CivilEng

Review

A Review on the Use of Plastic Waste as a Modifier of Asphalt Mixtures for Road Constructions

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Abstract: Rising industrialization and population growth contribute to the increasing generation of plastic waste, which poses significant environmental and health challenges. Despite its potential as a resource, plastic waste is often discarded without proper treatment. Repurposing it in road construction offers both economic and environmental benefits, providing a sustainable waste management solution. This paper thoroughly examines various types of plastic waste used in asphalt mixtures, considering both wet and dry processing methods and their impact on bituminous binders and asphalt performance. Overall, incorporating waste plastics into asphalt mixtures has been shown to improve fatigue resistance, rutting resistance, moisture resistance, and high-temperature performance. However, challenges related to compatibility and low-temperature performance persist in plastic-modified asphalt applications. To address these issues, modified approaches, such as the use of chemical additives, have been identified as effective in enhancing the bonding between waste plastics and bituminous binders while also increasing the amount of plastic that can be incorporated. While plastic-modified asphalt shows significant promise, overcoming these challenges through targeted research and careful implementation is essential for its sustainable and effective use in asphalt mixtures, ensuring long-term performance.

Keywords: plastic waste; bituminous binders and asphalt mixtures; wet and dry process; stability; compatibility; performance

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Academic Editor: Angelo Luongo

Received: 6 January 2025

Revised: 15 February 2025

Accepted: 25 March 2025

Published: 1 April 2025

Citation: Ameur, A.B.; Valentin, J.; Baldo, N. A Review on the Use of Plastic Waste as a Modifier of Asphalt Mixtures for Road Constructions. *CivilEng* **2025**, *6*, 17. https://doi.org/10.3390/civileng6020017

1. Introduction

Plastic is regarded as a quasi-solid, insoluble, non-biodegradable, and synthetic material primarily derived from refined crude oil and petroleum products. It encompasses the main commercial plastics, including polyethylene terephthalate (PET), polyvinyl chloride (PVC), polypropylene (PP), polystyrene (PS), polyethylene (PE), and polyurethane (PUR), according to EN ISO 472:2013 [1]. It is considered a cost-effective raw material due to its large-scale production. Plastics are classified based on their origin, shape, color, and size. The size classification distinguishes between megaplastics (>1 m), macroplastics (<1 m), mesoplastics (<2.5 cm), microplastics (<5 mm), and nanoplastics (<1 μm) [2]. Currently, the use of plastics encompasses several vital economic sectors, including packaging, agriculture, automotive, electrical appliances, electronics, communication, and building constructions [3]. Plastic is defined as a non-biodegradable material, and according to some research, this type of material cannot be degraded, leading to an excessively long life cycle and potentially persisting on the Earth for up to 4500 years [4]. In the environment, the two primary contributors to plastic waste are plastic beverage bottles and disposable plastic garbage bags.

Plastics are extensively used in numerous fields due to their significant advantages in terms of affordability, lightweight properties, durability, and ease of manufacturing and longevity compared to many alternative materials [5,6]. The growing interest in different sectors contributes to the rapid expansion of plastic productivity, leading to concerning statistics. In that context, the global production of plastic has significantly surged from 1.5 million tonnes in 1950 to 299 million tonnes in 2013, achieving 335 million tonnes in 2016 [7]. Projections suggest that worldwide plastic manufacturing might increase threefold by 2050 [8]. Nonetheless, the environmental challenges associated with plastics span their entire life cycle. Firstly, the production of plastic goods generates carbon gas emissions. Secondly, the very attributes that render plastic materials valuable also pose challenges in waste management, leading to a negligible portion of plastic waste being recycled due to contamination and technical constraints [9,10]. Thirdly, a substantial aggregation of plastic waste is environmentally evident, exemplified by trash patches in the Pacific and Atlantic Oceans, believed to constitute around 100 million tonnes, with approximately 80% comprising plastic [11]. Once in the environment, especially within marine ecosystems, plastic waste can endure for centuries [12]. By 2015, global plastic consumption had escalated to approximately 297.5 million tonnes, with Asia leading the way as the largest consumer, accounting for 30% of global utilization in recent years. Plastic waste constitutes an estimated 16% of the overall weight of household waste [13].

In addition to its substantial volume, plastic waste raises numerous concerns. The primary threat posed by plastic waste stems from the inclusion of plasticizers. These additives, incorporated to enhance flexibility and workability in plastics, lack a covalent bond with plastic, making them susceptible to leaching into the environment. The presence of plasticizers has detrimental effects on the reproductive organs of mammals. Their prevalence has been verified in the soil, water, air, animals, and even human bodily secretions, indicating that plastics have entered our food chain and raising significant alarm. Consequently, “plastic pollution”, also called “white pollution”, stands out as among the most urgent environmental issues in the modern world [14]. Furthermore, a significant concern is the prolonged leaching of chemicals, a process that may extend over several decades, and possibly centuries, given that most plastics are non-biodegradable. On the flip side, incineration proves effective in reducing both the mass and volume of plastic waste. However, this method comes with the drawback of air pollution during the incinerator’s heat treatment process, leading to the release of harmful substances such as dioxin (POP), carbon monoxide (CO), and other poisonous emissions [15]. Additionally, waste plastics often include heavy metals like lead (Pb) and cadmium (Cd), which are emitted from fumes, dust, and residues generated throughout the incineration procedure [16].

Several studies and research initiatives have explored potential uses of plastic waste in asphalt manufacturing. These investigations delve into the characteristics of asphalt incorporating waste plastic, examining modification mechanisms and addressing environmental considerations [17,18]. Waste plastics may be utilized as asphalt modifiers in various forms throughout further processing. Initially, the plastics were transformed into pellets, derived entirely from waste plastics, and intended for direct integration into asphalt production plants [19,20]. Recently, waste plastics have also been refined into a shredded form. However, both pelletized and shredded waste plastics necessitate complex industrial systems for processing. Based on the type and intended application, the incorporation of waste plastics can enhance either the rheological properties of the bituminous binder or the mechanical and performance characteristics of asphalt mixtures [14,21]. Two primary approaches are employed to integrate waste plastics into asphalt: the wet process and the dry process [22]. In the wet method, waste plastics are straightforwardly introduced into the bituminous binder at elevated temperatures, necessitating mechanical mixing to attain a uniform blend of a plastic-modified binder. The specific mixing temperature and duration vary based on the characteristics of the waste plastic material and the bituminous binder. Waste plastics are integrated into the bituminous binder through the wet process to alter its characteristics before interacting with aggregates [23]. Conversely, the dry process involves directly integrating waste plastics into the asphalt mixture, serving as both a partial substitute for aggregates and a modifier for the mixture [24]. In this technique, waste plastics are blended with aggregates, effectively employing them as reinforcement materials [22].

In the realm of sustainability and the exploration of asphalt modifiers, the increasing global apprehension regarding plastic waste has prompted researchers to delve into the viability of employing recycled waste plastics as modifiers for asphalt. This approach not only addresses environmental concerns but also proposes a possible remedy for the sustainable management of plastic waste. The current literature indicates that integrating certain recycled plastics has demonstrated promising outcomes as modifiers for both bituminous binders and mixtures [25].

The detailed abbreviations and definitions used in the paper are listed in Table 1.

Table 1. List of abbreviations and acronyms used in the paper.

Abbreviation	Definition	Abbreviation	Definition	Abbreviation	Definition
ABS	Acrylonitrile–butadiene–styrene terpolymer	LDPE	Low-density polyethylene	PE	Polyethylene
AM	Asphalt mixture	LLDPE	Linear low-density polyethylene	PWM	Plastic waste materials
Cd	Cadmium	LAS	Linear Amplitude Sweep	RAP	Reclaimed asphalt pavement
CDI	Construction Densification Index	MDPE	Medium-density polyethylene	SBR	Styrene–butadiene–styrene random copolymer
CO	Carbon monoxide	MEPDG	Mechanistic-Empirical Pavement Design Guide	SBS	Styrene–butadiene–styrene block copolymer
DEG	Diethylene glycol	MSCR	Multiple stress Creep recovery	SEBS	Styrene-ethylene-butylene-styrene triblock copolymers
DETA	Diethylenetriamine	NR	Natural rubber	SMA	Stone mastic asphalt
DSR	Dynamic shear rheometer	Pb	Lead	TEG	Triethylene glycol
EVA	Poly (ethylene-vinyl acetate)	PBR	Polybutadiene rubber	TGA	Thermal gravimetrical analysis
FTIR	Fourier-transformed infrared spectroscopy	PCA	Plastics coated aggregates	TSR	Tensile strength ratio
FT-wax	Fischer–Tropsch wax	PET	Polyethylene terephthalate	UP	Unsaturated polyester
GMA	Glycidyl methacrylate	PG	Propylene glycol	VMA	Voids in mineral aggregates
GPC	Gel-permeation chromatography	PG	Performance-grade	WPET	Waste poly (ethylene terephthalate)
GRP	Graphene-enhanced recycled plastic	PMB	Polymer-modified binders	WPM	Waste polymer modifier
GWP	Graphene and waste hard plastic	POP	Dioxin	WPT	Waste packing tape
HDPE	High-density polyethylene	PP	Polypropylene	WSBS	Warm Mix with SBS Binder
HSBS	Hot Mix with SBS Binder	PPA	Polyphosphoric acid	WTT	Wheel-tracking test
HVS	Heavy vacuum slopes	PS	Polystyrene	WWPT	Warm Mix with WPT Binder
HWPT	Hot Mix with WPT Binder	PUR	Polyurethane		
ITS	Indirect tensile strength	PVC	Polyvinyl chloride		

2. Literature Review

This paper categorizes research based on modification processing techniques, distinguishing between two conventional approaches: the wet process and the dry process. However, certain researchers have innovatively adapted these conventional techniques to enhance pavement performance, resulting in modified processing techniques.

2.1. Wet Process

The wet process, one of the modification methods, involves adding a modifier to bitumen and blending it in a mechanical blender at 170 °C until a homogeneous solution is achieved. Subsequently, the modified bitumen is combined with hot aggregates (170 °C) and mixed again to ensure consistency in the modified asphalt mixture (AM). The mixture is compacted onto the pavement at 120 °C [26]. Figure 1 presents a diagram of the wet process. This method, introduced by Flynn in 1993, was the initial approach used for modification, with subsequent methods developed later [27]. Some studies have asserted that the wet process exhibits superior effectiveness when compared to the dry process [28]. Moreover, the wet process allows the incorporation of plastic exceeding 10% of the optimal bitumen content (the indicated % refers to the percentage by weight related to the optimal binder content in an asphalt mixture) [29,30]. Notably, the wet process has become more popular than the dry process, leading to more extensive research in this area.

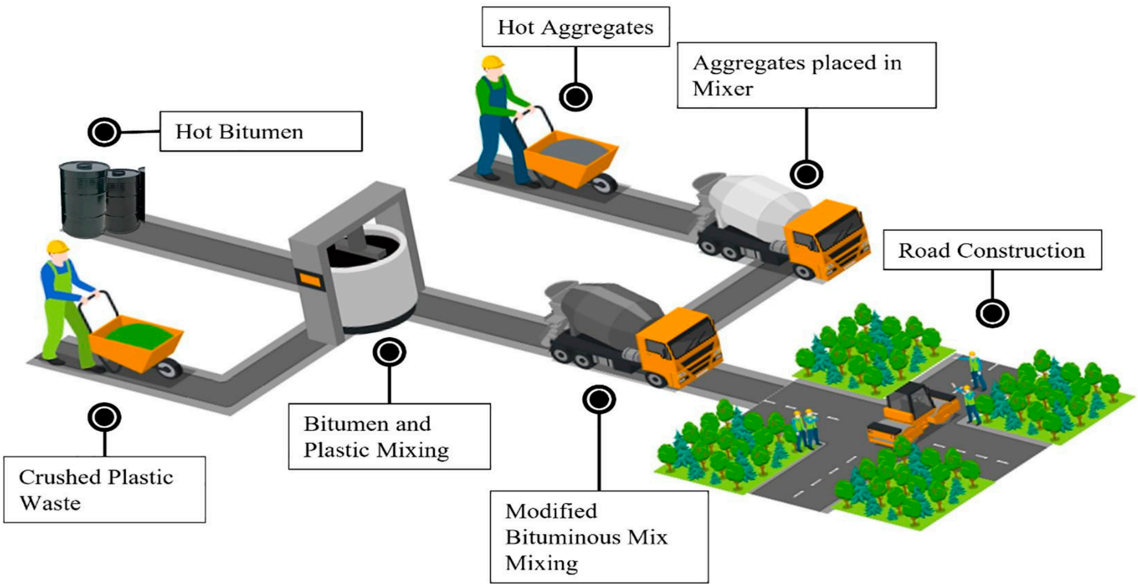

Figure 1. The wet process scheme [31].

A. Tuncan et al. (2000) [32] conducted a study on the impact of incorporating plastic waste and crumb rubber into asphalt pavements. The study utilized limestone aggregate and a binder with a penetration grade of 75/100. Plastic waste, sourced from grocery bags and pallet wrap and predominantly composed of low-density polyethylene (LDPE), was used in particle sizes between 4.75 mm and 2 mm. Crumb rubber, derived from old automobile tires, was used in particle sizes ranging from 4.75 mm to 0.075 mm. These materials were added to the bituminous binder at concentrations of 5, 10, and 20 percent by weight. Results from the Marshall test, a method used to evaluate the stability and flow properties of asphalt mixtures, indicated that incorporating more than 10 percent rubber decreased the Marshall stability, while adding plastic improved stability by enhancing the bonding between the modified binder and the aggregates. Furthermore, the study observed that the indirect tensile strength of the asphalt mixtures was influenced by the amounts of rubber and plastic used. The indirect tensile strength was augmented with higher amounts of rubber particles sized between 4.75 mm and 0.850 mm. Similarly, plastic-modified mixtures demonstrated a significant boost in indirect tensile strength, with a 69 percent rise observed when 20 percent plastic was added to the bituminous binder.

Gao et al. (2002) [6] proposed a novel technique for producing storage-stable bituminous binders modified with both styrene–butadiene–styrene block copolymer (SBS) and low-density polyethylene (LDPE). The LDPE, characterized by a melt flow rate of 2.0 g/10 min, and a base binder with a softening point of 47.5 °C, a viscosity of 0.35 Pa.s at 135 °C, and a penetration of 90 dmm were utilized. The modification process involved blending styrene–butadiene–styrene block copolymer (SBS) and low-density polyethylene (LDPE) into a bituminous binder at 180 °C for one hour using a high-shear mixer operating at 4000 rpm. Sulfur was then added, and the mixture was blended for an additional hour. A 1:2 ratio of LDPE/SBS copolymer was incorporated at dosages of 1.5, 3.0, and 4.5 percent by weight of the bituminous binder, with sulfur added at 0.05, 0.1, and 0.15 percent by weight. Haake curves, which are used to measure the viscosity and rheological properties of polymeric materials under controlled temperature and shear conditions, indicated possible crosslinking or grafting between SBS macromolecules. Storage stability tests using cigar tubes showed phase separation in binders modified with direct LDPE and SBS addition without sulfur. The addition of sulfur decreased softening-point variations but did not eliminate viscosity differences, particularly at higher LDPE dosages. Binders modified with preblended LDPE/SBS copolymer demonstrated improved storage stability, confirmed through optical micrographs, and exhibited enhanced rheological properties, especially high-temperature rutting resistance in dynamic shear rheometer (DSR) temperature-sweep tests.

A.A Yousefi (2003) [33] evaluated, in his study, the influence of polyethylene and rubber admixtures on bituminous binder properties. The research included various grades of polyethylene (LDPE, LLDPE, and HDPE) and rubber types (PBR, SBR, NR, and SEBS). The 40-penetration grade bituminous binder underwent modification with polyethylene and rubber with a high-shear mixer at 170–180 °C for 30 min. Additives, excluding LLDPE, were introduced at a rate of 3 percent by weight, whereas LLDPE was introduced at a rate of 1 percent. PBR-PE blends formed a physical network, unlike SBR, NR, and SEBS blends. SBR-PE blends showed superior elastic recovery and film-forming properties. LLDPE was more effective than LDPE and HDPE in altering bituminous binder properties. The incorporation of heavy vacuum slope (HVS) oil, a byproduct obtained from crude oil refining, can enhance rubber–PE–bituminous blends. During the refining process, crude oil undergoes heating and separation into various fractions based on their boiling points. HVS oil is a fraction obtained from a vacuum distillation unit, and it typically has a higher boiling point compared to lighter fractions like gasoline or diesel. It offers enhanced low-temperature characteristics, and its dosage can be adjusted to meet specific performance-grade requirements. Adding HVS oil to rubber–PE–bituminous mixtures has been shown to expand the volume of rubber particles, contributing to improved material performance.

S. Hinislioglu et al. (2004) [34] conducted an exploration using recycled high-density polyethylene (HDPE) in a wet bitumen modification with an AC-20 paving-grade binder, which is a type of bitumen with a viscosity of 2000 poises at 60 °C (140 °F), making it suitable for regions with moderate to hot climates. HDPE in a powdered form (with particles smaller than 2 mm but larger than 0.425 mm) was tested. Modified HDPE binders were created using a low-shear mixer (200 rpm) at varying temperatures (145 °C, 155 °C, and 165 °C) and durations (5 min, 10 min, 15 min, and 30 min) with three dosages (4, 6, and 8 percent by weight). Post-modification, binders were blended with aggregates, conditioned, and compacted. The Marshall stability test, which measures the maximum load an asphalt mixture can withstand before failure, showed decreasing values with an increasing HDPE dosage, except for 4 percent HDPE mixtures at 165 °C for 30 min, which consistently achieved higher stability than the unmodified mix. The Marshall flow test, which measures the deformation (in mm) of an asphalt mixture under load, showed an inverse pattern. Rutting resistance, assessed through the Marshall quotient, which is the ratio of Marshall stability to Marshall flow and indicates the stiffness of the asphalt mixture, indicated a 50 percent increase for the 4 percent HDPE mixture at 165 °C for 30 min, highlighting enhanced resistance due to HDPE modification.

G. Polacco et al. (2005) [35] explored the suitability of various polyethylene (PE)-based polymers for bitumen modification through the wet process, using a 70/100 paving-grade bitumen. Eight PE-based polymers, including LDPEs, PE-AA copolymer, LDPE with ethylene-based reactive terpolymers, LLDPE, and PE modifications incorporating glycidyl methacrylate (GMA) functional groups, which are reactive monomers containing both epoxy and methacrylate groups, commonly utilized in polymer chemistry to introduce reactive sites for subsequent chemical modifications or crosslinking processes, were tested at a 6.0 percent weight ratio of the bituminous binder. Polymer-modified binders were prepared through a 2 h heating process at 180 °C, followed by high-speed mixing at 4000 rpm for an additional 2 h. Despite efforts, all PE-based polymer-modified binders exhibited storage instability and phase separation. While ethylene-based reactive terpolymers and GMA functional groups enhanced compatibility, achieving a fully homogeneous and stable binder blend remained elusive. Among the polymers, LLDPE showed the highest compatibility with the bituminous binder, with noticeable differences in rheological and viscosity characteristics, suggesting potential crosslinking during high-shear mixing.

S. Ho et al. (2006) [36] also explored the utilization of recycled polyethylene (PE) materials in bitumen enhancement through the wet process. They tested various blends of three PE waxes and three low-density polyethylene (LDPE) materials with a base binder having a performance grade (PG) of 52-34 [37]. PE-modified binders, prepared with a high-shear mixer, were tested at concentrations up to 4 percent by weight of the bituminous binder. Characterization included assessments based on the Superpave grading system, phase separation, direct tension test failure strain criteria, and fluorescent microscopy. The results showed an overall trend of improved rutting resistance but reduced thermal cracking resistance with added PE wax and LDPE. The effectiveness varied among recycled PE materials, with phase separation and low-temperature cracking resistance influenced by the polydispersity index and molecular weight of the LDPE. LDPE with a reduced molecular weight and broader molecular weight distribution was identified as being better suited for asphalt enhancement.

D. Casey et al. (2008) [38] explored the utilization of recycled plastics in stone mastic asphalt (SMA) binders. They evaluated various recycled plastics, including high-density polyethylene (HDPE), low-density polyethylene (LDPE), medium-density polyethylene (MDPE), polyvinyl chloride (PVC), polypropylene (PP), polyethylene terephthalate (PET), and acrylonitrile–butadiene–styrene terpolymer (ABS). Feasibility experiments showed that MDPE, PVC, PET, and ABS were unsuitable for asphalt enhancement, while HDPE, LDPE, and PP at concentrations up to 5 percent achieved homogeneous binder blends. Testing revealed increased viscosity and softening points and decreased penetration values in LDPE, HDPE, and PP-modified binders. However, none met agency requirements for polymer-modified binders (PMBs). To improve, LDPE and HDPE binders were optimized with two chemical additives, namely polyphosphoric acid (PPA) and diethylenetriamine (DETA). Unfortunately, incorporating DETA yielded unsatisfactory results, as binders modified with 1 and 2 percent DETA exhibited decreased storage stability. Conversely, the addition of 0.8 percent PPA enhanced performance properties and storage stability, identifying the binder with 0.8 percent PPA and 4 percent HDPE as optimal. Indirect tensile fatigue and wheel-tracking tests revealed that the HDPE-plus-PPA modified mixture did not exhibit performance levels comparable to the proprietary PMB mixture. However, it surpassed the performance of the unmodified control mixture.

A. Moatasim et al. (2011) [39] investigated the application of high-density polyethylene (HDPE) for bitumen modification through the wet process. HDPE, supplied in pelletized form, was added to an 80/100 paving-grade bitumen at dosages of 1, 3, 5, and 7 percent by weight. The high-shear mixer thoroughly mixed HDPE into the binder for a duration of 2 h at a temperature of 170 °C. Laboratory analyses showed that the HDPE addition stiffened the bituminous binder, with increased softening points and reduced penetration and ductility values, especially at higher dosages. HDPE-modified binders demonstrated improved resistance to temperature fluctuations and decreased mass loss attributed to heat and air in comparison to the base binder. The evaluation of asphalt mixtures revealed increased stability and rutting resistance with higher HDPE contents in Marshall stability and TSR (tensile strength ratio) tests, which are used to assess the moisture sensitivity of asphalt mixtures. The TSR test compares the indirect tensile strength of conditioned and unconditioned asphalt samples, with a higher ratio indicating better resistance to moisture-induced damage and improved durability. HDPE-modified mixtures also exhibited superior moisture resistance, increased stiffness at 25 °C, and improved thermal cracking resistance at low temperatures, particularly the 5 percent HDPE-modified mixture.

R.E. Villegas-Villegas et al. (2012) [40] explored, in their study, the use of recycled bags from banana production waste for bitumen modification through the wet process. After processing, including air blowing and washing, the bags were identified as primarily composed of high-density polyethylene (HDPE). They were added at 3% wt. of the bituminous binder using a low-shear mixer at 160 °C for 2 h. The resulting modified binder met Superpave PG 70-xx requirements [41], showing enhanced resistance to high-temperature permanent deformation compared to the base binder. However, no notable impact on fatigue resistance was observed. Mixture-performance tests indicated that the inclusion of banana bags increased the mixture's stiffness and improved its resistance to rutting and moisture damage without altering the aggregate structure or optimum binder content.

Costa et al. (2013) [42] examined the utilization of waste plastics for bitumen modification through the wet process, with a focus on low-density polyethylene (LDPE) and high-density polyethylene (HDPE). Various alternative polymers were also evaluated, including styrene–butadiene–styrene block copolymer (SBS), acrylonitrile–butadiene–styrene terpolymer (ABS), poly (ethylene-vinyl acetate) (EVA), and crumb rubber. Both powder and granulate forms of these polymers were tested. The research employed a low-shear mixer to blend the polymers with the bituminous binder at a dosage of 5.0 percent by weight of the bituminous binder. The results showed that some polymers did not disperse uniformly, affecting binder blends. However, the incorporation of polymers raised the softening points and diminished the penetration value of the base binder, particularly with HDPE, EVA, and SBS. Modified binders exhibited resilience comparable to or better than commercial products. Notably, binders modified with EVA, SBS, and crumb rubber showed significant elasticity, while those with recycled LDPE, HDPE, and ABS displayed minimal elasticity. Overall, polymer addition increased binder viscosity, with SBS-modified binders having the highest viscosity. Recommendations were made to address phase separation issues, including adjusting polymer dosage and incorporating compatibility additives.

Ambika Behl et al. (2014) [43] proposed a sustainable approach to use PVC pipe waste in road construction. They employed two contents: 3% and 5% of PVC waste in bitumen for asphalt mixtures. After chemical modification and blending at 160 °C, laboratory results showed increased binder stiffness and viscosity with PVC waste addition. The 5% PVC waste-modified binder exhibited the highest complex modulus values, indicating enhanced resistance against permanent deformation (rutting). The modified binders showed high consistency and elasticity, with stiffness increasing with higher PVC waste percentages and decreasing at higher temperatures. Mechanical tests on modified asphalt mixtures demonstrated increased retained stability and improved moisture susceptibility. The mixtures also exhibited enhanced resistance against permanent deformation and cracking, with decreased rutting values and increased fatigue life with higher PVC waste percentages. The study concluded that PVC pipe waste can be effectively employed in road construction, enhancing the durability of both binders and asphalt mixtures.

M.A. Dalhat and H.I. Al-Abdul Wahhab (2015) [44] evaluated the effectiveness of modified bituminous binder by incorporating recycled plastic waste through the wet process. They utilized and tested three varieties of recycled plastic: high-density polyethylene (HDPE), low-density polyethylene (LDPE), and polypropylene (PP). The plastics underwent washing, shredding, and grinding before being blended with the bituminous binder with a high-shear mixer. Experimental tests showed increased viscosity in all modified binders, with HDPE and PP exhibiting more significant viscosity changes compared to LDPE. The plastic-modified binders displayed improved viscoelastic behavior, indicating enhanced rutting resistance. However, none of the plastic-modified binders met elastic recovery requirements. Resilient modulus tests showed bitumen hardening due to plastic modification, with the mixture containing 2% PP exhibiting the greatest stiffness. Pavement design analysis using MEPDG software [45] revealed that plastic modification significantly enhanced predicted rutting and fatigue performance in asphalt pavements, with PP showing a more pronounced improvement than HDPE and LDPE.

I.M. Khan et al. (2016) [46] carried out research to assess the efficacy of high-density polyethylene (HDPE) and low-density polyethylene (LDPE) in modifying bitumen through the wet process. They utilized a PG 64-10 base binder obtained from a local Saudi refinery. The PG 64-10 is characterized by a maximum pavement temperature of 64 °C, at which the binder retains its desired properties under traffic loading and environmental conditions, and by a minimum pavement temperature of 10 °C, at which the binder remains flexible and resistant to cracking. However, they incorporated 2%, 4%, 8%, and 10% by weight of LDPE and HDPE into the bituminous binder. The modification process involved blending the base binder with HDPE or LDPE at 165 °C for a duration of 2 h, though the specific type of mixer was not specified. The resulting modified binders were tested in a dynamic shear rheometer to assess their rheological properties over a temperature range of 46 to 70 °C. The test outcomes revealed that the inclusion of HDPE and LDPE led to enhancements in the elastic behavior and resistance to rutting of the base binder. This improvement was evidenced by a decrease in the phase angle (δ) and an increase in the Superpave binder rutting parameter ($|G^*|/\sin(\delta)$). Significantly, the inclusion of 4 percent HDPE and 10 percent LDPE exhibited the most effective resistance against rutting. Consequently, these proportions were determined as the optimal blends for modifying bitumen.

Shubham Bansal et al. (2017) [47] assessed the effectiveness of modified asphalt concrete mixtures integrating rubber and plastic waste sourced from used polyethylene bags and smashed plastic bottles. Marshall stability analysis was conducted by replacing the optimum bitumen content with crumb rubber (5%, 10%, and 15%) and waste plastic (4%, 6%, 8%, and 10%). Three series of binders were created, involving bitumen, plastic, and rubber in various proportions. The study revealed that partial replacement of bitumen with plastic waste increased strength by up to 16%, while rubber materials showed a remarkable 50% improvement compared to conventional mixtures. Mixtures with over 10% rubber replacement exhibited high flow values, and both modified and non-modified mixes met allowable air void content standards. Incorporating post-service life material wastes in asphalt–concrete mixtures not only enhanced strength and durability but also had the potential to reduce environmental pollution and minimize construction costs. The recommended waste content from this research is 6% and 8% for plastic and 10% for rubber.

Zhen Leng et al. (2018) [48] investigated the application of waste polyethylene terephthalate (PET) in asphalt mixtures containing a significant proportion of reclaimed asphalt pavement (RAP), with a focus on its value-added potential. The study aimed to enhance pavement durability and address environmental concerns related to plastics. Through ammonolysis, waste PET-derived additives were incorporated into asphalt mixtures containing RAP, and extensive laboratory tests were conducted on various binder samples. The results indicated improvements in softening point, permanent deformation, resistance to stripping, and fatigue cracking resistance in PET-modified binders with RAP compared to conventional binders. The addition of PET-derived additives positively influenced the elastic characteristics and low-temperature performance of the mixtures. Overall, the study concluded that incorporating PET-based additives from recycled materials in RAP blends offers a sustainable solution, demonstrating a 15% improvement in rutting resistance and a 60% enhancement in fatigue crack resistance. This approach contributes to recycling efforts and recovers two value-added materials simultaneously.

Huayang Yu et al. (2019) [49] investigated a potential enhancement of the mechanical characteristics of asphalt mixtures through the incorporation of waste packing tape (WPT). They compared hot and warm mixtures with WPT (HWPT and WWPT) to hot and warm SBS mixtures (HSBS and WSBS). Various tests and simulations were conducted, evaluating workability, moisture susceptibility, fatigue and rutting resistance, tensile strength, stiffness modulus, and long-term service performance using AASHTO Mechanistic-Empirical Pavement Design software [50]. The results indicated that the mechanical performance of WPT asphalt mixtures matched SBS asphalt mixtures. WPT asphalt mixtures exhibited enhanced long-term service performance, surpassing raw asphalt mixtures in moisture susceptibility, fatigue, and rutting resistance. Additionally, the results of the MEPDG prediction indicated that WPT asphalt mixtures exhibited high rutting resistance and provided a smoother pavement compared to conventional surface course mixtures realized with neat bitumen over a 20-year service life. The study demonstrated the feasibility of utilizing recycled waste packing tapes in road construction, with warm mix asphalt additive added at 3% of the weight of the asphalt mixture (FT-wax: Fischer–Tropsch wax is a type of synthetic wax produced via Fischer–Tropsch synthesis) contributing to improved mechanical properties in WPT asphalt mixtures.

G. White (2019) [51] conducted a study evaluating the applicability of three proprietary recycled plastic products (MR6, MR8, and MR10 from MacRebur) for bitumen modification through the wet process. The three products are entirely derived from recycled plastic waste materials sourced from both domestic and industrial origins. MR6 and MR10 are provided in pellet forms, enabling seamless integration into bitumen production plants. MR6 is engineered to enhance resistance to deformation, while MR10 is designed to enhance fracture resistance. Conversely, MR8 comprises shredded plastic and serves as an extender for bituminous binder in any asphalt mixtures, with a primary objective of reducing production costs or better performance. The base binder, graded with a penetration of 40/60, was modified with each plastic product at a weight ratio of 6 percent. The study assessed leachability and fume generation, finding no adverse impacts on either. Stone mastic asphalt (SMA) mixtures incorporating the plastic products showed significant improvements in stiffness and rutting resistance, with higher fracture toughness under stress-control conditions. While there was no substantial impact on moisture damage resistance, the study noted increased fatigue life with MR6 and MR10, with MR8 showing no improvement over the control mixture under strain-control conditions.

S. L. Hake et al. (2020) [52] conducted a study on integrating plastic waste from PET bottles into bitumen for flexible pavement. They replaced varying amounts of bitumen (5%, 7.5%, 10%, 12.5%, and 15%) with plastic waste and identified the optimal content as 10% with 5.25% bitumen. Testing revealed improved properties in plastic-modified semi-dense asphalt–concrete mixtures, including a 1.6% decrease in Marshall stability and an 8.1% reduction in air voids compared to neat mixtures. Bulk density increased by 0.43% in neat mixtures, meeting set limits for voids in mineral aggregates and bitumen-filled voids. As plastic content increased, the bituminous mixture, as well as the binder properties, improved. The study concluded that incorporating plastic waste enhanced road durability, led to extended service life to withstand heavier loads and resulted in a 5.18% reduction in construction and maintenance costs. This approach presents a viable solution to addressing environmental pollution issues.

Needhidasan Santhanam et al. (2020) [53] conducted an experimental study on asphalt pavement (VG30) using electronic waste or e-waste plastics to enhance strength and promote environmental sustainability. They added varying percentages (5% to 20%) of e-waste plastic powder to bitumen, aiming to evaluate its behavior in the VG30 grade according to Indian standards. The results showed a decrease in ductility values with increasing e-waste powder, reaching a maximum at 5%. Penetration and softening tests indicated lower values in the absence of e-waste plastic, increasing significantly with higher percentages. The viscosity test revealed a gradual increase in viscosity with more e-waste plastic, reaching a minimum without any addition. Substituting 10% of e-waste led to a 10% reduction in bitumen need, enhancing flexibility and strength by 11.28%. However, exceeding 7.5% e-waste decreased binder stability, and adding fly ash improved Marshall stability by up to 25%. The study concluded that incorporating e-waste in road construction offers benefits in enhancing properties, improving resistance to rutting, strengthening pavements, and addressing environmental concerns.

Elnaml et al. (2023) [54] examined the effectiveness of asphalt mixtures that include plastic waste materials (PWM), particularly high-density polyethylene (HDPE), and compared the results with those of two conventional asphalt mixtures. They used three distinct asphalt mixtures, including two mixtures with bituminous binder PG 76-22 and PG 70-22 modified with styrene–butadiene–styrene block copolymer (SBS) polymer and a mixture with bituminous binder PG 67-22 modified with HDPE added at a dosage of 3% by weight of the bituminous binder. The rheological characteristics and effectiveness of both modified bituminous binders and asphalt mixtures were assessed. Testing revealed that the bituminous binder modified with HDPE waste plastic, graded as PG 70-22, demonstrated rheological characteristics comparable to the SBS-modified PG 70-22 bituminous binder. The asphalt mixture, which includes HDPE plastic waste named M673H, exhibited greater stiffness compared to conventional mixtures M76 (mixture with binder PG 76-22) and M70 (mixture with binder PG 70-20). It also matched the rutting resistance of these conventional mixtures, adhering to the LaDOTD's maximum 6 mm threshold for traffic level 2 with ESALs greater than 3 million [55]. Additionally, the inclusion of HDPE plastic waste in the M673H mixture enhanced resistance to moisture in comparison to mixtures M70 (mixture with binder PG 70-20) and M76 (mixture with binder PG 76-22). The M673H mixture showed crack resistance, characterized by the J_c parameter (critical J_c-integral), which quantifies the energy release rate per unit fracture surface area and indicates resistance to crack initiation. Its J_c value was similar to that of M70, suggesting comparable crack resistance, and only marginally different from M76, implying a slight variation in fracture resistance. Finally, predictions for long-term field cracking performance, conducted through the AASHTOWare Pavement Mechanistic–Empirical (ME) software (v.1.1.6) [50], revealed that the pavement configuration featuring an M673H wearing course layer demonstrated comparable cracking resistance to that observed in a pavement structure incorporating an M70 layer.

M. Tušar al. (2023) [56] investigated the impact of blending plastic waste with bitumen through inter-laboratory experiments. Two types of polyethylene (PE) waste—primary (pellets) and secondary (shreds)—were used at a 5% concentration. The plastic was shredded and sieved to 1 mm before blending to enhance compatibility. The results showed that the blending process is purely physical, without altering the chemistry of bitumen. Temperature significantly influenced the material's behavior: at low temperatures, the mix exhibited elastic properties, while at higher temperatures, bitumen became viscoelastic, leading to greater variability in laboratory results. The inhomogeneity and instability of PE blends were more pronounced at high temperatures. Rheological testing indicated a filler-like effect above 34–40 °C, with helical spindle measurements providing more stable viscosity trends. Multiple Stress Creep Recovery (MSCR) tests demonstrated that PE blends improved resistance to permanent deformation. Meanwhile, Linear Amplitude Sweep (LAS) tests, used to characterize the fatigue performance of binder blends, indicated better performance in terms of stress and fatigue life for the PE blends. Overall, no significant performance differences were found between shreds and pellets, suggesting that secondary waste (shreds) can serve as a viable alternative to primary waste (pellets).

The synopsis of the investigations employing the wet process for flexible pavement preparation is depicted in Table 2.

Table 2. Overview of research papers employing the wet process for modification.

Year	Author	Type of Recycled Plastic Used	Recycled Plastic (%)	Impact on Properties	Refs.
2000	A. Tuncan et al.	LDPE	5, 10, and 20% by weight of bituminous binder	**Marshall stability**: Improved stability was achieved by adding plastic, indicating enhanced bonding between the modified binder and aggregates. **Indirect tensile strength**: Significant boost, with a 69% increase when 20% plastic was added to the binder.	[32]
2002	Gao et al.	LDPE	0.5 to 1.5% by weight of bituminous binder	**Storage stability**: Improved storage stability using pre-blended LDPE/SBS. Softening-point variations were reduced through the addition of sulfur, but viscosity differences at higher LDPE dosages were not eliminated. **Rheological properties**: Improved high-temperature rutting resistance, as evidenced by dynamic shear rheometer (DSR) temperature-sweep tests.	[6]
2003	A.A Yousefi	HDPE, LDPE, LLDPE	1 and 3% by weight of bituminous binder	**Physical network formation**: A physical network was formed via PBR-PE blends, unlike SBR, NR, and SEBS blends. **Elastic recovery and film-forming properties**: Superior elastic recovery and film-forming properties were exhibited by SBR-PE blends. **Effectiveness of LDPE types**: Bituminous binder properties were more effectively altered through LLDPE compared to LDPE and HDPE. **Incorporation of HVS oil**: Enhanced low-temperature characteristics are offered via HVS oil. **Expansion of rubber particles with HVS oil**: The volume of rubber particles was expanded by adding HVS oil, contributing to improved material performance.	[33]

Table 2. *Cont.*

Year	Author	Type of Recycled Plastic Used	Recycled Plastic (%)	Impact on Properties	Refs.
2004	S. Hinisli-oglu et al.	Recycled HDPE	4, 6, and 8% by weight of bituminous binder	**Marshall stability**: Decreasing values were observed in the Marshall stability test with increasing HDPE dosage, except for 4% HDPE mixtures. **Marshall flow**: An inverse pattern was observed in Marshall flow findings. **Rutting resistance**: A 50% increase in rutting resistance for the 4% HDPE mixture.	[34]
2005	G. Polacco et al.	PE-based polymers	6% by weight of bituminous binder	**Storage instability and phase separation:** Storage instability and phase separation were exhibited by all PE-based polymer-modified binders. **Effect of polymer types:** Enhanced compatibility for ethylene-based reactive terpolymers and GMA functional groups. The highest compatibility with the bituminous binder was shown for LLDPE. **Rheological and viscosity characteristics:** Noticeable differences in rheological and viscosity characteristics were observed in LLDPE, suggesting potential crosslinking during high-shear mixing.	[35]
2006	S. Ho et al.	Recycled (PE) wax, recycled LDPE	Up to 4% by weight of bituminous binder	**Rutting resistance and thermal cracking resistance**: Improved rutting resistance but reduced thermal cracking resistance with added PE wax and LDPE was exhibited. **Suitability of LDPE for asphalt enhancement**: LDPE with a reduced molecular weight and broader molecular weight distribution was identified as better suited for asphalt enhancement.	[36]
2008	D. Casey et al.	Recycled LDPE, recycled MDPE, recycled HDPE, recycled PP, recycled PVC, recycled PET	Up to 6% by weight of bituminous binder	**Impact of DETA on storage stability:** Decreased storage stability was exhibited by binders modified with 1 and 2% DETA. **Performance enhancement with PPA:** Performance properties and storage stability were enhanced through the addition of 0.8% PPA, identifying the binder with 0.8% PPA and 4% HDPE as optimal. **Indirect tensile fatigue and rutting tests:** Better performance was achieved using an HDPE-plus-PPA modified mixture.	[38]
2011	A. Moatasim et al.	HDPE	1 to 7% by weight of bituminous binder	**Effects on binder properties:** The bituminous binder was stiffened through the addition of HDPE, as indicated by increased softening points and reduced penetration and ductility values, especially at higher dosages. **Resistance to temperature fluctuations and mass loss:** Improved resistance to temperature fluctuations and decreased mass loss attributed to heat and air were demonstrated by HDPE-modified binders. **Stability and rutting resistance in asphalt mixtures:** Increased stability and rutting resistance were observed in asphalt mixtures with higher HDPE dosages. **Moisture resistance and stiffness:** Superior moisture resistance, increased stiffness at 25 °C, and improved thermal cracking resistance at low temperatures were exhibited by HDPE-modified mixtures, particularly the 5% HDPE-modified mixture.	[39]
2012	R.E. Villegas-Villegas et al.	Recycled HDPE	3% by weight of bituminous binder	**Impacts on high-temperature deformation:** Enhanced resistance to high-temperature permanent deformation compared to the base binder. **Impact on fatigue resistance:** No notable impact on fatigue resistance was observed. **Mixture-performance tests:** Increased stiffness and improved resistance to rutting and moisture damage were noted.	[40]

Table 2. *Cont.*

Year	Author	Type of Recycled Plastic Used	Recycled Plastic (%)	Impact on Properties	Refs.
2013	Costa et al.	Recycled HDPE, recycled LDPE	5% by weight of bituminous binder	**Effect on binder properties:** Raised softening points and reduced penetration were shown with the incorporation of polymers, particularly with HDPE, EVA, and SBS. **Resilience and elasticity of modified binders:** Comparable or better resilience was exhibited by modified binders, especially binders modified with EVA, SBS, and crumb rubber. **Impact on binder viscosity:** Increased binder viscosity was exhibited by polymer addition, with SBS-modified binders exhibiting the highest viscosity.	[42]
2014	Ambika Behl et al.	Recycled PVC	3 and 5% by weight of bituminous binder	**Increased binder stiffness and viscosity**: Increased binder stiffness and viscosity with PVC waste addition after chemical modification and blending were observed. **Enhanced rutting resistance**: Enhanced resistance against permanent deformation (rutting) was exhibited with 5% PVC waste-modified binder. **High consistency and elasticity of modified binders**: Increased retained stability and improved moisture susceptibility were demonstrated by modified asphalt mixtures in mechanical tests. **Enhanced rutting and cracking resistance**: Enhanced resistance against permanent deformation and cracking was observed, with decreased rutting values and increased fatigue life, particularly with higher PVC waste percentages.	[43]
2015	M.A. Dalhat and H.I. Al-Abdul Wahhab	Recycled PP, recycled HDPE, recycled LDPE	4% by weight of bituminous binder	**Increased viscosity in modified binders:** Increased viscosity was observed in all modified binders, with more significant viscosity changes noted in HDPE and PP compared to LDPE. **Enhanced rutting resistance:** Improved viscoelastic behavior was displayed by the plastic-modified binders, indicating enhanced rutting resistance. **Bitumen hardening and stiffness:** Bitumen hardening was evidenced due to plastic modification, with the mixture containing 2% PP demonstrating the greatest stiffness. **Predicted performance in asphalt pavements:** Enhanced predicted rutting and fatigue performance in asphalt pavements, with PP showing a more pronounced improvement compared to HDPE and LDPE were displayed.	[44]
2016	I.M. Khan et al.	Recycled HDPE, recycled LDPE	2, 4, 8, and 10% by weight of bituminous binder	**Enhancements in elastic behavior and rutting resistance:** Enhancements in the elastic behavior and resistance to rutting of the base binder were displayed via the inclusion of HDPE and LDPE. **Optimal blends for modifying bitumen:** The most effective resistance against rutting was exhibited with the inclusion of 4% HDPE and 10% LDPE	[46]
2017	Shubham Bansal et al.	Not specified	4, 6, 8, and 10% by weight of bituminous binder	**Increase in strength with partial replacement of bitumen:** An increase in strength by up to 16% was observed with the partial replacement of bitumen with plastic waste, while rubber materials showed a remarkable 50% improvement. **Flow values and air void content standards:** High flow values were exhibited by mixtures with over 10% rubber replacement, and allowable air void content standards were met using both modified and non-modified mixes. **Environmental benefits and cost reduction:** Enhancements in strength and durability, as well as the potential to reduce environmental pollution and minimize construction costs, were achieved by incorporating post-service life material wastes in asphalt–concrete mixtures.	[47]

Table 2. *Cont.*

Year	Author	Type of Recycled Plastic Used	Recycled Plastic (%)	Impact on Properties	Refs.
2018	Zhen Leng et al.	Recycled PET	1, 1.5, and 2% by weight of bituminous binder	**Improvements in binder properties:** Improvements in softening point, permanent deformation, resistance to stripping, and fatigue cracking resistance were indicated in PET-modified binders with RAP. **Influence on elastic characteristics and low-temperature performance:** Positive influence on the elastic characteristics and low-temperature performance of the mixtures was observed with the addition of PET-derived additives. **Impact on rutting resistance and fatigue crack resistance:** A 15% improvement in rutting resistance and a 60% enhancement in fatigue crack resistance were achieved by incorporating PET-based additives.	[48]
2019	Huayang Yu et al.	Not specified	6% by weight of bituminous binder	**Mechanical performance:** Comparable mechanical performance was noted between WPT and SBS asphalt mixtures. **Enhanced long-term service performance:** Enhanced long-term service performance was exhibited by WPT asphalt mixtures. **Prediction by MEPDG:** High rutting resistance and smoother pavement were indicated by the results of the MEPDG prediction for WPT asphalt mixtures.	[49]
2019	G. White	Products from MacRebur	6% by weight of bituminous binder	**Assessment of environmental impact:** Leachability and fume generation were assessed in the study, with no adverse impacts found on either. **Improvements in asphalt mixtures:** Significant improvements in stiffness and rutting resistance were observed in stone mastic asphalt (SMA) mixtures incorporating plastic products, with higher fracture toughness noted under stress-control conditions. **Impact on moisture damage resistance and fatigue life:** Increased fatigue life was noted with MR6 and MR10, while MR8 showed no improvement over the control mixture under strain-control conditions, although there was no substantial impact on moisture damage resistance.	[51]
2020	S. L. Hake et al.	Recycled PET	5, 7.5, 10, 12.5, and 15% by weight of bituminous binder	**Improved properties in plastic-modified asphalt mixtures:** Improved properties in plastic-modified semi-dense asphalt–concrete mixtures, including a 1.6% decrease in Marshall stability and an 8.1% reduction in air voids. **Increase in bulk density:** A 0.43% increase in bulk density was observed in neat mixtures, meeting the set limits for voids in mineral aggregates and bitumen-filled voids. **Road durability and cost reduction:** Enhanced road durability was observed through the inclusion of plastic waste, resulting in an extended service life capable of withstanding heavier loads and a 5.18% reduction in construction and maintenance costs.	[52]
2020	Needhidasan San-thanam et al.	Not specified	5 to 20% by weight of bituminous binder	**Effect on ductility, penetration, and softening point:** A decrease in ductility values was observed with increasing e-waste powder, reaching a maximum at 5% penetration and softening tests indicated lower values in the absence of e-waste plastic, which increased significantly with higher percentages. **Impact on viscosity and bitumen need:** A gradual increase in viscosity was revealed with more e-waste plastic, reaching a minimum without any addition. Substituting 10% of e-waste resulted in a 10% reduction in bitumen needs, leading to an enhancement in flexibility and strength by 11.28%. **Effect on binder stability and Marshall stability:** Binder stability was decreased when exceeding 7.5% e-waste, and Marshall stability was improved by up to 25% with the incorporation of fly ash.	[53]

Table 2. *Cont.*

Year	Author	Type of Recycled Plastic Used	Recycled Plastic (%)	Impact on Properties	Refs.
2023	I.Elnaml et al.	Recycled HDPE	3% by weight of bituminous binder	**Stiffness and Rutting Resistance of HDPE-Modified Asphalt Mixture:** Greater stiffness and rutting resistance compared to conventional mixtures M76 and M70 were exhibited by the HDPE asphalt mixture. **Resistance to Moisture and Crack Resistance:** Enhanced resistance to moisture was observed in the M673H mixture due to the inclusion of HDPE plastic waste.	[54]
2023	M. Tušar al.	Polyethylene (PE)	5% by weight of bituminous binder	**Temperature-Dependent Behavior:** Elastic properties were exhibited by the mix at low temperatures, while at high temperatures, bitumen became viscoelastic, leading to inhomogeneity and instability. **Filler-Like Effect:** PE was observed to act as a filler above 34–40 °C, influencing viscosity trends. **Resistance to Permanent Deformation:** Improved resistance to permanent deformation was indicated through MSCR tests. **Fatigue Performance and Stress Resistance:** Enhanced fatigue performance and stress resistance were demonstrated through LAS tests. **Feasibility of Secondary Waste Usage:** No significant performance difference was observed between shreds and pellets, making secondary waste a viable alternative.	[56]

By adopting the wet process, various plastic and rubber additives significantly enhance the characteristics of asphalt mixtures, improving stability, viscosity, and rutting resistance. HDPE stands out for its exceptional high-temperature performance and positive impact on moisture susceptibility, whereas LDPE enhances adhesion properties without affecting moisture resistance. SBS and PP contribute to storage stability and stiffness, respectively, while PVC and PET extend service life and enhance deformation resistance. Rubber additives boost elastic recovery and durability, and waste materials like e-waste and packing tape show promise in enhancing flexibility, strength, and resistance to environmental factors. Despite these benefits, challenges persist: LDPE fails to improve moisture susceptibility, which is crucial for long-term durability, while HDPE's increased stiffness could lead to potential thermal cracking and mixture-heterogeneity issues. PP, which is beneficial for viscosity and rutting resistance, may worsen fatigue resistance and stiffness suitability across climates. PVC raises environmental concerns, and PET modifications may reduce Marshall stability and air voids, affecting density and performance over time. Additionally, rubber additives pose compatibility issues, and the long-term impacts and optimal proportions of additives remain unclear, complicating practical application. Further research is needed to address these weaknesses and fully understand the environmental and health impacts of these additives in asphalt mixtures.

2.2. Dry Process

The dry process involves modifying asphalt mixtures by adding a modifier to preheated aggregates (at 170 °C). This mixture ensures a consistent coating of modifiers over the aggregates, turning them into reinforcement materials. Subsequently, hot bitumen (at 160 °C) is introduced into the mixer and blended to achieve uniformity in the modified asphalt mixture (AM) [26,57]. In this method, waste plastics are incorporated directly into the asphalt mixture, serving as either a partial substitute for aggregates or a modifier for the mixture [24]. Figure 2 demonstrates the diagram of the dry process. In contrast to the wet process, the dry process demonstrates greater cost-effectiveness and features a simpler production method, eliminating the requirement for specialized equipment. It can be implemented in any asphalt plant lacking the need for substantial modifications [22]. However, because of the absence of standardized guidance and engineering expertise for the dry process, further research is imperative. Moreover, unlike the wet process where bitumen emits fumes during modification, in the dry process, no fumes are released during modification, distinguishing between the two methods [58,59].

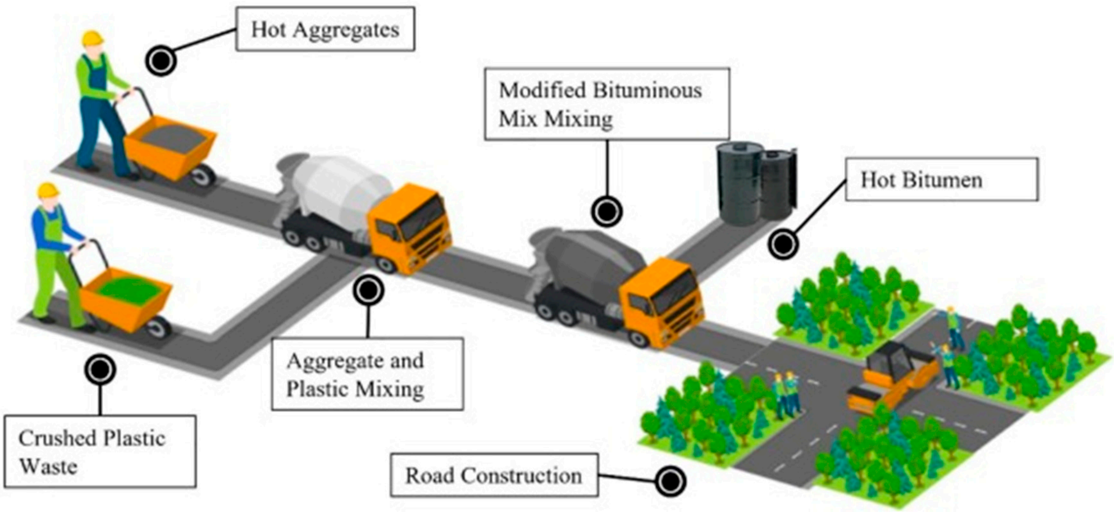

Figure 2. The dry process scheme [31].

O. Kamada et al. (2002) [60], in their study, utilized recycled polyethylene (PE) and polypropylene (PP) in modifying asphalt mixtures through a dry process. The study focused on two categories of asphalt mixtures: open-graded and dense-graded. Up to 10 percent recycled plastics were incorporated as a substitute for aggregates, and various performance tests were carried out, including immersion wheel tracking, wheel tracking, oil-resistant tests (for open-graded mixtures), and bending fatigue (for dense-graded mixtures). The findings showed that the incorporation of PE enhanced fatigue, rutting, and stripping resistance in dense-graded mixtures, with outcomes varying based on the specific type of recycled PE. Conversely, PP-modified dense-graded mixtures showed enhanced rutting resistance but no improvements in fatigue and stripping resistance. For open-graded mixtures, the addition of PE resulted in improved resistance to rutting, stripping, and gasoline immersion. This was evidenced by improvements observed in dynamic stability throughout the wheel-tracking test, an increase in resistance to failure over time in the immersion wheel-tracking test, and an enhancement in stability under oil exposure in the oil-resistant test, respectively.

A. Hassani et al. (2005) [61] explored the incorporation of PET (polyethylene terephthalate) in asphalt mixtures as a sustainable alternative for aggregate replacement, known as Plastiphalt. PET supplied in granule pellet form was incorporated into the asphalt mixture by replacing 20 to 60% (by volume) of aggregates within the 2.36 mm to 4.75 mm size range. Plastiphalt mixtures followed a “drop-in” approach, maintaining the same aggregate structure and optimal binder content as the control mixture. Testing for Marshall stability, flow, Marshall-quotient value, and density revealed that, as the PET dosage increased, Plastiphalt mixtures exhibited decreased stability and increased flow. Except for the 5 percent dosage, Plastiphalt consistently showed lower stability and Marshall-quotient values, attributed to reduced friction between PET granules. Interestingly, at the 5 percent dosage, the Plastiphalt mixture displayed a slightly higher Marshall-quotient value than the control mixture. Because of the reduced specific gravity of PET, all Plastiphalt mixtures achieved lower density values than the control mixture. The study estimated that substituting 5 percent of aggregates with PET in constructing a 1 km road could save 625 tonnes of natural resources while utilizing 315 tonnes of PET, resulting in significant environmental benefits.

M.T. Awwad et al. (2007) [62] assessed the effectiveness of polyethylene (PE) in modifying asphalt mixtures through the dry method, utilizing both high-density polyethylene (HDPE) and low-density polyethylene (LDPE) polymers. The dry process involved adding PE polymers directly into coarse aggregates at elevated temperatures, resulting in the creation of a thin polymer coating over the aggregate surfaces. Different forms (ground and unground) and seven dosage levels (6–18% by weight of the bituminous binder) were assessed for each PE polymer. Various tests, including bulk density, air voids, voids in mineral aggregates (VMA), Marshall flow, and Marshall stability, were performed on both PE-modified and unmodified mixtures. The findings indicated that blends containing PE modifications consistently exhibited reduced bulk density compared to the unmodified control, with the highest bulk density observed at a 12% dosage for both HDPE and LDPE. The addition of HDPE and LDPE improved the Marshall stability flow, with ground HDPE consistently outperforming unground HDPE. Nevertheless, LDPE did not show a similar pattern. Blends with PE modifications demonstrated elevated air voids and VMA compared to the control, with these values decreasing up to a 12% dosage and increasing at higher dosages. The study suggested that utilizing 12% ground HDPE would be the optimal modification for the mixture based on the observed performance across various parameters.

Sangita et al. (2011) [63] evaluated how a waste polymer modifier (WPM) influenced the engineering properties of asphalt mixtures. The WPM employed consisted of a mixture of recycled polyethylene (PE) and shredded nitrile rubber in a 1:4 ratio, with approximately 98 percent passing a 2.36 mm sieve and 73% passing a 1.18 mm sieve. The dry process was used to add WPM, coating the aggregate surface, which was subsequently blended with the regular bituminous binder to create WPM-modified mixtures. WPM contents ranged from 6 to 15 percent by weight of the bituminous binder. All mixtures modified with WPM were generated through a “drop-in” method, maintaining the optimal binder content and the same aggregate structure as the control mixture. In accordance with the results of the Marshall stability test, an optimal dosage of 8 percent WPM was identified. Subsequently, the optimal modified mixture with WPM underwent testing for indirect tensile strength, creep stiffness, resilient modulus, retained stability, and wheel tracking. The test outcomes showed that incorporating WPM augmented the stiffness of the control mixture, thereby enhancing its ability to resist permanent deformation and moisture damage.

R. Vasudevan et al. (2012) [58] examined the application of waste plastics (polyethylene, polypropylene, and polystyrene) in modifying asphalt mixtures through the dry method. Waste plastics were introduced to aggregates prior to mixing with bituminous binder, forming plastic-coated aggregates (PCAs). The PCAs exhibited enhanced properties, including crushing resistance, improved soundness, impact resistance, and abrasion resistance, alongside reduced water absorption compared to uncoated aggregates. The Marshall stability of asphalt mixtures was also augmented with PCAs. Between 2002 and 2006, evaluations of paving projects employing PCAs showed either comparable or superior performance regarding smoothness, field density, rebound deflection, texture depth, and skid resistance. These projects exhibited no instances of rutting, cracking, potholes, or edge flaws associated with PCA usage. Additionally, a cost analysis revealed potential material cost savings of around 10 percent for asphalt mixtures incorporating PCAs.

Umadevi Rongali et al. (2013) [64] conducted a study on enhancing asphalt–concrete (AC) mixtures for flexible pavement construction by incorporating a composite of fly ash and plastic waste. They tested various percentages of plastic waste in the mixture and found that the optimal content was 0.75%. The study also identified optimal binder content for both the fly ash and the fly ash–plastic waste composite. Two laboratory-produced asphalt mixtures, AC A (with fly ash) and AC B (with a fly ash–plastic waste composite), were created. Performance tests, including static creep, resilient modulus under various temperature conditions, rutting resistance, and indirect tensile strength, were conducted. AC B demonstrated a 10.3% greater indirect tensile strength ratio, indicating enhanced durability against moisture damage. The static creep test revealed higher deformation and recovery percentages for AC B at elevated temperatures. Additionally, AC B exhibited higher resilient modulus values and a 15.9% lower rut depth than AC A, showcasing improved resistance to rutting. The study found that the asphalt–concrete pavement with a composite of plastic waste and fly ash displayed enhanced properties, making it suitable for asphalt road construction.

T.B. Moghaddam et al. (2014) (2015) [65,66] investigated the permanent deformation behavior of stone mastic asphalt (SMA) mixtures enhanced with recycled polyethylene terephthalate (PET) from waste plastic bottles. PET was added at varying dosages (0.2% to 1.0% by weight of aggregate) using a dry method. The optimal binder content of the stone mastic asphalt (SMA) mixture decreased until reaching a PET dosage of 0.6%, beyond which it increased. At the 0.6% PET dosage, the modified SMA mixture exhibited a 6.29% optimal binder content, marking a decrease of 0.48% compared to the unmodified control. Dynamic creep tests at different stress levels and temperatures revealed that PET modification significantly improved rutting resistance in SMA mixtures. This improvement was evident in reduced cumulative permanent strain, higher flow number values, and increased load cycles during primary and secondary deformation stages, particularly at higher PET contents and stress levels.

S. Angelone et al. (2016) [67] explored the inclusion of plastic waste into asphalt mixtures using the dry process, focusing on polypropylene (PP in chip form) and polyethylene (PE) derived from silo bags (recycled into flakes and pellets). Each plastic type was used to prepare three samples at different percentages (2%, 4%, and 6% by weight of the asphalt mixture). The study conducted extensive laboratory analyses, including Marshall, indirect tensile strength (ITS), moisture susceptibility, dynamic modulus creep compliance, and wheel-tracking (WTTs) tests. PE-modified mixtures exhibited increased stability values with rising plastic content, while PP-modified mixtures showed decreased stability. PE-modified mixtures demonstrated comparable permanent deformation resistance and better fatigue and thermal cracking resistance, while PP-modified mixtures achieved lower performance in these aspects. Both PE- and PP-modified mixtures showed good resistance to water immersion. PE-modified mixtures exhibited low thermal susceptibility, whereas PP-modified mixtures displayed similar dynamic modulus results to control mixtures at 2% and 4% PP. Overall, the study concluded that incorporating recycled PE from silo bags significantly improved mixture performance compared to control mixtures, with a cautious recommendation for the use of flakes at a 2% dosage.

A.A. Adedayo Badejo et al. (2017) [68] investigated the utilization of recycled polyethylene terephthalate (PET) as a performance modifier in asphalt mixtures. The process of preparing PET-modified mixtures involved incorporating ground PET into the mixture through the dry method. PET content varied from 1% to 5% of the bituminous binder's weight. For each PET dosage, two sets of modified mixtures were produced: one through the "binder replacement" technique and the other through the "direct addition" approach. The Marshall stability test was conducted on the mixtures modified with PET at different contents and employed various addition approaches. Overall, mixtures enhanced with PET showed decreased Marshall stability and increased Marshall flow values in comparison to the unmodified mixture, suggesting the decreased stability and deformation resistance of the mixture. Nevertheless, a contrasting trend was noted for the modified mixture with 1 percent PET employing the "direct addition" technique. The Marshall test outcomes for this specific modified mixture satisfied the agency standards. As a result, the study recommended incorporating recycled PET at a 1 percent dosage as a viable method for enhancing asphalt mixtures.

G. White et al. (2018) [20] investigated the utilization of three recycled plastic products from MacRebur, produced from 100% recycled waste, for asphalt mix modification. The products, MR6 (pellet form), MR8 (shredded form), and MR10 (pellet form), were introduced into asphalt mixtures through the dry method, substituting 6 percent of the volume of the bituminous binder. Two asphalt mixtures (AC20 and SMA10) were tested, and laboratory results, following British specifications, demonstrated that the AC20 mixture, when modified with MR6, displayed enhanced stiffness, improved rutting resistance, and superior resistance to moisture damage in contrast to the unmodified mixture. For the SMA10 mixture, the incorporation of MR6, MR8, and MR10 resulted in increased rutting resistance, fracture toughness, and stiffness. However, the impact on moisture damage resistance varied between the three products. An economic evaluation analysis indicated that employing MR6 and MR10 as a replacement for 6% vol. could present a financially viable option compared to typical modified binders in Australia.

M. Pasetto et al. (2022) [69] conducted a comparative experimental investigation on dense-graded asphalt blends integrating different proportions of recycled plastics (0%, 0.25%, and 1.5% of the asphalt mixture's weight) using the dry method. To prepare PE-modified asphalt mixtures, preheating the aggregates at 160 °C for 3 h was essential. Following this, the desired amounts of PE shreds, stored at room temperature, were added to the hot aggregates if required. The PE recycled waste and hot aggregates were blended for a duration of 1 min, after which hot bitumen (at 160 °C) was added and mechanically stirred for 2 min to achieve visual homogeneity. Following this, filler at room temperature was added to the hot mixture for a final mixing period of 1 min. Additionally, a control mixture devoid of plastic waste was analyzed for comparative analysis. The prepared asphalt blends underwent several laboratory tests to investigate their linear viscoelastic characteristics, strength, workability, resistance to permanent deformation, susceptibility to moisture, and stiffness. The overall findings from the study revealed several key insights. Firstly, the incorporation of waste PE up to 1.5% of the mixture's weight showed no notable impact on the workability of the asphalt mixture under the investigated production conditions. However, when utilizing the maximum recycling rate in the study, significant alterations in the rheological characteristics of the asphalt mixtures were observed, demonstrating a shift towards a more elastic response across the entire time–temperature domain. This change was accompanied by a notable stiffening effect in the high-temperature/low-frequency domain. Moreover, mixtures incorporating recycled waste plastic exhibited significantly higher stiffness and resistance to permanent deformation, with a clear trend showing improved material response as the PE dosage increased. Indirect tensile tests also revealed a proportional increase in fracture resistance and strength with the addition of plastic waste, indicating the potential reinforcement of the asphalt mastic through chemo-physical interactions between the asphalt binder and plastic particles. Importantly, the investigation found no detrimental impacts on the resistance to moisture of the asphalt mixture with the inclusion of PE waste.

L.D. Poulikakos et al. (2022) [70] elaborated on an interlaboratory study conducted by RILEM TC 279-WMR (TG1: waste plastic-modified asphalt binders; TG3: waste aggregates in asphalt mixtures), which evaluated the effect of incorporating polyethylene (PE) waste into asphalt mixtures at dosages of 0.25%, 0.5%, 1%, 1.5%, and 5% by weight of the asphalt mixture. The objective was to determine whether the benefits observed at the binder level would translate into improved asphalt mixture performance while addressing stability and homogeneity concerns. Standardized protocols were followed, using locally sourced bitumen and aggregates, while the PE waste was supplied from a single source. The experimental campaign included tests on strength, stiffness, and permanent deformation. The results indicated that, although asphalt mixing temperatures exceed the melting point of PE, the plastic does not fully dissolve and instead behaves as an elastic particle within the mixture. PE-modified mixtures exhibited a lower construction densification index (CDI), indicating improved workability and easier compaction, with the CDI proving more sensitive to PE content than EN methods. The addition of PE increased indirect tensile strength (ITS), suggesting improved cohesion in the mastic phase, with a slight but consistent increase in ITS at higher PE contents. Moisture resistance remained comparable to the reference mixture for PE contents up to 1.5%, except in cases where water-sensitive granite aggregates were used. Stiffness generally increased with higher PE content (up to 5%), and under axial sinusoidal loading, the 1.5% PE-modified mixture exhibited reduced time dependency compared to the reference mix. PE-modified mixtures also demonstrated greater elasticity, lower creep rates, and a higher creep modulus. Resistance to permanent deformation improved, as confirmed via cyclic compression tests, while wheel-tracking tests in air showed stable or better results with 1.5% PE. However, wheel-tracking tests in water indicated increased deformation at higher PE doses (>5%), suggesting that excessive PE content could lead to rutting issues. Based on these findings, the optimal PE content for balancing performance improvements and stability was identified as 1.5% of the asphalt mixture mass.

The summaries of the investigations employing the dry process for flexible pavement preparation are illustrated in Table 3.

Table 3. Overview of the research papers employing the dry process for modification.

Year	Author	Type of Recycled Plastic Used	Recycled Plastic (%)	Impact on Properties	Refs.
2002	O. Kamada et al.	Recycled PE, recycled PP	Up to 10% by volume of asphalt mixture	**Fatigue, rutting, and stripping Resistance in dense-graded mixtures**: Enhanced fatigue, rutting, and stripping resistance in dense-graded mixtures were achieved with the incorporation of PE, with outcomes varying based on the specific type of recycled PE. **Rutting resistance in PP-modified dense-graded mixtures:** Enhanced rutting resistance was observed in PP-modified dense-graded mixtures, with no improvements in fatigue and stripping resistance. **Resistance to rutting, stripping, and gasoline immersion in open-graded mixtures:** Improved resistance to rutting, stripping, and gasoline immersion in open-graded mixtures was achieved with the addition of PE.	[60]
2005	A. Hassani et al.	PET	5 to 15% by weight of asphalt mixture	**Marshall stability and flow:** With increasing PET dosage, decreased stability, and increased flow were exhibited by Plastiphalt mixtures. **Marshall-quotient values:** Except for the 5% dosage, lower stability and Marshall-quotient values were consistently observed with Plastiphalt, attributed to reduced friction between PET granules. **Density:** The lower density values of all Plastiphalt mixtures compared to the control mixture were attributed to the reduced specific gravity of PET. **Aggregate replacement:** Natural resources could be saved by substituting 5% of aggregates with PET in the construction of a 1 km road.	[61]

Table 3. *Cont.*

Year	Author	Type of Recycled Plastic Used	Recycled Plastic (%)	Impact on Properties	Refs.
2007	M.T. Awwad et al.	HDPE, LDPE	6 to 18% by weight of bituminous binder	**Bulk density:** Reduced bulk density was consistently exhibited by blends containing PE modifications, with the highest bulk density observed at a 12% dosage for both HDPE and LDPE. **Marshall stability and flow:** Marshall stability flow was improved with the addition of HDPE and LDPE with ground HDPE. **Air voids and VMA:** Air voids and VMA were elevated in blends with PE modifications, decreasing up to a 12% dosage and increasing at higher dosages.	[62]
2011	Sangita et al.	Blend of recycled PE and shredded nitrile rubber	6, 8, 12, and 15% by weight of bituminous binder	**Marshall stability:** An optimal dosage of 8% WPM was identified. **Indirect tensile strength, creep stiffness, resilient modulus:** The optimal modified mixture with WPM was observed to have augmented stiffness, thereby enhancing its ability to resist permanent deformation and moisture damage. **Retained stability and rutting resistance:** Improved resistance to permanent deformation and moisture damage in the asphalt mixture was exhibited.	[63]
2012	R. Vasudevan et al.	Recycled PE, recycled PP, recycled PS	5 to 20% by weight of bituminous binder	**Enhanced properties of plastics coated aggregates (PCA):** Various properties, such as crushing resistance, soundness, impact resistance, abrasion resistance, and reduced water absorption, were improved via the introduction of waste plastics to aggregates. **Improved Marshall stability:** Enhanced Marshall stability, indicating improved resistance to deformation and structural integrity, was exhibited. **Performance of paving projects:** Comparable or superior performance in terms of smoothness, field density, rebound deflection, texture depth, and skid resistance was observed. **Absence of pavement defects:** Instances of rutting, cracking, potholes, or edge flaws commonly associated with conventional asphalt mixtures were absent in projects utilizing PCA. **Cost savings**: Potential material cost savings of around 10% were suggested by a cost analysis for asphalt mixtures incorporating PCA, indicating economic benefits associated with this approach.	[58]
2013	Umadevi Rongali et al.	Not specified	0.25 to 1% by weight of asphalt mixture	**Enhanced indirect tensile strength:** A 10.3% greater indirect tensile strength ratio was exhibited by AC B compared to AC A, indicating enhanced durability against moisture damage. **Higher deformation and recovery:** Higher deformation and recovery percentages were revealed via static creep tests for AC B at elevated temperatures, suggesting improved resistance to deformation under thermal stress. **Higher resilient modulus values:** Higher resilient modulus values were exhibited by AC B compared to AC A, indicating greater stiffness and structural integrity. **Lower rut depth:** A 15.9% lower rut depth was demonstrated by AC B than AC A, highlighting improved resistance to rutting, a common distress mechanism in asphalt pavements. **Suitability for asphalt pavement structure:** Enhanced properties were displayed by asphalt–concrete pavement containing a composite of plastic waste and fly ash, making it suitable for use in asphalt road construction.	[64]
2014–2015	T.B. Moghaddam et al.	Recycled PET	0.2 to 1% by weight of aggregate	**Improvement in rutting resistance:** Significant improvements in rutting resistance were observed in PET-modified SMA mixtures at higher PET contents and stress levels.	[65]

Table 3. *Cont.*

Year	Author	Type of Recycled Plastic Used	Recycled Plastic (%)	Impact on Properties	Refs.
2016	S. Angelone et al.	Recycled PE, recycled PP	2, 4, and 6% by weight of asphalt mixture	**Stability enhancement:** Increased stability values with rising plastic content were demonstrated by PE-modified mixtures, whereas decreased stability was shown for PP-modified mixtures. **Rutting Resistance:** Comparable permanent deformation resistance to control mixtures was exhibited by PE-modified mixtures, while lower performance in this aspect was shown by PP-modified mixtures. **Fatigue and thermal cracking resistance:** Better fatigue and thermal cracking resistance were exhibited by PE-modified mixtures, whereas lower performance in these aspects was shown for PP-modified mixtures. **Water immersion resistance:** Good resistance to water immersion was shown for both PE and PP-modified mixtures. **Thermal susceptibility:** Low thermal susceptibility was exhibited by PE-modified mixtures, whereas similar dynamic modulus results in control mixtures at 2% and 4% PP were displayed by PP-modified mixtures.	[67]
2017	A.A. Adedayo Badejo et al.	Recycled PET	1 to 5% by weight of bituminous binder	**Marshall stability and flow:** Decreased Marshall stability was shown for mixtures enhanced with PET compared to the unmodified mixture. Increased Marshall flow values, indicating the decreased stability and deformation resistance of the mixture, were exhibited by mixtures enhanced with PET.	[68]
2018	G. White et al.	Not specified	6% by volume of bituminous binder	**Impact on AC20 mixture:** Enhanced stiffness, improved rutting resistance, and superior resistance to moisture damage were displayed by the AC20 mixture when modified with MR6 compared to the unmodified mixture. **Impact on SMA10 mixture:** Increased rutting resistance, fracture toughness, and stiffness resulted from the incorporation of MR6, MR8, and MR10 in the SMA10 mixture. **Moisture damage resistance:** The impact on moisture damage resistance varied between the three plastic products. **Economic evaluation:** A financially viable option compared to typical modified binders in Australia could be presented by employing MR6 and MR10 as a replacement for 6% of the volume, as indicated through economic evaluation analysis.	[20]
2022	M. Pasetto et al.	Recycled PE	0, 0.25, and 1.5% by weight asphalt mixture	**Impact on workability:** No notable impact on the workability of the asphalt mixture under the investigated production conditions was shown via the incorporation of waste PE up to 1.5% of the mixture's weight. **Rheological characteristics:** Significant alterations in the rheological characteristics of the asphalt mixtures were observed when the maximum recycling rate was utilized. **Stiffness and rutting resistance:** Significantly higher stiffness and resistance to permanent deformation, with improved material response as the PE dosage increased, were exhibited by mixtures incorporating recycled waste plastic. **Fracture resistance:** A proportional increase in fracture resistance and strength with the addition of plastic waste was revealed by indirect tensile tests. **Resistance to moisture:** No detrimental impacts on the resistance to moisture of the asphalt mixture with the inclusion of PE waste were found through the investigation.	[69]

Table 3. *Cont.*

Year	Author	Type of Recycled Plastic Used	Recycled Plastic (%)	Impact on Properties	Refs.
2022	L.D. Poulikakos et al.	Polyethylene (PE)	0.25%, 0.5%, 1%, 1.5%, and 5% by weight of asphalt mixture	**Compaction Efficiency:** A lower construction densification index (CDI) was exhibited by PE-modified mixtures, indicating improved workability and easier compaction. **Strength Enhancement:** Indirect tensile strength (ITS) was increased through the addition of PE, suggesting improved cohesion in the mastic phase. A slight but consistent increase in ITS was observed with a higher PE content. **Moisture Sensitivity:** Moisture resistance in PE-modified mixtures (≤1.5% PE) was found to be similar to that of the reference mixtures, except when water-sensitive granite aggregates were used. **Stiffness Variation:** Stiffness was generally increased through higher PE content (up to 5%), with 1.5% PE showing reduced time dependency under axial sinusoidal loading. **Viscoelastic Behavior:** Enhanced elasticity was demonstrated by PE-modified mixtures compared to the reference mixture. **Creep Performance:** Lower creep rates and a higher creep modulus were observed in PE-modified mixtures. **Resistance to Permanent Deformation:** Resistance to rutting was improved via PE. Stable or improved results were shown in wheel-tracking tests in air with 1.5% PE, while increased deformation was observed in water at higher PE doses (>5%), indicating that caution should be exercised with excessive PE content. **Optimal PE Content:** Based on the findings, 1.5% PE was identified as the optimal dosage for balancing performance improvements without compromising stability.	[70]

The inclusion of various plastic and rubber additives in asphalt mixtures through the dry process generally enhances performance characteristics such as stability, stiffness, rutting resistance, and resistance to moisture damage. PE and PP are particularly effective, with PE showing broad improvements in both dense- and open-graded mixtures, while PP primarily enhances rutting resistance. Recycled PE, even at higher dosages, significantly improves mechanical properties without compromising workability or moisture resistance. PET's performance is mixed, as it offers benefits in rutting resistance but may reduce stability and resistance to deformation. However, there are notable weaknesses to consider. PP fails to enhance fatigue and stripping resistance, PE may lower bulk density and increase stiffness, potentially leading to cracking, and PET can decrease stability and deformation resistance. Moreover, the variability and consistency of plastic waste sources could affect the reliability of these improvements. Despite these concerns, the benefits of enhanced durability, cost-effectiveness, and environmental friendliness make the use of these additives promising. Nevertheless, further research and careful consideration of these weaknesses are necessary to optimize their application in asphalt mixtures for long-term performance and sustainability.

2.3. Modified Process

Several researchers have proposed innovative modifications to traditional techniques to enhance mixture properties and alleviate shortcomings. In the dry process, challenges such as homogeneity and limited bitumen–plastic interaction time have been addressed [71]. Conversely, the wet process encounters issues such as problematic fumes, increased energy loss, and the need for additional stirring [72].

E. Ahmadina et al. (2011) [73] investigated the benefits of using inexpensive polymers such as plastic bottle waste (PET) on the mechanical characteristics of stone mastic asphalt (SMA) mixture. They also acknowledged the potential of incorporating plastic into flexible pavement construction to lower construction costs. Dissatisfied with the conventional dry processing technique, the authors made modifications. They adjusted the preheating time and temperature for aggregates to 2 h at 200 °C and for bitumen to 1 h at 150 °C. Another modification involved adding plastic after the mixing of binder and aggregates, rather than before the binder addition. While the authors successfully improved the characteristics of the asphalt mixture by incorporating plastic, it was noted that the modification itself did not demonstrate significant improvements in properties, particularly with only a 6% inclusion of PET.

J. Jafar (2016) [74] investigated the positive effects of incorporating chemically treated plastic waste and additives on the volumetric and mechanical characteristics of asphalt mixtures. Recycled waste plastics were chemically treated using an oxidizing blend, and bitumen underwent treatment with a crosslinking agent. Three variations of modified asphalt mixtures were created and compared with a standard mixture. The results showed that, at the optimum binder content, incorporating chemically treated plastic as a partial substitute for aggregate in asphalt mixtures led to higher stiffness compared to untreated plastic. The improvement was attributed to increased adhesion between bitumen and surface particles of chemically treated plastic. Despite control samples having lower bitumen content, the mixture samples with recycled plastic had higher bitumen content, contributing significantly to strengthening the bond between aggregate and bitumen. After ten cycles of soaked conditions, the chemically treated plastic–modified asphalt mixtures showed a 10% higher retained tensile strength than unconditioned samples, indicating enhanced stability due to chemical additives improving the adhering between aggregates and bitumen.

Leng et al. (2018) [48], in their research, assessed the viability of utilizing additives produced from PET waste via an aminolysis technique to create a PET additive for bitumen. The goal is to enhance the effectiveness of asphalt mixtures incorporating RAP (recycled asphalt pavement) by examining the properties of the binder. To accomplish this, binder samples were prepared, comprising neat bitumen, aged bitumen at different percentages, and additives sourced from PET. The samples underwent characterization using different laboratory tests, such as bending beam rheometer, dynamic shear rheometer, moisture susceptibility, fluorescence microscopy, and infrared spectroscopy. The findings revealed that the samples incorporating both RAP- and PET-sourced additives exhibited, in general, superior effectiveness when contrasted with the standard binder, with a minimum 15% boost in resistance to rutting and up to 60% enhancement in resistance to fatigue cracking resistance. Using waste PET-derived additives in RAP mixtures not only addresses recycling challenges but also contributes to the recovery of two value-added materials simultaneously.

Martin-Alfonso et al. (2019) [71] explored the feasibility of using recycled low-density polyethylene (LDPE) to modify asphalt mixtures through a dry process. Recycled LDPE from agricultural greenhouses was employed, and a reclaimed mineral-based lubricating oil was assessed as an adhesion promoter. Various bituminous binders were tested, and the results indicated that additives comprising recycled LDPE pre-swollen with mineral oil or bitumen could reduce mixing time and enhance the integration of waste plastic into asphalt mixtures. The blend containing 72.2% recycled LDPE and 27.8% mineral oil showed the most promising results in mitigating the long-term aging of the bituminous binder. While binders incorporating recycled polymer exceeded viscosity limits, mixture-performance testing showed achievable compaction when incorporating 0.5% recycled LDPE through a dry process. This addition demonstrated improvements in resistance to rutting and moisture sensitivity, especially for asphalt mixtures with high modulus. However, stiffness and rutting resistance showed a decrease in comparison to the control mixture, meeting agency requirements. The introduction of recycled LDPE through the dry method reduced air voids in porous asphalt mixtures. Notably, LDPE-modified porous mixtures demonstrated a different level of overall durability and fatigue resistance compared to the SBS-modified mixture.

Bary et al. (2020) [75] have considered the chemical treatments of waste poly(ethylene terephthalate) (WPET) by using various kinds of glycols such as propylene glycol (PG), triethylene glycol (TEG), and diethylene glycol (DEG) to produce unsaturated polyester (UP) for later use as a bituminous modifier. Several glycolysis agents were employed in the creation of three distinct glycolysis WPETs, which were subsequently utilized in the formation of three distinct UPs—namely, UP_{pro}, UP_{tri}, and UP_{di}. Modifiers were mixed at 4% and 8% (wt/wt) to produce modified bituminous binders, resulting in improved physical and engineering properties. The resulting UPs underwent characterization through GPC, TGA, and FTIR analyses. The modified bituminous samples were subjected to assessments encompassing physical, chemical, TGA, colloidal stability, and rutting resistance using a dynamic shear rheometer. The findings demonstrated an enhancement in bitumen characteristics, showcasing increased temperature stability and improved resistance to rutting and plastic deformation and rendering the bitumen more adaptable to diverse environmental conditions. Additionally, the research indicated that the toughness of modified bitumen increased because of the strong interaction between bitumen and UP. The optimal modification for the bitumen was determined to be 4%wt of UP_{tri}, as it exhibited the greatest resistance to rutting and decomposition temperature.

Francesca Russo et al. (2022) [76] conducted an extensive research investigation on asphalt pavement incorporating a modifier consisting of recycled hard plastics and graphene nanoplatelets. The modifier, introduced through the dry method, was compared with an SBS polymer-modified bitumen (PMB) modified through the wet process. The study focused on investigating mechanical and performance properties, addressing rutting distress in flexible pavements. The asphalt mixtures, incorporating 10% and 20% reclaimed asphalt pavement (RAP) for surface and base/binder courses, respectively, underwent various European standard tests. The findings indicated that the asphalt modified with waste hard plastic (GWP) and graphene demonstrated enhanced both strength and stiffness, with remarkably similar resistance to permanent deformation in both laboratory and field tests. The fatigue life of the GWP-modified bituminous binder was either greater or comparable to the SBS PMB counterpart. The dry method used for GWP modification proved sustainable and eco-friendly with no logistical or compaction issues. Over a two-year monitoring period, no distress signs were observed, underscoring the efficacy of utilizing recycled waste plastics as a viable bitumen modifier. This approach supports environmental preservation and promotes circular-economy principles.

Gaetano Di Mino et al. (2023) [77] explored in their study the multiple recycling potential of asphalt mixtures through a binder-scale characterization. The research involved three sets of data: a reference bitumen (50/70), unmodified binders derived from a control mixture, and binders obtained from a mixture incorporating a recycled plastic bitumen modifier. The study considered a recycling rate of 50%, involving three recycling cycles. The study revealed that the recycled plastic bitumen modifier increased the equi-shear modulus temperature, softening point, and upper PG. In the initial cycle, a slightly increased dosage of rejuvenator was necessary for the graphene-enhanced recycled plastic (GRP)-modified asphalt mixtures, attributed to the modifier's augmenting effects. However, subsequent cycles demonstrated consistent optimal dosages for both control and test mixtures. Rheological analysis emphasized the critical role of rejuvenator optimization in asphalt recycling, particularly for mixtures containing high levels of reclaimed asphalt pavement (RAP). Chemical characterization through FTIR spectroscopy indicated a decrease in carbonyl and sulfoxide bands, influenced by the rejuvenator. Despite the diverse effects observed on the reference bitumen, binders derived from reclaimed asphalt with the recycled plastic modifier showcased similar or comparable properties to binders in control mixtures throughout all recycling cycles. The study suggests that incorporating recycled materials as partial substitutes for virgin ones can yield end products with comparable or even superior performance, contingent upon the specific property under investigation.

The summaries of the investigations employing the modified process for flexible pavement preparation are illustrated in Table 4.

Table 4. Overview of the research papers employing the modified process for modification.

Year	Author	Type of Recycled Plastic Used	% Recycled Plastic	Impact on Properties	Refs.
2011	E. Ahmadina et al.	Recycled PET	2, 4, 6, 8, and 10% by weight of bituminous binder	**Impact on asphalt mixture characteristics:** Improved characteristics by incorporating plastic were noted, particularly with only a 6% addition. **Potential to lower construction costs**: The potential of incorporating plastic into flexible pavement construction to lower construction costs was acknowledged.	[73]
2016	J. Jafar	Not specified	8% by weight of total aggregate	**Stiffness of chemically treated plastic**: Higher stiffness was observed by incorporating chemically treated plastic as a partial replacement for aggregate in asphalt mixtures, indicating increased adhesion between bitumen and surface particles of chemically treated plastic. **Retained tensile strength under soaked conditions**: A 10% higher retained tensile strength was shown by the chemically treated plastic–modified asphalt mixtures, indicating enhanced stability due to chemical additives improving the adhesion between aggregates and bitumen.	[74]
2018	Leng et al.	Recycled PET	1, 1.5, and 2% by weight of bituminous binder	**Improved rutting and fatigue resistance:** Superior effectiveness was exhibited when incorporating both RAP and PET-sourced additives, with a minimum 15% boost in resistance to rutting and up to a 60% enhancement in resistance to fatigue cracking.	[48]
2019	Martin-Alfonso et al.	Recycled low-density polyethylene (LDPE)	0.5, 1, and 3% by weight of asphalt mixture	**Mixing time and integration:** Mixing time was reduced, and the integration of waste plastic into asphalt mixtures was enhanced via additives comprising recycled LDPE pre-swollen with mineral oil or bitumen. **Mitigation of long-term aging:** Mitigation of long-term aging of the bituminous binder was achieved using a blend containing 72.2% recycled LDPE and 27.8% mineral oil. **Viscosity limits and compaction:** Viscosity limits were exceeded with binders incorporating recycled polymer. Achievable compaction was demonstrated when incorporating 0.5% recycled LDPE through a dry process. **Rutting and moisture sensitivity:** Improvements in resistance to rutting and moisture sensitivity were observed, especially for asphalt mixtures. **Air voids in porous mixtures:** Air voids in porous asphalt mixtures were reduced via the introduction of recycled LDPE through the dry method. **Durability and fatigue resistance:** Different levels of overall durability and fatigue resistance were demonstrated by LDPE-modified porous mixtures.	[71]
2020	Bary et al.	Recycled polyethylene terephthalate (PET)	4 and 8% by weight of asphalt mixture	**Enhancement in bitumen characteristics**: An enhancement in bitumen characteristics was demonstrated, showing increased temperature stability and improved resistance to rutting and plastic deformation. **Increased toughness of modified bitumen:** An increased toughness of modified bitumen was exhibited due to the strong interaction between bitumen and USP.	[75]

Table 4. *Cont.*

Year	Author	Type of Recycled Plastic Used	% Recycled Plastic	Impact on Properties	Refs.
2022	Francesca Russo et al.	GWP and graphene	6% by weight of bituminous binder	**Enhanced strength, stiffness, and rutting resistance:** Enhanced strength and stiffness were demonstrated by the asphalt modified with waste hard plastic (GWP) and graphene, with remarkably similar resistance to permanent deformation observed in both laboratory and field tests. **Fatigue life and sustainability of GWP modification:** Greater or comparable fatigue life of the GWP-modified bituminous binder was demonstrated, proving to be sustainable and eco-friendly with no logistical or compaction issues. **Long-term monitoring and environmental Benefits:** No distress signs were observed, underscoring the efficacy of utilizing recycled waste plastics as a viable bitumen modifier.	[76]
2023	Gaetano Di Mino et al.	GRP	6% by weight of bituminous binder	**Effects of recycled plastic bitumen modifier**: The equi-shear modulus temperature, softening point, and upper PG of the asphalt mixtures were increased via the recycled plastic bitumen modifier. **Performance of recycled mixtures**: Similar or comparable properties to binders in control mixtures were showcased by binders derived from reclaimed asphalt with the recycled plastic modifier throughout all recycling cycles.	[77]

Incorporating chemically modified recycled plastics such as PET, LDPE, and GRP into asphalt mixtures significantly enhances material properties, operational efficiency, and sustainability in pavement construction. Studies indicate improvements in asphalt characteristics with as little as a 6% addition of recycled PET, increased stiffness and tensile strength from chemically treated plastics, and notable resistance boosts to rutting and fatigue cracking from RAP and PET additives. Recycled LDPE, especially when pre-swollen with mineral oil or bitumen, reduces mixing time, mitigates long-term aging, and enhances durability and moisture resistance. Additionally, these modifications lower construction costs and contribute to environmental sustainability. Nevertheless, several challenges need to be overcome by achieving uniform mixes and ensuring compatibility can be complex, and increased viscosity may complicate workability and compaction. The variability in recycled plastics' quality can lead to inconsistent performance, and long-term durability under varying conditions needs further study. Environmental concerns include potential microplastic generation and recycling complexities at the end of life. Economically, the initial investment in specialized equipment and additives can be high, and regulatory hurdles, due to the lack of standardized guidelines and lengthy approval processes, pose additional challenges. Addressing these issues is crucial for the sustainable and effective use of recycled plastics in pavement construction.

3. Conclusions

The growing emphasis on waste plastic-modified bituminous binders and blends is driven by their favorable material characteristics, alongside the economic and environmentally sustainable advantages they offer. This paper has presented an international literature review on the widespread adoption of waste plastics in both bituminous binders and asphalt mixtures. It examined various production methodologies, compared wet and dry processes, and discussed their impact on the properties of modified bitumen and asphalt mixtures. The wet process enhances the moisture resistance, rutting resistance, and fatigue resistance of binder mixtures, but it may encounter challenges such as low-temperature performance and phase separation. Methods addressing compatibility and low-temperature issues, such as incorporating rubberized materials and chemical additives that promote polymer network development, play crucial roles. Rubberized materials enhance the ductility of binder mixtures, while chemical additives facilitate the formation of resilient polymer matrices. While the wet process shows improved thermal behavior, the dry process emerges as a more economically viable and convenient option for producing waste plastic-modified asphalt. It demonstrates versatility by accommodating all types of plastics to improve rutting and moisture resistance in asphalt pavements. Field projects confirm that incorporating plastics can enhance moisture resistance, improve binding properties, and enhance high-temperature performance without increasing construction costs or emitting harmful gases. This literature review highlights consistent advancements in the stiffness and rutting resistance of bitumen and asphalt mixtures, with emerging studies exploring fatigue effects. However, gaps remain in understanding resistance to thermal cracking at low temperatures and comprehensively addressing moisture susceptibility, signaling areas that require further investigation.

Authors frequently cite diverse sources of waste plastics, including polyethylene (PE) variants such as high-density (HDPE) and low-density (LDPE), polypropylene (PP), polyethylene terephthalate (PET), and polyvinyl chloride (PVC). Managing mixed plastics poses challenges due to variations in characteristics across sources within the waste industry, necessitating improved strategies for effective recycling. The advancements made using novel polymer modifiers like EcoFlakes® [78] and Duroflex® [79], derived from recycled plastics, underscore ongoing innovation in enhancing the sustainability and performance of bitumen and asphalt mixtures. These innovations hold promises for addressing current challenges and driving future developments in plastic waste management within the asphalt industry.

Future studies in the field of waste plastic-modified asphalt could focus on several key areas to advance knowledge and application. Long-term performance studies are essential to assess durability and longevity under varying conditions, validating initial findings on moisture resistance, binding properties, and high-temperature performance. Optimizing process parameters for both wet and dry processes, including refining mixing temperatures and ratios, could maximize performance while minimizing drawbacks like viscosity increase or phase separation. Mechanistic studies would deepen understanding of how waste plastic modifiers affect fundamental asphalt properties such as fatigue resistance, thermal cracking at low temperatures, and moisture susceptibility through advanced testing methods. Life-cycle assessments are crucial to quantify environmental impacts and potential benefits in terms of reduced waste disposal and resource conservation. Economic analyses could assess the cost-effectiveness of waste plastic-modified asphalt over its life cycle, considering initial costs, maintenance requirements, and processing expenses. Exploring composite materials and innovative additives derived from waste plastics could further enhance asphalt mixture properties and sustainability. Lastly, investigating policy frameworks and incentives could promote widespread adoption in infrastructure projects, addressing regulatory barriers and scaling up production and applications in real-world construction scenarios.

Author Contributions: Conceptualization, A.B.A. and J.V.; methodology, A.B.A. and J.V.; investigation, A.B.A.; resources, J.V. and N.B.; data curation, A.B.A.; writing—original draft preparation, A.B.A.; writing—review and editing, J.V. and N.B.; visualization, A.B.A., J.V. and N.B.; supervision, J.V. and N.B.; project administration, J.V. and N.B. All authors have read and agreed to the published version of the manuscript.

Funding: This paper was supported by project no. SGS24/043/OHK1/1T/11.

Data Availability Statement: This paper is not linked to any additional datasets. It is a review paper.

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

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