Type of contribution:
Editorial
Research Paper
Case Study
▶ Review Paper
Scientific Data
Report of Tech. Application

e-issn. 2798-5245

Mechanical Engineering for Society and Industry
Vol. 3, No.3 (2023) pp 120-136
Special Issue on Technology Update 2023
https://doi.org/10.31603/mesi.10133

Utilization of plastic waste to improve properties of road material: A review

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This article contributes to:

9 INDUSTRY, INNOVATION AND INFRASTRUCTURE
SUSTAINABLE DEVELOPMENT GOALS

Highlights:
- The use of plastic waste as an asphalt mixture was studied.
- The addition of plastic waste to the asphalt mixture has been shown to increase stability and load-bearing capacity.
- Inappropriate dosing can have a negative impact on pavement performance.
- Further investigation is needed to assess environmental and economic impacts.

Abstract
The failure of asphalt pavement occurs due to heavy traffic loads and weather conditions such as humidity, temperature, and UV radiation. To address or minimize these failures, significant efforts have been made in recent years to improve the properties of asphalt materials, ultimately enhancing field performance, and extending the lifespan of pavements. Asphalt with plastic modification is considered one of the most suitable and popular approaches. Plastic offers several advantages and is generally known to improve stiffness at high temperatures, although some types are more susceptible to phase separation. Therefore, it is necessary to use the right methods, temperatures, and proportions when designing plastic asphalt mixes to produce a homogeneous mixture. Plastic mixing with asphalt blends is done through two methods: the dry mixing method and the wet mixing method. The ideal amount of plastic added to the mix should modify the asphalt blend to make it more resistant to rutting, fatigue cracking, thermal cracking, and moisture resistance. Failure to determine the correct plastic dosage can lead to negative effects on pavement performance. In general, incorporating plastic waste into asphalt mixes has shown improvements in performance metrics such as stiffness, resistance to cracking, and fatigue resistance. The result of the asphalt and plastic mixture is an increase in stability, making the mixture stronger in bearing loads. Adding plastic waste to the mix makes it stiffer, resulting in a higher MR value, thus providing better resistance to permanent deformation compared to conventional mixtures. Additionally, in wheel tracking tests, the asphalt-plastic mixture reduced rutting depth by 29% compared to conventional mixtures. Similarly, in fatigue testing, the asphalt-plastic mixture yielded a higher load cycle value, making it more resistant to repeated loads. This article explains the details of using plastic in asphalt mixes to enhance asphalt performance and road durability. Various types of plastics, including PET, HDPE, LDPE, PVC, LDPE, PP, and PS, have been successfully used to modify asphalt. However, each type has its advantages and disadvantages, as discussed comprehensively in this journal. Essentially, the utilization of plastic waste in asphalt blends will help reduce the need for landfill disposal, decrease dependence on non-renewable resources, and expand options for asphalt pavement construction.

Keywords: Waste plastics, Recycling, Asphalt pavement, Asphalt modification, Performance asphalt mixture

Article info
Submitted: 2023-09-01
Revised: 2023-10-24
Accepted: 2023-10-25

Publisher
Universitas Muhammadiyah Magelang

1. Introduction

One of the most significant environmental issues is the increasing waste generated on earth every day. Plastic waste has become an extreme problem worldwide. According to data from the World Population Review in 2022, the top five countries contributing the most to plastic pollution in the oceans in 2021 were countries in the Asian region. The country with the largest production of plastic waste was the Philippines, with 356,371 tons, followed by India, Malaysia, China, and Indonesia ranking fifth, with a production of 56,333 tons of waste in 2021. Plastic waste has garnered attention in recent years. However, the recycling rate of plastic waste remains low. Recycling plastic waste poses a challenge due to the complex nature of plastic waste mixtures and inefficient mechanical recycling. Plastic waste is difficult to decompose and requires a long time, so efforts must be made to reduce it. One way to reduce waste is to utilize it and add value to it.

Researchers and engineers are exploring alternative methods to reuse plastic waste in civil infrastructure, such as using crushed PET waste in asphalt [1], Glass asphalt with HDPE waste [2], mixing three types of PVC waste: window waste, blind waste, and cable waste into asphalt [3], shredding LDPE plastic bag waste [4], using PP plastic fibers in Recycled Foamed Asphalt (RFA) [5], and adding types of PS waste, namely High Impact Polystyrene (HIPS), General Purpose Polystyrene (GPPS), and Polystyrene from hangers (HPS) to asphalt mixtures [6]. Generally, the addition of plastic waste to asphalt mixtures has shown improvements in performance metrics such as stiffness, crack resistance, and fatigue resistance.

One of the challenges in using plastic waste is the homogeneity between plastic and asphalt mix, which is influenced by mixing temperature, compaction temperature, and plastic size. In addition, the method used in mixing (wet and dry) also significantly affects the mixture's performance. While some previous research has been published on the performance of asphalt modification using plastic, some of them focus on the influence of mixing conditions and the resulting modified asphalt properties. However, to the best of the author's knowledge, there is still limited information on understanding the performance of asphalt pavement containing recycled plastic at various doses and types. Therefore, the primary objective of this paper is to provide a broad overview of waste materials (originating from recycling activities) and pure plastomer asphalt modifications for road pavement applications. This journal will focus on reviewing the use of plastic as a substitute for aggregates and plastic (PET, HDPE, PVC, LDPE, PP, and PS) as additive materials in asphalt mixtures because, in addition to improving asphalt quality, the use of plastic waste can also be a solution to reduce environmental damage caused by plastic, and it is expected that road construction costs can become more efficient with the addition of plastic waste to asphalt mixtures.

The characteristics of various types of plastic's physical properties are briefly discussed in this paper. Furthermore, the polymer mixing method with asphalt mixtures is evaluated through testing. This research examines various attributes of asphalt modified with plastomers, including chemical, thermal, rheological, structural, and mechanical properties, with specific investigations for each plastic variant. Using a systematic approach, this study aims to conduct a comprehensive literature review spanning the past decade (2012-2022) to comprehensively survey and collect a substantial body of scholarly work. Nonetheless, important research before 2012 is also referenced in this study.

2. Methods

This paper is a literature survey. Data was obtained from Internet sources, especially from articles published in international journals. Data was collected, reviewed, and concluded, as well as compared to the current condition. Data was also compared with current research trends using bibliometric analysis from the Scopus database. Detailed information for the Scopus database is explained in previous studies [7].

3. Results and Discussion

3.1. Bibliometric Analysis

Figure 1 shows the simplified bibliometric analysis based on scopus database taken on 24 October 2023. The first research on topic of “plastic” and “waste” is in 1931. Then, it continues to increase, reaching more than 6600 documents per year.

3.2. Recycled Plastic Types

Plastic is a type of macromolecule formed through polymerization, which involves combining simple molecules (monomers) to create large molecules. Plastics are primarily composed of carbon and hydrogen and are commonly produced from raw materials like Naphtha, derived from crude oil or natural gas [8]. Plastics are divided into two categories based on their properties: thermoplastics, which can be reshaped when heated, and thermosetting plastics, which retain their shape even when heated. Recyclable plastics, such as PET, HDPE, PVC, LDPE, PP, and PS, belong to the thermoplastics category (see https://wedocs.unep.org/20.500.11822/8638). These plastics are identified with numerical codes for easy recognition and use, with their properties detailed in **Table 1**.

Table 1. Summary of Recyclable Plastic Waste based on ASTM D7611. Data was taken from Wu & Montalvo [9]

Plastic symbol and Product		Description
1 PETE POLYETHYLENE TEREPHTHALATE	Single-use bottles are like containers for vegetable oil, sauce, and peanut butter	• PET is a water and gas impermeable, clear/transparent material. • The material with PET polymer is recommended for one-time use only. • If used repeatedly and exposed to hot/warm water, it will cause this polymer layer to melt and release carcinogenic substances. • Tensile strength of PET = 0.8 ± 0.14 N/mm^2 and Density of PET = 1.15 ± 0.03 g/cm^3. • Biodegradable. • Specific gravity = 1.32. Softening point = 170-180 °C [10].
2 HDPE HIGH DENSITY POLYETHYLENE	Shampoo bottles, motor oil bottles, milk/juice bottles, butter packets.	• The density of HDPE ranges from 0.93 - 0.97g. • Although the density of HDPE is only slightly higher than Low Density Polyethylene, HDPE has more strength than Low Density Polyethylene. • Softening point of HDPE = 131 °C, • HDPE is a type of plastic that is easily moldable, corrosion-resistant, and has strong durability. • HDPE (High-Density Polyethylene) is not capable of degrading or decomposing naturally. • Decomposition temp = > 450 °C.
3 V POLYVINYL CHLORIDE	Trays for sweets, plastic packing (bubble oil), food foils to wrap the foodstuff and plumbing pipes.	• PVC has stable physical characteristics and is resistant to chemicals, weather, electrical properties, and flow. • This type of material is the most difficult to recycle. • PVC contains DEHA (diethyl hydroxylamine) as a solvent which makes it the most difficult polymer material to recycle. • PVC Density: 1.3 -1.6. • Softening Point PVC = 180 – 200 °C [11].
4 LDPE LOW DENSITY POLYETHLYENE	Crushed bottles, sheeting, shopping bags, highly resistant sacks, and most of wrapping.	• LDPE has translucent mechanical properties, is strong, flexible, and has good resistance to chemical solvents. • Density of LDPE <0.930 g/cm^3. • Softening point of LDPE = 85 °C. • Tensile strength of LDPE = 8.96 MPa.
5 PP POLYPROPLYENE	Wrapping, rope, straw, luggage, medicine bottles, caps syrup packing tape, and potato chip bags.	• Density of PP = 0.9 g/cm^2. • It has mechanical properties like LDPE but is not transparent and relatively more heat and chemical resistant. • Biodegradability. • SG of PP = 0,91 g/cm^3 (20 °C), Softening Point = 140 °C. • Decomposition temp = > 280 °C, Solubility in water = Insoluble, Tensile Strength = 32 MPa (4700 psi), Yield Strength (σt) = 6000 psi, Elasticity Percentage = 50 - 150%.
6 PS POLYSTYRENE	Meat trays, compact disc cases, hard packing, refrigerator trays, cosmetic bags, costume jewelry audio cassettes, CD cases, vending cups.	• Density of PS = 1.1 ± 0.19 g/cm^3. • Tensile strength of PS = 3 ± 1.13 N/mm^2. • Melting point PS = 210 – 249 °C. • PS is non-biodegradable: it has a short lifespan compared to many other polymers, the fastest rate of degradation when exposed directly to sunlight.

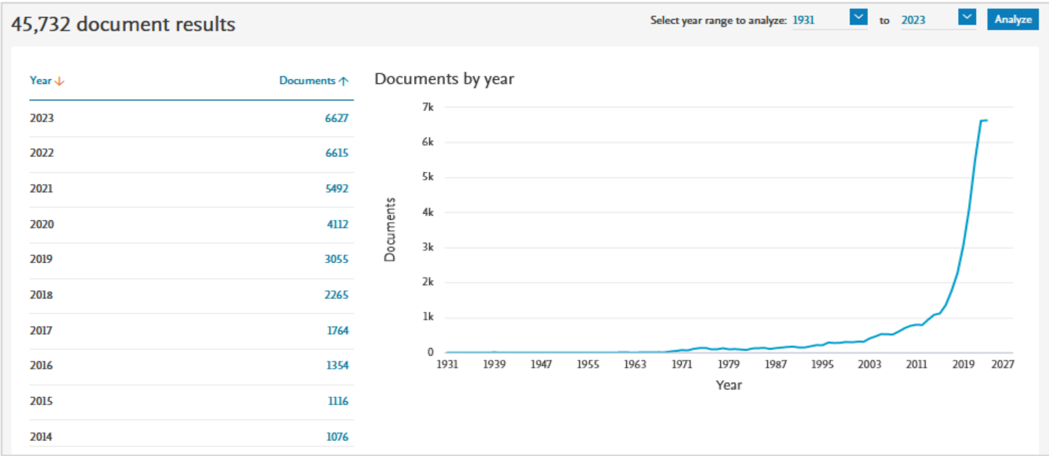

Figure 1. Publication of "waste" and "plastic" based on Scopus database on 24 October 2023

3.3. The Utilization of Plastic Waste in Flexible Pavement

Density is the level of compactness of a mixture after the compaction process (See **Figure 2**). A higher density value indicates better compactness, and it can be affected by various factors, including the mix's components, compaction methods, temperature, asphalt content, and the use of additives like polymers. High-density mixtures can withstand greater loads and effectively seal voids, preventing water and air infiltration. The density of plastics is crucial for their compatibility in asphalt mixing. Different plastics have varying densities compared to asphalt, with some being lower (HDPE, LDPE, PP, EVA) and others being higher (V, ABS, PC, PU), while PET and PS have densities like asphalt [9].

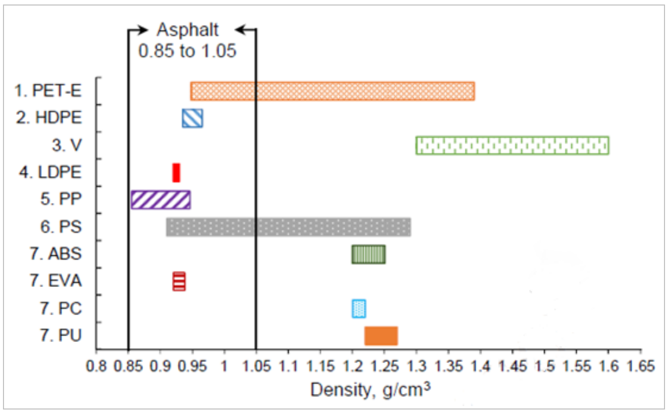

Figure 2. Density range of recycled plastic. Data was taken from Wu & Montalvo [9]

Optimal plastic content is crucial for enhancing asphalt performance. **Figure 3** and **Figure 4** provide a summary of plastic waste content used for asphalt modification. In **Figure 3**, there is no research on the use of PC for asphalt mixture modification. PS is used as a substitute for aggregate at 2%, equivalent to a weight substitution of 23% of asphalt [6]. **Figure 4** shows that the percentage of polyethylene added to the mixture varies from 1 to 10% of the asphalt's weight, with the most used range being 3 to 5%. For PVC, **Figure 4** displays variations from 1% to 20%, with 5% being the most used content. The amount of plastic used depends on factors like aggregate grading and the type of asphalt, leading to different plastic content levels between **Figure 3** and **Figure 4**.

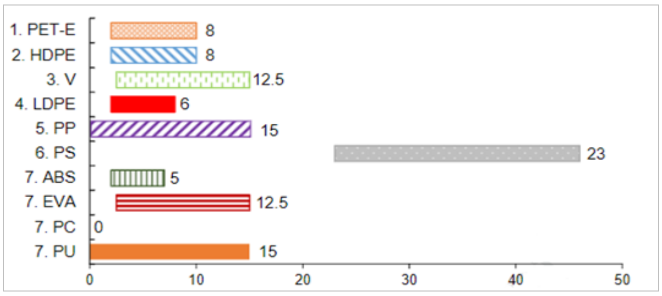

Figure 3. Plastic content in asphalt mixtures. Data was taken from Wu & Montalvo [9]

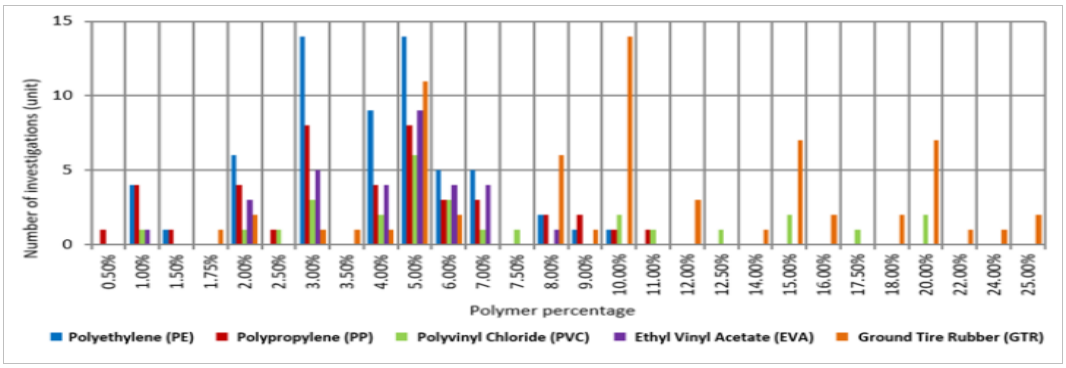

Figure 4. Percentage of different polymers by weight of bitumen. Data was taken from Brasileiro et al. [12]

3.4. Mixing Method (Dry Process and Wet Process)

There are two methods used in mixing plastic waste into asphalt mixtures, namely the wet mixing method and the dry mixing method. The wet mixing method involves adding plastic waste as a modifier directly into the binding asphalt before mixing it with aggregates. The wet method is suitable for plastic waste with low softening points, such as LDPE and PP [9]. On the other hand, the dry mixing method involves incorporating plastic waste particles into hot aggregates, which are then added to the asphalt. This method is widely used for rigid and hard plastic types with a high melting point, such as PET and HDPE. The hardness and stiffness of the plastic particles contribute to the integrity of the asphalt mixture, where the plastic acts as fine aggregates within the asphalt mix.

The mixing temperature varies for each type of plastic when combined with asphalt and aggregates, as it is influenced by the softening point, viscosity, and density. **Figure 5** explains the temperature variations during the mixing process of different types of plastic with asphalt using the wet mixing method and the mixing speed. **Figure 5** illustrates the amalgamation process of PE plastic and asphalt, wherein mixing temperatures span from 150 to 180 °C, mixing durations range from 3 minutes to 4 hours, and mixing velocities range from 120 to 7200 rpm.

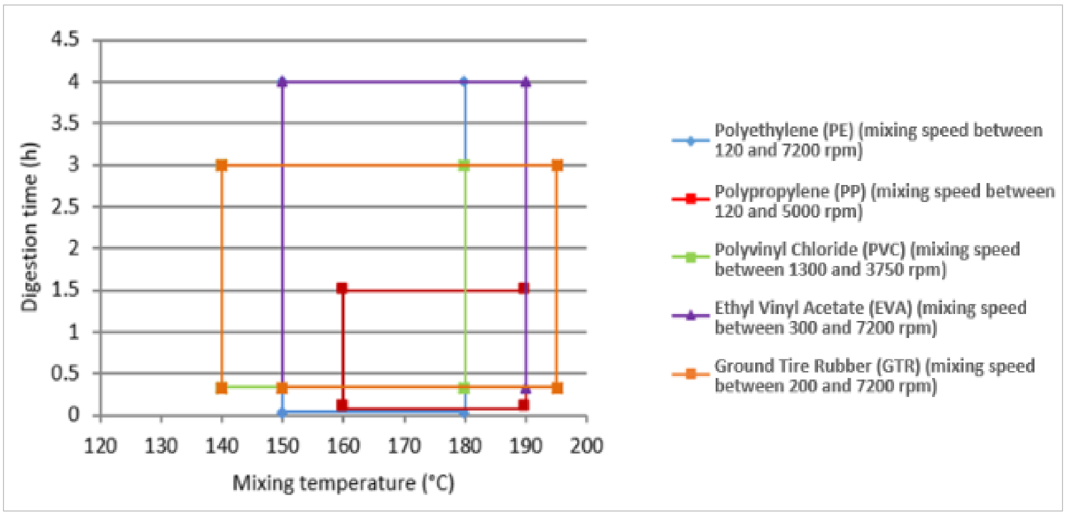

Figure 5. Variation of temperature, digestion time, and mixing speed in polymer blending process. Data was taken from Brasileiro et al. [12]

3.5. Performance of Asphalt Mixtures Using Plastic Waste

To determine the effect of plastic waste on asphalt strength, the testing methods conducted are usually like those used for general asphalt testing. The evaluation of flexible pavement performance is carried out through Marshall testing, resilient modulus testing, wheel tracking testing, and fatigue testing. From several previous studies, it is known that the addition of plastic waste to asphalt mixtures can enhance pavement performance in general. The findings can be summarized as follows:

a. Marshall test parameters. This test is explained in the following:
   (1) Stability is the ability of road pavement to withstand traffic loads without experiencing permanent deformation such as waves, ruts, and bleeding. A higher stability value indicates a stronger mixture in withstanding loads. However, excessive stability can make the pavement layer rigid and susceptible to cracking.
   (2) Flow is a test that measures the ability of asphalt concrete to undergo repeated deformation under load until it reaches the point of flow, indicated by the presence of rutting and cracking.
   (3) MQ (Marshall Quotient) is an indication of the resistance to deformation of asphalt concrete. A higher MQ value indicates a mixture with high stiffness, which has a greater capacity to distribute the applied load and resist rutting deformation [13].
   (4) VIM (Void in Mineral Aggregate) should not be too high or too low. If the VIM value is too high (above 5%), there will be more voids within the asphalt concrete, leading to a decrease in asphalt concrete stability and an increase in vulnerability to failure. However, if the VIM value is too low (below 3%), there will be fewer voids within the asphalt concrete, reducing its ability to drain water from the surface into the ground.

(5) VFB (Void Filled with Bitumen) is a part of VMA (Void in Mineral Aggregate) that is filled with asphalt, excluding asphalt adsorbed by each aggregate particle.

b. Resilient modulus test. This test assesses the stress-strain relationship in asphalt mixtures, focusing on their elastic characteristics. It is performed using the indirect tensile test, with temperature and loading frequency being significant factors influencing the results [14].
c. Wheel tracking. In the laboratory, a rutting device can be used to simulate a wheeled vehicle to assess the permanent deformation resistance of test specimens based on the rut depth. The rut depth is considered an appropriate index for comparing the sensitivity of asphalt mixtures to permanent deformation [15].
d. Fatigue. Fatigue testing assesses a pavement layer's ability to withstand repeated loading and cyclic deformation without developing fatigue cracks or ruts [1]. The test helps determine the fatigue life of the pavement, which is the number of load repetitions leading to failure or a sharp change in the flexural curve. Asphalt content and volume play a significant role in the fatigue performance of asphalt mixtures [16].
e. Penetration and Softening Point Testing of Plastic and Asphalt.

Figure 6 and **Figure 7** indicate that a reduction in penetration coupled with an elevation in the softening point contributes to enhanced asphalt mixture efficiency, as higher stiffness in asphalt renders it less susceptible to temperature fluctuations. Consequently, asphalt samples derived from this type of exhibit heightened resistance against permanent deformation and rutting under elevated temperatures. In **Figure 6** and **Figure 7**, it can be observed that an increase in polymer content leads to a decrease in penetration and an increase in the softening point of the asphalt mixture.

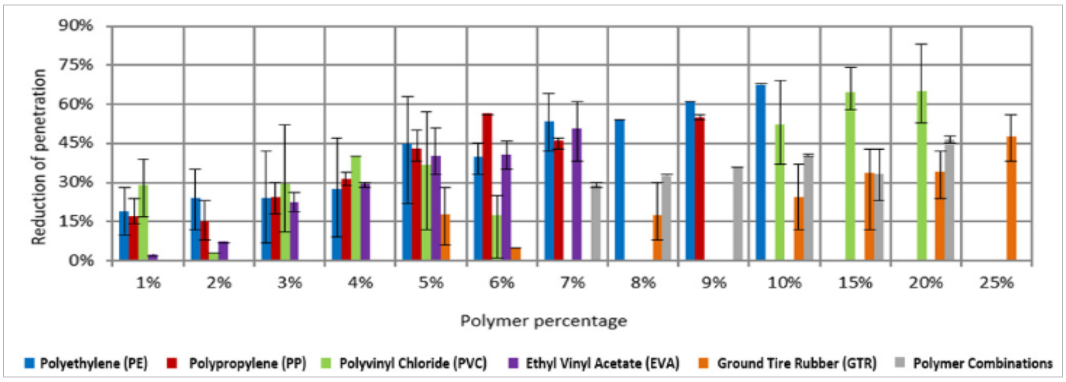

Figure 6. Decrease in penetration values rate with the inclusion of the polymer. Data was taken from Brasileiro et al. [12]

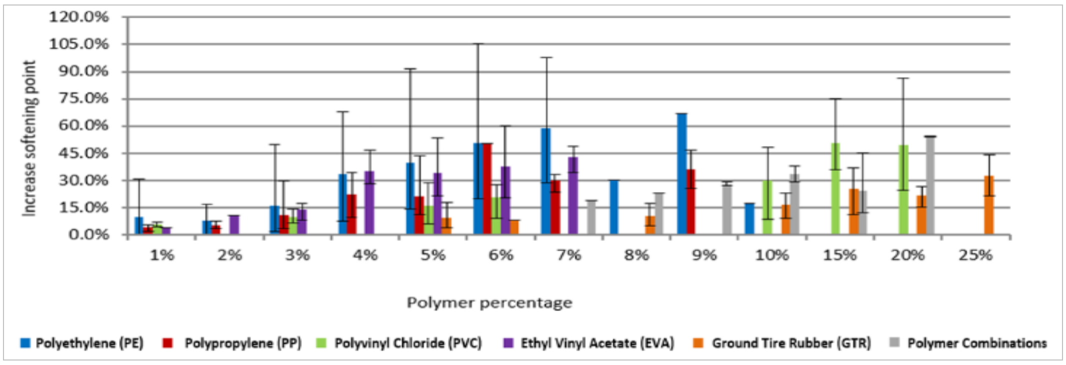

Figure 7. Rate of increase in softening point values with the incorporation of the polymer. Data was taken from Brasileiro et al. [12]

3.5.1. Polyethylene Terephthalate (PET)

PET is represented by the chemical formula $(C_{10}H_8O_4)_n$ and can be employed as a substitute for aggregates in asphalt mixtures in the form of small fragments 1.18 to 2.36 mm [17]. Previous research has shown that incorporating PET waste into asphalt mixtures enhances their stability, making them stiffer and resulting in higher values of MR (resilient modulus). For instance, in a study by Ahmadinia et al. [18], Stone Mastic Asphalt (SMA) mixtures containing 6% PET exhibited a 16% increase in MR and better resistance to permanent deformation. Mixtures with 4% PET showed a 29% reduction in rut depth. Additionally, fatigue testing indicated that the addition of PET to asphalt mixtures resulted in a higher load cycle value [1]. **Table 2** provides a summary of research findings regarding the use of PET plastic waste in asphalt mixtures.

Table 2. Summarizes the research on asphalt mixtures with the addition of PET plastic

Type of mixture and Refs.	Size of PET plastic	PET content	Optimum plastic content	Method	Description
AC-WC 14 Pen 80/100 [19]	Shreds PET (2mm to 5mm)	2%, 5%, 10%, 15%, 20%.	10%	Dry Process	• The optimal asphalt content (4.8%) • The optimal PET at a 10% content meets all the Marshall parameter specifications.
AC [20]	Shreds PET sizes used: (a) Size 1 (2.36–1.18 mm). (b) Size 2 (300–150 µm)	2.5%, 5%, and 7.5%	5%	Dry process	• This research is aimed at determining the optimal size of PET in the mixture. • PET mixture with a size of (2.36–1.18 mm) demonstrates relatively superior performance considering volumetrics, Marshall parameters, and resistance to moisture-induced damage.
Semi Dense Asphalt (SDA) [21]	Shreds PET and Crumb Ruber (CR)	2.5% and 5.1%		Dry Process	• This study investigated the replacement of semi-dense asphalt (SDA) sand by untreated mechanically shredded CR and PET. • The replacement of sand by CR and PET is not recommended, and the more common use as asphalt mixture modifiers with low addition contents of around 1% is sounder.
SMA Pen 80/100 [18]	PET shreds that pass the 1.18mm sieve	0%, 2%, 4%, 6%, 8%, and 10%.	6%	Dry Process	• The addition of PET enhances SMA characteristics, leading to increased stiffness and higher asphalt viscosity at standard temperatures. • Resilient modulus (MR) testing shows a significant 16% increase in MR value for SMA mixtures with PET waste, compared to conventional asphalt mixtures. • The wheel tracking test reveals that using 4% PET content results in a notable 29% reduction in rut depth compared to standard mixtures.
Laston AC-WC Pen 60/70 [1]	Shreds PET waste 0.425–1.18 mm	2%, 4%, 6%, 8% and 10%	2%-10%	Dry Process	• The Optimum Asphalt Content is 5.7%. • Based on fatigue testing, the mixture with the addition of PET has a higher load cycle value, indicating that the fatigue life of the PET mixture is greater. • The addition of PET in tKöfteci, (2016)- 10% effectively affects fatigue properties.

3.5.2. High Density Polyethylene (HDPE)

High-density polyethylene (HDPE) has strong intermolecular bonds because the polymer chain is linear with a few branches, and the molecules can be close to each other. Therefore, HDPE has more strength than LDPE [9]. For asphalt modification with HDPE waste, both wet and dry methods can be used. In the wet mixing method, the addition of a high-speed mixer is required. For instance, research conducted by Arabani & Pedram [2] combined glass waste and plastic bottles into asphalt mixtures using a high-speed mixer with a speed of 4,500 rpm and a temperature of 180 °C for 40 minutes. Asphalt mixtures modified with HDPE are better suited for moderate climate regions. The addition of HDPE waste can reduce asphalt production costs and enhance mixture performance. **Table 3** summarizes the research findings on the utilization of HDPE plastic waste for asphalt mixtures.

Table 3. The research on asphalt mixtures with the addition of HDPE plastic

Type of mixture and Refs.	Size of HDPE plastic	HDPE content	Optimum plastic content	Method	Description
HMA [22]	Shreds HDPE waste	1%, 2%, 3% and 4%	4%	Wet Process	From the tensile strength (TSR) results, the best resistance was obtained at HDPE levels of 2% and 4%.
AC-20 [23]	Shreds HDPE waste	4%, 6% and 8%	4%		Specimens prepared with a mixing temperature of 165 °C and a mixing time of 30 minutes for 4% HDPE exhibit the highest stability and the lowest flow, resulting in the highest Marshall Quotient. An increase of 50% in MQ indicates higher stiffness of the mixture for effective load distribution, thereby enhancing the pavement's resistance to permanent deformation.
SMA Pen 40/60 [24]	Shreds HDPE waste	2% - 5%	4%	Dry Process	• The most effective polymer in reducing penetration is HDPE. • From the wheel tracking test results, it is found that Polymer Modified Binder (PMB) is more resistant to rutting compared to Recycled Polymer Binder. • From the fatigue test results, it is found that PMB has a higher load cycle than Recyle Polimer.
Glassasphalt, PG 64-16 [2]	Shreds HDPE waste Max size 4.75 mm	2%, 4%, 6%, 8%, 10%	6%, 8%, 10%	Wet Process	• Based on the fatigue test, HDPE with a content of 6% - 10% is the most optimal. • HDPE waste exhibits good resistance at low and moderate temperatures (25 °C). The use of asphalt mixtures modified with HDPE is more suitable for regions with moderate climates and average temperatures.
Dense graded HMA, 35/50 [25]	HDPE pellets size 4mm	2%, 4%, 6%, 8%	6%		Recycled asphalt mixtures that are supplemented with HDPE plastic pellets with a content above 6% yield mixtures that behave like new asphalt.

3.5.3. Polyvinyl Chloride (PVC)

PVC is the third most widely used thermoplastic polymer in the world. However, PVC contains diethyl hydroxylamine (DEHA) that can lead to air pollution due to the presence of hazardous chemicals. Due to dioxin emissions during combustion, direct heating of PVC with aggregates at high temperatures is not suitable. Nevertheless, PVC waste can be effectively utilized by homogeneously mixing it with asphalt at a controlled temperature of 160 °C. Given the inherent incompatibility between PVC and asphalt, a two-step approach is employed: initial processing of PVC waste with a chemical modifier, followed by further mixing with asphalt [26]. In some literature sources, PVC can be used as an additive for asphalt mixtures. **Table 4** summarizes the research findings regarding the utilization of PVC in asphalt mixtures.

Table 4. Summarizes the research on asphalt mixtures with the addition of PVC plastic

Type of mixture	Size of PVC plastic	PVC Content	Optimum plastic content	Method	Description
AC-WC 40-50 [11]	Shreds PVC waste Size: 2.5-3 mm	2.5%, 5%, 7.5%, 10%, 12%,15% of asphalt weight	-	Wet Process	After the addition of 15% PVC to the mixture, it affected the penetration value with a decrease of 62.8%, reduced ductility by 16 cm, and increased the softening point by 6%. The loss on heating (LOH) increased from 0.3% to 0.6%.
X-90 [27]	Shreds PVC waste Size: 1.5x2.5 cm^2	0%, 4%, 8%, 10% of asphalt weight	-	Wet Process	• Mixing temperature at 150 °C for 30 minutes. • Increasing the softening point and reducing the penetration value of the asphalt. • Improving resistance to alkali, salt corrosion, acid, and enhancing the performance against aging.
Pen 80/100 [26]	PVC pipe waste shredded to 2-4 mm size	3% and 5% of asphalt weight	5%	Wet Process	• Mixing temperature of 160 °C, stirring frequency of 2000 rpm, and a required time of 2-3 hours. • Incorporating PVC pipe waste can enhance the mixture's strength, improve stability, increase resistance to permanent deformation, yield higher indirect tensile strength, effectively countering cracking tendencies. • Moreover, it can reduce rutting in asphalt mixtures and extend the fatigue life of the asphalt mixture.
AC Pen 60/70 [28]	PVC waste passed through No.50 sieve	1%, 3%, 5% of asphalt weight	5%	Wet Process	• A mixing temperature of 165 °C, stirring frequency of 3000 rpm, and a required time of 45 minutes. • Mixtures containing 5% PVC waste are much more resistant to rutting and result in reduced sensitivity to temperature changes, enhancing the performance of HMA mixtures at higher temperatures.
Pen 160/220 [3]	PVC waste consists of three types of waste: window waste, blind waste, and cable waste. PVC waste passes through sieve number 50.	1%, 3%, and 5% of asphalt weight	window waste with 3% PVC	Wet Process	• Investigating the performance of asphalt modified with three types of plastic waste (window waste, blind waste, and cable waste) based on polyvinyl chloride (PVC). • The asphalt heating temperature is 160-165 °C, and the mixing speed is 500 rpm for 15 minutes. PVC waste is added gradually, and once the mixing temperature reaches 180 °C, the mixer speed is increased to 1300 rpm for 60 minutes. • Fracture Toughness: Blind PVC waste > Window PVC waste > Cable PVC waste. • Incorporating PVC waste results in increased viscosity, an increase in softening point, elevated mixing and compaction temperatures, improved resistance to rutting based on Dynamic Shear Rheometer (DSR) analysis, reduced penetration value, increased Performance Grade (PG) value, and increased stiffness in the Bending Beam Rheometer (BBR) results.

3.5.4. Low Density Polyethylene (LDPE)

LDPE has flexible, long, and linear polyethylene chains that exhibit greater adaptability to external forces, resulting in lower density, strength, and temperature resistance compared to HDPE [29]. Commonly used LDPE waste in asphalt mixtures includes plastic bags, as indicated in the study by Bagampadde [30], where plastic bags need to be chopped into sizes of 5 mm x 5 mm or smaller. In **Table 5**, it's known that the addition of Low-Density Polyethylene to asphalt mixtures can enhance resistance against rutting, stability, and fatigue resistance. As suggested by Maharaj et al [31], the inclusion of used oil can serve as a facilitator to enhance fatigue crack resistance and mitigate friction during the mixing process.

Table 5. Summarizes the research on asphalt mixtures with the addition of LDPE plastic

Type of mixture and Refs.	Size of LDPE plastic	LDPE Content	Optimum plastic content	Method	Description
AC Pen 80/100 [4]	Shredding Plastic bag waste	5%	5%	Wet Process	• Using a 1/5 HP mixer with 3500 rpm for 20 minutes at a temperature of 170 °C. • The addition of LDPE to asphalt significantly reduces penetration (by 37%) and ductility (by 38%), while there is a significant increase in the softening point value (by 41%) and specific gravity (by 0.17%), with values increasing as the LDPE content increases.
HMA [32]	Shredding Plastic bag waste	5%, 7%, 10%	5%	Wet Process	• The LDPE increased the PG in the asphalt binder at high service temperatures, due to the significant increase it generated in its stiffness. • The mixtures with LDPE can be used for thick layers in high-temperature climates to control rutting.
AC [33]	Shreds LDPE waste Size: 5-2.36 mm	LDPE, 29.7%	29.7 %	Dry Process	• Asphalt mixtures with LDPE reduce the unit weight of the mixture by 16%, resulting in lower costs. • Asphalt mixtures with the addition of PET increase the stability of the mixtures by 2.5 times, with increased flow values making the mixtures stronger and more elastic.
SMA [34]	LDPE plastic pellets	2%, 4%, 6%, and 8%		Wet Process	• Optimal Asphalt Content = 5.82%. • Penetration decreases with increasing LDPE content, indicating better shear resistance at moderate to high temperatures. The softening point increases, indicating improved resistance to deformation. The tensile strength ratio is greater than 85%, showing that this type of additive does not weaken the mixture when exposed to moisture. • High-performance, durable, and cost-effective flexible pavement can be achieved with a pyrolysis LDPE content of 6%.

3.5.5. Polypropylene (PP)

Polypropylene finds application in various domains such as food packaging, heat-resistant containers like those used in microwaves, pipes, and automotive components. As a plastomer, PP possesses a melting point that surpasses that of HDPE. From **Table 6**, the addition of PP can increase the softening point and decrease the penetration value, thereby increasing the asphalt stiffness and resistance to rutting, which is shown by the improvement of Marshall stability.

Table 6. Summarizes the research on asphalt mixtures with the addition of PP plastic

Type of mixture and Refs.	Size of PP plastic	PP content	Optimum plastic content	Method	Description
Pen 60/70 [35]	The PP waste passes through the No. 30 sieve but is retained on the No. 40 sieve.	25% of aggregate weight		Dry Process	• Optimum Asphalt Content = 5.82% • Incorporating plastic waste as a partial replacement for aggregates yields a notable enhancement in Marshall stability value, tensile strength, and asphalt concrete stiffness modulus. • The inclusion of plastic waste in the mixture triggers a reduction in moisture susceptibility and particle loss, thereby mitigating disintegration effects.
PG 64-22 [5]	PP Fibre with 10mm Length	0.15% of asphalt weight	0.15 %	Wet Process	• Conducting research on the addition of PP plastic fibers to Recycled Foamed Asphalt (RFA). • From the Marshall test results, it is known that the addition of 0.15% PP fibers produces 4 times higher stability at a temperature of 250 °C. • The wheel tracking results show that the addition of PP fibers results in 1.5 times higher deformation resistance compared to RFA mixture without PP addition.
AC-WC [36]	PP fibre and glass fibre each with a length of 12mm	0%, 2%, 6%	6%	Wet Process	• The addition of PP fibers reduces the penetration value and ductility but increases the softening point temperature compared to conventional mixtures. • Using a combination of 0.1% glass fiber and 6% PP results in the best hybrid reinforcement, with a stability increase of more than 25% and reduced flow. • This mixture provides improved resistance to rutting and deformation due to traffic. It can be concluded that this hybrid AC type is suitable for use in tropical regions.
Pen 60/70 [37]	PP plastic pellets	5% and 7%	5%	Wet Process	• The optimum PP plastic content of 5% for this mixture shows the highest Marshall stability and maximum ITS test results. • From the compressive test, it is known that the increase in the percentage of PP plastic content in the mixture increases the compressive strength value.
AC-WC Pen 60/70 [38]	PP plastic waste	0.5%, 0.8% and 1%	1%	Wet Process	• The addition of PP plastic will decrease the asphalt mixture's density, asphalt solubility, and penetration value. Viscosity, softening point, and flash point values increase with an increase in plastic content. • A PP plastic content of 1% is the optimal level, providing the highest stability, improved Rutting Susceptibility Index (RSI), and promising potential for practical applications. However, from an economic and energy usage perspective, a 0.5% PP plastic content is the most optimal because it shows the highest cost reduction with the least energy consumption.

3.5.6. Polystyrene (PS)

Polystyrene is a polymer made from the monomer styrene; a liquid hydrocarbon commercially produced from petroleum. **Table 7** presents several studies on the use of polystyrene (PS) for asphalt mixture modification. Incorporating PS into asphalt at very low densities results in increased stiffness and resistance to rutting [29]. However, in a study conducted by Vila-Cortavitarte et al. [6], it is observed that adding PS waste makes the asphalt mixture stiffer and enhances its resistance to moisture-related damage. Nevertheless, its impact on resistance to rutting and fatigue cracking remains uncertain.

Table 7. Summarizes the research on asphalt mixtures with the addition of PS plastic

Type of mixture and Refs.	Size of PS plastic	PS Content	Optimum plastic content	Method	Description
Pen 50/70 [6]	PS plastic waste	1% and 2%	1% and 2%	Dry Process	• This study aims to add three types of PS waste to asphalt concrete to replace bitumen: High Impact Polystyrene (HIPS), General Purpose Polystyrene (GPPS), also known as Crystal Polystyrene, and Polystyrene from hangers (HPS). • Incorporating 1% PS content into the mixture led to a notable 50% reduction in deformation during the rutting test. • The addition of a 2% PS content in the mixture led to a mixture with higher air voids and a lack of cohesion.
A-90 [29]	PS plastic waste Size: 1.5cm x 2cm	0%, 2%, 3%, 4%, 5%	4%	Wet Process	• The asphalt mixing temperature with PS waste is 180 °C. It is mixed for 30 minutes. • Research results indicate a significant increase of 74.4% in the fatigue life of the asphalt mixture modified with PS waste. • The high-temperature stability of the modified asphalt mixture shows remarkable improvement. Properties related to low-temperature cracking resistance, resistance to rutting, resistance to fatigue, and resistance to water also increase after modification.
50/70-pen, Semi-dense HMA [39]		1% of aggregate replaced with polymer waste	1%	Dry Process	• Asphalt concrete modification includes the use of four polymer waste materials: polyethylene (PE) sourced from microcontainers, polypropylene (PP) taken from ground covers, polystyrene (PS) obtained from hangers, and rubber from used tires (ELT). • From this research, PS is found to be the least advantageous asphalt binder because it has the lowest elasticity among all modified mixtures. Additionally, its resistance to plastic deformation decreases, resulting in poorer performance.
HMA [40]	PS plastic waste passes sieve no 16	2.5% and 5%	2.5%	Wet Process	• Modifying asphalt pavement materials by adding common electronic waste plastics such as acrylonitrile butadiene styrene (ABS) and high impact polystyrene (HIPS). • Generally, ABS-modified pavements perform better than HIPS-modified pavements.

3.6. Advantages and Disadvantages of Using Polymer in Asphalt Modification.

The use of plastic waste in asphalt mixtures can improve the properties of the mixture; however, there are also disadvantages in using plastic in asphalt mixtures as listed in **Table 8**.

Table 8. Advantages and disadvantages of using polymer in asphalt modification

Polymer	Advantage	Disadvantage
Polyethylene Terephthalate (PET)	•Increased stability, deformation resistant, stiffness modulus and fatigue resistance •Improved high temperature properties, aging resistance •Improving the value of the resilient modulus of the mixture •Superior resistance to rutting •Relative low cost	•Debatable performance at low temperatures •Some are hard to blend in the bitumen •Requisite for achieving desirable properties is the addition of a significant polymer content.
High-density polyethylene (HDPE)	•Improved high temperature properties and aging resistance •Increased deformation resistant, stiffness modulus and fatigue resistance •Relative low cost •Superior resistance to rutting	•The HDPE mixture performance is not suitable at low temperatures. •Some are hard to blend in the bitumen •Requisite for achieving desirable properties is the addition of a significant polymer content.
Polyvinyl Chloride (PVC)	•PVC application in roads helps deal with its recycling problem •Enhanced asphalt stiffness •Reduce cracking •Increased deformation resistant	•Cannot be directly heated with aggregates at high temperatures. •Cannot be directly mixed with bitumen; requires a chemical modifier. •Mostly plays a filler role •Toxic
Low Density Polyethylene (LDPE)	•Improved high temperature properties, stability, durability value, and aging resistance •Superior resistance to rutting •Increased stiffness modulus, deformation resistance, fatigue resistance and MR (Modulus Resilience) •Relative low cost	•Debatable performance at low temperatures •Some are hard to blend in the bitumen •Requisite for achieving desirable properties is the addition of a significant polymer content.
Polypropylene (PP)	•Increased stability and rutting resistance •Improve high temperature and deformation resistance •Improved load resistance by widening the plasticity range •Relatively low cost •Reduced temperature susceptibility	•Insoluble in bitumen •Phase separation •High tendency to crystalized •Minimal enhancement observed in elastic recovery. •Thermal and fatigue cracking resistance at a low level.
Polystyrene (PS)	Improved stiffness of the mixture	•Its impact on rutting resistance cannot be determined yet. •Not homogenous •Lowest elasticity compared to other plastic types like PE and PP

3.7. The Utilization of Multilayer Plastic Waste as An Additive for Asphalt Mixtures

Multi-Layer Plastic (MLP) commonly found in sachet-type packaging, consists of several layers with different melting points, making it challenging to recycle. Most existing research has focused on the effects of using homogeneous plastic waste in asphalt mixtures, such as pellets or shredded waste. One study related to MLP plastic was conducted by Saragi R Yetty & Sinaga Josua Andrean [41] and Rangan Parea Rusan et al. [42]. These studies involved adding multilayer plastic waste containing aluminum, and the Marshall test results indicated that the mixture did not improve asphalt properties. Instead, it made the mixture susceptible to permanent deformation, with stability values falling below the standard. Furthermore, the mixture did not meet the minimum standard values for VIM and VFB at asphalt content, resulting in poor asphalt layer characteristics and early cracking. However, a study by Nugraha et al. [43] focused on using multilayer plastic waste based on polypropylene and found that a 4% content of instant noodle plastic had the potential to enhance asphalt mixture performance when incorporated using the wet method. Future research should further investigate the use of other types of multilayer waste to improve asphalt mixture performance.

4. Conclusion

One of the efforts to reduce plastic waste is by utilizing it as a component in asphalt mixtures. Mixing is done through two methods, the dry method, and the wet method. The dry method has two variations, using plastic waste as a partial aggregate substitute or as an asphalt additive. Additionally, the wet method involves using plastic waste as an asphalt additive. Based on previous research, it is known that asphalt mixing using the wet method results in a mixture with higher stability compared to the dry method.

During the mixing process, it is crucial to pay attention to the mixing temperature among plastic, aggregates, and asphalt because the resulting mixture must be homogeneous. The plastic being heated should melt entirely, and it should not be heated for an extended period. The maximum plastic particle size for achieving a homogeneous mixture is 5 mm. However, some types of plastics are not compatible with asphalt; therefore, a chemical modifier is required to achieve a homogeneous mixture when combined with asphalt.

The plastic content in the mixture should be determined based on Marshall parameters such as stability, flow, VIM, VMA, VFA, and MQ. Additional tests, including wheel tracking tests, fatigue tests, and resilient modulus testing, are required. Overall, the results of these tests have shown that incorporating plastic waste into asphalt mixtures improves performance characteristics such as stiffness, resistance to rutting, and fatigue resistance. However, PS plastic provides conflicting performance results, especially lower resistance to deformation and less elastic mixtures. Furthermore, asphalt mixtures with PVC plastic should be done using the wet method because PVC contains DEHA (diethyl hydroxylamine), which can cause air pollution when burned due to its hazardous chemical content, making it unsuitable for direct heating with aggregates at high temperatures.

For future research, further investigation is needed to assess environmental and economic impacts. Another area requiring more study is methods to enhance compatibility between plastic and asphalt. Additionally, research has primarily focused on single-layer plastic blending and asphalt mixtures, indicating a need for studies on the effects of multilayer plastics on asphalt mixtures to potentially enhance asphalt mixture performance.

Acknowledgments

We acknowledged Direktorat Jenderal Pendidikan Tinggi, Riset, dan Teknologi of Indonesia for the research grant Matching Fund Kedaireka 2023, No: 32/E1/PPK/KS.03.00/2023.

Authors' Declaration

Authors' contributions and responsibilities - The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation, and discussion of results. The authors read and approved the final manuscript.

Funding –No funding information from the authors.

Availability of data and materials - All data are available from the authors.

Competing interests - The authors declare no competing interests.

Additional information – No additional information from the authors.

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