the absence of diverse regulations can be addressed through stringent feedstock requirements, advanced compatibilization, and performance-based regulations. Plastic-modified pavements can outperform the conventional systems economically and environmentally if processing is optimized and under supportive policy frameworks, according to lifecycle and economic assessments. The results generally confirm that recycled plastic integrated into pavement infrastructure is a high-performing financially feasible solution consistent with the objectives of the circular economy and global climate.
Keywords: *Plastic Waste; Asphalt Modifier; Pavements; Modified Bitumen; Sustainability; Circular Economy; Road Construction; Recycling.*

1. INTRODUCTION

Plastic waste is a recently emerged environmental issue that has drawn tremendous global attention since the advent of mass industrialization, urbanization and economic growth, resulting in an unprecedented speed of waste production [1]. Every year, approximately 400 million tons of plastic waste are produced globally, with only 9% estimated to be recycled appropriately. The majority is incinerated, leading to additional environmental impacts, or ends up in landfills, polluting our waters and causing significant environmental damage, as well as Greenhouse gas (GHG) emissions. Approximately 2060, global plastic waste is expected to almost triple to 1 billion tons per year [2]. The lack of biodegradability in plastics the reason for their value in so many sectors, from packaging to aeroplanes also makes them a galling and almost incomprehensibly persistent pollution problem [3]. Plastics can break down over hundreds of years to become microplastics, which then contaminate water and soil, harm wildlife and ultimately enter the human food chain [4].

(a) (b) (c)

Figure 1: (a) Burning plastic waste [5]; (b) Landfill disposal of plastic waste [6]; (c) plastic waste in the ocean [7].

Agricultural plastic waste, electronic and equipment sales, packaging, manufacturing-produced plastic waste, including building materials, as well as the automotive sector, are all among the significant contributors to the hoarding of much of this material. Specifically, a notable quantity of the post-consumer waste consists of single-use plastics such as polyethylene (PE) systems, polypropylene (PP) and polyethylene terephthalate (PET) systems [8,9]. For decades, the growing waste crisis and depletion of global resources have gained widespread attention and driven efforts across the globe to transition to a circular economy, in which waste is minimized and resources are durably recycled or made available for alternative uses [10,11].

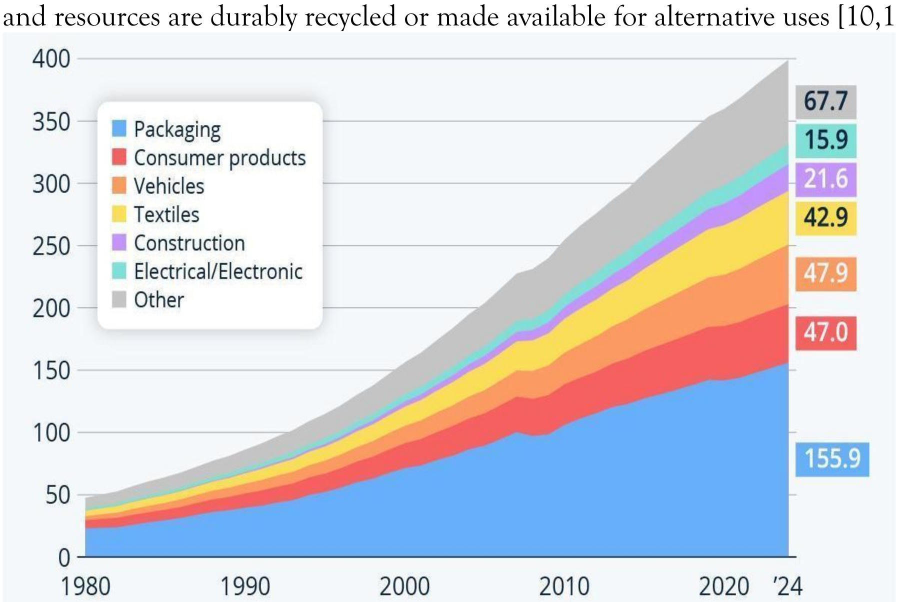


Figure 2: Global plastic waste production in million tons [12]

Recently, recycling of various types of municipal and industrial waste, like waste plastics, has raised considerable promise in the pavement sector. With over 64 million kilometers of roads worldwide, there is a growing requirement for longer-lasting and sustainable pavement materials. Infrastructure includes roads and highways, waterways, and railways It is forecast that in 2050, there will be an additional 25 million kilometers of road construction worldwide, spurred on by rapid urbanization and economic growth in the developing nations [13]. Traditional pavement materials, especially asphalt pavements, are composed of natural aggregates (sand, gravel, crushed stone) and bitumen as a binder. This creates environmental issues, such as energy use and emissions and land degradation, because they are heavily dependent on natural resources that help to deplete the stock of non-renewable materials and work against a well-built society [14]

In order to reduce these issues, researchers and engineers have been investigating the utilization of waste plastics as a partial modifier or substitution in concrete and asphalt pavements. Plastic waste was collected, sorted into different types, shredded and then pelletized to be added to bitumen for enhancement of its mechanical properties such as rutting resistance, fatigue life and moisture susceptibility. They can be mixed directly with an aggregate mix as well [15,16]. For instance, bitumen mixes modified with PET exhibited improved stiffness and reduced ageing phenomena, along with a notable effect of introducing PE and PP on enhancing strength at high temperatures [17,18]. When applied to pavements, the use of waste plastics generates environmental benefits such as controlling GHG emissions caused by road construction, saving resources and reducing artificial materials for landfilling all by sustainable development premises [19,20].

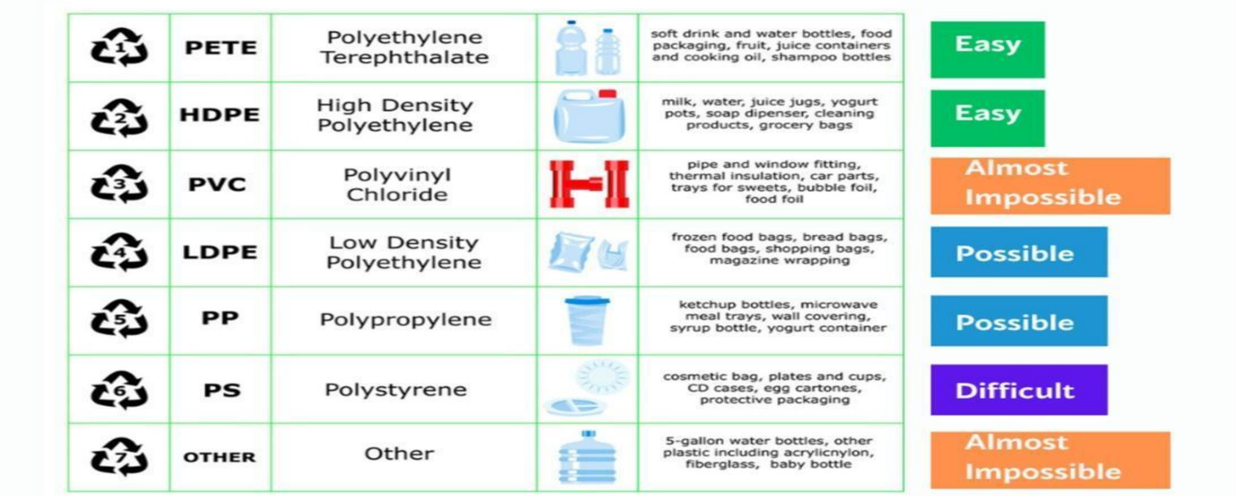
Figure 3: Plastic recycling process [21]

Plastic roads have been tested and some are already in use worldwide, including Australia, South Africa, India and the UK. These countries have indicated improved operational efficiency and durability compared to traditional methods [22,23]. In 2015, for instance, the government of India made it mandatory to use plastic in bituminous mixes, and almost 40,000 kilometers of roads have since been constructed from waste plastics. However, despite these achievements, problems relating to economic existence, environmental protection issues, i.e. safety and quality assurance, as well as the standardization of processes still exist [24]. However, for global application of these processes, concerns relating to long-term performance of plastic-modified pavements, microplastic release and preferred processing technologies need to be critically evaluated [25]. Accordingly, the use of waste plastic in road construction is being actively debated among scientists, politicians and industry partners [26]. In this paper, the techniques employed and improvements made to recycle waste plastics in the pavement industry nowadays are reviewed extensively. In addition to defining research gaps and future development opportunities, the aim is to explore other mechanisms through an intended evaluation of their feasibility, effectiveness, and environmental impacts.

2. Plastic Overview and Constituents

Most plastics are made of carbon and hydrogen with other elements like oxygen, nitrogen, or chlorine. These materials are frequently used in the modern world due to their low cost, light weight, maintainability and wide range for various shapes [27]. Though plastics composts are a useful item they remain as pollutions in the ecosystem for extra time. Plastic waste is the worst kind of waste made by people, as it lasts for hundreds of years before it degrade and that is what makes it one of the most problematic and long-term post-consumer stream [28]. Based on their categories, thermoplastics and thermosetting plastics are two of the most common types. Packaging and consumer goods are typical applications for thermoplastics because they require a rigid material that, when heated, achieves the right level of flexibility to mould and then returns to its original state after repeated shaping. Some of them are, namely, polyvinyl chloride (PVC), polystyrene (PS), PE, PP, and

PET [29,30]. However, when they cure, thermosetting plastics such as epoxy and phenolic resins create a permanent chemical bond and are used in applications that require higher strength and heat resistance [31].



Code	Abbreviation	Name	Uses	Recyclability
1	PETE	Polyethylene Terephthalate	soft drink and water bottles, food packaging, fruit, juice containers and cooking oil, shampoo bottles	Easy
2	HDPE	High Density Polyethylene	milk, water, juice jugs, yogurt pots, soap dipenser, cleaning products, grocery bags	Easy
3	PVC	Polyvinyl Chloride	pipe and window fitting, thermal insulation, car parts, trays for sweets, bubble foil, food foil	Almost Impossible
4	LDPE	Low Density Polyethylene	frozen food bags, bread bags, food bags, shopping bags, magazine wrapping	Possible
5	PP	Polypropylene	ketchup bottles, microwave meal trays, wall covering, syrup bottle, yogurt container	Possible
6	PS	Polystyrene	cosmetic bag, plates and cups, CD cases, egg cartones, protective packaging	Difficult
7	OTHER	Other	5-gallon water bottles, other plastic including acrylicnylon, fiberglass, baby bottle	Almost Impossible

Figure 4: Common uses, recyclability levels, and identification codes for plastic resin [32]

Table 4 provides the resin identification codes for common polymer types, and associated chemical classification, consumer applications and recyclability. Bottles, packaging films, and containers for materials of thermoplastic character such as PET, high-density polyethylene (HDPE) and PP also may be particularly suitable starting materials in jackets modification given their ubiquity and frequent post-consumer availability [33]. Plastics like PVC and PS are more difficult to recycle, causing them to be used less frequently. PET has better tensile strength, stiffness and thermal stability which are required to work with asphalt binder modification and resistance of HDPE and low density polyethylene (LDPE) for fatigue response and permanent deformation control in asphalt mixtures. Collectively, this demonstrates the ubiquity in municipal waste applications and the diversity of recyclability with these polymers; highlighting a requirement for selective recovery strategy for use in pavement engineering [23,34].

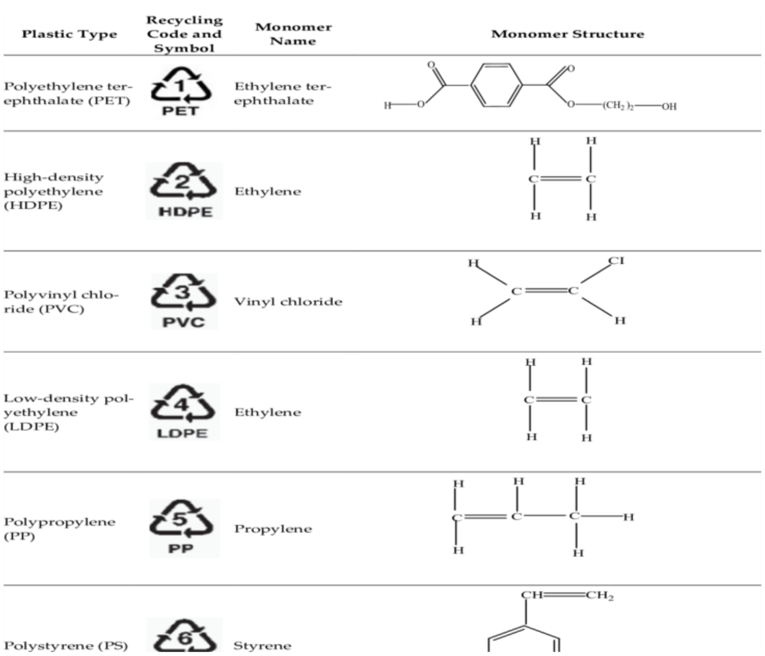


Figure 5: common plastic polymer and their basic monomeric structures [35]

When it comes to how plastics behave in hot and stressful situations, their chemical makeup is crucial. Figure 5 displays a schematic that outlines the backbone and monomeric structures of some standard plastic polymer chains. For example, the more branched HDPE has higher densities and tensile strength but less flexibility, whereas to give LDPE a degree of flexibility, linear structures are needed [36]. Table 1 Overview of physical and chemical properties needed for plastic type applied in pavements, which include degradation temperature, tensile strength, melting point, etc. To achieve the desired performance improvement of waste plastics altered asphalt mixtures, it is important to understand these characteristics. Moreover, incorporating these materials in bituminous mixtures may further reduce the bitumen content, which probably maximizes the use of material and may result in the realization of construction savings [37] [38]. In plastic-modified asphalt designs, plastics are typically wet or dry processed in order to shred, pelletize, or granulate the plastics prior to adding them to a mix. Plastic is used as an aggregate filler in the dry process and changes rheological parameters after blending with hot bitumen during the wet process [39,40]. Both approaches aim to minimize mechanical property losses and life-cycle costs, and to move towards a more sustainable environment by diverting plastic from landfills. However, the specific method chosen depends on the plastic type, intended performance characteristics and monetary considerations [41].

Table 1: Common waste plastic types and their pavement-relevant properties

Plastic Type	Melting Point (°C)	Density (g/cm^3)	Common Waste Forms	Pavement Relevance
LDPE	105–115	0.91–0.93	Bags, wrappers	Good binder compatibility [42]
HDPE	120–130	0.94–0.97	Containers, bottles	Enhances stiffness and durability [42]
PP	160–170	0.90–0.92	Caps, packaging	Improves rutting resistance [43]
PET	245–265	1.35–1.38	Bottles, trays	Requires modification for asphalt use [44]
PS	90–100	1.04–1.06	Cups, foam packaging	Less commonly used in pavements [45]

Nonetheless, the variety of plastic waste streams hampers standardization and broad use. The performance and long-term serviceability of the resultant pavement material may be influenced by certain additives, dyes, stabilizers or fillers that are commonly included with waste plastic materials [46]. Similarly, if waste plastics are not properly separated and different types of plastic, such as PVC or thermosetting resins, are added during the lifetime service, then undesirable chemical reactions or mechanical failures might also occur. Accordingly, detailed knowledge on plastic constituents, concentration levels, as well as pre-treatment protocols is critical to ensure the optimal utilization of waste plastics in pavement materials [47]. The use and composition of different raw material plastics significantly impact their thermal behavior, making it crucial to make informed choices to achieve the desired results in engineering and environmental applications [37]. To support the implementation of plastic waste in national road-building strategies, research is ongoing to identify the optimal processing conditions for this practice, which should interact well with bitumen polymer and demonstrate good field performance [48].

3. Waste Plastic Recyclability Challenges

Though the application of waste plastics in pavement infrastructure is emerging as a viable technology, multiple technical, legal and environmental barriers are limiting its penetration. Post-consumer plastic waste – This is one of the most significant problems [49]. Various polymers such as, PE, PP, PS and PET were used due to their different melting points, densities, chemical composition, and compatibility with cementitious matrices or asphalt. Commonly, these polymer mixtures are detected in municipal and industrial plastic waste streams [20]. This diversity complicates recycling, as incompatible polymers can phase separate and show poor interfacial bonding, and a composite with inferior mechanical properties will result [50]. For instance, though low melting point polymers such as LDPE and HDPE can be incorporated into bitumen by dry mixing quite easily, high-melting-temperature plastics such as PET or PVC may require processing temperatures beyond the norm offered in traditional asphalt plants to enable attachment of the polymer to the conventional bituminous mix [37]. Its lack of uniformity of material especially stiffness, resistance to rutting and long-term durability can skew performance results one way or the other. More specific and especially significant is the technology challenge for non-bhermestic materials, say, for bottle plastics in mixed waste streams particularly (PE) [51]. For instance, recycling loses efficiency if it is contaminated with different types of municipal solid waste, and the process requires a high energy input for polyethylene pyrolysis (which often requires specially prepared catalysts). LDPE when burned is also not the cleanest fuel and downgrades other more recyclable plastics due to its low density in mixed waste post-collection. The position, difficult to handle and expensive to dispose of, demands developed sorting systems and processing equipment for which there is not a thriving secondary market in recycled plastics [52]. The resulting product quality of LDPE and PET are heavily influenced by this interaction of the catalysts with thermal degradation behaviors. The absence of viable separation technologies, coupled with better processing routes and market drivers that enable the recyclability of plastics in all its forms must be solved together [53].

A second significant barrier is the contaminants and chemical additives in plastic waste. Most consumer-grade plastics include some combination of stabilizers, colorants, plasticizers, and flame retardants. In addition, these substances can decompose during the mixing process and give off toxic gases called volatile organic compounds, dioxins and furans [54]. Compounding the problem are residual food waste, as well as adhesives and inks remainders that often require additional cleaning steps that drive up costs and energy use. Other impurities and contaminants are mixed in this mixture material, which also reduces the mix quality, smoothness, and safety of production/maintenance life for asphalt or concrete, as well as presenting health and environmental hazards [55]. Moreover, the effects of these additives on ageing behavior, oxidation resistance and binder-plastic compatibility are not easily discerned, leading to a challenge in terms of prediction and optimization of their performance. Processing inefficiencies are yet one more issue. The most commonly used form of end-of-use plastic for pavement is through mechanical recycling, which requires heavy chopping, grinding and sorting to create homogeneous, clean particles. These processes often require provisioning of energy and are feedstock dependent [23]. Current practice also leads to a lack of long-term field performance data regarding fatigue resistance, low-temperature cracking, and moisture susceptibility at least under different loading and climatic conditions. However, laboratory studies often indicate improvements for some specific performance parameters such as stiffness or rutting. This uncertainty, combined with fears over potential microplastic leaching and long-term environmental impacts, suggests there is a case for further research before the widespread adoption of plastic-modified pavements [47]. Table 2 lists some of the primary recycling processes by plastic type. This table lists the recycling processes, resources, and properties of some common polymers in post-consumer waste streams

Table 2: Recycling Methods by Plastic Type

Plastic Type	**Recycling Method**	**Process**	**Waste Source**	**Characteristics**	**Common Products**	**Ref.**
PET, HDPE	Closed-Loop (Mechanical)	Re-extrusion, pelletizing	Post-industrial	High-quality reuse; minimal degradation; cost-effective	Bottles, containers	[56]
LDPE, PP, PS	Mechanical Recycling	Shredding, washing, melting	Post-consumer	Downcycling common; requires sorting/cleaning; lower-quality output	Bags, packaging, toys	[56]

PET, PU, PA	Chemical Recycling	Pyrolysis, glycolysis, hydrolysis	Post-consumer	Breaks down to monomers/oils; high cost but sustainable	Textiles, foam, nylon	[57,58]
PVC, Multilayer Films	Energy Recovery	Incineration, gasification	Non-recyclable waste	Toxic emissions (HCl); last resort for energy	Pipes, cling films	[56,59]

Table 2 shows how the recycling method of each plastic type can affect both its technical feasibility for reutilization and the environmental and economic trade-offs related to it. There are still human health and environmental safety concerns. One of the research studies found that plastic-modified pavements are likely to release microplastics due to mechanical stress, Ultraviolet (UV) degradation or surface wear over their lifespan [20]. The spread of microplastics into stormwater networks and nature contaminates the environment, raising concerns about the long-lasting effects of plastic-based pavement technologies on ecological systems [60] . Furthermore, the emergence of toxic air contaminants when asphalt is produced with high-temperature processing, particularly in open systems without proper emission controls, has prompted calls for enhanced environmental assessments and best-practice guidelines [61]. From a regulatory and economic perspective, the inability of recycled plastics for pavements to meet any uniform quality standards or performance specifications, compounded with disparate approval mechanisms in various jurisdictions, is acting as a significant barrier towards their universal adoption. Governments in most countries are still hesitant to adopt plastic-modified materials due to a dearth of longevity data, an unknown safety profile and insufficient technical validation [62]. For instance, the use of recycled plastics can become more economically viable when oil prices are reduced, and as a result, virgin resources are less cost-effective. This drawback is especially noticeable during times of low oil prices, when preprocessing and quality control costs are too high to make recycled plastics competitive [63]. Other limitations include the absence of infrastructure necessary for proper sorting and quantification of recovered plastics to meet construction-grade expectations, as well as potential difficulties in ensuring consistency and compliance in plastic sourcing due to the lack of tracking technology [64].

4. Waste Plastic Recycling Techniques

Although recycling of plastic waste into asphalt pavement applications presents an environmentally sound solution for minimizing the environmental impact of disposing of plastics, it also imparts various beneficial mechanical properties to the asphalt mixtures. The different results obtained with this method, among others, are due to the choice of recycling method, type of plastic and interaction mechanisms between plastic and matrix. The concern over plastic waste and the exploitation of natural resources is gaining importance, leading to the development of incorporating plastic waste into asphalt pavement materials [15].

4.1. Dry process: incorporation of plastics as aggregate modifiers

For asphalt mixture, the dry process is one of the most common methods to combine waste plastics [39]. This method involves adding plastic either in pelletized form or as shredded material straight to the heated aggregates, before mixing in bitumen [37]. This is especially effective for thermoplastics like PP, HDPE and LDPE, since these polymers have very low melting temperatures, and are also abundantly available in the post-consumer waste streams [65]. Most plastic added by the dry process mainly functions as stiffening agents or filler modifiers, thus improving the pavement's resistance to permanent deformation, especially at high temperatures as well as heavy traffic conditions [66]. The rutting resistance of various LDPE and HDPE polymer bituminous mixtures has been reported to improve in several experimental studies, where tensile strength and Marshall stability have been comparatively increased [67,68]. The size, shape and dispersion of particles of the plastic additive also play a significant role in determining the efficacy of dry-processed asphalt mixes. Typically, finer particle sizes allow improved dispersion and adhesion [39]. Dry processing does not require the modification of existing asphalt manufacturing facilities and is therefore scalable, as well as cost-effective. If not appropriately addressed, the issues of poor bond between plastic and binder or segregation of plastic particles during mixing and compaction can compromise the performance of the pavement as a whole [69].

4.2. Wet process: plastics as binder modifiers

Melting plastic waste in hot bitumen by a wet process contributes more molecular interaction of the components of bitumen with polymer chains [70]. This process can be particularly useful for tuning the binder rheology to improve its viscoelastic properties and resistance to thermal cracking and ageing [71]. For the wet process, combinations of recycled polyolefins as well as HDPE, LDPE and PET are used with plastics being the most frequently quoted form. In particular, PET has attracted attention due to its high melting point, stiffness and oxidation resistance. The modified binders containing PET exhibit improved performance grading behavior than that of the unmodified binder as per Superpave protocols, as seen from significantly lower penetration value and higher softening point values [18,72,73]. Generally, the wet processing requires a shear mixing system to incorporate shredded plastic (now <1 mm) into molten bitumen at 160–180 °C, gradually. In contrast, development time can vary from as short as 30 min to about 90 min based upon the concentration and type of plastic material Although the wet method improved homogeneity and precision of dry process, it is expensive, time-consuming and demand more technological availability compared to the dry approach [61,74,75]. This process also necessitates the proper dispersion within the asphalt matrix, and accurate mixing conditions are applied in order to prevent heat degradation of the polymer [23,76]. The effects of different plastic types such as PE, PP, PET on the rheological and mechanical properties of asphalt mixtures are summarized in Table 3. PET provides stiffness and moisture resistance but can reduce flexibility in cold climates, while the co-PET plastomers do not. The use of these plastics increases rutting resistance and high-temperature stability for hot-climate applications. Naturally, performance will depend on processing formula and amount of the followed additive.

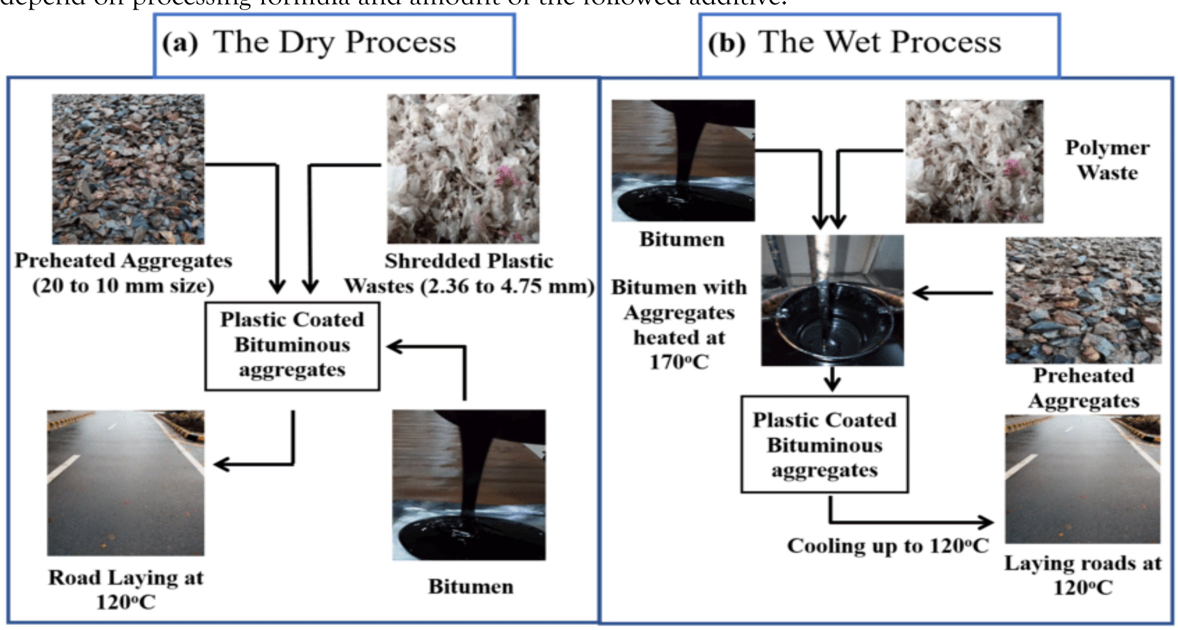


Figure-6: (a) Dry and (b) Wet process for plastic roads manufacturing [77]

4.3. Pre-treatment and compatibility enhancement

The preparation method in advance is an essential process to apply the waste plastics into asphalt effectively, which can ensure compatibility and environmental friendliness. Impurities, food residues, pigments and multilayer coatings are common with raw plastic debris, especially from post-consumer sources, which could hinder the durability and performance of the modified asphalt [78]. Hence, the pre-treatment steps, sorting, cleaning, shredding, drying and palletization are needed to ensure uniformity in composition and compatibility [79]. The compatibility of bitumen and polymer will also affect the mechanical properties and storage stability of hot mixtures. Compatibilizers like wax-based additives such as PE wax or copolymers with maleic anhydride grafted onto their molecules have also been investigated to enhance the interaction between non-polar plastics chains and polar bitumen components [17,80]. These additives allow a better dispersion of the plastic in the bitumen, reducing phase separation, which increases the homogeneity and mechanical performance of the asphalt mixture [81]. Formulations like this are important to address not just the environmental issue of using plastic waste as a component in roads, but also the structural and long-life integrity of road infrastructure [82]. Moreover, recent studies addressed the utilization of nanomaterials such as graphene oxide (GO) or nano-clays to improve the compatibility and dispersion of recycled plastics in asphalt binders [83].

4.4. Hybrid techniques and emerging approaches

Hybrid recycling methods have become increasingly common; this means that either a variety of polymers are blended or polymer waste is mixed with other industrial byproducts such as fibers, fly ash, or crumb rubber (CRM). These techniques aim at maximizing the stiffness, flexibility and fatigue performance of asphalt mixtures [84]. For example, there exist synergistic effects on the improved resistance against rutting and cracking for PET and CRM combined [85]. These generic hybrid processes not only reinforce the mechanical properties of asphalt, but they are also very efficient recycling technologies in the circular economy, utilizing various waste streams [86,87]. This integration can generate material performance benefits to aid sustainable infrastructure development whilst reducing dependence on virgin materials and thereby environmental impact [88]. The continued development of such approaches highlights the key role performance-based design principles must play to guarantee that new and novel materials, including even wastes in a variety of forms, can meet the challenging engineering needs for achieving long service life [89]

Chemical depolymerization, solvent dissolution and pyrolysis are some promising new recycling techniques of mixed plastic waste into bitumen-compatible compounds. However, these approaches are still in their embryonic stage and often suffer from high energy consumption involved, complex processing overheads, and limited scalability [87]. Despite these challenges, ongoing research to explore such innovative methods is crucial for providing a holistic and financially sustainable solution towards mainstream application of plastic waste in asphalt pavements [90]. Moreover, the sustainable design of road infrastructure will require moving beyond just mechanical properties of new mix designs to more comprehensive life cycle assessment in order to understand carbon footprints and other environmental benefits from using waste materials such as plastics in asphalt mixes [91]

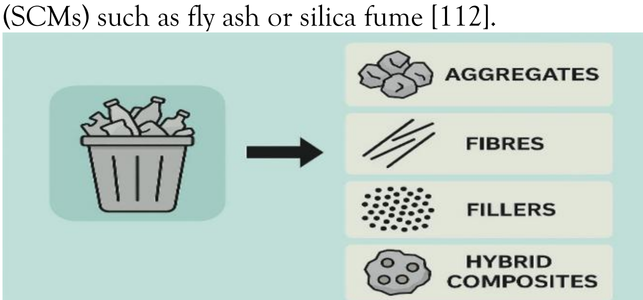
Table 3. Effects of waste plastic modifiers on asphalt performance

Asphalt Attribute	Observations	Explanation	Sources
High-temperature performance	Increased complex modulus and reduced phase angle; enhanced rutting resistance.	Plastics like LDPE and HDPE increase stiffness and elasticity at high temperatures, reducing deformation.	[92,93,94]
Fatigue resistance	Improved fatigue life under repeated loading at moderate strain levels.	Plastic modifiers enhance binder elasticity, reducing crack propagation under cyclic loads.	[95,96]
Moisture resistance	Enhanced adhesion with aggregates and decreased stripping.	Plastics increase cohesive-adhesive strength and decrease binder permeability in wet conditions.	[97]
Low-temperature cracking	Results differ; some research indicates a rise in brittleness and stiffness.	Due to the excessive stiffening caused by the plastic content, cracks may appear at temperatures below freezing.	[98,99]

Aging resistance	Enhanced ability to withstand binder hardening and oxidative ageing.	Plastics slow down the bitumen's ageing process by acting as antioxidants.	[100]
Workability and mixing	A slight decrease in workability necessitates higher mixing temperatures.	The melting points of thermoplastics, which necessitate higher processing temperatures, affect workability.	[34,101]
Environmental performance	Decreased dependency on virgin polymers; possible issues with microplastic production while in storage.	Enhances sustainability, but further investigation is required to fully comprehend the long-term environmental impacts (such as microplastics).	[102,103]

5. Possible waste plastic recycling techniques in concrete

Integrated approach using waste plastics in concrete aggregate for reducing mechanical loading on basic traditional concrete ingredients as well as plastic pollution [104]. Plastic waste is converted into various raw material forms, yielding different roles within the concrete matrix, as demonstrated in Figure 7. These include aggregates, fibers, fillers, and Hybrid Composites. One of the most common applications is that plastic waste such as PET, HDPE, LDPE and PP is replacing natural aggregates. These plastics can be used as a filler in the form of either shreds or granulates and can partially replace coarse and fine aggregates. Mixing plastic granules into concrete, a practice that ranges from 5–20% in volume, was reported to significantly reduce the density of composites and enhance their impact resistance features and thermal insulation [64,105]. Nevertheless, plastics offer considerable potential in this area because the Interfacial Transition Zone (ITZ) between polymer and cement paste is deteriorated due to the hydrophobic nature and chemical inertness of their surfaces, which causes an adverse effect on reducing compressive and flexural strength commonly [106]. Therefore, to enhance the surface wettability and bonding, some pre-treatment methods have already been proposed such as silane coupling and alkali soaking [107].Another innovative recycling method involves the manufacture of isolated fibers from recycled plastic waste for secondary reinforcement. When these fibers are added to concrete in small amounts, generally 0.25–2% by volume, which can vary depending on the nature of the fiber, they significantly increase ductility, crack control, and post-cracking energy absorption capability compared to conventional concrete [108]. When tensile strength and shrinkage resistance are critical, fiber-reinforced concrete with recycled plastic is particularly advantageous for slabs on-grade, precast panels and pavement overlays [109]. Fiberization is also a strategy, not only for the mechanical, but more importantly, because it enables the use of thin plastic films and multi-layer plastics, which are difficult to recycle properly [110]. It can be employed as a partial cement replacement and also for micro-filling after grinding to fine particles. Although it is not pozzolanic, plastics serve to intermix the matrix and decrease permeability and water absorption up to particle sizes: < 300 μm [105]. At low replacement ratios (usually less than 10% by weight of cement), plastic powders improve concrete durability, but excessive use can retard early strength development and workability [111]. Recent studies have shown that these drawbacks may be reduced and overall performance may be enhanced by blending plastic powders with supplementary cementitious materials (SCMs) such as fly ash or silica fume [112].



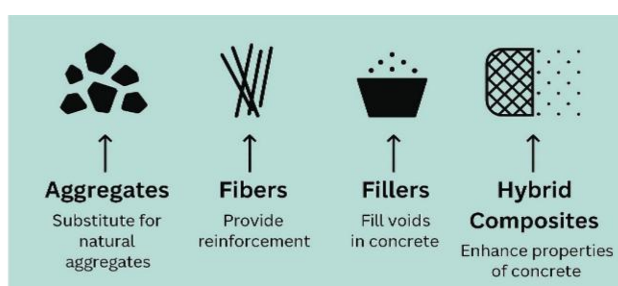


Figure 7: Concrete raw materials from plastic waste

Besides direct substitution methods, one creative way to include waste plastic into the concrete is engineered plastic-based aggregates. In most cases, waste plastics and industrial by-products such as fly ash, slag, or silica fume, are combined with cold bonding or thermal extrusion methods to produce these aggregates. The resulting aggregates are well suited for non-structural applications and thermal insulation layers as they are lightweight, chemically inert and may be tailored for strength and porosity [113,114]. Additionally, waste sheet plastic and laminate have been utilized to create elongated shape likely needle type plastic inclusions. This was achieved through the recycling of wind turbine blade materials, which were incorporated into concrete to enhance energy dissipation and deformation capacity. Such micro-impurities also contribute to enhancing the toughness under dynamic and flexural loading [115,116]. The poor interfacial bonding between the cementitious and plastic phases always remained a common technical problem in each recycling route. This chemical reactivity difference leads to reduced durability and stress transfer between the hydrophilic cement matrix and the smooth, hydrophobic surfaces of plastics [117]. In recent research, the use of sophisticated surface modification methods, such as oxidative grafting, plasma treatment, and the use of chemical compatibilizers, such as silanes or maleic anhydride grafted polymers, is under consideration to overcome this. Reactions such as these may assist in generating proper interfacial adhesion, in enhancing load transfer and in maintaining composite strength under conditions of environmental exposure. Furthermore, to overcome such incompatibility and attain an enhanced-durability Calcined Clay Fines (CCF) composite, new methodologies such as embedding plastic into cementitious matrices or using hybrid binders are investigated [118].

6. Other applications of plastic waste and repurposing alternatives

Plastic waste has successfully been recycled into various civil and construction applications, including the use as a constituent of asphalt and concrete pavements, which provides economic benefits and offers environmentally friendly alternatives to traditional materials [20,22]. One of the most popular techniques is also using recycled plastic in order to produce hollow blocks, prefabricated panels and interlocking bricks for modular building components. These components, which are often produced from processed or recycled PET or HDPE by compression or injection molding methods and their favorable characteristics such as lightness in weight, water-resistance as well as thermal insulation, render them suitable for provisional shelters, affordable housing developments and non-conventional load-bearing walls [119,120,121]. In addition, waste plastic, particularly expanded PS and polyurethane (PU), has been recycled into thermal and acoustic insulation boards. For example, it has been demonstrated that these panels can perform well in low-energy buildings by reducing thermal bridging as a result of creating more comfortable indoor conditions [122,123]. Novel composite insulation boards that use fly ash or biomass residues with plastic waste have also shown promising potential for enhanced environmental sustainability and fire resistance [124].

Roadside and urban infrastructure is also a typical application of plastic waste, using the material to create benches, bollards, curbstones, drainage covers or other street furniture. Such applications use plastic composites, often reinforced with wood fibers or mineral fillers for structural stability. However, they have poor corrosion resistance, lack impact durability, and are prone to chemical attack [125]. Led by the unique combination of rot resistance, dimensional stability and lower maintenance requirements, plastic lumber is an increasingly popular substitute for natural timber in decking, fencing and marine structures that are typically made from recycled polyolefins [126]. A more recent progression of this idea is to apply a hybridization concept to plastic boards, which can enhance their mechanical and environmental performance by integration with recycled plastic waste and industrial fibers or agricultural waste [127]. Waste plastics were also among the raw materials to produce geosynthetics, such as drainage grids, nonwoven geotextiles and erosion control mats, for landfills, slope stabilization and soil reinforcement. PP plastic mesh systems and erosion mats have demonstrated effectiveness in scripture revision by conditioning shallow surface runoff patterns and vegetative stabilization on steep slopes, promoting ecological resilience within geotechnical projects. In some Mumbai experiences, plastic waste is difficult to recycle mechanically due to presence of other contaminates (moisture, food residue, etc.), than this such type of a contaminated plastic waste can be utilized as alternative fuel in cement kilns or waste-to-energy systems because their high calorific value (30–40

MJ/kg) [128]. While this provides a way of removing waste in an environmentally friendly manner and lowers fossil fuel usage, it also results in the need for stringent emission control programs to mitigate the release of harmful pollutants that must be thoroughly evaluated before proceeding [129].

7. Cost-effectiveness aspects in plastic recycling and reuse

The most important factor for the application of plastic waste in the construction and pavement industry is its feasibility which solely depends on its economic viability. Traditionally, plastic waste valorization has been promoted mainly by concern for the environment, but now with some focus on cost-efficiency, life-cycle performance and long-term economic benefit of use of infrastructure solutions based on recycled plastics [130]. Plastic recycling is generally cost-effective due to several factors. However, the logistics of waste collection, infrastructure for sorting and processing, energy consumption, binder compatibility and the market value of final products are just some of the variables that must be evaluated [131]. With low capital and operating costs, mechanical recycling (whereby plastic is shredded, cleaned and processed into flakes, pellets or fibers) is the most feasible option for construction applications at present [132]. The dry process has been found to be more affordable for asphalt modification when integrated form of shredded plastics like LDPE, HDPE or PP is applied because a wet procedure demands specialized binder blending equipment or chemical additives. Studies have reported that substantial amounts of waste plastics can be added to the asphalt mixes (5–10%) to extend the life of pavement by 30–50% challenging use at higher initial mixing temperature and increasing complexities in handling [70]. Recycled plastic, on the other hand, can be used as an economical alternative to virgin polymer-modified bitumen's with similar rheological features when appropriately processed wherever it is expensive or not readily available [133].

The first is for composites, where using plastic waste in place of filler materials or fiber reinforcement adds a lower-cost filler that can be more attractive if post-consumer plastics processing streams are limited. Plastic waste as a low-cost raw material: Plastic waste is another solution for non-structural purposes like curbs and partitions, walls and pavement blocks [134]. However, the application of compatibilizers or advanced surface treatments or the development of hybrid aggregate production techniques negatively impacts the cost efficiency depending on whether high-energy thermal processes or chemical reagents are required to improve durability and bonding [135]. Finely ground plastic powders as cement replacements, if not synergistically used with a secondary cementitious material to make up for the strength reductions and maintain performance, may also not show clear economic advantages [128]. Besides the cost of materials, consider numerous other indirect economic benefits. There are lower demand for virgin materials, potential tax incentives and reduction in landfill tipping fees; preparation of sustainability certification programs such as manufactured or even more commonly known green procurement policies [136]; Therefore, engaging local isolated efforts of plastic recycling programs can be highly effective in stimulating local economies and contributing to creating jobs by using locally available plastic-based building materials. On the other hand, in low-income areas and developing communities with very little infrastructure for a formal waste management system, it could reduce infrastructure costs [137]. However, the price variance remains one of the most significant barriers to implementing the processes mentioned above on a vast industrial level. The crude oil price and its impact on the landfill mining processes. The competition of recycled materials to virgin plastic and bitumen-produced materials [138]. In addition, the lack of standardized specifications and performance certificates among infrastructure agencies hinders the broad application of plastic-modified pavements or plastic concrete, which also poses an obstacle to market penetration [139].

8. CONCLUSIONS

We need innovative and sustainable solutions as plastic waste accumulates in landfills much faster than it can be recycled. In this review, the current waste plastic recycling techniques in pavement construction have been demonstrated.

1. Asphalt pavements: Dry and wet processing of waste plastics can be used as aggregate modifiers and binder modifiers in asphalt pavements, respectively. The combination of these methods can be explained as enhancing fatigue life, ageing resistance, rutting resistance, and high-temperature stability, while reducing

dependency on virgin polymers. Problems such as incompatibility of polymers, variation in performances based on processes and heterogeneity of waste stream remain to be the major hurdles.

2. Concrete pavements: Waste plastics can be used as aggregates, fibers or fillers in concrete pavements, which will reduce the density, enhance ductility and only additional impact resistances will be needed. While a decrease in flexural and compressive strength often comes with these advantages, the limitations experienced underscore the need for surface modification, particle engineering, as well as hybridization with other cementitious materials to achieve full mechanical compatibility.

3. Wider applications: Recycled plastics are being used in other road-safety infrastructure products, thermal insulation materials, geosynthetics and pre-cast construction elements in addition to asphalt and concrete. It created untapped potential plastic valorization opportunities and enabled the fulfilment of circular economy targets.

4. Common challenges: There are numerous factors which present a challenge to the implementation of a variety of technologies on a larger scale, such as; contamination, mixed waste compositions, polymer incompatibilities, potential release of microplastics during service life and limited databases with standard requirements.

5. Economic and environmental perspectives: The cost-effectiveness of recycling depends on local waste collection, processing facilities, and market incentives. Policy settings should support advanced chemical or hybrid recycling processes. Dry-process asphalt can turn the demand for mechanically recycled plastics, with promising results. Environmental aspects, such as microplastics production, require large-scale monitoring and mitigation. Life-cycle economics includes more than processing, and policy setting should be tailored accordingly.

8.1 Future studies and recommendations

Future research should:

- Develop advanced feedstock characterization and compatibility enhancement strategies to ensure consistent performance.
- Extended field tests should be undertaken in a variety of traffic loads and climates to verify the lab results.
- Standardizing test methods for measuring and mitigating the release of microplastics from products to the environment across their life-cycles.
- Combine techno-economic and environmental evaluations to assess the integration of new advanced recycling technologies into current production flows.
- Develop Performance-based specifications, digital traceability systems, and harmonized policy measures to encourage broad, long-term support for solutions.

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