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Systematic Review

Recycled Plastics in Asphalt Mixtures: A Systematic Review of Mechanical Performance, Environmental Impact and Practical Implementation

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Abstract

The growing environmental impact of plastic waste and the high energy consumption in traditional asphalt production have driven the search for more sustainable alternatives in road construction. This systematic review evaluates the incorporation of recycled plastics into Hot Mix Asphalt (HMA) and Warm Mix Asphalt (WMA), focusing on their effects on mechanical performance and environmental outcomes. Using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA/ScR) methodology, 39 studies published between 2012 and 2023 were analyzed to compare plastic types, incorporation methods (dry, wet, and pyrolysis), and dosage levels. Results show that plastics such as Polyethylene Terephthalate (PET), Low-Density Polyethylene (LDPE), and Polypropylene (PP) can improve stiffness, rutting resistance, and fatigue life. WMA technologies, while less commonly applied, offer significant environmental advantages by reducing greenhouse gas emissions and energy consumption. The review highlights the critical role of plastic type, blending method, and local conditions in optimizing performance. Overall, integrating recycled plastics into asphalt mixtures presents a promising pathway toward more durable and sustainable pavement infrastructure.

Keywords: asphalt mixtures; recycled plastic; sustainability; road construction; plastic waste

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Academic Editors: Paulo Santos and Roberto Zivieri

Received: 10 July 2025
Revised: 23 August 2025
Accepted: 1 September 2025
Published: 10 September 2025

Citation: Calderón-Ramírez, J.; Sepúlveda-Valdez, D.; García, L.; Lomeli-Banda, M.A.; Salazar-Briones, C.; Montoya-Alcaraz, M. Recycled Plastics in Asphalt Mixtures: A Systematic Review of Mechanical Performance, Environmental Impact and Practical Implementation. *Appl. Sci.* **2025**, *15*, 9901. https://doi.org/10.3390/app15189901

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1. Introduction

The world is undergoing constant environmental change, with one of the most critical challenges being the growing proliferation of plastic waste. Plastics, or polymers, are synthetic materials derived from petroleum-based compounds through polymerization processes, and their widespread use has led to severe environmental pollution. As a response, various strategies are being explored to mitigate this problem, including their integration into road construction materials. Furthermore, oceans constitute approximately 70.9% of the Earth's surface, while the remaining 29.1% is terrestrial. Of this land surface, approximately 5.8% is occupied by road infrastructure [1,2].

The extent and use of road networks directly influence both the generation and management of plastic waste in the transport sector. Incorporating recycled plastics into pavements depends on the availability of suitable waste, which varies widely across

regions due to population density, consumption patterns, collection systems, and regulatory frameworks. While countries with advanced recycling technologies and strict policies, such as Japan or parts of Europe, achieve recovery rates above 70%, many developing regions face technical and policy constraints that limit plastic valorization. These disparities affect the feasibility and performance of plastic-modified asphalt, highlighting the need for solutions tailored to local conditions [3].

According to the United Nations Development Program (UNDP), approximately 139 million metric tons of single-use plastic waste were generated globally in 2021 [4]. Plastic consumption has increased steadily over the past three decades, surpassing 30 million tons in 2017, and it is projected to double by 2050 [5]. Most virgin plastic is produced in North America (18%), Europe (19%), and Asia (50%), particularly in China, Japan, and neighboring countries. Over 90% of these plastics are manufactured using fossil fuels, which are non-renewable resources formed over millions of years. Excessive dependence on fossil fuels results in greenhouse gas emissions and environmental degradation, making plastic waste a significant pollutant. Currently, only 9% of the plastic generated worldwide is recycled, with the rest ending up in landfills, being incinerated, or accumulating in natural environments such as oceans and forests [6,7].

Initially, it is necessary to define the properties, symbolism, and origins of plastic, as shown in Table 1, emphasizing their densities and the main products derived from the waste.

Table 1. Type of plastics, table manufactured according to [7].

Plastic	Symbol	Major Products	Major Physical Property and Biodegradability
Polyethylene terephthalate (PET)		Beverage bottles, food bottles/jars (salad dressing, peanut butter, honey, etc.), and clothing or polyester rope.	• Excellent mechanical properties (resistant to wear and folding). • Very good barrier to CO_2 and acceptable to oxygen and humidity. • High chemical resistance and thermal non-deformability. • Transparent and crystalline, and accepts some colorants. • Density ¼ 1.15 ± 0.03 g/cm^3, tensile strength ¼ 0.8 ± 0.14 N/mm^2 [8].
High-density polyethylene (HDPE)		Milk cartons, detergent bottles, cereal box liners, toys, buckets, park benches and rigid tubes.	• Tensile strength of 0.20–0.40 N/mm^2. • A density of 0.944–0.965 g/cm^3. • Its coefficient of thermal expansion varies between 100 and 220 × 10^{-6}. • Its maximum temperature for continuous use is 65 °C [9]. • Melting point = 131 °C, melt flow rate = 6.12 g/10 min [10].
Polyvinyl Chloride (PVC)		Plumbing pipes, credit cards, human and pet toys, rain gutters, teethers, IV fluid bags, medical tubing, and oxygen masks.	• Density = 0.77 to 0.88 g/cm^3 [11]. • Relatively resistant to sunlight and weathering, PVC will, after many years, cause granulation. • Melting point of 212–310 °C. • It comes from crude oil (43%) and salt (57%).
Low-density polyethylene (LDPE)		Plastic/Cling Wrap, Sandwich and Bread Bags, Bubble Wrap, Garbage Bags, Grocery Bags, and Drink Cups.	• HDPE density: 0.93 to 0.97 g/cm^3. • Moderate resistance to oils and greases. • Continuous temperature: −50 °C to +60 °C, relatively rigid material with useful temperature capabilities [12]. • Softening point = 85 °C, tensile strength = 8.96 MPa [13]. • Melting rate of 0.8 g/min at 190 °C [14].
Polypropylene (PP)		Straws, bottle caps, prescription bottles, hot food containers, packing tape and DVD/CD cases	• Polypropylene is highly neutral to acids, bases and solvents. • Low water vapor permeability. • Odorless and relatively easy to process. • It degrades at temperatures above 270 °C. • Density = 0.9 g/cm^3, melt index = 12 g/min [15].

Table 1. *Cont.*

Plastic	Symbol	Major Products	Major Physical Property and Biodegradability
Polystyrene (PS)		Cups, takeaway containers, product and shipping packaging, egg cartons, cutlery and building insulation.	• Easily attached by many organic solvents. • Melting point: 210–249 °C. • Density ¼ − 1.1 ± 0.19 g/cm^3. • Short service life compared to many other polymers and is likely to end up in the environment more frequently [8]. • Ultimate tensile strength of 28 MPa; heat deflection temperature of 92 °C [16].
Other		Acrylonitrile Butadiene Styrene (ABS) Used for electronic devices, Legos, personal protective equipment and helmets [17].	• Glass transition temperature ¼ 105 °C, no true melting point due to amorphous form. • ABS can be used between −20 and 80 °C. • Non-biodegradable.
		Ethylene Vinyl Acetate (EVA) Footwear industry, including soles and insoles [18].	• Linear molecular structure, specific gravity = 0.92, processing temperature = 65–80 °C [19]. • Provides the modification of asphalt through a crystallization of three-dimensional rigid networks, resulting in a considerable change in the physical, chemical and morphological properties of the asphalt [20].
		Polycarbonate (PC) CD and DVD.	• PC is one of the most important engineering plastics, as it has excellent mechanical performance, biodegradability, dimensional stability, flame resistance, and high stability at different environmental conditions [21]. • Specific gravity = 1.2, water absorption = 0.15%, compressive strength = 86.1 MPa [22].
		Polyurethane (PU) This is used in the food cold chain, in upholstered furniture and mattresses, shoes, automobiles, medical devices, as well as for thermal insulation of buildings and technical equipment.	• A 3D printing product [23]. • The resistance of PCs recycled from CDs and DVDs is only 20% lower than that of virgin PCs [24]. • A thermostable polymer, without degradation at high temperatures. • Density ¼ 1.12 g/cm^3, tensile strength ¼ 45 N/mm^2 [25].

According to Table 1, plastic is a material used in everyday life and is manufactured in many parts of the world. Despite being a material of great importance in daily life, it is also a waste product that negatively impacts many ecosystems. Therefore, new campaigns and recycling methods are needed to create healthier and less polluted environments. For instance, the recycling rate in the United States, a higher-income country, is very low compared to other countries that have reported recycling rates ranging from 30% to 60% of plastic reuse, with Japan boasting a plastic recycling rate of 78% [26]. The impacts generated by plastic waste have become recognized as a significant global conservation issue with implications for industries, tourism, marine life, human health, and the sustainable livelihoods of the population at large [27]. It is because of this type of waste that new ways to reduce this pollutant are being sought. Of course, reducing plastic use and advocating for a total ban on the material could be a quicker alternative. However, this could be a highly unorthodox method and complicated to implement, as it would be challenging to enforce and monitor [28].

Due to such cases, a considerable amount of research has been conducted, providing new perspectives on how to address this dilemma, particularly in the construction sector. For instance, the use of plastic waste as a substitute for sand in concrete offers a promising approach to reducing material costs and waste issues [29].

Additionally, the utilization of clean, dry, and crushed plastic waste in asphalt mixtures as aggregate for each nominal size aims to enhance their fracture resistance [30]. Furthermore, plastic usage is explored to determine its effect as an additive on the creep recovery behavior of HMA [31]. This residual polymer can be commonly used in asphalt mixtures to create sustainable pavements that provide environmental benefits and reduce pollution.

In road infrastructure, pavement structures are classified into flexible and rigid types, composed of one or more layers that facilitate land transport while providing safety, comfort, and cost efficiency [32]. Flexible pavements are roadways composed of granular materials, also known as aggregates, such as gravel and fines derived from rock crushing, along with asphalt materials obtained from petroleum distillation, thus constituting asphalt pavements.

Asphalt, also known as bitumen, plays a crucial role in asphalt mixtures, and it is important to define its classifications and functions when incorporating plastics, as this can be a significant factor to consider when aiming to create a polymer-modified mixture. Asphalt is a thermoplastic, bituminous, and viscous material with a dark appearance, composed of a mixture of hydrocarbons primarily derived from the distillation of crude petroleum. It is used to coat the aggregate entirely, facilitating material bonding [33]. When heated, asphalt gradually becomes soft to the point of a liquid and viscous consistency, primarily divided into Asphalt Cements (ACs), asphalt emulsions, and cutback asphalts, depending on their intended use [34].

It is important to note that there are different classifications for asphalts based on their Penetration Grade (PEN), which measures softness or hardness at specific temperatures, usually at 25 °C. The higher the penetration value, the softer the asphalt, typically in ranges of 10 units [35]. Another classification is based on Performance Grade (PG), which focuses on the material's performance at extreme temperatures and under traffic conditions. PG classification is specified by two numbers, such as PG 64-22, where the first number indicates the minimum temperature at which the asphalt will still maintain viscoelastic properties. The second number indicates the maximum temperature at which the asphalt will retain its properties, typically in ranges of 6-degree increments [36], as shown in figur.

The PG asphalt classification provides detailed information on the bitumen's behavior under different environmental and traffic conditions (Table 2).

Table 2. Asphalt classifications, table manufactured according to [33].

PG	**Maximum Performance Grade Temperature**						
	46 °C	52 °C	58 °C	64 °C	70 °C	76 °C	76 °C + n6 °C
	Minimum Performance Grade Temperature						
	+2 °C	−4 °C	−10 °C	−16 °C	−22 °C	−28 °C	−28 °C − n6 °C
PEN	**Penetration Ranges**						
	40–50		60–70		80–100		120–150

Asphalt mixtures are also categorized by mixing temperature: Cold Mix Asphalt (CMA), WMA, and HMA (Figure 1). HMA, the most common, is produced at 150–180 °C and requires significant energy input, whereas WMA is produced at lower temperatures (110–140 °C), offering environmental advantages such as reduced fuel consumption and lower emissions [37]. CMA is typically reserved for minor repairs and has limited large-scale application [38]. WMA, however, is gaining attention for its potential in sensitive environments due to its compatibility with recycled materials and reduced environmental impact [39].

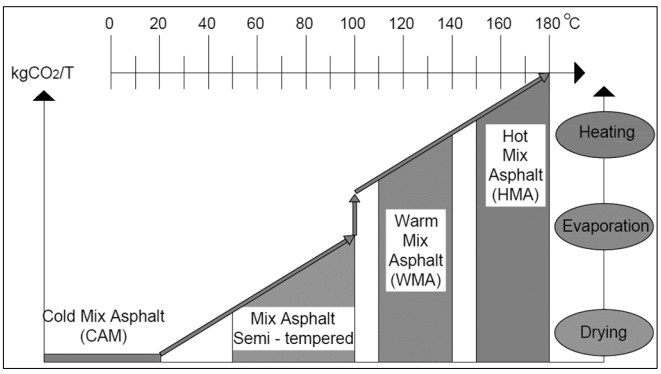


Figure 1. Mixture temperatures, according to Reference [37].

Over time, numerous research studies have been conducted on this particular topic, resulting in literature reviews covering key points such as engineering performance, cost benefits, and environmental impact [6,33]. However, despite the existence of these documents, there is a need for complementary research that compares the results of plastic incorporation into pavement and the methods of addition in asphalt mixtures used. Therefore, this study aims to conduct a systematic literature review that allows for a comparison of the main results between WMA and HMA incorporating plastics, and also indicates the best way to combine them, using the PRISMA/ScR methodology as a support to ensure proper document selection and information extraction. In this context, the present review seeks to answer the research question: Which type of recycled plastic and incorporation method offers the best balance between mechanical performance and environmental benefits in HMA and WMA mixtures [40]?

2. Materials and Methods

This study employed the PRISMA/ScR methodology [40], a structured protocol designed to ensure transparency and rigor in the identification, selection, and analysis of relevant scientific literature. The process involved a systematic series of steps to identify and extract studies that provided quantitative or qualitative data on the use of recycled plastics in asphalt mixtures. To facilitate the screening and organization of references, the Rayyan tool (Rayyan Systems Inc., Doha, Qatar; web application as of December 2023) [41] was used for managing duplicates and refining article selection.

2.1. Data Sources and Search Strategies

A three-stage filtering process was applied during the literature search. In the first stage, titles and abstracts were reviewed to eliminate irrelevant studies. In the second stage, articles meeting the inclusion criteria were read in full to extract key variables such as the type of plastic used, incorporation method (dry, wet, or pyrolysis), dosage levels, and operating temperature. Priority was given to studies that included laboratory evaluations or offered critical reviews of plastic use in asphalt mixtures.

Two distinct search strategies were implemented using major scientific databases, including Google Scholar, Scopus, EBSCO, and Web of Science, to gather a diverse and representative collection of studies involving HMA and WMA modified with recycled plastic waste. Search filters were applied to limit the results to peer-reviewed articles published between 2012 and 2023, written in English, and focused on experimental or analytical research.

The first search strategy employed the keywords “Effect”, “plastic waste”, “asphalt pavement”, and “asphalt mixture”, which primarily returned studies focused on HMA. Given the limited number of results for WMA, a second strategy was developed using the

keywords: “asphalt mix”, “sustainable pavements”, “plastic waste”, and “warm asphalt mixes”. Both search strategies were structured using logical chains tailored to each database, enabling the identification of relevant studies based on predefined criteria

2.2. Inclusion and Exclusion Criteria

The inclusion criteria for this study consisted of scientific articles in development or experimental state, journals, and scientific reviews in the specified language, with publication dates between 2012 and 2023, containing relevant information on the addition of waste plastic to hot or warm asphalt mixtures.

The exclusion criteria used involved documents excluded due to insufficient data, those that dealt with a material not under consideration, with publication dates outside the provided range, or at some point were identified as duplicate works of those included.

2.3. Article Selection Process

The article selection followed the four PRISMA/ScR stages: Identification, Screening, Eligibility, and Inclusion. In the Identification phase, an initial search using the keywords “Plastic” and “Mixes Asphalt” across the selected databases yielded 7441 records. To refine the results, two logical search chains were constructed, which reduced the dataset significantly. The first chain returned 555 records (mostly related to HMA), while the second produced 227 records (focused on WMA). After applying the inclusion and exclusion filters, a refined set of 350 articles remained.

In the Screening phase, the Rayyan reference manager (Rayyan Systems Inc., Doha, Qatar; web application as of December 2023) [41] was used to identify and remove 85 duplicates. The remaining 265 studies were assessed by reviewing their titles and abstracts, leading to the exclusion of 180 studies due to irrelevance or lack of data, leaving 85 articles for full-text analysis.

In the final Selection phase, the 85 full text articles were reviewed for eligibility. After further assessment, 33 articles met all criteria and were included in the review. Addition-ally, six relevant studies were manually identified and added, resulting in a total of 39 studies selected for systematic analysis.

The complete article selection process is summarized in Figure 2, which presents the PRISMA/ScR flow diagram used in this study [40].

2.4. Risk of Bias Assessment

To estimate the methodological quality of the included studies, a qualitative assessment of the risk of bias was conducted based on three key criteria: clarity of experimental design, control of variables, and completeness in the reporting of results. Due to the methodological heterogeneity of the studies analyzed, it was not feasible to apply standardized tools such as the Newcastle Ottawa Scale or ROBINS-I. Therefore, a grouped qualitative classification was adopted, as presented in Table 3, which organizes the studies according to common methodological characteristics and allows the identification of relative levels of bias (low, moderate, or high) to support the critical analysis of the findings.

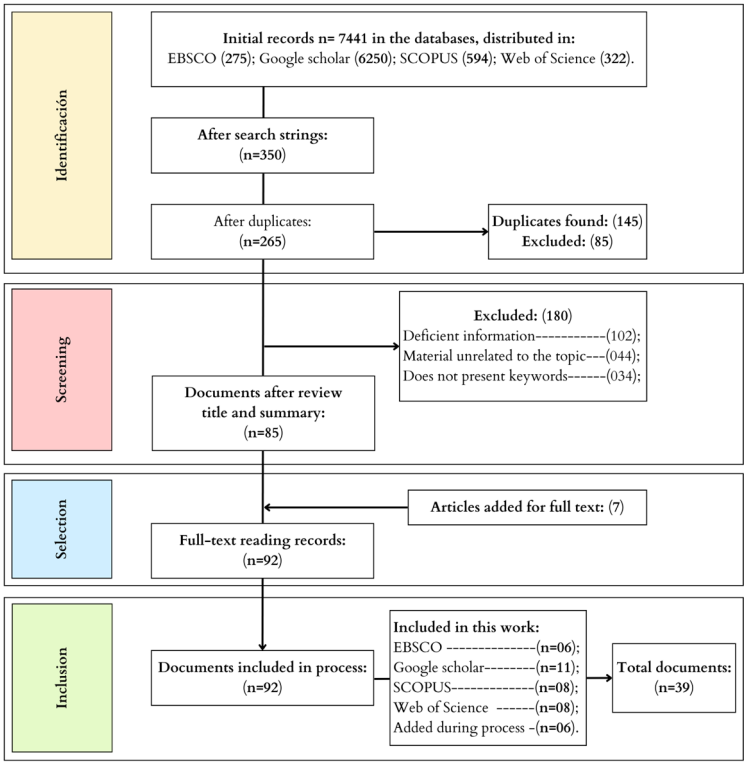


Figure 2. PRISMA/ScR process flow diagram.

Table 3. Risk of Bias Assessment.

Study Group (IEEE Reference)	Clear Design	Control of Variables	Risk of Bias
[30,31,36,42,43]	Yes	Partial	Moderate
[44–59]	Yes	Yes	Low
[60–70]	Partial	Partial/No	Moderate
[67,71–73]	No	No	High
[74,75]	Yes	Yes	Low

The PRISMA 2020 guidelines were followed when conducting this systematic review to ensure methodological transparency, consistency in article selection, and robustness in data synthesis [76]. The structured approach enhances the reliability of the findings and supports reproducibility across similar studies. The protocol was registered in the OSF platform (https://osf.io/4mr2q/, accessed on 25 July 2025)

3. Results

The findings of this review highlight the benefits of incorporating recycled plastics into asphalt mixtures as a strategy to promote cleaner environments and more sustainable pavements while maintaining performance and safety standards. Most of the studies analyzed focus on high-temperature applications, primarily through HMA, due to the relatively recent adoption and limited diffusion of WMA technologies [42]. In general, the selected research predominantly used conventional penetration grade asphalt binders such as 60/70 under standard test conditions [29,41–45].

3.1. Characteristics of the Included Studies

The temporal distribution of the included studies is shown in Figure 3, revealing a progressive increase in the use of technologies applied to asphalt mixtures. While HMA

dominated early studies, recent years have seen a significant rise in research focused on WMA. This shift reflects a growing awareness of environmental concerns and a trend toward lower energy technologies in pavement construction.

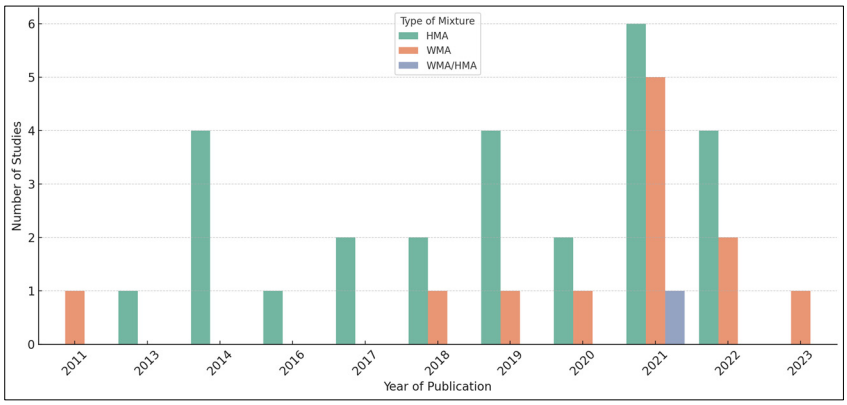


Figure 3. Temporal distribution of studies by type of asphalt mixture.

3.2. Data Extraction

This study focuses on research that explores the incorporation of plastic waste into asphalt mixtures using various methodologies. Articles were selected through the PRISMA/ScR framework, primarily targeting publications from 2012 to 2023. However, some studies outside this range were also included due to their substantial contribution to the research objectives and final analysis.

The selected studies were systematically categorized according to the type of plastic used, the incorporation method applied (such as dry, wet, or pyrolysis), and the type of asphalt mixture, whether HMA or WMA. For each study, key findings were extracted, including the type and percentage of plastic replacement, the asphalt grade employed, and the primary performance outcomes observed.

3.3. Ways of Incorporating Plastic into Asphalt Mixtures

Plastic is a synthetic or organic polymeric material designed to be molded into a wide range of shapes and densities. Its incorporation into asphalt depends on physical and thermal properties, which vary by type. As presented in Table 1, different plastics exhibit distinct characteristics (e.g., melting point, hardness, viscosity), making it necessary to select the appropriate incorporation method based on the type of waste available and desired performance.

Three primary incorporation methods were identified: dry method, wet method, and pyrolysis, each offering advantages and limitations depending on the type of plastic and mixture conditions.

The dry method consists of adding shredded or granulated plastic waste directly to the aggregates before mixing with the binder. This approach typically uses rigid plastics with high melting points, such as HDPE or PET, which can withstand mixing temperatures without degrading prematurely [46–48]. For instance, one study evaluated the use of PET flakes by replacing aggregate fractions passing through a 2.36 mm sieve with specific weight percentages of plastic [50]. Another investigation analyzed the effect of HDPE and LDPE on moisture resistance in HMA, assessing dry and wet incorporation through indirect tensile strength and stiffness modulus tests.

In contrast, the wet method involves modifying the asphalt binder itself by blending it with molten plastic prior to mixing with the aggregates. This technique is better suited for plastics with lower melting points, such as LDPE or PP, which can be more easily incorporated into the bitumen matrix [42,44,47,50]. For example, in the study by [44],

PP was added directly to the binder as a partial replacement, and the resulting modified asphalt was later blended with the aggregates, aiming to improve rheological behavior and durability.

The incorporation of recycled plastics into asphalt mixtures can be achieved mainly through the wet and dry methods. Each approach has specific characteristics, advantages, and limitations that determine its suitability depending on the type of plastic, asphalt mixture, and environmental conditions. Table 4 summarizes the key differences between these two methods.

Table 4. Comparison of Wet and Dry Processing Methods.

Aspect	Dry Method	Wet Method
Procedure	Shredded or granulated plastic is mixed with aggregates before adding the binder.	Molten plastic is blended with the binder before mixing with aggregates.
Type of plastics	Plastics with high melting points (HDPE, PET).	Plastics with low melting points (LDPE, PP).
Advantages	Simple, low cost, maintains plastic integrity.	Improves rheological properties and binder durability.
Limitations	Risk of non-uniform distribution, weaker interaction with binder.	Requires higher temperature control and specialized equipment.

The pyrolysis method involves the thermal decomposition of plastic waste in the absence of oxygen, converting solid plastic into waxes or oils that can later be blended into asphalt binders [74]. This method is primarily used to incorporate plastic into asphalt mixtures, mainly for support in the wet method. Pyrolysis is a beneficial process for facilitating the addition of plastic to asphalt due to the procedure it entails, as illustrated in Figure 4.

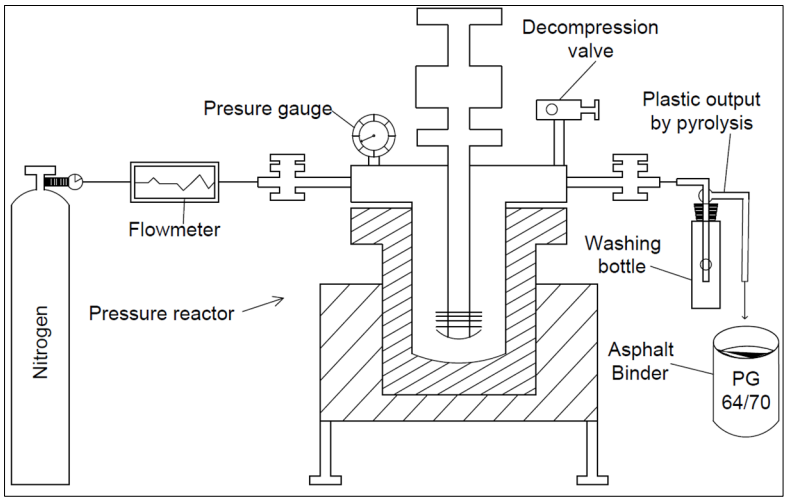


Figure 4. Schematic of pyrolysis process, according to Reference [62].

For example, Zhou et al. [62] employed pyrolysis to process PP waste by sealing it in a pressurized reactor, extracting oxygen using nitrogen gas, and heating the material while stirring at 120 rpm for 20 min. The resulting waxy compound was cooled and stored for later use as a bitumen modifier. In a similar study, Wang et al. [63] modified a base 70-grade asphalt with plastic-derived pyrolysis wax, evaluating the effects through rotary viscosity, Differential Scanning Calorimetry (DSC), and Dynamic Shear Rheology (DSR) tests. These

analyses demonstrated promising results in terms of binder consistency, workability, and resistance to high-temperature deformation.

3.4. Plastic in Asphalt Mixture Results

3.4.1. Polyethylene Terephthalate (PET)

PET is the most widely used plastic in asphalt studies due to its chemical properties and availability. In China, adding 70% pyrolyzed PET wax improved the softening point and viscosity of Crumb Rubber Modified Asphalt (CRMA) in WMA. Studies in Pakistan and Iran showed enhanced fatigue resistance and durability in HMA with PET, though doses above 2% may reduce resilient modulus. In Algeria, PET improved stability, moisture resistance, and deformation behavior. Thermally Linear Polypropylene (TLPP) and Viscous Polypropylene (VPP) variants in Turkey increased low-temperature performance and fatigue life. Regional conditions influence PET performance, as summarized in Table 5.

Table 5. PET Wet Method.

Mixture Type and Binder	Dosage and Size	Main Results	Country, Reference
WMA, PEN 70	1, 3, 5, 7%, Through a pyrolysis sintering process for PET.	• The effects of Recycled Pyrolytic Polyethylene Wax (RPPW), produced by a thermal cracking process, on the properties of CRMA were investigated. • RPPW showed a superior viscosity lowering effect on CRMA at high temperature (>100 °C) where the addition of RPPW increased the softening point and complex modulus but reduced the phase angle of CRMA.	China, [65].
WMA, PEN 60/70	3, 6, 9, 12%, Through particles with measurements of 3.5 mm and 1.75 mm.	• This study recommends the use of PET waste with aggregates of a basic nature (relatively more hydrophobic) to make smarter asphalt pavements. • The added minerals of calcium carbonate (limestone) and dolomite have created a stronger bond (less sensitive to moisture) with the residual PET modified asphalt binder. • The use of residual PET in flexible pavements improves the useful life, which would be a sustainable waste management solution in smart cities, especially in underdeveloped countries.	Pakistan, [60].
HMA, PEN 60/70	2, 4, 6, 8, 10%, With size of 0.425, 1.18 mm.	• The effect of PET was compared with that of Styrene Butadiene Styrene (SBS), which is a conventional polymer additive that has been widely used to modify asphalt mixtures. • Addition of more than 2% PET reduced the resilient modulus at both test temperatures of 5 and 20 °C. However, at all PET contents, the amounts of resilient modulus were within an acceptable limit. • Both additives improved the fatigue response of the studied mixtures. In any case, the SBS-modified blends showed to some extent better fatigue behavior than the PET modified blends, especially at strain levels above 200 microstrains.	Iran, [43].
HMA, PEN 40/50	3, 5, 7%, With size of 2.5–1.25 mm and 0.315–0.160 mm.	• PET polymer yields better results that could increase the resistance of bituminous asphalt against permanent deformation. • Improved stiffness at different temperatures because it is more thermally stable and can limit the risks of degradation of bituminous mixtures compared to the control mixture. • Flow resistances and creep recovery behavior were changed by adding waste PET particles. • With thicker PET size showed comparatively higher performance than thin size.	Algeria, [51].
HMA, PEN 45	1, 2, 3, 5, 10%, Crushed into flakes under a 10 mm sieve	• TLPP and VPP improve low-temperature performance and fatigue resistance of asphalt. • They improve Marshall stability and stripping resistance of HMA mixtures based on test results. • The modification process was carried out in an oil bath at 120 °C by mixing the base asphalt and additive for 10 min with a four-arm mechanical mixer rotating at 1300 rpm. • TLPP and VPP, except 1% (*w*/*w*) VPP, were found to decrease the viscosity and softening point and increase the penetration of the base bitumen.	Turkey, [64].

Table 6 summarizes studies using PET via the dry method to replace aggregates partially. Optimal content varies by country, often around 0.5%, with results showing improved stability, strength, and moisture resistance. In Iraq and India, PET enhanced cracking resistance and binder stiffness under short aging. In Canada and Chile, longer

PET fibers and higher polymer content improved low-temperature performance. Studies from Malaysia, the USA, the UAE, and the UK reported gains in adhesion, rutting, and durability. Fine PET particles showed the best outcomes in terms of Marshall stability and moisture resistance, particularly in Iraq.

Table 6. PET Dry Method.

Mixture Type and Binder	Dosage and Size	Main Results	Country, Reference
WMA	0.1, 0.3, 0.5, 0.7, 0.9, 1.1% of the weight of aggregate, 2.36 mm size PET.	• The testing program included Marshall, rutting susceptibility, and Indirect Tensile Strength (ITS) tests. • Results showed improvements in the properties of the modified mixtures with the optimal PET content (0.5%) by weight of the aggregate, producing an increase in stability, rigidity, ITS and resistance to moisture damage. • PET particles function as reinforcing fibers that resist tensile stresses.	Iraq, [66].
HMA, VG-30	0, 2, 4, 6%, With size grinding of 0.5 × 0.5 cm.	• The addition of this residue provides more resilience to the asphalt binder where Viscosity Grade (VG) asphalt was used VG-30, especially with a shorter aging time. • The storage modulus master curves (at lower frequencies) and relaxation modulus values (at longer times) indicate that the residue provides additional stiffness to the binder. • The overall results indicate that the residual plastic improves the properties of the asphalt binder over a prolonged loading period when it is heated for a shorter time during mixing.	India, [48].
HMA, PG 64-28	10%, With size of 18 and 6.5 mm.	• The reinforcing effect of PET fiber in terms of crack resistance of HMA depends on the dimensions of the fiber longer fibers with larger diameters tend to improve the crack resistance more effectively. • When the test temperature was lowered from ambient to −10 °C, the crack propagation path shifted from the asphalt binder phase to the aggregate interface. The reinforcing effect of PET fibers was more pronounced at room temperature.	Canada, [36].
HMA, AC-24	6, 10, 18, 22%, With size of 10, 5, 2.36 mm.	• The flow increases with the addition of polymers, generating greater deformability upon reaching stability failure. • AC-24 was used and the optimal percentage of PET additions in this research was 14% PET particles by weight of a binder when added via the dry process. • A mixture is created with greater stability, fluidity within regulatory limits and less rigidity, thus favoring reduced behavior at low temperatures.	Chile, [52].
HMA, PEN 80/100	Plastic particles of 0, 0.2, 0.4, 0.6, 0.8, 1% to 2.36 mm were crushed and used.	• Waste PET showed great potential to be reused as a modifier in the asphalt mixture. • The permanent deformation characteristics of the PET modified asphalt mixtures were markedly improved compared to the control mixture, and the mixture modified with a higher amount of PET was shown to have better resistance against permanent deformation. • At a temperature of 40 °C and stress level of 300 kPa and 400 kPa, the flow number (FN) was significantly increased by applying PET modification.	Malaysia, [50].
HMA, PG 58-28	PET from 2 water bottles (0–20%) was cut, dried at 45 °C for 2 h, conditioned at 18 °C for 4 h, and then crushed.	• Binder Bond Strength (BBS) and Tensile Strength Ratio (TSR) test results and Surface Free Energy (SFE) analysis suggest improved adhesion and resistance to moisture induced damage because of using MPET-modified binder in asphalt mixtures with granite and quartzite aggregates. • Superpave asphalt mixtures containing Modified Polyethylene Terephthalate (MPET) modified PG 58-28 asphalt binder mixtures and their resistance to cracking, rutting and moisture induced damage was evaluated by performing semicircular curvature, Hamburg wheel tracking and strength to traction. • Testing of asphalt mixtures showed that an increase in MPET content resulted in an increase in resistance to cracking, rutting, and moisture-induced damage.	USA, [53].

Table 6. *Cont.*

Mixture Type and Binder	Dosage and Size	Main Results	Country, Reference
HMA, PEN 60/70	0, 10, 15, 20, 25, 30%, With size of 2.36 mm (Crushed and cut).	• Stability was observed to increase by 14.2% compared to the conventional mixture and each sample exceeded the standards established by the Asphalt Institute. • In this study, the optimal asphalt mixture with PET as a reinforcing additive was determined. The volumetric and Marshall properties of the specimen were evaluated based on the Asphalt Institute standard specification. • It is determined that the optimal design is with 15% PET by weight of asphalt and 5% binder content.	Philippines, [49].
HMA, PG 64-22, AC 60-70	0.5, 1%, (Shredded and cut into fibers).	• At low temperatures, the tensile stress required to break the analyzed samples increased with increasing residual plastic fiber content. • The resistance to rutting at a temperature of 54.4 °C was increased by the addition of waste plastic fibers. • The optimal content of residual plastic fiber was 0.5% by weight of the mixture.	United Arab Emirates (UAE), [71].
HMA, PEN 40/60	6%.	• Asphalt containing recycled waste plastic products showed better resistance to deformation and fracture compared to conventional binder with 40/60 penetration rate. • Recycled plastic waste has been shown to improve the fracture and deformation resistance of typical UK asphalt mixtures compared to conventional 40/60 asphalt.	United Kingdom, [72].
HMA, PEN 40/50	5–25% plastic with thicknesses of 0.2–1 mm, passing 19.0 mm to No. 50 (0.3 mm) sieves.	• This article focused on the Marshall test and retained strength index to determine the properties of plastic waste particles, such as (size, thickness and percentage content), that provide maximum hot mix asphalt performance. • It was concluded that the addition of plastic waste with fine particle size of fine thickness and at 15% by weight of the total aggregate resulted in improving the Marshall stability and resistance to water damage. • Adding fine particles of crushed plastic waste (passing through the No.16 sieve (1.18 mm)) to the asphalt mixture increases the Marshall stability and the retained strength index by (18% and 12%) respectively compared to the conventional mix.	Iraq, [67].

3.4.2. Low-Density Polyethylene (LDPE)

Table 7 summarizes the application of LDPE in asphalt mixtures via the wet method. LDPE, often from shredded bags, improves mixture flow, reduces air voids, and increases resistance to moisture and deformation. In India, stability improved with 4% LDPE and 3% Sasobit. Iraq reported gains in crack resistance and durability using LDPE powder. In Ethiopia, LDPE enhanced stiffness and rigidity. In Malaysia, adding 20% LDPE by binder weight significantly improved tensile strength and moisture resistance. Results show LDPE's effectiveness varies by region, dosage, and application method.

Table 7. LDPE Wet Method.

Mixture Type and Binder	Dosage and Size	Main Results	Country, Reference
WMA, VG-10	4.2, 4.7, 5.2, 5.7%.	• An organic Sasobit additive was used for WMA Technology at a constant percentage of 3% by weight of bitumen with varying percentages of LDPE, namely 2%, 4%, and 6%, respectively, alongside VG-30 asphalt. • The incorporation of plastic increased the stability of the mixtures. Maximum stability is achieved with 4% plastic and 3% Sasobit. • The density of mixtures containing LDPE showed a decrease, accompanied by an increase in air voids within the mixtures.	India, [54].
WMA, PEN 40/50	2, 4, 6%, HDPE is used in powder form.	• Waste LDPE improves resistance to low temperature cracks and crack progression, in which the creep compliance value decreased by 83% compared to the control mixture when 6% of LDPE. • The addition of waste LDPE to the asphalt binder increases the stability and flow of the mixture by 48% and 33%, respectively, compared to the control mixture. • Durability in terms of water sensitivity is significantly improved as a result of the incorporation of waste LDPE.	Iraq, [61].

Table 7. *Cont.*

Mixture Type and Binder	Dosage and Size	Main Results	Country, Reference
HMA, PEN 60/70	7, 13,17%, With size of 2.36 and 4.75 mm.	• It was made with 6 to 18% with an increase of 3% by weight of the optimal bitumen content. • The application of Waste Plastic Bottles (WPB) is studied by incorporating it into the asphalt mixture; the result showed that the incorporation of this residue improves the stability and rigidity of the mixture and is environmentally friendly. • The modified asphalt mixture with WPB replacement shows lower bulk density, higher flow, air void and VMA.	Ethiopia, [30].
HMA, PEN 60/70	0.5, 1%, With size of 5–10 mm.	• The results demonstrate that the gradation of the aggregates was greatly affected by the method of adding plastic waste. • Results showed improvement in moisture damage, tensile strength and permanent deformation. • The improved dry process developed in this study presents a substantial improvement in asphalt performance, particularly with plastic waste representing 20% of the weight of the asphalt binder.	Malaysia, [55].

Table 8 presents the results of using LDPE in asphalt via the dry method, primarily in HMA. In China, combining LDPE with EVA improved thermal sensitivity resistance under specific mixing conditions. In Indonesia, LDPE enhanced adhesion, Marshall stability, and resistance to rutting and moisture, with strength gains up to 20%. In Algeria, using 5% LDPE led to significant reductions in total strain and improved stiffness and durability. These findings highlight that LDPE performance depends on plastic type, dosage, and process control under local conditions.

3.4.3. Polypropylene (PP)

Studies across several countries highlight the varied use of PP in asphalt mixtures, particularly through wet methods and pyrolysis processes. In China, pyrolyzed polypropylene improved asphalt penetration and reduced viscosity, enhancing elasticity, rutting resistance, and adhesion. In Iraq, combining PP with nanosilica improved durability and fatigue resistance, while Jordan identified 7% PP as the optimal content for mechanical stability. Another Chinese study using recycled PP additives showed better binder workability and extended fatigue life.

Overall, PP enhances mixture performance, though results depend on dosage, additive use, and local conditions. Details are summarized in Table 9.

Table 8. LDPE Dry Method.

Mixture Type and Binder	Dosage and Size	Main Results	Country, Reference
HMA, PEN 60/80	0, 2, 4, 6%.	• The permanent deformation resistance and deformation recovery capacity of asphalt were significantly improved after modification. • The three-dimensional rigid network formed by EVA could envelop LDPE particles, which could prevent the aggregation of LDPE, and it is beneficial for the thermal storage stability of the modified asphalt. • LDPE/EVA-modified asphalt exhibited optimal properties when prepared at 3500 rpm for 60 min at 180 °C.	China, [46].
HMA, PEN 60	0, 5, 10%. With size grinding of 9.5 mm and 0.6 mm.	• Mixtures with the addition of plastic waste are approximately 20% more resistant than the conventional mixture. • Molten plastic will adhere to the surface of the aggregate, increasing the adhesion of the grit and aggregate. • Addition of plastic waste in HMA will increase the Marshall stability and resilient modulus of the mixture, improve the stripping resistance, moisture sensitivity and also the resistance to rutting.	Indonesia, [73].

Table 8. *Cont.*

Mixture Type and Binder	Dosage and Size	Main Results	Country, Reference
HMA, PEN 40/50	5%. Shredded plastic bags of 1 and 3 mm^2.	• Two asphalt mixtures were prepared, basic and modified, and a four-point bending test was carried out at two different temperatures, medium (20 °C) and high temperature (50 °C). • A decrease in total strain by 51% and 13% at 20 °C and 50 °C respectively. • Improved resistance to creep, permanent deformation, rigidity and life span.	Algeria, [31].

Table 9. PP Wet Method.

Mixture Type and Binder	Dosage and Size	Main Results	Country, Reference
WMA, PEN 70	6%. Through a pyrolysis sintering process for PP.	• Pyrolysis temperature and pressure play a key role in producing wax-based WMA from Waste Polypropylene (WPP). • At 380 °C and 1 MPa, the product increased asphalt penetration by 61% and reduced viscosity at 135 °C by 48.6%, enhancing elasticity, rolling resistance, and adhesion. • The incorporation of WPP also improved the softening point, contributing to greater thermal stability.	China, [62].
WMA, PEN 40/50	3%.	• The addition of nanosilica and PP via the wet method improved mixture performance, increasing durability, fatigue resistance, and moisture damage resistance. • Nanosilica (2–5% binder weight) was added after polymer melting using a 3500 rpm mixer at 150 °C.	Iraq, [77].
HMA, PEN 60/70	2, 2.5, 3, 3.5, 4, 4.5%.	• PP asphalt mixtures showed improved physical properties and greater stability than conventional samples, especially at an optimal content of 7%. • Experiments conducted at 60 °C with asphalt contents from 5% to 7.5% confirmed 7% as the optimal proportion.	Jordania, [44].
HMA, PEN 70	5%. Through a pyrolysis sintering process for PP.	• This study evaluated the use of Waste Rubber Powder (WRP)-derived additives to improve the workability and mechanical performance of asphalt binder, analyzing viscosity, rutting factor, and fatigue life using laboratory methods Fourier Transform Infrared Spectroscopy (FTIR), Differential Scanning Calorimetry (DSC), and Fatigue Measurement (FM). • The additive improved binder workability and significantly extended its fatigue life.	China, [47].

3.4.4. Other Plastics

Studies demonstrate a wide range of plastics used in asphalt mixtures, offering diverse approaches and results across countries Table 10. In Egypt, using Superplast, a compound of EVA, LDPE, and other low-molecular-weight polymers, led to improved adhesion, stiffness, and moisture resistance. In China, Pyrolysis Wax (PW) from recycled plastics enhanced viscoelasticity, storage stability, and deformation resistance. The UK reported that chemically treated plastics mixed with rubber increased stiffness by 10% due to better bonding at the aggregate–bitumen interface.

Table 10. Other plastics, Wet Method.

Plastic Explanation	Mixture Type and Binder	Dosage and Size	Main Results	Country, Reference
Superplast	WMA, PEN 60/70	3, 4, 5%.	• Superplast is a compound of EVA, LDPE, and other low-molecular-weight polymers with medium melting points. • Its incorporation improves bitumen–aggregate adhesion and enhances stiffness, wear resistance, and moisture resistance in WMA mixtures. • An organic additive (fatty acid in wax medium) is used to enable WMA production at lower temperatures.	Egypt, [42].

Table 10. *Cont.*

Plastic Explanation	Mixture Type and Binder	Dosage and Size	Main Results	Country, Reference
WPP, PW	WMA, PEN 60/80	6%, via pyrolysis sintering of landfill-sourced WPP, crushed to 0.177–0.25 mm red granules.	• PW, derived from recycled plastics, acts as a WMA additive, enhancing viscoelasticity, aging resistance, anti-fatigue behavior, and deformation resistance. • PW-modified bitumen shows improved storage stability without noticeable chemical reactions, maintaining desirable physical performance. • The optimal production condition for PW was determined as 400 °C, 0.5 MPa, and 6% concentration.	China, [56].
Plastic and rubber mix	HMA, PEN 125	8%. With size of 1–4 mm.	• Plastics were chemically treated with oxidizing agents, while bitumen was modified with PET mine to enhance bonding at the aggregate-bitumen interface. • Chemically treated plastic increased stiffness by 10% across 10 cycles due to improved adhesion, outperforming untreated plastic in rigidity. • The observed stiffness gain is linked to stronger bonding forces, supported by a proposed mechanism explaining the effect of chemical additives.	United Kingdom, [57].
Commercial plastic waste MR6 and MR10	HMA, PEN 100/150	6%.	• The addition of plastic polymers increased binder stiffness after short-term aging, with effects comparable to conventional polymers. • Binder modified plastic waste was deemed a sustainable alternative to traditional polymers.	Australia, [58].
UHMWPE	HMA, PG 64/16	2%. It comes in the form of very fine solid particles between 150 and 120 µm.	• The use of 2% UHMWPE improved asphalt–aggregate adhesion and significantly enhanced fatigue life, especially in mixtures with granite and limestone. • Although it reduced the overall stiffness of the mixtures, it increased resistance to fatigue cracking.	Iran, [68].

In Australia, commercial plastic waste (MR6 and MR10) improved binder stiffness after short-term aging, showing potential as sustainable polymer alternatives. Iran's use of Ultra-High-Molecular-Weight Polyethylene (UHMWPE) improved adhesion and fatigue life, particularly with granite and limestone mixtures.

Overall, results highlight the potential of both conventional and modified plastics in enhancing asphalt mixture performance. However, the wide variability across countries and mixture types underscores the need for region-specific adaptation and implementation strategies.

Studies in Portugal evaluated the use of plastic film flakes and Cross-linked Polyethylene (PEX) in asphalt mixtures. The flakes increased stiffness in both WMA and HMA, although moisture resistance decreased in WMA. PEX, applied using the dry method, reduced mixture density by 5%, favoring its use in structural applications. As shown in Table 11, these findings highlight the importance of properly selecting the type of plastic, asphalt mixture, and binder content to balance mechanical strength and environmental durability.

Table 11. Other plastics, Wet/Dry Method.

Plastic Explanation	Mixture Type and Binder	Dosage and Size	Main Results	Country, Reference
Waste plastic film flakes	WMA/HMA, PEN 35/50	6%, plastic film flakes	• A WMA produced at 100 °C with 6% waste plastic film flakes slightly increased stiffness, showing similar fatigue resistance in both WMA and HMA. • Although WMA with plastic had lower humidity resistance, its Indirect Tensile Strength Ratio (ITSR) remained close to 80%, despite having the highest air void content. • Plastic incorporation improved stiffness at 20 °C in WMA (over 6000 MPa), though still lower than HMA values (above 8000 MPa), supporting roads with low-to-medium traffic.	Portugal, [69].

Table 11. *Cont.*

Plastic Explanation	Mixture Type and Binder	Dosage and Size	Main Results	Country, Reference
PEX mostly made of HDPE.	HMA, PEN 50/70	5% PEX, with laminar flakes ($Ø_e$q: 0.5–10 mm) and crushed plastic ($Ø_e$q: 0.5–4.0 mm).	• PEX added using the dry method reduced mixture density by ~5%, which can be advantageous for transport and structural applications like bridges. • While water sensitivity tests showed no significant improvement unless binder content was increased, PEX mixtures showed better resistance to permanent deformation. • Improved stiffness and lower phase angle in PEX mixtures indicate better thermal stability and reduced sensitivity to temperature variation.	Portugal, [70].

3.4.5. Studies with More than 1 Type of Plastics

The incorporation of multiple plastics, such as HDPE and LDPE, in asphalt mixtures has shown promising results, especially in WMA. In Australia, mixtures modified with both plastics using wet and dry methods were tested, revealing that the wet method reduced binder loss, rutting depth, and improved TSR and Marshall stability. HDPE provided better resistance to moisture damage, while LDPE enhanced overall performance. Tests like the Hamburg Wheel Tracking Test demonstrated greater effectiveness under moisture conditions. These findings, summarized in Table 12, highlight the importance of selecting appropriate plastics and modification methods based on environmental conditions and project needs.

Table 12. HDPE/LDPE Wet/Dry Method.

Plastic	Mixture Type and Binder	Method	Dosage and Size	Main Results	Country, Reference
HDPE/LDPE	WMA, PEN 50/70	Wet/Dry	3, 6, 9 and 12% in Wet process using HDPE/LDPE, 9% in dry process using HDPE/LDPE	• The performance of dry and wet methods using HDPE/LDPE in WMA was evaluated with PEN 50/70 binder. Wet method showed better results in reducing moisture sensitivity and improving TSR, rut depth, and Marshall stability. • HDPE improved resistance to moisture damage, while LDPE enhanced the overall performance of asphalt mixtures. • Hamburg wheel tests showed better results than Marshall tests for compacted mixtures, especially with wet-modified samples.	Australia, [45].

The incorporation of multiple plastic types, such as HDPE, LDPE, and PET, using pyrolysis methods demonstrates significant improvements in asphalt performance across diverse contexts, as can be seen in Table 13. In China, HDPE/LDPE pyrolysis wax enhanced high-temperature resistance and stability, while, in Nigeria, PET/HDPE combinations improved Marshall properties (stability, stiffness, flow) for both hot and warm mixes. These findings emphasize the role of pyrolysis in improving viscosity, thermal behavior, and structural performance. Nevertheless, successful application depends on precise control of proportions, types of plastics, and mixture conditions.

Table 14 presents results from studies using HDPE, LDPE, PP, and Polyethylene (PE) in asphalt mixtures via the dry method, showing stiffness and fatigue resistance comparable to SBS-modified mixes under extreme weather conditions in both warm and cold climates. In Pakistan, incorporating HDPE and LDPE in HMA reduced density due to increased air voids and enhanced both stability and flow. In Iraq, HDPE-treated aggregates improved moisture resistance and adhesion, particularly with acidic aggregates. Meanwhile, Italy evaluated PP and PE modified with plastomeric polymers and recycled plastics, finding stiffness and fatigue resistance comparable to SBS-modified mixes. These

findings underscore the potential of dry methods to improve key mechanical properties of asphalt while highlighting the importance of adjusting plastic types and proportions based on local conditions and performance goals.

Table 13. HDPE/LDPE; PET/HDPE; PET/LDPE Wet Method.

Plastic	Mixture Type and Binder	Method	Dosage and Size	Main Results	Country, Reference
HDPE/LDPE	WMA, Asphalt Hard (AH), AH-70 = PEN 60/70	Wet	Through a pyrolysis sintering process for HDPE and LDPE.	• Mixed polyethylene plastic cracking wax (HDPE/LDPE) produced via pyrolysis showed a good viscosity-reducing effect on asphalt, depending on the cracking time. • The addition of this pyrolysis wax improved high-temperature performance and enhanced asphalt stability over a wide temperature range. • The PET plastic used was a blend of high and LDPE waste, and its use positively influenced both viscosity and thermal properties of asphalt.	China, [63].
PET/HDPE	WMA, VG 30 = PEN 60/70	Wet	1, 3, 5, 7, 9, 11, 13, 15, 17%, Through a pyrolysis sintering process for PET/HDPE.	• PET/HDPE (1–17%) was incorporated through pyrolysis with straight-run bitumen to produce modified hot and warm mixtures, using 60/70 grade and 3% Sasobit. • The addition of PET/HDPE improved Marshall properties stability, flow, and stiffness by up to 13% in both HMA and WMA mixtures. • Optimal values achieved: WMA (54.67 kN, 8.70 mm, 6.28 kN/mm) and HMA (54.00 kN, 10.40 mm, 5.19 kN/mm), indicating notable performance enhancements.	Nigeria, [75].

Table 14. HDPE/LDPE; PP/PE Dry Method.

Plastic	Mixture Type and Binder	Method	Dosage and Size	Main Results	Country, Reference
HDPE/LDPE	HMA, PEN 60/70	Dry	5, 15, 25%.	• Incorporating HDPE/LDPE reduced asphalt mixture density due to increased air voids and improved stability and flow (up to 15%) by partially replacing natural aggregates. • LDPE-25 showed the lowest groove depth, followed by HDPE-25. • HDPE-15 showed the highest resilient modulus, with a 168.5% increase over the control sample.	Pakistan, [78]
HDPE/LDPE	HMA, PEN 60/70	Dry	0.43, 0.48%. With melted plastic and incorporated into the aggregate at temperatures of 180 to 190 degrees.	• PE polymer (HDPE/LDPE) improved moisture resistance in asphalt mixtures with both granite and limestone aggregates, with better performance observed in limestone mixtures. • PE increased asphalt binder wettability and adhesion, especially in acidic granite aggregates prone to moisture damage. • HDPE-treated aggregates showed improved resistance to moisture damage across both aggregate types tested.	Iraq, [79].
PP/PE	HMA, PEN 50/70	Dry	3.8% SBS (bitumen), 5.2% (binder), Ø 5 mm.	• Mixtures with plastomers, recycled plastics, or graphene showed performance similar to SBS-modified asphalt. • SBS and plastomer-modified mixes maintained good fatigue resistance, with deformation sensitivity depending on compaction method.	Italy, [59].

3.5. Structural Properties and Environmental Impact

The incorporation of recycled plastics into asphalt mixtures significantly alters their structural properties. Polymers such as PET and HDPE increase the binder's stiffness, enhancing load-bearing capacity and resistance to heavy traffic. However, high-melting-point plastics like PP may reduce flexibility, making mixtures more prone to cracking under

extreme weather conditions. In contrast, LDPE, due to its low density, provides greater ductility and improves performance in cold climates. Recent studies also highlight that the use of recycled plastic aggregates and Reclaimed Asphalt Pavement (RAP) enhances rutting resistance, while adding LDPE to the binder improves key properties like viscosity and penetration, allowing for industrial-scale production without additional costs [80,81].

Beyond mechanical benefits, the use of recycled plastics offers significant environmental advantages. By partially replacing virgin materials, the consumption of non-renewable resources is reduced, and plastic waste is diverted from landfills. The application of WMA technologies with plastic additives enables production at lower temperatures, reducing greenhouse gas emissions and energy consumption. Altogether, these innovations contribute to more durable, efficient, and sustainable road infrastructure.

3.6. Challenges of High Melting Point Plastics in WMA Blends

High melting point plastics, such as PP and certain types of HDPE, present significant challenges in the production of WMA. Due to the lower temperatures used in the manufacturing of WMAs (generally between 100 °C and 140 °C), these plastics do not fully reach their melting point, which can result in uneven distribution within the asphalt mixture. This phenomenon negatively affects the workability of the mixtures, as the unmelted plastics tend to behave like rigid particles, making it difficult for them to be homogeneously incorporated into the asphalt and aggregates.

Moreover, the lack of complete melting can compromise the adhesion between the asphalt binder and the aggregates, reducing the cohesion of the mixture and its resistance to deformation and cracking. To mitigate these challenges, techniques such as the use of plasticizers or pre-treatment of the plastics have been proposed, which facilitate their dispersion and melting in the asphalt at lower temperatures. However, these methods may increase costs and the complexity of the production process, highlighting the need to optimize the choice of plastic types and mixing conditions for each specific application.

3.7. Summary and Comparison of Results

The review of studies on the integration of plastics into asphalt mixes highlights a series of key conclusions based on various parameters of interest. A summary is provided in Table 15, offering an overview of how different types of plastics affect crucial properties compared to conventional mixes and asphalts.

Table 15. Summary of results for plastics.

Plastic Type	Parameters of Interest (As Compared to Conventional Asphalt Binder/Mixtures)							
	Binders' Stiffness	**Binders' Viscosity**	**Mixtures' Air Voids Content**	**Mixtures' Strength**	**Mixtures' Rutting Resistance**	**Mixtures' Fatigue Resistance**	**Thermal Cracking Resistance**	**Mixtures' Moisture Resistance**
PET	↑	N/A	↑	↑	↑	↑	↓	↓
LDPE	↑	↓	↔	↑	↑	↑	↑↓	↑
PP	↑↓	↑	↑	↑↓	↑↓	↑	N/A	↓
Other Plastics	↑	↑	N/A	↑	↑	↑	↑	↑

Note : ↑: Increases; ↓: Decreases; ↑↓: Does not affect; ↔: Remains the same; N/A : Not viable .

For PET, there is a general increase in the stiffness of the binder and the air void content in the mixtures, although there is a decrease in thermal cracking resistance and moisture resistance. On the other hand, LDPE shows improvements in binder stiffness and mixture strength, although accompanied by a decrease in binder viscosity. PP, in

contrast, has mixed effects, with increases in binder stiffness and viscosity but decreases in several mixture properties. The results for other plastics generally suggest improvements in binder stiffness and various mixture properties. It is crucial to highlight that these impacts vary according to the specific type of plastic, the dosage, and the application method. These results provide valuable guidance for pavement engineers and designers, emphasizing the need for careful consideration when selecting plastics for specific applications in road construction.

The findings of this study confirm that no single type of recycled polymer improves all aspects of asphalt performance on its own. The effectiveness of plastic-modified asphalt depends on various interrelated factors, including the polymer type, incorporation method (dry, wet, or pyrolysis-based), and mixing technology used for HMA or WMA. Figure 5 provides a qualitative visual comparison of PET, LDPE, PP, and HDPE across eight key parameters: binder stiffness, binder viscosity, air void content, mixture strength, rutting resistance, fatigue resistance, thermal cracking resistance, and moisture resistance. This helps identify the specific strengths and limitations of each plastic, supporting informed selection based on mechanical needs and environmental conditions in sustainable pavement design.

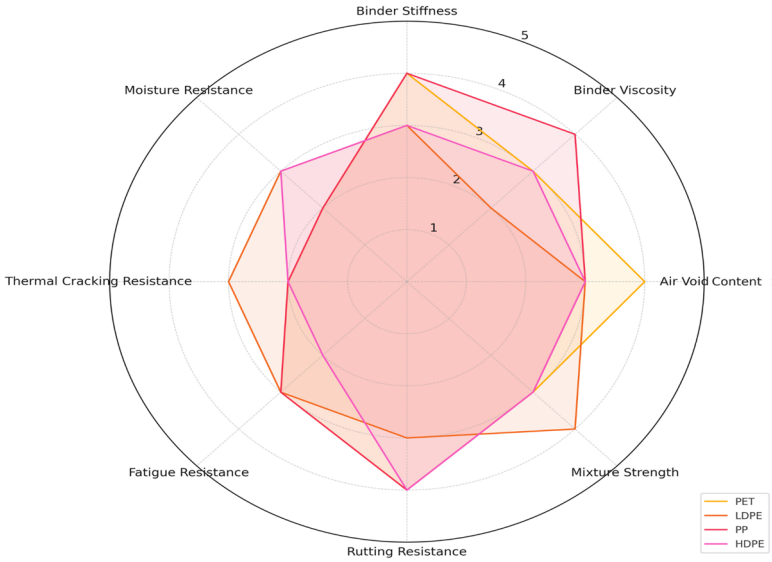


Figure 5. Qualitative comparison of the performance of recycled plastics (PET, LDPE, PP, and HDPE) in asphalt mixtures. The scale from 1 to 5 indicates relative performance, where 1 = lowest and 5 = highest for each property.

Table 16 presents a comparative summary of the improved properties, limitations, and ideal use conditions for these recycled plastics, based on asphalt type and incorporation method. For example, PET used via the dry method in HMA enhances stiffness, fatigue resistance, and rutting resistance but may reduce moisture resistance and perform poorly in WMA. LDPE, applied through the wet method in WMA, improves workability, ductility, and moisture resistance, though it requires well-controlled mixing and has limited high-temperature performance. PP, incorporated through wet methods or pyrolysis-derived waxes, offers excellent stiffness and thermal stability in HMA but faces challenges in WMA due to its high melting point and incomplete dispersion. This synthesis offers practical guidance for choosing plastic types and incorporation strategies based on pavement needs, climate, and technical capacity while highlighting the importance of field validation and standardization for real world implementation.

Table 16. Comparative Summary: Plastic in Asphalt Mixtures.

Plastic Type	Incorporation Method	Asphalt Type (HMA/WMA)	Improved Properties	Limitations	References
PET	Dry	HMA	Stiffness, fatigue resistance, rutting resistance	May reduce moisture resistance; limited performance in WMA	[44,45,50]
LDPE	Wet	WMA	Workability, moisture resistance, ductility	Requires optimized mixing; poor high-temp performance	[44,48,63]
PP	Wet/Pyrolysis	HMA/WMA	Stiffness, temperature stability	Incomplete melting in WMA; reduced flexibility	[44,61,63]

4. Discussion

High melting point plastics such as PET and HDPE have shown notable improvements in stiffness, fatigue resistance, and rutting resistance, particularly when incorporated into HMA via the dry method (Tables 5, 6 and 12 and Figure 5). PET enhances load-bearing capacity but may reduce moisture resistance at dosages above 2% (Table 15). HDPE, when applied as a pyrolysis-derived wax (Table 13), improves thermal stability and lowers binder viscosity, making it more suitable for WMA.

In contrast, LDPE and EVA/LDPE blends are more compatible with WMA due to their lower melting points, which allow better dispersion without compromising cohesion. LDPE contributes to ductility, workability, and moisture resistance (Tables 7 and 8); while EVA/LDPE blends enhance thermal stability without sacrificing low-temperature performance. PP offers excellent stiffness and thermal stability in HMA (Table 9) but shows limited integration in WMA due to incomplete melting; nanosilica additives have been shown to improve dispersion and moisture resistance without reducing flexibility. Multicomponent blends, such as HDPE/LDPE and PET/HDPE (Tables 11 and 12), combine moisture resistance from HDPE with flexibility from LDPE, achieving rut depths under 5 mm in wheel tracking tests.

The dry method offers scalability and cost efficiency, especially for PET and LDPE at optimized dosage ranges, but excessive PET may reduce moisture resistance, and LDPE requires careful mixing to avoid density loss and increased air void content. The wet method enhances polymer binder interaction, particularly for LDPE and EVA blends, improving workability and moisture protection in WMA. Pyrolysis-derived waxes from HDPE or PP reduce binder viscosity and increase thermal stability, offering an effective approach for WMA where direct melting is incomplete, though industrial adaptation remains necessary for large-scale adoption.

HMA mixtures modified with PET, PP, or HDPE exhibit superior structural performance under high temperatures and heavy traffic loads (Table 15), making them suitable for urban corridors with high demand. WMA mixtures, while slightly less robust, offer adequate performance in mild or cold climates with lower traffic volumes. Low-melting plastics such as LDPE or EVA in WMA improve workability, reduce energy consumption, and enhance low-temperature performance. Considering the balance between mechanical performance and environmental benefits, PET in HMA via the dry method and LDPE in WMA via the wet method appear to provide the most favorable combinations for durability and sustainability.

Integrating recycled plastics into asphalt mixtures diverts significant waste from landfills and waterways, reduces dependency on virgin bitumen, and lowers greenhouse

gas emissions particularly when combined with WMA technologies. The immobilization of plastics within the asphalt matrix (Figure 5) minimizes microplastic release and extends pavement lifespan, lowering maintenance frequency. From a sustainability perspective, this practice aligns with circular economy objectives, supports green job creation in waste processing, and fosters public acceptance of sustainable infrastructure. Nonetheless, quantifying these benefits remains limited due to the absence of standardized Life Cycle Assessment (LCA) protocols and region-specific datasets.

Despite the promising results, several technical challenges still hinder the large-scale implementation of recycled plastics in asphalt mixtures. These include the absence of standardized protocols for dosage, particle size, and binder polymer compatibility; the scarcity of long-term field performance data under real operating conditions; variability in waste plastic supply and quality affecting reproducibility; and strict emission control requirements during incorporation, particularly in pyrolysis-based processes.

Future research should focus on advancing plastic pretreatment and recycling technologies to ensure consistent quality, developing optimized mixing protocols tailored to different polymer types and asphalt grades, and conducting comprehensive LCAs to quantify environmental gains. Additionally, new characterization methodologies could better predict long-term performance, and adapting these technologies to regional contexts especially in low-resource settings may maximize both social and environmental benefits, facilitating integration into sustainable infrastructure practices.

5. Conclusions

The escalating accumulation of plastic waste and its long-term environmental consequences have made it essential to identify strategies that transform this pollutant into a valuable resource. This systematic review demonstrates that the integration of recycled plastics particularly PET, LDPE, and PP into HMA and WMA can serve as both a technical and environmental solution. By repurposing post-consumer plastics in road construction, this approach diverts significant volumes of waste from landfills and natural ecosystems while reducing the reliance on virgin petroleum-based binders.

From a social perspective, the use of recycled plastics in asphalt mixtures supports the principles of the circular economy, reduces the environmental footprint of infrastructure projects, and can generate local employment through waste collection, processing, and supply chain activities. Additionally, the adoption of WMA technologies further amplifies these benefits by lowering production temperatures, which translates into reduced greenhouse gas emissions, improved worker safety due to lower fumes, and minimized energy consumption. These advantages are especially valuable for regions with limited resources and high environmental vulnerability.

Key Findings:

- PET increases binder stiffness and fatigue life while contributing to the valorization of large volumes of post-consumer beverage containers, thereby reducing environmental contamination.
- LDPE enhances ductility, workability, and moisture resistance, enabling the reuse of common single-use plastics such as bags and packaging materials, which are among the most persistent pollutants in urban and marine environments.
- PP offers improved stiffness and high-temperature performance, allowing the recycling of packaging and industrial plastics, but requires careful control in WMA to avoid dispersion issues.
- HMA ensures maximum mechanical durability for heavy traffic roads, whereas WMA delivers substantial environmental gains, such as reduced energy demand and lower CO_2 emissions, making it ideal for projects in environmentally sensitive zones.

- Dry methods provide a scalable pathway for integrating PET and LDPE with minimal adaptation costs, while wet and pyrolysis methods allow for more uniform binder modification and the incorporation of high-melting-point plastics.
- The use of recycled plastics in pavements directly reduces landfill pressure, marine litter, and microplastic release by immobilizing plastics within a durable road matrix.
- This technology supports social benefits by promoting waste-to-resource initiatives, creating local jobs in plastic collection and processing, and enabling municipalities to demonstrate visible sustainability actions.
- The integration of plastics into asphalt aligns with global sustainability goals, linking infrastructure development with climate change mitigation and responsible resource management.

This systematic review aimed to identify which type of recycled plastic and incorporation method provides the best balance between mechanical performance and environmental benefits in HMA and WMA. Based on the analysis of 39 studies, PET and LDPE, particularly when incorporated through the dry method in HMA, consistently enhanced stiffness, fatigue resistance, and rutting resistance, with LDPE also improving ductility and moisture resistance, making it suitable for WMA applications. PP demonstrated superior high-temperature stability and stiffness, especially in HMA, though its high melting point poses challenges for WMA without pre-treatment. From an environmental perspective, WMA technologies combined with recycled plastics reduced energy consumption and greenhouse gas emissions while diverting substantial volumes of waste from landfills and oceans. These findings confirm that selecting the appropriate plastic type and incorporation method according to local climatic, traffic, and technical conditions can optimize both mechanical durability and environmental sustainability, aligning road construction with circular economy principles and climate change mitigation goals.

These findings confirm that plastic-modified asphalt is not only a technically viable solution but also a strategic environmental intervention capable of linking infrastructure performance with ecological preservation. By integrating recycled plastics into HMA and WMA, this approach offers tangible benefits for both urban and rural communities, including cleaner surroundings, extended pavement service life, and reduced maintenance costs.

Looking ahead, strengthening the evidence base on environmental outcomes is essential. Future research should quantify the long-term benefits through standardized life-cycle assessments, with particular attention to CO_2 emission reductions, waste diversion metrics, and resource savings. Such data would provide policymakers with the necessary tools to embed plastic-modified asphalt into broader climate action strategies. In doing so, road construction can evolve into a key driver of environmental stewardship, social progress, and sustainable development.

Author Contributions: Conceptualization, D.S.-V. and J.C.-R.; methodology, D.S.-V. and L.G.; software, D.S.-V. and J.C.-R.; validation, L.G. and M.A.L.-B.; formal analysis, D.S.-V. and C.S.-B.; investigation, D.S.-V. and M.M.-A.; resources, D.S.-V. and L.G.; supervision, M.A.L.-B. and M.M.-A.; project administration, D.S.-V., M.M.-A. and C.S.-B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: This study has not generated any new data that can be shared, and no data has been uploaded to any external databases. The results and analysis of the study are available in this document.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

Acrylonitrile Butadiene Styrene (ABS), Asphalt Cement (AC), Asphalt Hard (AH), Binder Bond Strength (BBS), Crumb Rubber-Modified Asphalt (CRMA), Cross-linked Polyethylene (PEX), Differential Scanning Calorimetry (DSC), Dynamic Shear Rheology (DSR), Ethylene Vinyl Acetate (EVA), Fatigue Measurement (FM), Fourier Transform Infrared Spectroscopy (FTIR), High-Density Polyethylene (HDPE), Hot Mix Asphalt (HMA), Indirect Tensile Strength (ITS), Indirect Tensile Strength Ratio (ITSR), Life Cycle Assessment (LCA), Low-Density Polyethylene (LDPE), Modified Polyethylene Terephthalate (MPET), Penetration Grade (PEN), Performance Grade (PG), Polycarbonate (PC), Polyethylene (PE), Polyethylene Terephthalate (PET), Polypropylene (PP), Polyurethane (PU), Polyvinyl Chloride (PVC), Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA/ScR), Pyrolysis Wax (PW), Reclaimed Asphalt Pavement (RAP), Recycled Pyrolytic Polyethylene Wax (RPPW), Styrene Butadiene Styrene (SBS), Tensile Strength Ratio (TSR), Thermally Linear Polypropylene (TLPP), Ultra-High-Molecular-Weight Polyethylene (UHMWPE), Viscosity Grade (VG), Viscuous Polypropylene (VPP), Waste Polypropylene (WPP), and Warm Mix Asphalt (WMA).

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