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Review

Incorporation of plastic waste into road pavements: A systematic literature review on the fatigue and rutting performances

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ABSTRACT

The disposal of plastic waste has become a great challenge for the current generation due to the large-scale production and non-degradable properties of plastics. Additionally, fatigue and rutting are the most common problems that bituminous pavements face. Thus, the incorporation of plastic waste into road pavements has been studied as a possible solution to help mitigate the problems related to plastic disposal and possibly improve the performance of road pavements. This paper presents a systematic review of the literature regarding the incorporation of plastic waste into asphalt mixtures and its impact on rutting and fatigue performance. The main objective is to evaluate the effect of adding plastic on rutting and fatigue performance by analyzing the results of the most commonly performed laboratory tests reported in a dataset, systematically selected following the PRISMA 2020 methodology for systematic reviews. Although deeper research considering short- and long-term ageing is still necessary, the incorporation of plastic waste generally improves the rutting resistance of asphalt mixtures. However, the effect on fatigue behaviour is not clear yet. Finally, it can be said that plastic waste has the potential to be incorporated into asphalt mixtures and help mitigate the environmental problem related to its disposal.

1. Introduction

Generally, the concept of plastics refers to a group of synthetic or naturally occurring materials that may be shaped while soft and then hardened to retain the given shape [1]. However, a more specific concept is related to a group of synthetic materials made from hydrocarbons formed by polymerization obtained from organic raw materials, mainly natural gas and crude oil [2]. The word polymer comes from two Greek words: poly, meaning many, and mero, meaning parts or units. A polymer can be thought of as a chain, in which each link is the monomer [1]. Thus, far from being one substance, plastics are chemical cocktails composed of monomers that have been combined to create polymers [3]. Due to the various types of polymerization, it is possible to produce plastics with particular properties: hard or soft, opaque or transparent, flexible or stiff [2]. Plastic has obtained tremendous marketing advantages thanks to its diversity of characteristics, such as its light weight, durability, versatility in colour, touch and shape, which means it can meet almost any requirement of designers and customers [4]. Despite delivering benefits to our society, plastic waste is responsible for the loss of biodiversity, climate change and the deterioration of human health. Primarily, because none of the commonly used plastics are biodegradable they may fragment but do not decompose and persist for hundreds to thousands of years, accumulating in the natural environment or landfills [3,5,6]. This situation has instigated policymakers to focus their efforts on reducing plastic production and pollution and promoting a circular economy for plastics. Following a review of eighteen international and thirty-six regional instruments, undertaken by the United Nations Environment Programme (UN Environment), there is a growing consensus on the need for a new global agreement that addresses the governance of plastic throughout its lifecycle, including upstream at the level of plastic production, to facilitate the dual objectives of reduction and circularity [7].

As society looks for solutions to the plethora of problems posed by plastic waste disposal, the asphalt pavement industry and scientific communities, propelled by their constant proactive attitude in looking at new sources of waste materials to use in their products, have turned their attention to plastic waste. Thus, provided that the characteristics of the final product meet the standard specifications, incorporating plastic waste into asphalt mixtures and/or road pavements might be a promising solution to help mitigate the problem of plastic disposal. The

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technique of combining other materials in bitumen or asphalt mixtures is not new. The first experimental projects in Europe using modified asphalt with virgin polymers dates back to around 1930, while the first asphalt-modified road was constructed in 1970. However, the first use of waste plastic in asphalt modification was in the 1990s, when plastic fibre was used [8]. Highway agencies have recognized the benefits of using modified asphalts to reduce the amount and severity of pavement distresses and to increase pavement service life, in response to the increase in the traffic load and intensity that have been damaging the roads overlaid with conventional bituminous mixtures [8,9]. Additionally, the depletion of crude oil sources and the technological development of refineries, which convert heavy crudes into fuel, has reduced the demand for bitumen over the years. Furthermore, the availability of mineral sources to extract stones to be used as aggregates will naturally reduce in the long run [10]. Finally, incorporating alternative materials into asphalt concrete and bitumen can relieve the amount of waste in landfills and help create sustainable practices for the pavement industry [11].

In the particular case of plastic waste, there are two main methods to incorporate it into asphalt mixtures, namely wet and dry processes [12–15]. The wet process refers to blending plastic waste with bitumen before mixing it with aggregates and producing the asphalt mixture. This process requires sophisticated equipment such as a high-shear mixer [13], and plastics must be well shredded or powdered to be mixed with bitumen at high temperatures to obtain a uniform plastic-modified binder [8]. On the other hand, the dry process consists of mixing plastic waste with aggregates before introducing the bitumen. Plastic particles can either replace a proportion of aggregate or be melted to coat the aggregates [8]. The dry process is more straightforward and economical as it can be carried out in any asphalt plant without significant modification [15]. Hot Mix Asphalt (HMA) includes different asphalt mixture types, such as dense-graded, gap-graded, and open-graded mixtures [16–18]. The mixture type depends greatly on the aggregate gradation. Dense-graded mixtures (e.g. asphalt concrete (AC)) are produced with continuously graded aggregate. Gap-graded mixtures (e.g. stone mastic asphalt (SMA)) are produced with aggregate ranging from coarse to fine with few or no intermediate sizes. In turn, open-graded mixtures (e.g. porous asphalt (PA)) are produced with relatively uniform-sized aggregates, characterized by a lack of intermediate-sized particles and a low proportion of fine aggregates [19–21].

Recently a few reviews have been published regarding the incorporation of plastic waste into asphalt mixtures [8,12,13,22]. However, none shed light on the effect of plastic waste on the fatigue and rutting performances assessed in the laboratory, nor for different mixing processes and types of asphalt mixture. Wu and Montalvo [12] evaluated the feasibility of adding recycled plastics into asphalt pavement with respect to engineering performance, cost benefits and environmental impact reduction. However, their review only focused on the major findings described by the author of each study instead of analyzing the direct effect of the addition of plastic waste on the result of the laboratory tests. Vargas and El Hanandeh [22] performed a systematic review to consolidate the investigations of the use of plastic waste as a bitumen modifier in terms of penetration, softening point and viscosity, aside from rheological properties. Since the investigation was only focused on bitumen modification, the performance of asphalt mixtures with plastic waste fell outside the scope of their review. Following the same trend, Duarte and Faxina [13] provided a comprehensive overview of the modification of asphalt binders with reclaimed polymers (polyethylene (PE), polyethylene terephthalate (PET), polystyrene (PS), crumb rubber, polypropylene (PP), composite polymers (CP)). They analyzed the main factors to be taken into account (polymer characteristics, chemical characteristics of the asphalt binder, mixing conditions, compatibility between polymer and asphalt binder, storage stability). Then, they presented the advantages and potential drawbacks of incorporating recycled polymers into asphalt mixtures. They concluded that this tends to improve pavement performance significantly. However, it can increase asphalt binder and air voids content, reduce skid and rutting resistance and decrease workability. Recently, Heydari et al. [8] published a critical literature review comparing the different mixing methods, namely dry and wet processes, and the relevant results were plotted in graphs to highlight the trends and inconsistencies in the literature. However, the study only considered Marshall properties, such as stability, flow and air voids.

Considering all the above, this paper presents a systematic literature review, following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement methodology [23], on the use of plastic waste in asphalt binders and mixtures, namely its effect on fatigue and rutting performances assessed in the laboratory, for different mixing processes (i.e., dry and wet), plastic types and contents, laboratory tests and type of asphalt mixtures (i.e., dense-, gap- and open-graded). This review aims to summarise the main findings of earlier studies on fatigue and rutting performance of asphalt mixtures which incorporate plastic waste (function plastic type, mixing process, mixture type and laboratory test), and outline the path for future developments in this domain.

The remainder of this paper is organized as follows. Section 2 presents the systematic review methodology. Section 3 describes the two pavement distresses in review (fatigue and rutting). Section 4 presents the review's results, i.e. studies per year and country, studies per plastic type and source, studies per mixture type, studies per laboratory tests, and the effect of plastic incorporation on fatigue and rutting performance. Then, in Section 5, the results are discussed, and finally, Section 6 presents the main conclusions and future developments.

2. Methodology

In order to create the main dataset of the systematic review, a protocol was developed with the steps of identification, screening, eligibility and included. Initially, the identification step consisted of an advanced search that was performed in the academic databases Scopus and Web of Science on May 31, 2023. The selected keywords "plastic" and "wast*" or "recycl*" and "asphalt" or "road*" or "pavement*" and "fatigue" or "rutting" were searched within the field title/abstract/keyword. Also, an asterisk was added to those words that were relevant to consider the singular, plural, and other word forms. Only papers written in English and published in the last six years were considered, as demonstrated in Table 1.

Second, the author, title and year of publication of the identified records were exported to an MS Excel spreadsheet. Also, author, title, year of publication and abstract were exported to a plain text file. The screening phase consisted of reading each record's title and abstract in the plain text file and indicating in the MS Excel spreadsheet whether that record should be included in the main dataset of the review.

The chosen eligibility criterion to include an article in the main dataset was whether the article addressed the effect of plastic waste incorporation into asphalt mixtures on fatigue or rutting performances. It is important to emphasize that papers related to bitumen modification with plastic waste are not included in the scope of this review.

By performing the advanced search with the above criteria, two

Table 1
Search query.

Keywords	Field	Limitations
Plastic Wast*[1] Recycl*[1] Asphalt Road*[1] Pavement*[1] Fatigue Rutting	Title Subject Abstract	Papers English Last Six Years

[1] Singular, plural and variations of the word were searched.

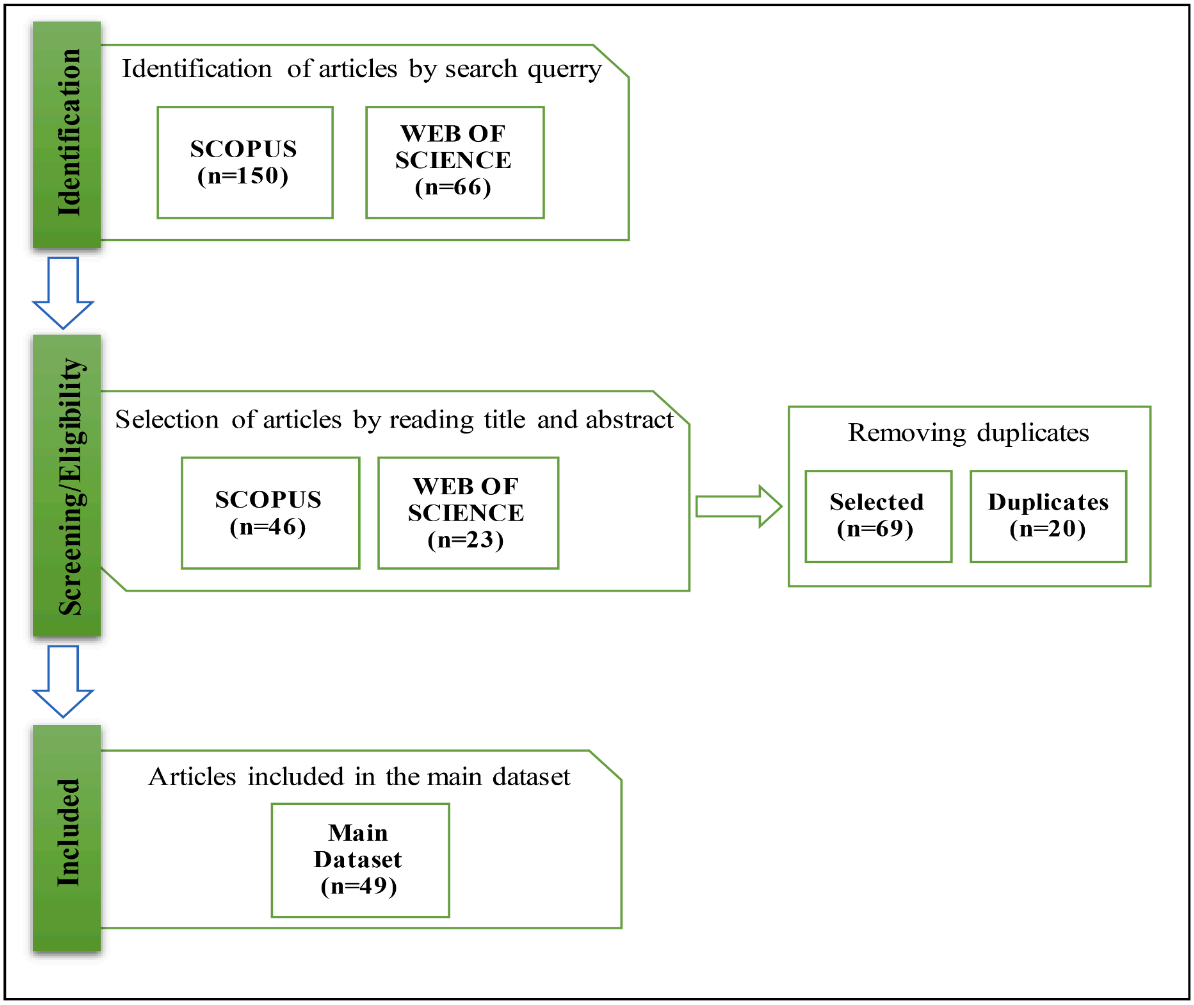

Fig. 1. Systematic protocol adopted.

hundred and sixteen papers were found. From those, one hundred and fifty were in Scopus and sixty-six in the Web of Science. After carefully reading all the abstracts, forty-six papers in Scopus met the eligibility criterion, while twenty-three met the eligibility criterion in Web of Science. Finally, after removing the twenty records that appeared in duplicate, the main dataset of this review consists of forty-nine papers. Fig. 1 shows the systematic protocol adopted.

Once the main dataset was selected, all the information required to perform the review was extracted from the papers. Although the main focus is the effect of plastic waste on fatigue and rutting performances, further information was also significant to achieve the goals of this review, such as mixing processes, shape, type and proportion of plastic used, and asphalt mixture configuration, as seen in Fig. 2. Besides that, the number of publications year by year, their geographic distribution and the plastic source were also considered.

3. Fatigue and rutting

HMA is a mix of aggregates, bitumen and air voids. Bitumen is a viscoelastic material. It means that part of its deformation is recoverable, and part is non-recoverable. For this reason, hot mix asphalt shows different behaviours under high and low temperatures. HMA becomes softer and more susceptible to permanent deformation in hot weather. In contrast, cold weather makes it brittle and more susceptible to fatigue cracking [24]. Additionally, good resistance against rutting (permanent deformation) is expected early in pavement service life. When the bitumen has aged and suffered oxidation, good behaviour against fatigue cracking is required [24]. Predicting the asphalt mixture behaviour is a complex task, even more when another material, such as plastic waste, is incorporated. Moreover, some undesirable effects can occur mainly due to the high number of vehicles imposing repetitive higher axle loads on roads, environmental conditions, and construction errors. These usually cause permanent deformation (rutting) and fatigue, thus decreasing road pavement life [25]. According to Moghaddam [25], fatigue and rutting are the most common distresses in road pavements. In addition to shortening pavement life, they increase maintenance and road user costs. So, finding ways to delay asphalt pavement deterioration and increase service life is vital. Thus, it is essential to understand the fatigue and rutting performance of asphalt mixtures with waste plastic. In the following sub-sections, fatigue and rutting distresses are detailed.

3.1. Fatigue cracking

Fatigue cracking is just one of the cracking modes. There are others, namely thermal (or low-temperature) cracking [26] and reflective cracking [27]. This paper addresses fatigue cracking since it is the most common cracking mode [28]. It is induced by traffic loads, which are cyclic loads of low magnitude. Therefore, it is not the load magnitude that causes pavement structure damage but the repeated passage of these loads. This repetition, combined with climatic loads, induces fatigue that can lead to cracks appearing.

Fatigue cracking was initially assumed to originate at the bottom of the asphalt layers. However, fatigue cracks can originate at the bottom

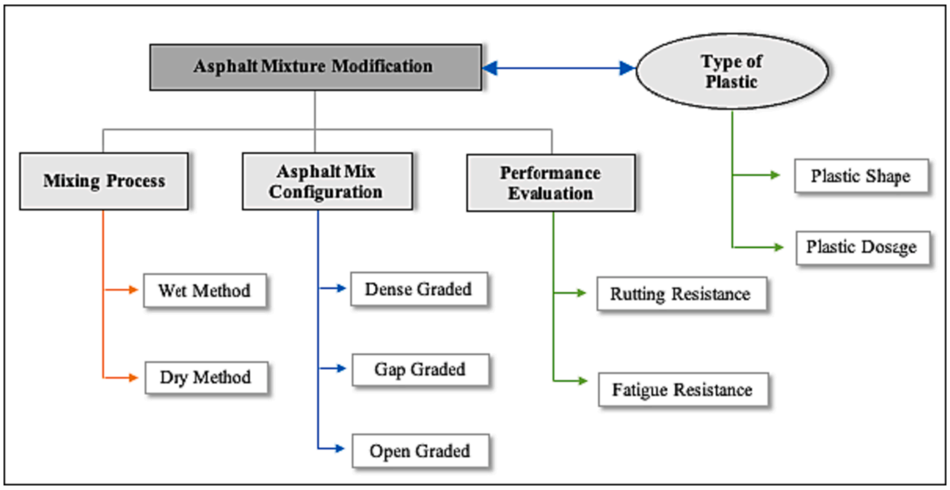

Fig. 2. Relevant aspects of the data collection process.

and/or at the top of the asphalt layers [29]. Top-down cracks can be due to bending surface tension that occurs in thinner pavements or due to shear stresses that occur in the tire-pavement contact in thicker pavements [30].

Fatigue resistance can be characterized using two approaches/models, the phenomenological (or traditional) approach and the mechanistic approach [31,32]. In the phenomenological approach [33], the fatigue characteristics are expressed as relationships between the initial stress or strain and the number of load repetitions; the pavement mechanics theory is not considered, and the materials are assumed to be homogenous. This is a simple approach that does not reflect fatigue complexity. In turn, mechanistic approaches attempt to characterize the fatigue phenomenon better. They study damage evolution and are based on the viscoelastic continuum damage (VECD) theory and/or on the fracture mechanics theory. VECD theory uses pseudo-variables to eliminate the time dependence of the viscoelastic material [34]; consequently, fatigue life can be predicted for any frequency and temperature. The fracture mechanics theory [35] relates fatigue life with the cracking mechanism, which develops progressively through three stages: crack initiation, propagation and failure.

Fatigue performance can be predicted in the laboratory using different types of tests but it is a time-consuming task. For loading mode, tests can be classified as (1) bending tests (on trapezoidal or prismatic shape specimens), (2) uniaxial tests (on cylindrical specimens) and (3) indirect tensile tests (on cylindrical specimens). The specimens are basically subjected to a sinusoidal or another controlled loading (strain-controlled or stress-controlled), and the tests can be done at different temperatures and loading frequencies. Other tests based on fracture mechanics and energy correlate with fatigue resistance, such as the overlay test [36], the semi-circular notched beam test [37], the disk-shaped compact tension test [38], and the wheel tracking test [39]. Each of these tests has its protocol and presents advantages and disadvantages. For more details on fatigue tests, please see [40].

3.2. Rutting

The Federal Highway Administration defines rutting as a longitudinal surface depression in the wheel path. It may have associated transverse displacement [41]. Rutting is also defined as the permanent pavement deformation due to the progressive accumulation of visco-plastic vertical compressive strains in the wheel tracks [42,43]. Rutting is related to repetitive loading from heavy traffic [25,41,42]. Each load can represent a minimal amount of unrecoverable strain, but this value can be significant when many loads are applied over a pavement's lifetime [41].

Mix design properties can impact rutting by the use of an incorrect asphalt binder, a poorly designed mix, or a mix with a high percentage of asphalt binder [41,43]. Rutting performance also closely correlates with the percentage of voids in asphalt mixtures, aggregate particle shape, toughness, and angularity of coarse and fine aggregates [25,43].

For instance, a higher-performance grade binder, i.e. a stiffer binder, tends to decrease the rut depth. Conversely, higher binder content increases the rut depth since the mixture will be more flexible [41]. The greater the maximum aggregate size, the greater the rut depth, considering that larger aggregates are stronger and more resistant to deformation. On the other hand, high content of small aggregates can reduce rutting since they will fill more voids in the mixture and have a high compaction level [41]. It was also corroborated by Moghaddam [25], who stated that stone mastic asphalt (SMA) mixture has more resistance against rutting when compared to a dense graded mixture because it consists of a coarse aggregate skeleton as well as higher binder content, which provides a stone-to-stone contact among the coarse aggregate particles. In addition, mineral filler, such as limestone powder, considerably improves the rutting performance of the asphalt mixture. Different tests have been used to assess the rutting resistance of asphalt mixture in a laboratory: the wheel tracking test, the Hamburg wheel tracking test, the cyclic compression test, the asphalt pavement analyzer test and the dynamic modulus test [25].

4. Results

4.1. Publications by year and country

The use of plastic waste in asphalt binders and mixtures has been in the public eye for at least a decade. However, seeking to provide updated information, in this review only the last six years were considered, which is important to limit the scope of the review aligned with the subjects that have been researched.

Fig. 3 presents a chart with the number of publications by year from 2018 to 2023. It can be seen that the number of publications in 2021 is five times the number in 2018, suggesting the incorporation of plastic into asphalt mixtures is doable from the point of view of elementary analysis, namely volumetric and Marshall properties. Nowadays, further analysis, such as evaluation in the laboratory of fatigue and rutting performances, has become essential to ensure the use of plastic in asphalt mixtures.

Another relevant piece of information considered is the geographic distribution of the publications, represented in Fig. 4, which displays the number of publications by country. As can be seen, most of the studies come from Asia, namely twenty-nine publications, which agrees with

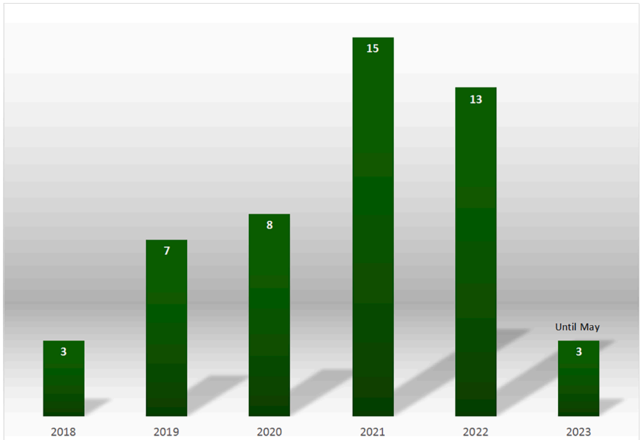

Fig. 3. Publications by year. Only five months were considered in 2023.

the fact that a large amount of all plastic waste produced worldwide has been shipped to Asian countries to be dealt with there. Nevertheless, a reasonable number of papers have also been published in Europe, America and Oceania.

4.2. Publications by plastic type and source

Sorting the papers by the type of plastic added to the asphalt mixture is crucial to visualize the different effects produced by each type of plastic. Table 2 presents the types of plastic and number of papers in the dataset reporting the use of each type. The most studied group was polyethylene terephthalate (PET), considered in fourteen papers, followed by low-density polyethylene (LDPE) considered in eleven papers, and the high-density polyethylene (HDPE) considered in eight papers. In turn, polyethylene (PE) and polypropylene (PP) considered in four papers each, polyvinyl chloride (PVC) in only two papers, and there is a trend to use a compound made of different types of plastic in the asphalt mixtures, which were considered in ten papers.

Table 3 classifies the source of the plastic waste into three streams, namely "direct stream", when the plastic waste was taken to be analyzed in this study directly after use; "municipal waste collection", when the plastic was collected by the municipal services and then sent to be considered in the research studies; and "recycling facility", when the plastic was taken from a recycling plant where it had been treated or partially treated. Most of the plastic was obtained from the direct stream or the municipal waste collection, which suggests it did not undergo any treatment before being used in the research studies. On the other hand, when the plastic waste was taken from a recycling facility, it is considered to have gone through several processes before being considered in the research studies.

4.3. Publications per mixture type

As mentioned in Section 1, there are three types of asphalt mixture according to gradation: dense, gap and open-graded. Table 4 presents

Table 2
Type of plastic.

Type of Plastic	Occurrence (Number of Papers/Total)
Polyethylene terephthalate (PET)	14/49
Low-density polyethylene (LDPE)	11/49
Polymeric compounds (PC)	10/49
High-density polyethylene (HDPE)	8/49
Polyethylene (PE)	4/49
Polypropylene (PP)	4/49
Polyvinyl chloride (PVC)	2/49
Acrylonitrile butadiene styrene (ABS)	1/49

Table 3
Plastic source.

Plastic Source	Occurrence
Direct Stream	19/49
Recycling Facility	13/49
Municipal Waste Collection	10/49
Unspecified	7/49

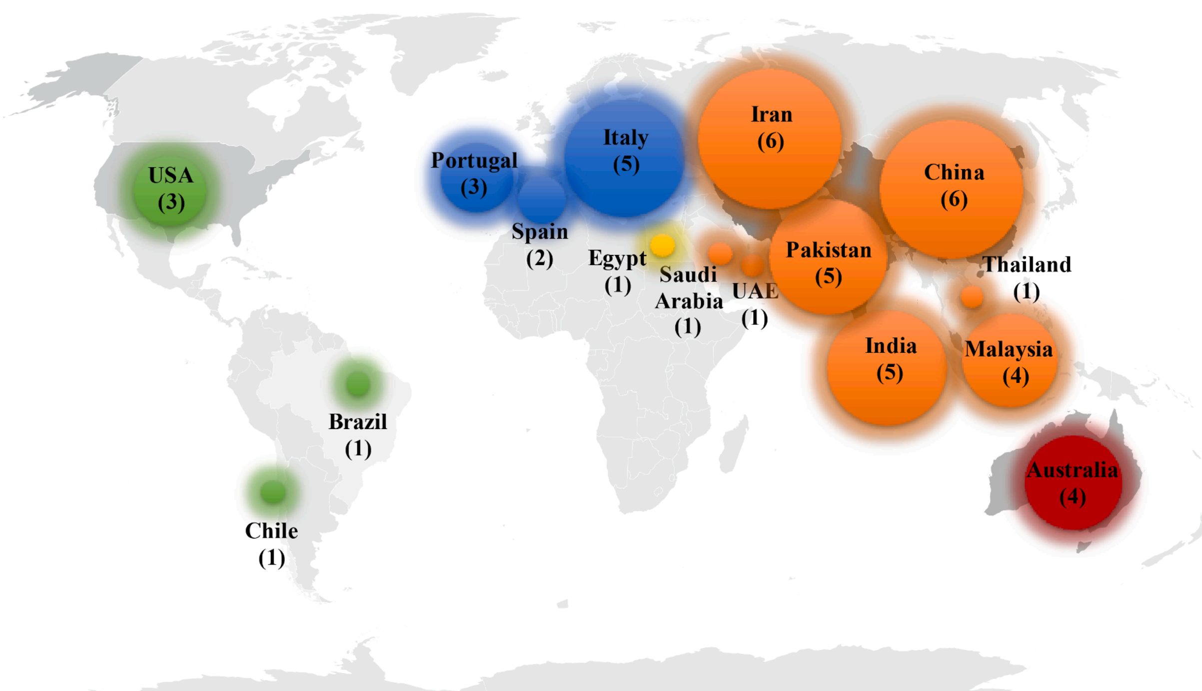

Fig. 4. Publications by country.

Table 4
Asphalt mixture type.

Gradation	Occurrence	Type	Occurrence
Dense graded	43/49		
		AC14	8/43
		AC20	4/43
		AC13	3/43
		AC16	1/43
		AC22	1/43
		RS 4.75A	1/43
		Unspecified	25/43
Gap graded	9/49		
		SMA	7/9
		SDA	1/9
		BBTM	1/9
Open graded	1/49		
		PA	1/1

AC: asphalt concrete; SMA: stone mastic asphalt; SDA: semi dense asphalt; PA: porous asphalt; BBTM: "béton bitumineux très mince" which refers to asphalt concrete for very thin layers.

the asphalt mixture types and number of papers in the dataset reporting the use of each type. Dense graded asphalt mixture standouts clearly from the rest as the most frequently studied mixture type (forty-three papers). It is followed by gap graded, which has been used increasingly over the years, with nine papers, of which Stone Matrix Asphalt (SMA) was studied in seven papers. Finally, open graded mixtures were only studied in one paper.

4.4. Publications per laboratory test

Table 5 shows the occurrence of tests related to fatigue and rutting carried out in a laboratory. To evaluate fatigue performance, the Four-point Bending Test and the Indirect Tensile Fatigue Test were carried out in twelve papers each, the Semi-circular Bending Test in seven papers, as well as lesson common tests that were studied in one paper each, such as the Three-point Bending Test, the Texas Overlay Test, the Disc-shaped Compact Tension Test and the Semi-circular Notched Beam Test.

To evaluate rutting performance the tests performed were as follows: the Wheel Tracking Test was considered in twenty-nine papers, the Hamburg Wheel Tracking Test was considered in four papers, the Dynamic Creep Test was considered in eleven papers, the Dynamic Modulus Test was considered in three papers, the Asphalt Pavement Analyzer was considered in two papers, the Static Creep and Deformation Strength Tests were also considered in one paper each.

4.5. Fatigue and rutting performance per plastic type

Considering that each type of plastic has its own characteristics, the effects of plastic waste addition on asphalt mixtures' fatigue and rutting performances are presented in the upcoming subsections sorted by the type of plastic, since it is important to analyze whether the effects produced are the same for the same type of plastic. The effects produced are represented in Tables 6–12 by a arrow pointing up and a arrow pointing down, for positive and negative effects, respectively.

4.5.1. PET

Adding PET had a positive result on rutting in ten studies, while only one study showed a negative result. Rutting was evaluated by the Wheel Tracking Test in six studies, the Hamburg Wheel Tracking Test in one study, Dynamic Creep Test in three studies and the Dynamic Modulus Test in two studies. The negative result appeared in one of the Dynamic Modulus Tests. On comparing the two studies in which this test was performed, the effect was positive when PET was added at a ratio of 1 % of the weight of the mixture using the dry method. However, when PET was added using the wet method at a ratio of 0.2 % of the weight of the mixture (5 % of the weight of the bitumen), the effect produced was negative.

As far as fatigue performance is concerned, the Indirect Tensile Fatigue Test was performed in four studies, the Four-point Bending Test in two studies, the Semi-circular Bending Test in two studies and the Semi-circular Notched Beam Test in one study. All the tests resulted in positive effects, as shown in Table 6.

4.5.2. LDPE

Table 7 presents the main characteristics of the studies assessing the fatigue and rutting performances of asphalt mixtures incorporating LDPE.

The effects created by the addition of LDPE on rutting were evaluated by the Wheel Tracking Test in eight studies, the Dynamic Creep Test in five studies and the Hamburg Wheel Tracking Test in two studies. Twelve tests showed positive effects, while only two tests presented negative effects. In addition, one of the negative effects reported was in the Dynamic Creep Test. When comparing the studies in which this test was performed, Almeida et al. [60] and Fonseca et al. [59] found contradictory results when the conditions were the same −6 % flakes of LDPE of the weight of bitumen (0.3 % of the weight of the mixture) using the dry method. However, Radeef et al. [58] had positive results when 5–10 mm LDPE particles were added at a ratio of 1 % of the weight of aggregates (0.95 % of the weight of the mixture) using the dry method.

As far as fatigue performance is concerned, the effects were evaluated by the Four Point Bending Test in four studies, in which three studies reported worse fatigue performance, whereas one study reported better performance, namely when ageing was considered.

4.5.3. Polymeric compounds (PC)

The effects on fatigue and rutting performance produced by the incorporation of different polymeric compounds on asphalt mixtures are presented in Table 8.

Rutting was evaluated by the Wheel Tracking Test in seven studies and by the Asphalt Pavement Analyzer in one study, all of them showing better rutting performance.

Fatigue was analyzed by the Four-point Bending Test, Semi-circular Bending Test and Indirect Tensile Fatigue Test in three studies each. Most of the records showed that plastic waste positively affected fatigue, excepting one record that presented worse performance and two that obtained similar behaviour.

Although Ranieri [75] found a significative reduction in the fatigue performance in terms of admissible strain, from the Four-point Bending

Table 5
Laboratory tests for fatigue and rutting.

Fatigue Test	Occurrence	Rutting Test	Occurrence
Four-point Bending Test	12/32	Wheel Tracking Test	29/41
Indirect Tensile Fatigue Test	12/32	Hamburg Wheel Tracking Test	4/41
Semi-circular Bending Test	7/32	Dynamic Creep Test	11/41
Three-point Bending Test	1/32	Dynamic Modulus Test	3/41
Texas Overlay Test	1/32	Asphalt Pavement Analyzer	2/41
Disc-shaped Compact Tension Test	1/32	Static Creep Test	1/41
Semi-circular Notched Beam Test	1/32	Deformation Strength Test	1/41

Table 6
Effect of PET on fatigue and rutting performance.

Plastic	Plastic Shape	Dosage	Mixing Method	Asphalt Mixture Type	Fatigue	Rutting	Reference
PET	grounded 0.45 mm	6 % of weight of bitumen	wet	Gap graded	⇧	⇧	[44]
PET	grounded 0.245 mm	8 % of weight of bitumen	wet	Dense and Gap graded	(2)	⇧	[45]
PET	shredded 1–3 mm	10 % of weight of bitumen	dry	Gap graded	(1)	(1)	[46]
PET	grounded 0.45 mm	8 % of weight of bitumen	wet	Dense graded	(2)	⇧	[47]
PET	shredded 1.18–3.35 mm	20 % of volume of aggregates	dry	Dense graded	(2)	⇧	[48]
PET	micronized #200-#400	20 % of weight of bitumen	wet	Dense graded	⇧	⇧	[49]
PET	shredded 0.425–1.18 mm	5 % of weight of portion of coarse aggregate	dry	Dense graded	(2)	⇧	[50]
PET	shredded 3–4 mm	5 % of weight of portion of coarse aggregate	dry	Dense graded	⇧	(2)	[51]
PET	fiber 30 × 5 × 1 mm	1 % of weight of the mixture	dry	Dense graded	⇧	⇧	[52]
PET	shredded small particles	0.50 % of weight of aggregates	wet	Gap graded	⇧	⇧	[53]
PET	shredded small particles	10 % of weight of bitumen	wet	Dense graded	⇧	⇧	[54]
PET	shredded small particles	12 % of weight of bitumen	dry	Dense graded	(2)	⇧	[55]
PET	shredded small particles	5 % of weight of bitumen	wet	Dense graded	⇧	⇩	[56]
PET	pellets ≤ 2.36 mm	6 % of weight of bitumen	dry and wet	Dense graded	⇧	(2)	[57]

(1) The mixtures were tested only to meet the specifications; there was no control mixture to allow a comparison.
(2) Only one property was tested.

Table 7
Effect of LDPE on fatigue and rutting performance.

Plastic	Plastic Shape	Dosage	Mixing Method	Asphalt Mixture Type	Fatigue	Rutting	Reference
LDPE	shredded 5–10 mm	1 % by the weight of aggregates	dry	Dense graded	(3)	⇧	[58]
LDPE	flakes	6 % by the weight of bitumen	dry	Dense graded	⇩	⇩	[59]
LDPE	plastic film flakes	6 % by the weight of bitumen	dry	Dense graded	⇩	⇧	[60]
LDPE	shredded 5–10 mm	1 % by the weight of aggregates	dry	Dense graded	(3)	⇧	[61]
LDPE	shredded small particles	15 % by the weight of aggregate	dry	Dense graded	(3)	⇧	[62]
LDPE	–	9 % by the weight of bitumen	dry	Dense graded	(3)	⇧	[63]
LDPE	–	9 % by the weight of bitumen	wet	Dense graded	(3)	⇧	[63]
LDPE	shredded to lower than 4.75 mm	3 % by the weight of the mixture	dry	Dense graded	(3)	⇧	[64]
LDPE	plastic film flakes size 2–100 mm	6 % by the weight of bitumen	dry	Dense graded	⇧	⇧	[65]
LDPE	pellets	0.5 % by the weight of the mixture	dry	Dense graded AC16	⇩	⇧	[66]
LDPE	pellets	0.3 % by the weight of the mixture	dry	Dense graded AC22	⇧	⇩	[66]
LDPE	pellets	0.5 % by the weight of the mixture	dry	Gap graded	⇩	⇧	[66]
LDPE	shredded to lower than 4.75 mm	8 % by the weight of bitumen	dry	Dense graded	(3)	⇧	[67]
LDPE	shredded to lower than 4.75 mm	7 % by the weight of bitumen	dry	Dense graded	⇧	⇧	[68]

(3) Only one property was tested.

Table 8
Effect of polymeric compounds on fatigue and rutting performance.

Plastic	Plastic Shape	Dosage	Mixing Method	Asphalt Mixture Type	Fatigue	Rutting	Reference
Benzyl ethylene block copolymer and Epoxy Resin	resin	9 % and 2 % by the weight of bitumen	wet	Dense graded	⇧	⇧	[69]
Polymeric compound	shredded lower than 2 mm	5 % by the weight of bitumen	dry	Dense graded	⇧	⇧	[70]
Polymeric compound	shredded lower than 2 mm	5 % by the weight of bitumen	dry	Dense graded	⇧	⇧	[71]
	shredded 5–10 mm	1 % by the weight of the mixture	dry	Dense graded	⇧	(4)	[72]
Polymeric compound HDPE, LDPE, PP	shredded #8 to #40 and #8 to #10	9.5 % by the weight of aggregate	dry and wet	Dense graded	⇧	⇧	[73]
Polymeric compound PET, HDPE, PVC	flakes 5–10 mm and 0.25–2 mm	20 % by the weight of bitumen	dry	Gap graded	(4)	⇧	[74]
Polymeric compound HDPE, PP	–	0.50 % by the weight of aggregates	dry	Dense graded	⇩	⇧	[75]
Plastomeric compound PE, PP	pellets lower than 5 mm	5.2 % by the weight of bitumen	dry	Dense graded	⇧	⇧	[76]
Compound EVA, APAO	–	6 % by the weight of bitumen	wet	Dense graded	⇧	(4)	[77]
Coumpound PE, EVA, PP	shredded to lower than 8 mm	25 % by the weight of bitumen	dry	Dense graded	=	⇧	[78]
Coumpound PP, PE	shredded to lower than 8 mm	25 % by the weight of bitumen	dry	Dense graded	=	⇧	[78]
Plastomeric compound PE	pellets 2–4 mm	5 % by the weight of bitumen	dry	Dense graded	⇧	⇧	[79]

(4) Only one property was tested.

Test, the values obtained can be considered satisfactory for road paving applications. Lastly, it is not possible to indicate a reliable pattern regarding how the polymers affect asphalt mixtures because each study with compounds uses different types of polymers.

4.5.4. HDPE

The incorporation of High-Density Polyethylene in asphalt mixtures was considered in eight studies. Rutting was evaluated by the Wheel Tracking Test in four studies, the Hamburg Wheel Tracking Test in two studies and the Dynamic Creep Test in one study, while fatigue was

Table 9
Effect of HDPE on fatigue and rutting performance.

Plastic	Plastic Shape	Dosage	Mixing Method	Asphalt Mixture Type	Fatigue	Rutting	Reference
HDPE	plastic film flakes	0.2 % by the weight of the mixture	dry	Dense graded	(5)	⇧	[80]
HDPE	shredded	6 % by the weight of bitumen	dry	Dense graded	⇧	⇧	[59]
HDPE		4 % by the weight of bitumen	wet	Gap graded	⇧	⇧	[81]
HDPE	shredded small particles	15 % by the weight of aggregate	dry	Dense graded	(5)	⇧	[62]
HDPE		9 % by the weight of bitumen	dry	Dense graded	(5)	⇧	[63]
HDPE		9 % by the weight of bitumen	wet	Dense graded	(5)	⇧	[63]
HDPE	shredded to lower than 4.75 mm	8 % by the weight of bitumen	dry	Dense graded	(5)	⇧	[67]
HDPE	shredded to lower than 4.75 mm	5 % by the weight of aggregate	dry	Dense graded	⇧	(5)	[82]
HDPE	shredded to lower than 8 mm	25 % by the weight of bitumen	dry	Dense graded	=	⇧	[78]

(5) Only one property was tested.

Table 10
Effect of PE on fatigue and rutting performance.

Plastic	Plastic Shape	Dosage	Mixing Method	Asphalt Mixture Type	Fatigue	Rutting	Reference
PE	pellets 2–3 mm	3 % by the weight of bitumen	wet	Dense graded	⇩	⇧	[83]
PE	pellets 2–3 mm	0.3 % by the weight of the mixture	dry	Dense graded	⇩	⇧	[84]
PE	pellets 2–3 mm	7 % by the weight of bitumen	wet	Dense graded	⇩	⇧	[85]
PE	shredded small particles	8 % by the weight of aggregates	dry	Gap graded	(6)	(6)	[86]

(6) The mixtures were tested only to meet the specifications; there was no control mixture to allow comparison.

Table 11
Effect of PP, PVC and ABS on fatigue and rutting performance.

Plastic	Plastic Shape	Dosage	Mixing Method	Asphalt Mixture Type	Fatigue	Rutting	Reference
PP	shredded 40 mm × 5 mm	1.5 % by the weight of the mixture	dry	Dense graded	(7)	⇧	[43]
PP	fiber 6 mm length	1 % by the volume of the mixture	dry	Dense graded	⇧	⇧	[87]
PP	fiber 12 mm length	1 % by the weight of bitumen	dry and wet	Dense graded	(7)	⇧	[88]
PP	filament 20–30 mm length and 0.2 mm diameter	0.2 % by the weight of bitumen	dry	Dense graded	⇧	⇧	[89]
PVC	powder #50	5 % by the weight of bitumen	wet	Gap graded	⇧	⇧	[90]
PVC	powder	10 % by the weight of bitumen	wet	Dense graded	(7)	⇧	[91]
ABS	shredded small particles	6 % by the weight of bitumen	dry	Dense graded	⇧	⇧	[59]

(7) Only one property was tested.

evaluated in four studies, by the Four-point Bending Test in three studies and the Indirect Tensile Fatigue Test in one study. All the studies resulted in positive effects either for rutting or fatigue, except one record where a similar fatigue behaviour was found. It is important to emphasize that Ullah et al. [62] achieved a considerable reduction in rut depth when a large amount of plastic was incorporated in the mixture, namely 15 % of the weight of aggregates. Table 9 shows the main characteristics of the studies.

4.5.5. PE

There are four studies in which Polyethylene, but it was not specified whether the polymer was of high or low density (Table 10).

Rutting was evaluated by the Wheel Tracking Test in three studies and the Hamburg Wheel Tracking Test in one study, and all found an improvement in rutting performance. In the study performed by Mithanthaya et al. [43], the tested mixtures were not compared with a control mixture, but only to ascertain whether the mixture would meet the standard specifications, which was accomplished.

Fatigue was evaluated by the Four-point Bending Test in one study, the Three-point Bending Test in one study and Texas Overlay Test and Disc-shaped Compaction Tension Test in one study each. All the studies showed that polyethylene addition negatively affected fatigue behaviour, as can be seen in Table 10.

4.5.6. PP, PVC and ABS

The main features of the studies reporting the use of PP, PVC and ABS are displayed in Table 11. PP was considered in four studies. Rutting was analyzed by the Wheel Tracking Test in three studies and by the Asphalt Pavement Analyzer in one study. Fatigue was analyzed by the Four-point Bending Test in one study and by the Indirect Tensile Fatigue Test in one study. All the studies presented positive results for rutting and fatigue.

PVC was considered in two studies. Rutting was analyzed by the Static Creep Test and Deformation Strength Test in one study and by the Dynamic Creep Test in another study. Fatigue was analyzed by the Semi-circular Bending Test in one study. All the studies presented positive results.

Finally, ABS was considered in only one study. Rutting was evaluated by the Dynamic Creep Test and fatigue was evaluated by the Four-point Bending Test. Both tests showed a positive effect of ABS addition on rutting and fatigue performances of asphalt mixtures.

5. Discussion

PET was the most frequently studied type of plastic (29 % of the studies). It was incorporated into asphalt mixtures by using the dry process [46,48,50–52,55] and the wet process [44,45,47,49,53,54,56]. Concerning rutting resistance, the effect is positive because PET is likely to enhance asphalt mixture strength. At high temperatures, rut depth decreased [48,49,55], and flow number increased [54]. However, a decrease in flow number was observed with the addition of micronized PET [56].

Fatigue resistance of asphalt mixtures with PET was also positively affected. For instance, the tensile stress to break the mixtures at low temperatures increased due to PET addition [54]. Following the same trend, the fracture energy required to fail a mixture at low and intermediate temperatures also increased due to PET incorporation [54]. The number of cycles to fail a mixture increased with the addition of PET [53,56].

The incorporation of HDPE resulted in a slight improvement of fatigue resistance [59,81,82] and in a considerable improvement in

Table 12
Overview of how plastics affect asphalt mixtures.

Plastic	Reasons behind major effects	Reference
PET	Increases adhesion between binder and aggregates.	[44,49,51]
	Provides more elasticity to the mixture.	[44,47,48,53,56]
	Coats the aggregates surfaces filling their pores.	[45,46 51,56]
	Improves mechanical interlocking.	[46,49]
	Strengthen the bond structure of the mixture, cohesion.	[45,47,48,55,56]
	Enhances binder flexibility, leading to a better ability to recover from applied strain.	[53]
LDPE	Improves adhesion between asphalt mixture components.	[58,61,68]
	Coats aggregates surfaces.	[58,61,64,67,68]
	Improves temperature susceptibility.	[64]
	Increases abrasion/wear and impact resistances of aggregates.	[67]
	Better interlocking of aggregates particles.	[68]
	Better bond structure inside the mixture, cohesion.	[64]
PC	Increases adhesion between aggregates and asphalt binder.	[72,73,77]
	Improves bitumen's flexibility, providing a better elastic response under repeated loads.	[70,76,77]
	Improves thermal susceptibility.	[76,78]
	Contributes to form a skeleton structure inside the asphalt mixture.	[69,74]
HDPE	Strengthen bond between bitumen and aggregates, cohesion.	[80]
	Coats aggregates surfaces and fill their pores.	[67]
	Increases abrasion/wear and impact resistances of aggregates.	[67]
	Provides elasticity to the asphalt mixture.	[82]
	Improves thermal suscetibility.	[78]
PE	Provides elasticity to the asphalt mixture.	[84,85]
	Increases adhesion between asphalt binder and aggregates.	[84,85]
	Better bond structure inside the mixture, cohesion.	[84]
PP	Enhanced adhesion between binder and aggregates	[43,89]
	Melts and coats the aggregates.	[43]
	Strengthen the mechanical bond between aggregates, cohesion.	[87,88,89]
PVC	Better interlocking of aggregates particles.	[90]
	Improves adhesion between asphalt mixture components.	[90,91]
	Better bond structure inside the mixture, cohesion.	[90,91]

rutting resistance [59,62,63,67,78,80,81]. That is because its high-density property makes the mixture stiffer, and therefore more energy is required to cause failure in the mixture by creating cracks or deformations.

On the other hand, the incorporation of LDPE decreased the fatigue resistance of the asphalt mixture [59,60,66]. However, it improved the fatigue resistance when the asphalt mixtures were aged [65], whereas the opposite effect was observed for unaged mixtures.

Although it was not specified whether the plastic was of high or low-density, the results of the incorporation of PE followed the same trend as that seen for LDPE, resulting in better rutting resistance [83–85] and worse fatigue resistance [83–85].

Mixtures with PP or PVC presented positive effects for both rutting resistance [43,87–91] and fatigue resistance [87,89,90]. Polymeric compounds also resulted in better rutting [69–71,73–76,78,79] and fatigue [69–73,76,77,79] performances, although a decrease in fatigue resistance occurred [75]. ABS also improved both rutting and fatigue performances for asphalt mixtures [59].

Once it has been demonstrated that plastics can improve asphalt mixture performances, the next step is to understand why these effects were reached. However, the laboratory tests studied in this paper do not address chemical reactions that can happen inside the asphalt mixtures but focus on their behaviour as a whole. As a consequence, it was inferred how plastics behave inside asphalt mixtures by comparing the results of the tests in specimens with and without plastic. Table 12 summarizes the main findings on how each type of plastic affects the asphalt mixture. Generally, their effects are quite similar, such as increasing adhesion between binder and aggregates, providing more elasticity to the mixtures, enhancing mixtures' cohesion, improving mechanical interlocking of the aggregate's particles, and coating and filling the pores of the aggregates.

Figs. 5 and 6 display rutting performance evaluated by the Wheel Tracking Test, Hamburg Wheel Tracking Test and Asphalt Pavement Analyzer sorted by the number of cycles for the wet and dry mixing method, respectively. It shows that the behaviour of mixtures in terms of rut depth decreases with the addition of plastic waste, although it remains satisfactory when large plastic contents are added. These results suggest that plastic supports rutting performance under medium and high temperatures, essential for extending pavement service life.

Regarding fatigue performance, Fig. 7 shows the results of the Four-point Bending Test performed on asphalt mixtures with different plastic contents. Specifically, it depicts the life (number of cycles) and deformation (strain-level). Further, only results for mixtures prepared by the dry method were available. When comparing the same level of cycles, the strain-level decreases with the presence of plastic. However, in a few cases, the presence of Low-density Polyethylene (LDPE) and Polyethylene (PE) reduced the fatigue life of the mixture. Fatigue behaviour is sensitive to low temperatures, and when the mixture ages, it becomes more brittle and consequently susceptible to cracking. These results suggest that the role of plastic in fatigue performance is positive. However, further studies are needed before more conclusive statements can be made.

The dry process was adopted in thirty-three studies, while the wet process was adopted in sixteen studies, and some studies analyzed both methods. It is a fact that the dry process is simpler to be replicated on a large scale because it does not require complex modifications of the

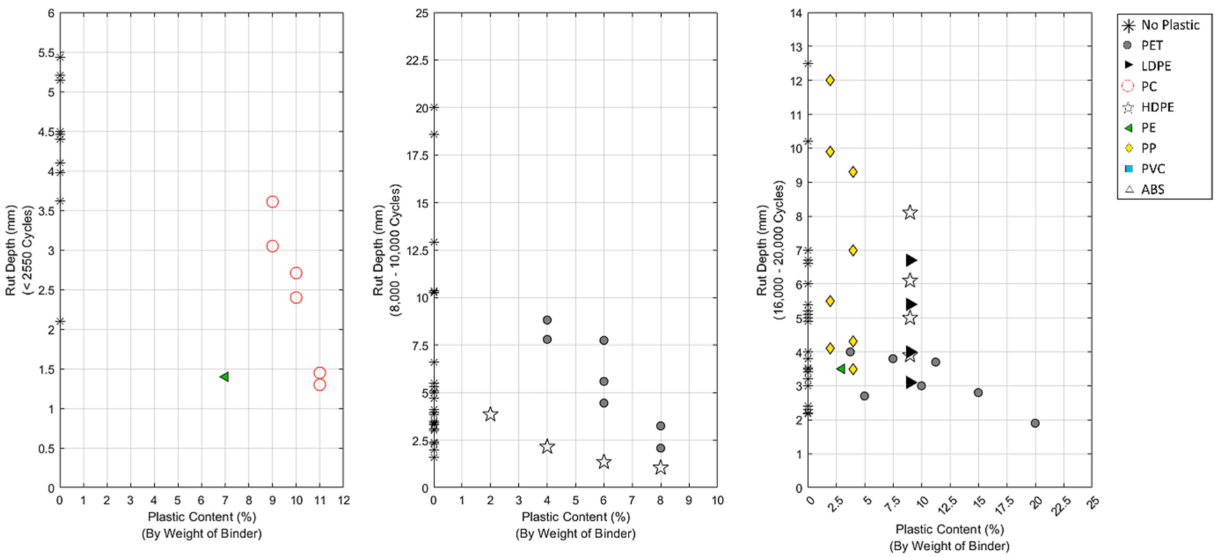

Fig. 5. Wheel tracking test results (wet mixing method).

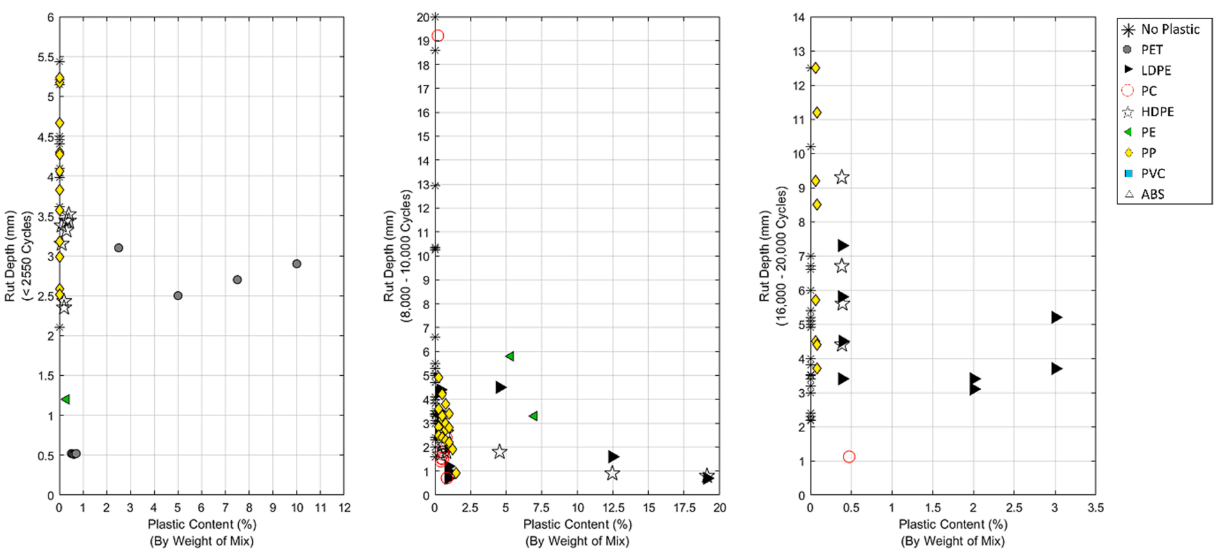

Fig. 6. Wheel tracking test results (wet mixing method).

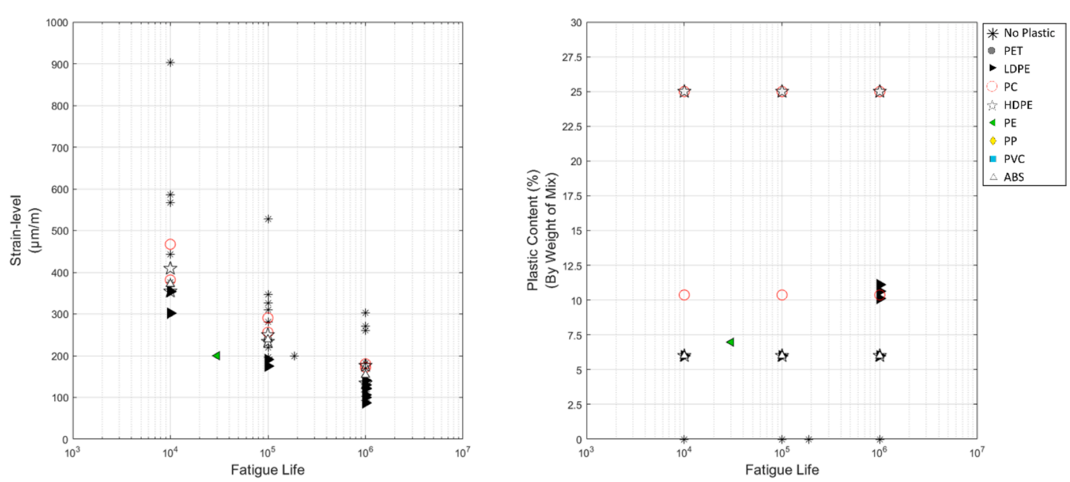

Fig. 7. Four-point bending test results.

asphalt plant. On the contrary, for the wet method to be performed on a large scale, sophisticated equipment is necessary. Additionally, the proportion of plastic waste added was generally small, for both dry and wet mixing process. Even though, in a few cases, larger amounts were added by the dry process resulting in satisfactory performances as well.

Dense and gap-graded asphalt mixtures presented a satisfactory performance with the addition of plastic waste, as it was outlined in this review. Nevertheless, one should remember that the open-graded mixture was considered in only one study. Specifically, the study attempted to produce a porous asphalt mixture with plastic waste. However, it did not succeed because the mixture did not meet the minimum of 20 % air void content required in the standard. According to the information presented in this review, there is no evidence of significant influence on the fatigue and rutting performances caused by the plastic shape and asphalt mixture gradation.

It is important to emphasize that more studies considering gap-graded and open-graded configurations/gradations are needed to expand the knowledge in the field. Moreover, waste plastic's specific role/function in the mixture is highly significant. For instance, it can act as an additive replacement, filler replacement, aggregate replacement, bitumen replacement, aggregate coating or stabilizer replacement. Few studies indicated whether plastic addition was supposed to be an additive replacement, bitumen replacement and/or aggregate replacement. In none of the studies was plastic waste added as filler or stabilizer replacement. Further, no study incorporated two types of plastic waste intending to play different roles.

6. Conclusions and future developments

The systematic review presented in this paper focused on the effect of plastic waste on the fatigue and rutting behaviour of asphalt mixtures. The main dataset of the study was systematically selected, covering the relevant aspects considered to achieve the objective of this review. The main points regarding fatigue and rutting were described, after which a detailed overview of the main characteristics of the relevant studies was provided.

The main findings of the review are as follows:

- In general, the incorporation of plastic waste in asphalt mixtures leads to better rutting performance.
- Plastic addition tends to enhance fatigue performance. However, further studies are needed before a more conclusive assertation can be made, given that the studies performed so far are insufficient to ascertain its behaviour.
- PET addition tends to lead to better rutting and fatigue performances.
- HDPE addition tends to lead to better rutting performance.
- LDPE addition tends to enhance rutting and worsen fatigue performances.
- PP and PVC addition is associated with improvements in both rutting and fatigue performances.
- In general, the optimum amount of plastic added is small, roughly 1 % of the weight of the mixture.
- There is no evidence of the influence of the asphalt mixture gradation and plastic shape on the effects generated by plastic on fatigue and rutting performances.
- Dense-graded mixtures were considered in most of the studies.
- Stone Matrix Asphalt (SMA) with plastic waste was considered in only seven studies, but this seems to be a promising solution and should be further studied.
- Porous Asphalt (PA) mixture with plastic waste is yet to be studied to produce suitable asphalt mixtures.

In order to further explore the technical viability of using plastic materials in asphalt mixtures concerning fatigue and rutting, more research is needed in the following aspects:

- As fatigue performance is relevant in cold climates and most of the studies were done at medium temperatures, further research is needed on the effect of plastic waste on fatigue properties at low temperatures.
- Short- and long-term ageing and their effects on both rutting and fatigue.
- Design of different asphalt mixture types, for instance, open-graded asphalt mixture with high air voids content.
- Addition of plastic waste as a filler replacement, for dense, gap and open graded mixtures.
- Addition of plastic waste as an aggregate coat for gap and open graded mixtures.
- Addition of plastic waste as an additive replacement for gap and open graded mixtures.
- Possibility of incorporating different types of plastic waste, one as a filler replacement and another as an aggregate coat and replacement, for dense-graded, open-graded, and gap-graded mixtures.

All in all, the literature reviewed in this study shows that plastic waste has the potential to be incorporated into road pavement, namely in asphalt mixtures, as a viable solution to improve their characteristics and to help mitigate the environmental problem related to plastic disposal, despite being used in relatively small quantities.

CRediT authorship contribution statement

Josué Cardoso: Investigation, Methodology, Validation, Writing – original draft. **Adelino Ferreira:** Conceptualization, Project administration, Supervision, Validation, Writing – review & editing. **Arminda Almeida:** Conceptualization, Supervision, Validation, Writing – review & editing. **João Santos:** Conceptualization, Supervision, Validation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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