INFLUENCE OF RECYCLED PLASTICS ON THE MECHANICAL BEHAVIOUR OF BITUMINOUS MIXTURES FOR HIGHWAY SURFACE LAYERS

H.M.B. Miranda
ISEL - Instituto Superior de Engenharia de Lisboa, Instituto Politécnico de Lisboa, Portugal
henrique.miranda@isel.pt
D. Domingues & M.J. Rato
BRISA - Auto-estradas de Portugal, S.A., Portugal
rosa.domingues@brisa.pt & maria.rato@brisa.pt

ABSTRACT

Europe is one of the largest producers of plastics in the world, with an annual turnover of over 350 billion euros, making it a strategic industrial sector as the global consumption of plastics increases. However, plastic is nowadays considered a serious environmental problem as it represents a large share of the world's waste generation, with Europe being one of the largest sources of plastic waste exports.

Therefore, the transition to a circular economy for plastics must be driven by Europe in order not to jeopardize the economic and environmental future of the plastics sector on the continent. Thus, it is crucial to investigate the feasibility of using recycled plastics in different applications, especially in the three main end-use markets for plastics (packaging, construction and automotive). In the construction sector, the use of plastics in road and highway construction and rehabilitation is currently being investigated due to the high potential for high-value applications and high raw material consumption. However, more knowledge is needed to make recycled plastic a common solution for road surfacing.

The current study was promoted by BRISA, which was ranked the most sustainable highway operator in Europe for the third time in 2021. It aims to contribute to European efforts to investigate the feasibility (ongoing study: mechanical, functional, and environmental laboratory and field evaluation) of using recycled plastic in the production of bituminous mixtures for highway pavements in Portugal, without limiting the recyclability of bituminous mixtures.

The present work focuses on the influence of recycled plastics on the water sensitivity and deformation susceptibility of bituminous mixtures under load. To perform the experimental study, the following materials were used: two bituminous mixtures with different types of coarse and fine aggregates (granodiorites and granites); a bitumen (PMB 45/80-65); a filler (limestone); and five recycled plastic additives (mainly consisting of LDPE, HDPE, LLDPE and PP, which represent about 50% of the plastics produced in Europe). The results were statistically analysed together with results of other studies on the volumetric and Marshall properties of the specimens.

The results show an overall improvement in resistance to permanent deformation, without a significant benefit in water resistance. However, efforts to validate performance regarding fatigue, ageing resistance, pollutant emissions during production, placement and in service pavements are ongoing. In the statistical analysis, the ratio between binder film thickness and porosity (BFT/Vv) showed a statistically significant strong correlation with the performance indicators for resistance to permanent deformation.

1. INTRODUCTION

The road network is a critically important global asset. The EU-27, the US, Japan and China together have 14.793 million kilometres of paved roads [1], of which 325.5 thousand are heavily trafficked highways, with the EU-27 accounting for about 30 % of the above total. These numbers represent highly developed economies, but they also come at a price: road maintenance in Europe amounted to an average of 23.1 billion euros per year between 2013 and 2019 [2]. Therefore, every small step towards improving sustainability in the paving industry is a big step in terms of global climate and economic challenges. The use of waste materials, which must be considered more and more as new raw materials, must thus be continuously increased in the production of bituminous mixtures, not based on personal beliefs and myths, but on the basis of knowledge, especially when it comes to the rejection of this course of action.

This also applies to end-of-life plastics, especially as plastics are nowadays considered a serious environmental problem [3], [4], as they account for a large share of the world's waste generation, with Europe being one of the largest producers, and sources of end-of-life plastic exports [5].

End-of-life plastic streams can contain a wide variety of materials with different properties (physical, mechanical, and chemical), characteristics and applications, such as standard thermoplastics:

- Polyethylene, PE (low density, LDPE; medium density, MDPE, high density, HDPE; and linear low density, LLDPE), polypropylene (PP), polyethylene terephthalate (PET) and polystyrene (PS), plastics commonly, but not exclusively, used for packaging.
- Polyvinyl chloride (PVC), expandable polystyrene (EPS), plastics commonly used for, but not limited to, construction.

To engineering plastics:

- Acrylonitrile butadiene styrene resin (ABS), styrene-acrylonitrile copolymer (SAN), polyamides (PA), polycarbonate (PC), polyurethane (PUR), polymethyl methacrylate (PMMA), plastics commonly, but not exclusively, used in automotive, electrical and electronics, household, recreational and sports applications.

The leading plastics in manufacturing and disposal are PE and PP. However, after collection (post-industrial or post-consumer), not all end-of-life plastics are suitable for recycling or use in road construction or rehabilitation (e.g., bituminous mixtures production), such as PVC, PS, and PA, which can be potentially hazardous to health and/or to the environment [6]–[8].

Therefore, research developed elsewhere for use in bituminous mixtures [9]–[23] focused on the use of recycled plastics (mostly from mechanical recycling, with or without extrusion, homogeneous pellets or plastic chips, respectively) whose properties are compatible with the temperatures used in the production of bituminous mixtures and their performance requirements, ending in most cases with the aforementioned leading plastics (PE and PP), in addition to PET and, to a lesser extent, PUR, PVC, and PS. These recycled plastics are usually added via the dry process (as aggregate replacement, mixture modifier, bitumen modifier, or a combination thereof) or by wet process (as polymer modifier or bitumen replacement), depending on the softening temperature of the recycled plastics.

Furthermore, given the relevance of this topic, several literature reviews have been conducted since 2019 [7], [8], [24]–[34], and extensive research is underway, particularly by FHWA ([35], through the end of 2023) and AUSTROADS ([6], [36], through the end of 2023) and BRISA (through the end of 2024), which provide a good starting point for researchers and stakeholders who want to investigate or use recycled plastics in road/highway pavements.

This study presents the main results obtained so far on the permanent deformation and water sensitivity properties of bituminous mixtures to which recycled plastics have been added via the dry process. The process method of adding the recycled plastics was chosen to ensure a simple and feasible technical procedure compatible with the existing technology of hot-mix plants in Portugal.

2. MATERIALS AND METHODS

2.1. Materials

The recycled plastics used in this study are commercial patented additives (referred to as P1, P2, P3, P4 and P5, due to confidentiality). The additives are mainly composed of polyethylene, PE (low density LDPE, high density HDPE and linear low density LLPE), and polypropylene (PP) in the case of additive P5. Different plastic forms were used (Figure 1), such as plastic chips (additives P1, P2) and pellets (additives P3, P4 and P5). Table 1 shows the properties of the recycled plastics according to the manufacturers.

Figure 1 – Recycled plastic additives used in the study

Table 1 – Properties of the recycled plastic additives

ID	Main plastics in the additive	Plastic form	Plastic source	Plastic content in the additive (%)	Specific mass (Mg/m^3)	Softening temperature (°C)	Particles dimension (mm)
P1	LDPE, HDPE	Plastic chips	Post-consumer	> 99	0.926	> 120	0.125-4
P2					1.380	> 100	0-4
P3	LDPE	Pellets			0.935	90-120	4-5
P4	LDPE, HDPE, LLDPE		Pre and Post-consumer	100	0.920	116	2-5
P5	PP				0.900	156	2-5

Abbreviations: LDPE: low density polyethylene; HDPE: high density polyethylene; LLDPE: linear low density polyethylene; PP: Polypropylene

Despite the manufacturer's data, according to Table 1, additive P1 has a similar specific mass to additive P3, so it is to be expected that P1 like additive P3 consists mainly of LDPE, but with an additional small content of HDPE. The opposite may be expected for P2, which should have a higher content of HDPE and possibly other plastics such as PET, whose specific mass is in the range of 1.380-1.455 Mg/m^3 [6], [8], which is more similar to the specific mass of additive P2.

Since surface layers are more susceptible to permanent deformation and direct exposure to water, two bituminous mixtures (AC 14 surf) commonly used as surface layers in the highway network of BRISA were used to evaluate the influence of recycled plastics on mechanical behaviour. The raw materials used to produce the bituminous mixtures consisted of common aggregates (granodiorite and granite, aggregates typically used in the south and north of Portugal, respectively), filler (commercial limestone), and polymer modified bitumen (PmB 45/80-65). Table 2 shows the bituminous mixtures used and their compositions.

Table 2 – Identification and compositions of AC 14 surf

ID	Aggregate nature	Filler nature	Bitumen type	Main plastics in the additive	Aggregates content (%)	Filler content (%)	Bitumen content (%)	Plastic content (%)	Total
M1	Granodiorites (Fractions 0/4, 4/10, and 10/14 mm)	Limestone	PmB 45/80-65	-	89.3	5.7	5.0	0	100
M1-P1				LDPE, HDPE	89.3	5.7	4.7	0.3	100
M1-P2									
M1-P3				LDPE					
M1-P4				LDPE, HDPE, LLDPE	89.3	5.7	5.0	0.1[a]	100.1
M1-P5				PP					
M2	Granites (Fractions 0/4, 4/10 and 8/14 mm)	Limestone	PmB 45/80-65	-	89.3	5.7	5.0	0	100
M2-P1				LDPE, HDPE	89.3	5.7	4.7	0.3	100
M2-P2									
M2-P3				LDPE					
M2-P4				LDPE, HDPE, LLDPE	89.3	5.7	5.0	0.1[a]	100.1
M2-P5				PP					

Abbreviations: LDPE: low density polyethylene; HDPE: high density polyethylene; LLDPE: linear low density polyethylene; PP: Polypropylene

[a]increment relative to the bitumen content

To assess the influence of the recycled plastics in the two bituminous mixtures, the aggregates and filler content were chosen to ensure similar gradation despite the different type of aggregates (coarse and fine aggregate fractions, see Table 3).

Table 3 – AC14 surf gradations

ID[a]	Sieve (mm) / Percentage passing by mass												
	20	14	12.5	10	8	6.3	4	2	1	0.500	0.250	0.125	0.063
M1	100	97	87	62	53	47	33	22	17	14	12	10	7.5
M2	100	99	91	72	57	44	29	23	20	16	13	11	7.7

[a]with and without recycled plastic additives

2.2. Mixing procedure

The recycled plastic additives selected for this study are from national and international manufacturers whose additives can be added via the dry process (regardless of the manufacturer’s industrial production process). The additives P4 and P5 are suitable for both processes (wet and dry), but in this study only the dry process was used.

During the production of the bituminous mixtures in the laboratory, the interaction with the recycled plastics was developed in two phases: the dry phase (1 minute interaction between the aggregates and the recycled plastic additive) and the wet phase (5 minutes interaction after the addition of the filler and the bitumen). Between the dry and wet phases, the recycled plastics rested in contact with the hot aggregates for 30 minutes to promote softening of the plastic, due to the lower mixing energy compared to mixing in the asphalt plant.

Additives P4 and P5 were added immediately after the addition of the bitumen (wet phase), as they are suitable for addition via the wet process (rapid softening in contact with the hot aggregates) and therefore possible absorption by the aggregates should be avoided.
Figure 2 shows the mixing equipment and the mixing procedure with the different time phases of interaction of recycled plastics with other raw materials. Regarding the mixing temperature: the reference bituminous mixtures (M1 and M2) were produced at a temperature of 165 °C, all other mixtures with recycled plastic additives at 170 °C.

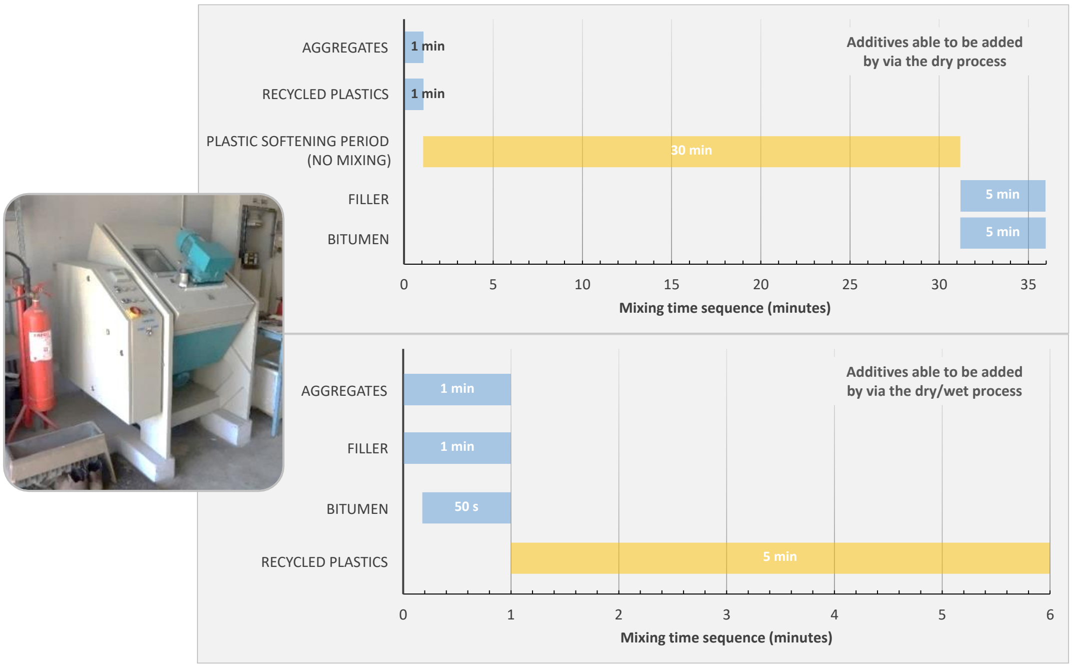

Figure 2 – Mixing equipment and procedure

2.3. Bituminous mix design

Bituminous mixtures were designed using the Marshall method according to the European standard EN 12697-34. The test specimens were prepared in the laboratory and compacted with 50 blows on each side according to EN 12697-30. The Marshall results for the optimum bitumen content are shown in Table 4.

Table 4 – Marshall results

ID	Main plastics in the additive	Specimen’s volumetric properties			Marshall properties		
		Vv (%)	VMA (%)	VFB (%)	Stability, S (kN)	Flow, f (mm)	Ratio Stability/Flow, Q (kN/mm)
M1	-	2.4	14.5	83.2	14.0	3.3	4.3
M1-P1	LDPE, HDPE	3.9	15.0	74.3	15.4	3.6	4.3
M1-P2		2.9	14.1	79.8	15.3	3.6	4.3
M1-P3	LDPE	3.8	14.9	74.7	15.8	4.1	3.9
M1-P4	LDPE, HDPE, LLDPE	3.5	15.7	77.3	13.9	3.2	4.4
M1-P5	PP	3.0	15.3	80.0	13.9	3.2	4.4
M2	-	2.2	14.0	84.2	15.5	3.6	4.3
M2-P1	LDPE, HDPE	4.6	15.4	70.4	16.5	3.6	4.6
M2-P2		2.9	13.9	79.0	14.0	4.0	3.5
M2-P3	LDPE	4.3	15.1	71.7	16.7	3.9	4.3
M2-P4	LDPE, HDPE, LLDPE	2.5	14.4	83.2	16.0	4.0	4.0
M2-P5	PP	2.7	14.6	81.9	16.9	3.2	5.3

Abbreviations: Vv: porosity of a compacted AC 14; VMA: air voids in the aggregate structure; VFB: air voids filled with bitumen; LDPE: low density polyethylene; HDPE: high density polyethylene; LLDPE: linear low density polyethylene; PP: Polypropylene

Table 4 shows that regardless of the type and form of recycled plastics used, the porosity and Marshall stability of the compacted specimens tend to increase. Similar results were also reported by [37], [38]. The additives causing the highest increase are P1 and P3 (mainly LDPE) for both type of aggregates (granodiorites and granites). The trade-off between stability and workability is due to the fact that the bituminous mixtures harden with the use of recycled plastics, despite the higher production temperatures, which favours the reduction of bitumen penetration and the increase of ring and ball temperature, as observed in the first phase of this experimental programme developed at BRISA, with the materials used in this study. In addition, despite the higher stability, the Marshall flow also tends to increase (with the exception of additive P5, which contains PP), which can be taken as an indication that the flexibility of the mixtures may not have been conditioned with recycled plastics.

2.4. Performance testing programme

Laboratory tests for water sensitivity and resistance to permanent deformation were developed to evaluate the effects of recycled plastic additives on the mechanical performance of bituminous mixtures.

The water sensitivity evaluation was developed in accordance with EN 12697-12 (Method A) and EN 12697-23, using the indirect tensile strength for dry and wet specimens (ITS_{DRY} and ITS_{WET}, respectively) and the indirect tensile strength ratio (ITSR) as performance indicators. The bituminous mixture specimens used for water sensitivity evaluation were prepared and compacted (50 blows on each side) in the laboratory according to EN 12697-30. The specimens were divided into two groups, one of which was conditioned in air (20 °C) for 72 hours and the other under vacuum and water (40 °C). The tests were performed at a constant temperature of 15 °C.

Resistance to permanent deformation of prismatic specimens of compacted bituminous mixture conditioned in air was performed for 10 000 cycles of a loaded wheel at a constant temperature of 60 °C according to EN 12697-22 (Method B). Maximum rut depth (RD_{AIR}), maximum wheel tracking slope (WTS_{AIR}), and maximum proportional rut depth (PRD_{AIR}) were used as performance indicators.

In addition, the performance indicators were used to evaluate the potential of the newly proposed property (ratio between the binder film thickness and the porosity, BFT/Vv) to contribute to the development of improved bituminous mixtures with recycled plastics.

This property was developed in [39] and statistically studied in [40]. It relates the BFT to the Vv of a compacted SMA and showed a statistically significant strong correlation with the resistance to permanent deformation (performance indicators), explaining up to 88 % of its variation.

According to [40], it is theoretically expected that for each SMA a certain ratio between binder film thickness and porosity should be used to optimise the resistance to permanent deformation (represented by the red dot in Figure 3). In this study, we intend to validate this property for other types of bituminous mixture (AC 14 surf) and for water sensitivity.

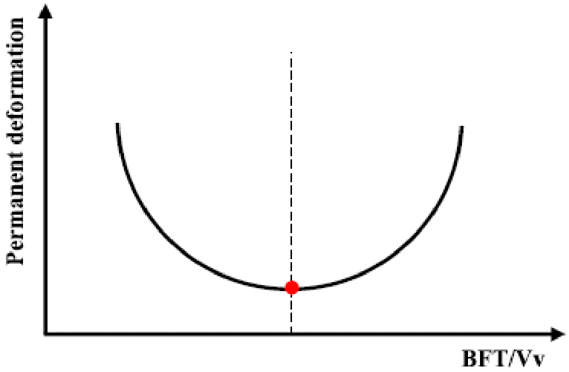

Figure 3 – Proposed optimisation of resistance to permanent deformation as a function of BFT/Vv [40]

Since in [40] the ratio between Marshall stability and the flow showed a statistically significant strong correlation with resistance to permanent deformation (performance indicators), it was also considered in this study. Table 5 shows all the properties used in the statistical analysis.

Table 5 – Properties used in the statistical analysis

Property		Property ID
Volumetric	Coarse aggregate content	CA
	Fine aggregate content	FA
	Filler content	F
	Ratio between binder film thickness and porosity	BFT/Vv
Marshall	Stability	S
	Flow	f
	Ratio between stability and flow	Q
Performance	Indirect tensile strength dry specimens	ITS_{DRY}
	Indirect tensile strength wet specimens	ITS_{WET}
	Indirect tensile strength ratio	ITSR
	Maximum rut depth, in air	RD_{AIR}
	Maximum wheel tracking slope, in air	WTS_{AIR}
	Maximum proportional rut depth, in air	PRD_{AIR}

3. INFLUENCE OF RECYCLED PLASTICS ON THE MECHANICAL BEHAVIOUR

This section presents the results and discussion of the current performance testing programme for the AC14 surf with different recycled plastics (P1 to P5). In addition, a statistical analysis was developed to evaluate the relationship between the performance indicators used in this study and the properties previously presented in Table 5 for a different type of bituminous mixture (AC 14 surf) than that used in [40] (SMA).

3.1. Influence on water sensitivity, results, and discussion

Table 6 and Figure 4 show the volumetric properties of the AC 14 surf specimens and the water sensitivity results.

Table 6 – Water sensitivity (volumetric properties and performance indicators)

ID	Main plastics in the additive	Specimen's volumetric properties							Water sensitivity (15 ºC)		
		Vv (%)	VMA (%)	VFB (%)	CA content (%)	FA content (%)	Filler content (%)	BFT/Vv	ITS$_{DRY}$ (kPa)	ITS$_{WET}$ (kPa)	ITSR (%)
M1	-	2.5	14.6	82.5	67.0[a]	25.5[b]	7.5[c]	2.1	2473	2233	90
M1-P1	LDPE, HDPE	3.8	14.9	74.8				1.4	2389	2138	89
M1-P2		2.9	14.2	79.2				1.9	2420	2112	87
M1-P3	LDPE	3.8	14.9	74.7				1.6	2194	2002	91
M1-P4	LDPE, HDPE, LLDPE	2.9	15.1	80.9				2.7	2400	2171	90
M1-P5	PP	3.2	15.4	79.3				1.5	2145	2044	95
M2	-	2.7	14.4	81.5	71.0[a]	21.3[b]	7.7[c]	2.2	2327	2065	89
M2-P1	LDPE, HDPE	4.9	15.7	68.9				1.6	2204	1870	85
M2-P2		1.8	12.9	86.1				1.9	2462	2273	92
M2-P3	LDPE	4.0	14.9	72.9				1.4	2176	2046	94
M2-P4	LDPE, HDPE, LLDPE	2.5	14.4	83.2				2.3	2474	2227	90
M2-P5	PP	2.9	14.9	80.0				2.3	2329	2091	90

Abbreviations: CA: coarse aggregate; FA: fine aggregate; BFT/Vv: ratio between binder film thickness and porosity; ITS$_{DRY}$: indirect tensile strength of dry specimen's; ITS$_{WET}$: indirect tensile strength of wet specimen's; ITSR: indirect tensile strength ratio; LDPE: low density polyethylene; HDPE: high density polyethylene; LLDPE: linear low density polyethylene; PP: Polypropylene

[a] particles with dimension equal to or higher than sieve 4 mm

[b] particles with dimension between sieve 4 mm and sieve 0.063 mm

[c] particles with dimension bellow sieve 0.063 mm

Although the recycled plastics resulted in higher Marshall stability (especially additive P1 and P3), this did not result in an overall increase in ITS (dry and wet) compared to the reference mixtures (M1 and M2). Figure 4 shows that ITS is similar to or higher for additives P2 and P4 (mainly composition of LDPE, HDPE and LLDPE for P4) and lower for all other mixtures with recycled plastics, regardless of the type of aggregates used. However, it can be seen from Table 6 that the differences in the results of ITS are mainly due to the differences in porosity of the specimens with recycled plastics compared to M1 and M2.

Regardless of the recycled plastic additives and the type of aggregate used, the indirect tensile strength ratio (ITSR) tends to be similar to or lower than the reference mixtures, as shown in Figure 4 and Table 6 (except for additives P3 with LDPE and P5 with PP, regardless of the higher porosity of the specimens).

In addition, all evaluated bituminous mixtures with recycled plastics showed good water sensitivity with an ITSR value higher than 85 %, which is usually recommended in the technical specifications of BRISA for surface layers.

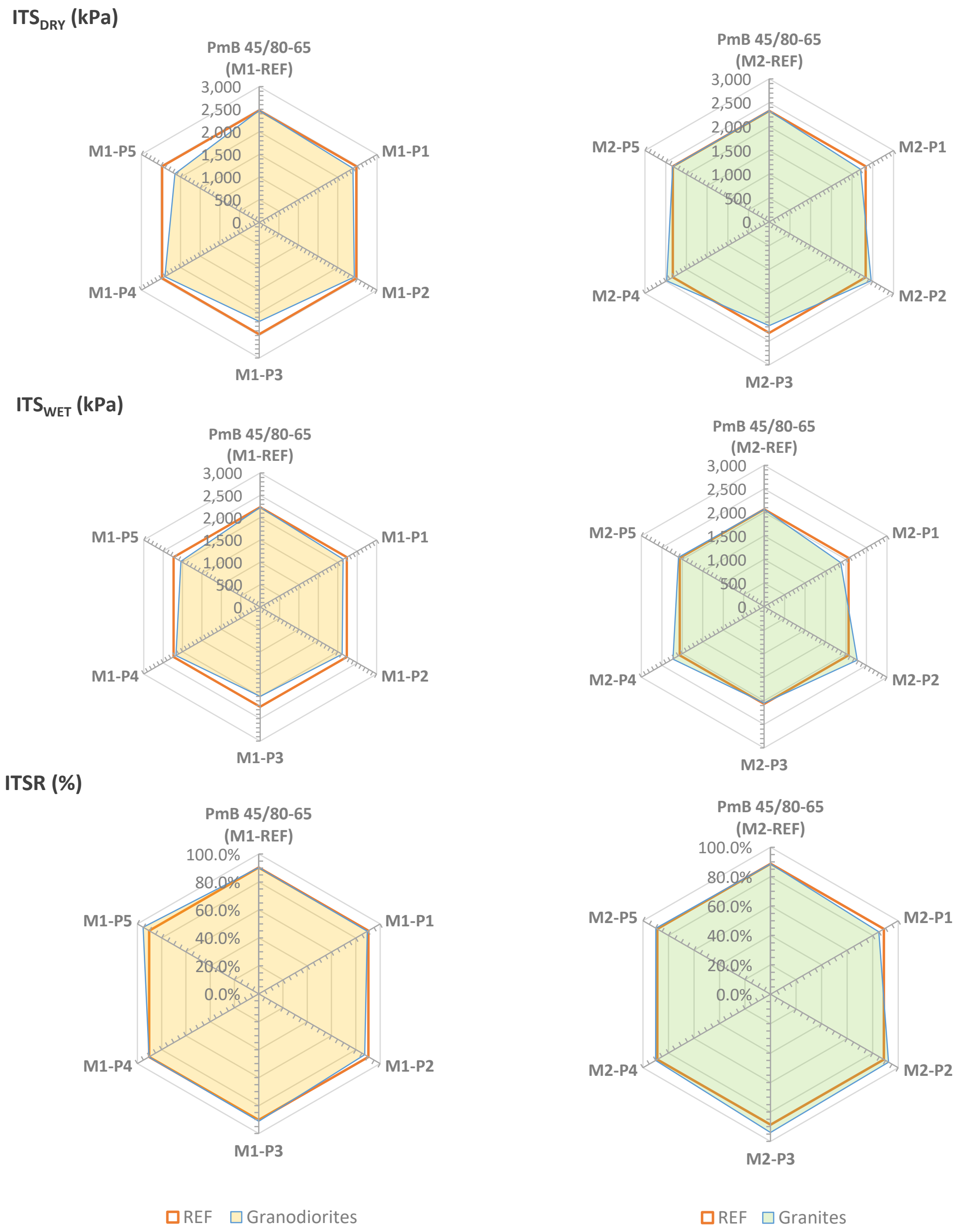

Figure 4 – Water sensitivity results

3.2. Influence on the resistance to permanent deformation, results, and discussion

Table 7, Figure 6, and Figure 7 show the volumetric properties of the AC 14 surf specimens and the results of resistance to permanent deformation. Figure 5 shows the wheel-tracking equipment used.

Figure 5 – Wheel-tracking equipment used

Table 7 – Permanent deformation (volumetric properties and performance indicators)

ID	Main plastics in the additive	Specimen's volumetric properties							Permanent deformation properties (60ºC)		
		Vv (%)	VMA (%)	VFB (%)	CA content (%)	FA content (%)	Filler content (%)	BFT/Vv	RD_{AIR} (mm)	WTS_{AIR} (mm/10^3 cycles)	PRD_{AIR} (%)
M1	-	4.4	16.2	72.9	67.0	25.5	7.5	2.1	1.9	0.04	3.5
M1-P1	LDPE, HDPE	5.9	16.8	64.9				1.4	1.2	0.03	2.1
M1-P2		4.5	15.6	70.9				1.9	1.6	0.04	3.0
M1-P3	LDPE	5.3	16.3	67.1				1.6	1.1	0.02	2.2
M1-P4	LDPE, HDPE, LLDPE	3.4	15.6	77.9				2.7	1.5	0.03	2.8
M1-P5	PP	6.1	17.9	66.2				1.5	1.9	0.05	3.5
M2	-	3.9	15.5	74.8	71.0	21.3	7.7	2.2	1.4	0.02	2.5
M2-P1	LDPE, HDPE	5.3	16.0	67.1				1.6	0.9	0.02	1.7
M2-P2		4.7	15.5	69.7				1.9	1.7	0.04	3.3
M2-P3	LDPE	6.1	16.8	63.2				1.4	1.0	0.02	2.0
M2-P4	LDPE, HDPE, LLDPE	3.8	15.6	75.8				2.3	1.5	0.03	2.8
M2-P5	PP	3.9	15.7	75.3				2.3	1.8	0.03	3.3

Abbreviations: RD_{AIR}: maximum rut depth, in air; WTS_{AIR}: maximum wheel tracking slope, in air; PRD_{AIR}: maximum proportional rut depth, in air; LDPE: low density polyethylene; HDPE: high density polyethylene; LLDPE: linear low density polyethylene; PP: Polypropylene

The addition of recycled plastics to bituminous mixtures did not always improve resistance to permanent deformation, especially for mixtures with granite aggregates, comparative to the reference bituminous mixtures (M1 and M2). Figure 6 and Figure 7 show similar or lower RD_{AIR} and WTS_{AIR} values for additives P1 and P3 (mainly LDPE), regardless of the nature of the type of aggregate used. All other additives show similar or lower resistance to permanent deformation, mainly due to the excellent behaviour and lower porosity of the reference mixtures.

Despite the higher porosity, all bituminous mixtures with recycled plastics show excellent behaviour to permanent deformation, with a WTS_{AIR} value well below 0.1 mm/10^3 cycles, which is usually recommended in the technical specifications of BRISA for surface layers. Similar results were also reported, namely, by [37].

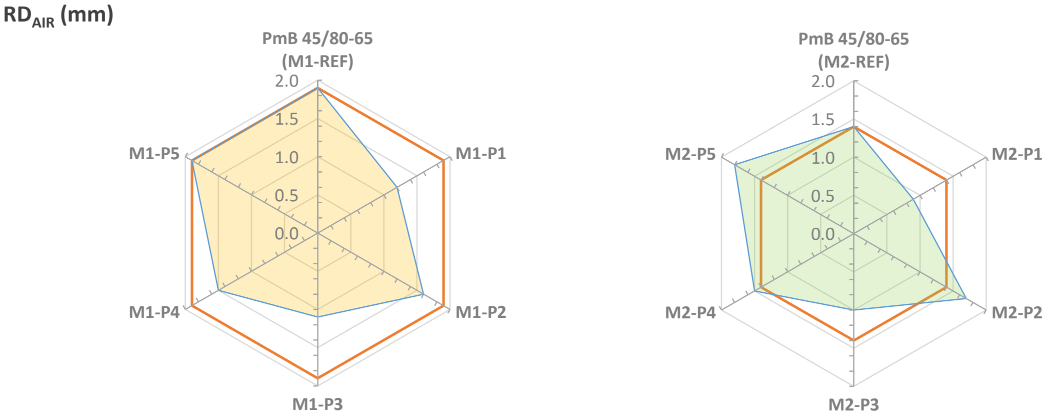

Figure 6 – Results of resistance to permanent deformation (RD_{AIR})

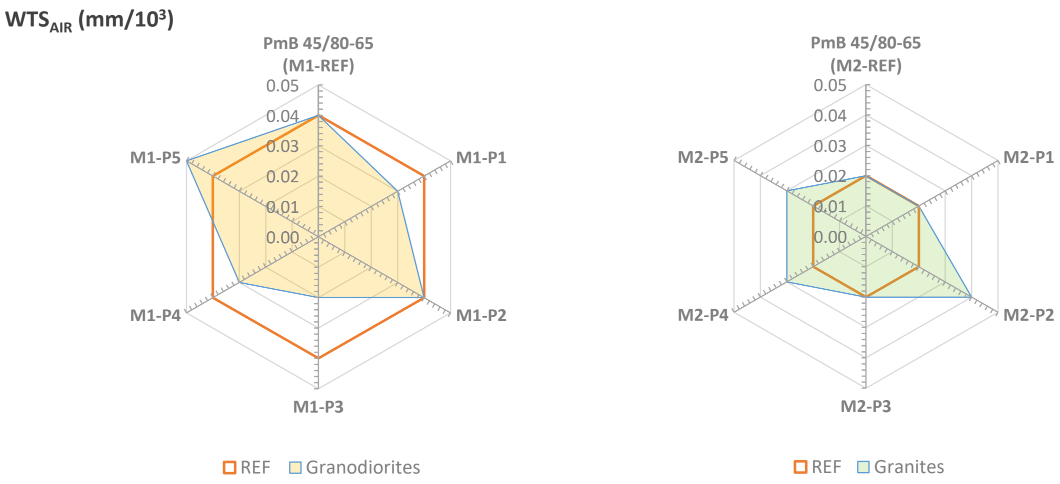

Figure 7 – Results of resistance to permanent deformation (WTS_{AIR})

The results show that, despite the higher porosity of the laboratory specimens, the additive P3 composed exclusively of LDPE (pellets), has better behaviour than the reference mixtures (M1 and M2), which is also confirmed by the results of water sensitivity. Therefore, it can be considered for further studies to develop more open-graded mixtures with better surface properties (i.e., higher noise absorption capacity), which are crucial for highway pavements. However, this conclusion must first be supported by the evaluation of fatigue and ageing resistance, as porosity is a key factor for both of these properties.

3.3. Statistical relationships with performance indicators

The preliminary analysis assessed the normality and outliers of the data used, as shown in Table 8.

Table 8 – Results of the Shapiro-Wilk and Kolmogorov-Smirnov tests

Property		Property ID	Shapiro-Wilk, p-value	Kolmogorov-Smirnov p-value	Outliers count
Volumetric	Coarse aggregate content	CA	0.003	0.125	1
	Fine aggregate content	FA	0.024	0.284	0
	Filler content	F	0.077	0.251	2
	Ratio between binder film thickness and porosity	BFT/Vv	0.002	0.560	1
Marshall	Stability	S	0.030	0.272	0
	Flow	f	0.013	0.251	3
	Ratio between stability and flow	Q	0.275	0.365	0
Performance	Indirect tensile strength dry specimens	ITS_{DRY}	0.011	0.295	0
	Indirect tensile strength wet specimens	ITS_{WET}	0.046	0.267	0
	Indirect tensile strength ratio	ITSR	0.054	0.543	4
	Maximum rut depth, in air	RD_{AIR}	0.001	0.582	1
	Maximum wheel tracking slope, in air	WTS_{AIR}	<0.001	0.305	1
	Maximum proportional rut depth, in air	PRD_{AIR}	0.001	0.359	1

The results presented in Table 8 show significant deviation from normality assessed by the Shapiro-Wilk test ($p \leq 0.05$) and conversely by the Kolmogorov-Smirnov test for normality. In Table 8, the outliers were evaluated based on the deviation from normality according to Tukey's fences. However, despite the presence of outliers, they were not identified as invalid observations and were therefore used in further statistical analysis.

Due to the significant deviation from normality (Shapiro-Wilk test), the Spearman correlation coefficient (r_S) was used for the statistical analysis in addition to the Pearson correlation coefficient (r). Table 9 shows the results of the correlation coefficients considering a sample size of 21, obtained from the results of the present study combined with the results of the study developed in [39].

Under the theory developed in [39] and statistically studied in [40] to optimise the resistance to permanent deformation (Figure 3), the polynomial regressions are shown in Figure 8 in comparison with the linear regressions between BFT/Vv and RD_{AIR}, WTS_{AIR} and PRD_{AIR}.

Table 9 – Correlation coefficients according to Pearson and Spearman

Property ID	Water sensitivity			Permanent deformation		
	ITS_{DRY}	ITS_{WET}	ITSR	RD_{AIR}	WTS_{AIR}	PRD_{AIR}
	r_s / r	r_s / r	r_s / r	r_s / r	r_s / r	r_s / r
CA	-0.31 / -0.14	-0.36 / -0.18	-0.13 / -0.15	0.34 / 0.10	0.38 / 0.18	0.34 / 0.10
FA	0.60^{b} / **0.69**^{b}	0.57^{b} / **0.68**^{b}	-0.13 / 0.03	-0.62^{b} / -0.54^{c}	-0.62^{b} / -0.60^{b}	-0.62^{b} / -0.55^{c}
F	-0.31 / -0.19	-0.18 / -0.12	0.18 / 0.17	0.31 / 0.31	0.28 / 0.33	0.31 / 0.32
BFT/Vv	0.26 / -0.09	0.35 / 0.01	0.24 / 0.32	0.87^{a} / **0.94**^{b}	0.79^{b} / **0.90**^{b}	0.87^{a} / **0.94**^{b}
S	0.48^{c} / **0.66**^{b}	0.41 / **0.62**^{b}	-0.19 / -0.03	-0.76^{b} / -0.71^{b}	-0.84^{a} / -0.78^{b}	-0.77^{b} / -0.72^{b}
f	-0.33 / 0.46^{c}	-0.30 / -0.30	0.36 / **0.54**^{c}	0.19 / 0.66^{b}	0.15 / 0.58^{c}	0.21 / 0.66^{b}
Q	0.66^{b} / **0.77**^{b}	0.63^{b} / **0.67**^{b}	-0.23 / -0.27	-0.79^{b} / **0.86**^{b}	-0.79^{b} / **-0.87**^{b}	-0.81^{b} / **-0.88**^{b}

[a] statistically significant at $p = 0$
[b] statistically significant at $p < 0.005$ level
[c] statistically significant at $p < 0.05$ level

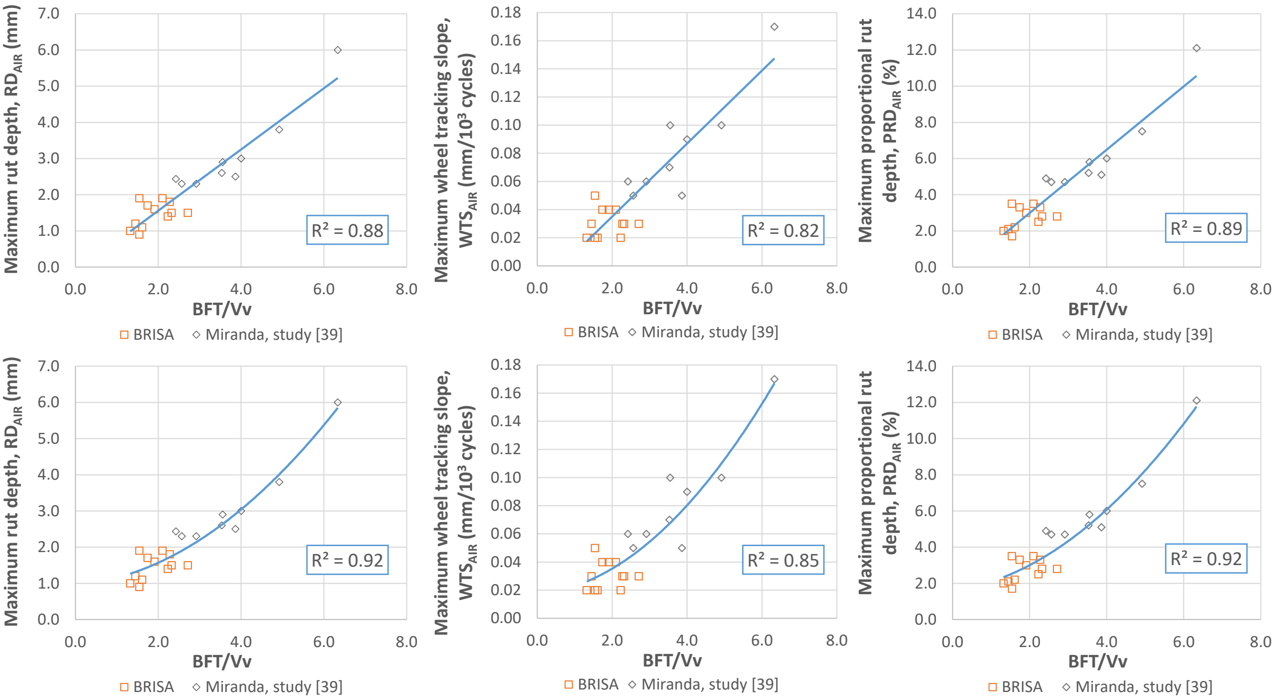

Figure 8 – Linear and polynomial regression between BFT/Vv and RD_{AIR}, WTS_{AIR}, PRD_{AIR}

Regarding water sensitivity in Table 9, none of the evaluated properties shows a statistically significant correlation with ITSR (f explains only 29 % of the variation). For the ITS_{DRY} and ITS_{WET} performance indicators, FA, S, and Q showed a statistically significant medium correlation, but it only explained between 38 % and 59 % of the variation in the indicators. Nevertheless, the use of a higher content of fine aggregate in a well-designed mix may statistically contribute to an increase in indirect strength resistance (dry and wet), likely due to a higher interlocking of the bituminous mixture aggregate skeleton.

In agreement with the results in [40], the coarse aggregate content did not show a statistically significant correlation with the performance indicators of resistance to permanent deformation (RD_{AIR}, WTS_{AIR}, PRD_{AIR}). Thus, statistically, the use of a higher coarse aggregate content does not necessarily result in a bituminous mixture with a higher resistance to permanent deformation.

Among all the properties analysed in Table 9 and presented in Figure 8 for the performance indicators of resistance to permanent deformation, the new property (BFT/Vv) proposed in [39] and statistically studied in [40] stands out from all the others with statistically significant strong correlations. BFT/Vv explained 88%, 82%, and 89% of the variations in RD_{AIR}, WTS_{AIR}, and PRD_{AIR}, respectively. Figure 8 also shows that polynomial regression is possible under the theory developed in [39], which further improves the explanation of the variations (to 92%). This means that BFT/Vv can be used for a preliminary verification of the performance of a bituminous mixture (SMA or AC) in terms of permanent deformation.

In addition, the property Q pointed in [40] also showed a strong correlation with the performance indicators and explained 74%, 76% and 77% of the variations of RD_{AIR}, WTS_{AIR}, and PRD_{AIR}, respectively. Other properties worth mentioning are FA, S, and f, which showed statistically significant medium correlations.

These results confirm those previously obtained in [40], despite the use of recycled plastics in the bituminous mixtures.

4. CONCLUSIONS

In the present work, the influence of patented recycled plastics mainly composed of PE (low density LDPE, high density HDPE, and linear low density LLDPE) and PP on the following aspects was investigated: (i) the mechanical behaviour of bituminous mixtures (AC 14 surf) for highway surface layers; (ii) the statistical relationship between the volumetric and Marshall properties of a bituminous mixture and the performance indicators (water sensitivity and resistance to permanent deformation).

From the results of the experimental programme, the following main conclusions can be drawn:

- The addition of recycled plastics via the dry process proved to be a simple and feasible technical procedure, regardless of the process recommended for each recycled plastic additive (dry or wet process), when the mixing procedure presented in this study is used.

- The form and source of the recycled plastics did not significantly affect the Marshall properties and mechanical behaviour of the bituminous mixtures (water sensitivity and resistance to permanent deformation).

- The bituminous mixtures with recycled plastics showed similar behaviour between both types of aggregates commonly used in Portugal.

- In general, the use of recycled plastics increased the porosity of the bituminous mixtures, the Marshall stability and flow properties, especially for additives composed mainly of LDPE (P1 and P3).

- Although additives containing LDPE, HDPE, and LLDPE exhibited higher indirect tensile strength values, additives consisting only of LDPE (P1) or PP (P5) showed higher ITSR values.

- Resistance to permanent deformation can be improved, especially when using additives composed mainly of LDPE (P1 and P3).

- Overall, the additive composed only of LDPE (P1) showed a systematic improvement in Marshall properties and mechanical behaviour compared to the reference bituminous mixtures, despite the higher porosity or type of aggregates used.

- All the recycled plastics used were found to be suitable for use in bituminous mixtures for the surface layer or others of highway pavements, considering the performance indicators related to water sensitivity and resistance to permanent deformation. Further studies are needed to evaluate the behaviour of the bituminous mixtures to fatigue and ageing, as well as possible pollutants.

As for the statistical analysis, the results allow the following main conclusions, regardless of the use of recycled plastics:

- The properties evaluated (including BFT/Vv) show no to medium statistically significant correlation with the water sensitivity performance indicators. Other properties should be considered in further studies.

- The use of a higher content of fine aggregates in a well-designed mix may contribute statistically (medium significant correlation) to an increase in indirect strength resistance to water sensitivity.

- The use of a higher coarse aggregate content did not show a statistically significant correlation with resistance to permanent deformation.

- The ratio between binder film thickness and porosity (BFT/Vv), proposed elsewhere, showed a statistically significant strong correlation with the performance indicators for resistance to permanent deformation of bituminous mixtures (SMA, AC).

The main results of this study reinforce the assumption that the use of recycled plastic additives via the dry process is possible, especially for the production of bituminous mixtures for the construction or rehabilitation of surface layers and others, with improved resistance to permanent deformation.

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REFERENCES

1. European Union Road Federation (2022). “Road Network 2022 – ERF,” 2019. https://erf.be/statistics/road-network-2022/ (accessed Jan. 24, 2023).
2. European Union Road Federation (2022). “Road Network 2022 – ERF,” 2019. https://erf.be/statistics/road-maintenance-and-investment-2022/ (accessed Jan. 24, 2023).
3. Woldemar D’ambrières (2019). “Plastics recycling worldwide: current overview and desirable changes,” The journal of field actions, no. 19, pp. 1–11.
4. R. Geyer, J. R. Jambeck, and K. L. Law (2017). “Production, use, and fate of all plastics ever made,” Sci Adv, vol. 3, no. 7, doi: 10.1126/SCIADV.1700782.
5. Plastics Europe - Association of plastics manufacturers (2000). “Plastics - The Facts 2020 An analysis of European plastics production, demand and waste data,” Brussels.
6. F. Giustozzi and Y. J. Boom (2021). “Use of road-grade recycled plastics for sustainable asphalt pavements. Overview of the recycled plastic industry and recycled plastic types,” Sydney.
7. Y. Ma et al. (2021). “The utilization of waste plastics in asphalt pavements: A review,” Cleaner Materials, vol. 2, p. 100031, doi: 10.1016/J.CLEMA.2021.100031.
8. R. Willis, F. Yin, and R. Moraes (2020). “Recycled plastics in asphalt part A: State of the knowledge,” Greenbelt.
9. N. Mashaan, A. Chegenizadeh, and H. Nikraz (2021). “Laboratory properties of waste PET plastic-modified asphalt mixes,” Recycling, vol. 6, no. 3, doi: 10.3390/RECYCLING6030049.
10. S. Hinislioglu and E. Agar (2004). “Use of waste high density polyethylene as bitumen modifier in asphalt concrete mix,” Mater Lett, vol. 58, no. 3–4, pp. 267–271, doi: 10.1016/S0167-577X(03)00458-0.
11. M. Vila-Cortavitarte, P. Lastra-González, M. Á. Calzada-Pérez, and I. Indacoechea-Vega (2018). “Analysis of the influence of using recycled polystyrene as a substitute for bitumen in the behaviour of asphalt concrete mixtures.,” J Clean Prod, vol. 170, pp. 1279–1287, doi: 10.1016/J.JCLEPRO.2017.09.232.
12. H. A. Shahane and S. S. Bhosale (2021). “E-Waste plastic powder modified bitumen: rheological properties and performance study of bituminous concrete,” Road Materials and Pavement Design, vol. 22, no. 3, pp. 682–702, doi: 10.1080/14680629.2019.1642944.
13. H. I. Al-Abdul Wahhab, M. A. Dalhat, and M. A. Habib (2017). “Storage stability and high-temperature performance of asphalt binder modified with recycled plastic,” Road Materials and Pavement Design, vol. 18, no. 5, pp. 1117–1134, doi: 10.1080/14680629.2016.1207554.
14. A. Modarres and H. Hamedi (2014) “Effect of waste plastic bottles on the stiffness and fatigue properties of modified asphalt mixes,” Mater Des, vol. 61, pp. 8–15, doi: 10.1016/J.MATDES.2014.04.046.
15. D. Movilla-Quesada, A. C. Raposeiras, L. T. Silva-Klein, P. Lastra-González, and D. Castro-Fresno (2019). “Use of plastic scrap in asphalt mixtures added by dry method as a partial substitute for bitumen,” Waste Management, vol. 87, pp. 751–760, doi: 10.1016/J.WASMAN.2019.03.018.
16. M. Ranieri, L. Costa, J. R. M. Oliveira, H. M. R. D. Silva, and C. Celauro (2017). “Asphalt Surface Mixtures with Improved Performance Using Waste Polymers via Dry and Wet Processes,” Journal of Materials in Civil Engineering, vol. 29, no. 10, doi: 10.1061/(ASCE)MT.1943-5533.0002022.
17. C. Fang et al. (2014). “Pavement properties of asphalt modified with packaging-waste polyethylene,” Journal of Vinyl and Additive Technology, vol. 20, no. 1, pp. 31–35, doi: 10.1002/VNL.21328.
18. M. A. Dalhat, H. I. Al-Abdul Wahhab, and K. Al-Adham (2019). “Recycled Plastic Waste Asphalt Concrete via Mineral Aggregate Substitution and Binder Modification,” Journal of Materials in Civil Engineering, vol. 31, no. 8, doi: 10.1061/(ASCE)MT.1943-5533.0002744.
19. H. Ziari, E. Nasiri, A. Amini, and O. Ferdosian (2019). “The effect of EAF dust and waste PVC on moisture sensitivity, rutting resistance, and fatigue performance of asphalt binders and mixtures,” Constr Build Mater, vol. 203, pp. 188–200, doi: 10.1016/J.CONBUILDMAT.2019.01.101.
20. M. Á. Salas, H. Pérez-Acebo, V. Calderón, and H. Gonzalo-Orden (2018). “Bitumen modified with recycled polyurethane foam for employment in hot mix asphalt,” Ingenieria e Investigacion, vol. 38, no. 1, pp. 60–66, doi: 10.15446/ING.INVESTIG.V38N1.65631.
21. C. Hu, W. Lin, M. Partl, D. Wang, H. Yu, and Z. Zhang (2018). “Waste packaging tape as a novel bitumen modifier for hot-mix asphalt,” Constr Build Mater, vol. 193, pp. 23–31, doi: 10.1016/J.CONBUILDMAT.2018.10.170.
22. R. K. Padhan, A. Sreeram, and A. Gupta (2020). “Evaluation of trans-polyoctenamer and cross-linking agents on the performance of waste polystyrene modified asphalt,” Road Materials and Pavement Design, vol. 21, no. 4, pp. 1170–1182, doi: 10.1080/14680629.2018.1533490.
23. A. Behl, G. Sharma, and G. Kumar (2014). “A sustainable approach: Utilization of waste PVC in asphalting of roads,” Constr Build Mater, vol. 54, pp. 113–117, doi: 10.1016/J.CONBUILDMAT.2013.12.050.
24. L. You et al. (2022). “Review of recycling waste plastics in asphalt paving materials,” Journal of Traffic and Transportation Engineering (English Edition), doi: 10.1016/J.JTTE.2022.07.002.
25. F. Yin, R. Moraes, and A. Anand (2020). “Recycled plastics in asphalt Part B: Literature review ,” Greenbelt.

26. B. P. Grady (2021). “Waste plastics in asphalt concrete: A review,” SPE Polymers, vol. 2, no. 1, pp. 4–18, doi: 10.1002/PLS2.10034.
27. L. Brasileiro, F. Moreno-Navarro, R. Tauste-Martínez, J. Matos, and M. del C. Rubio-Gámez (2019). “Reclaimed polymers as asphalt binder modifiers for more sustainable roads: A review,” Sustainability (Switzerland), vol. 11, no. 3, doi: 10.3390/SU11030646.
28. F. Canestrari, K. Formela, S. Hesp, F. Xu, Y. Zhao, and K. Li (2021). “Using Waste Plastics as Asphalt Modifier: A Review,” Materials 2022, Vol. 15, Page 110, vol. 15, no. 1, p. 110, doi: 10.3390/MA15010110.
29. M. Okan, H. M. Aydin, and M. Barsbay (2019). “Current approaches to waste polymer utilization and minimization: a review,” Journal of Chemical Technology and Biotechnology, vol. 94, no. 1, pp. 8–21, doi: 10.1002/JCTB.5778.
30. Z. N. Kalantar, M. R. Karim, and A. Mahrez (2012). “A review of using waste and virgin polymer in pavement,” Constr Build Mater, vol. 33, pp. 55–62, doi: 10.1016/J.CONBUILDMAT.2012.01.009.
31. S. Wu and L. Montalvo (2021). “Repurposing waste plastics into cleaner asphalt pavement materials: A critical literature review,” J Clean Prod, vol. 280, doi: 10.1016/J.JCLEPRO.2020.124355.
32. L. Cong, F. Yang, G. Guo, M. Ren, J. Shi, and L. Tan (2019). “The use of polyurethane for asphalt pavement engineering applications: A state-of-the-art review,” Constr Build Mater, vol. 225, pp. 1012–1025, doi: 10.1016/J.CONBUILDMAT.2019.07.213.
33. C. Vargas and A. el Hanandeh (2021). “Systematic literature review, meta-analysis and artificial neural network modelling of plastic waste addition to bitumen,” J Clean Prod, vol. 280, doi: 10.1016/J.JCLEPRO.2020.124369.
34. F. Canestrari, K. Formela, S. Hesp, F. Xu, Y. Zhao, and K. Li (2021). “Using Waste Plastics as Asphalt Modifier: A Review,” Materials 2022, Vol. 15, Page 110, vol. 15, no. 1, p. 110, doi: 10.3390/MA15010110.
35. R. West (2021). “NCHRP Project 9-66 Interim Report Performance Properties of Laboratory Produced Recycled Plastic Modified (RPM) Asphalt Binders and Mixtures,” Auburn.
36. F. Giustozzi, D. L. Xuan, M. Enfrin, H. Masood, R. Audy, and Y. J. Boom (2021). “Use of road-grade recycled plastics for sustainable asphalt pavements, Towards the selection of road-grade plastics - An evaluation framework and preliminary experimental results,” Sydney.
37. R. Vasudevan, A. Ramalinga Chandra Sekar, B. Sundarakannan, and R. Velkennedy (2012). “A technique to dispose waste plastics in an ecofriendly way – Application in construction of flexible pavements,” Constr Build Mater, vol. 28, no. 1, pp. 311–320, doi: 10.1016/J.CONBUILDMAT.2011.08.031.
38. M. T. Awwad and L. Shbeeb (2007). “The Use of Polyethylene in Hot Asphalt Mixtures,” Am J Appl Sci, vol. 4, no. 6, pp. 390–396, doi: 10.3844/AJASSP.2007.390.396.
39. H. M. B. Miranda (2016). “Stone Mastic Asphalt - Mix design, production, application and performance,” University of Lisbon, Lisbon.
40. H. M. B. Miranda, F. A. Batista, J. Neves, and M. de Lurdes Antunes (2020). “Influence of the aggregate skeleton matrix and volumetric composition on the resistance of Stone Mastic Asphalt to permanent deformation,” https://doi.org/10.1080/14680629.2020.1773303, vol. 22, no. 11, pp. 2538–2551, doi: 10.1080/14680629.2020.1773303.