



## Use of plastic scrap in asphalt mixtures added by dry method as a partial substitute for bitumen



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### ABSTRACT

In recent decades, the generation of plastic waste has increased substantially worldwide, with the result that more of such waste is introduced into the environment. Currently, most polymers (polyethylene terephthalate, polyethylene, polyvinyl chloride, and others) are recycled. However, some are rejected for recycling in the primary separation processes due to their physical condition, contamination, or size. These materials are called plastic scrap.

In this research, the use of plastic scrap added by dry method was evaluated as a replacement for bitumen in asphalt mixtures. Two sizes of plastic scrap, coarse and fine, were considered. An AC16S semi-dense mixture was designed for this purpose, with a 10% reduction in binder, and 10% and 20% of plastic scrap binder was added in coarse and fine sizes.

The results obtained in the Marshall stability and flow test showed reduced moisture damage, greater indirect tensile strength, higher air void content, and a 2% decrease in the conserved tensile strength ratio while the same usage field as the conventional mixture was maintained. Meanwhile, significant decreases in plastic deformations, as compared to traditional values, were obtained from resilient modulus and rutting tests.

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## 1. Introduction

### 1.1. Plastic waste generation and management

The use of polymers and their production has increased drastically in recent years, generating severe health, environmental, and territorial problems. Polymers are used in a multitude of day-to-day products, resulting in an increase in the quantity of accumulated urban solid waste. Plastic recycling plants process approximately 30% of the total received material, while the remaining 70% is disposed of in landfills (Dahlbo et al., 2018; General Directorate of Roads, 2002; Melotti et al., 2013; Ragaert et al., 2017). The refused material includes a mixture of different types of polymers that is difficult to use, which is called plastic scrap (Chen et al., 2018). The reuse of this material has become more relevant over time, with the appearance of new alternatives associated with its incorporation in the recycling process. These alternatives mainly involve re-extrusion and mechanical treatments (Al-Salem, 2009). These alternatives allow the reuse of this material, but at the same time there are certain drawbacks because the resulting polymers are of lower quality than the original

polymeric material. It is also necessary to carry out a preliminary treatment of decontamination, crushing, and classification in order for the material to be recycled.

An alternative use of this plastic scrap is its incorporation in asphalt mixtures as a durability improver. Asphalt mixtures are composed of aggregates and asphalt binder, which is a derivative of petroleum, as well as additives (Lesueur, 2009). Asphalt mixture behaviour varies according to two major parameters—climatic conditions and the speed and type of vehicular traffic—such that at high temperatures and low traffic speeds, the binder behaves like a viscous material, causing a higher possibility of rutting when the vehicle's weight is high. On the other hand, given temperatures lower than 0 °C, along with repetitive vehicular traffic loads and high traffic speeds, more solid, elastic characteristics are exhibited, which can create cracks in the pavement (Bera and Babadagli, 2015; Köfteci et al., 2014). Because the binder has the same origin as the polymers, most of them have an adequate affinity with aggregate and asphalt binders, complementing the original properties of asphalt mixtures. In this way, the range of temperatures in which the mixture maintains stability is extended.

## 1.2. Use of recycled polymers in asphalt mixtures

There are previous studies in which recycled polymer has been used as an additive in the manufacture of asphalt mixtures, resulting in behaviour similar to that of mixtures with modified binders (Polacco et al., 2015). Through the use of this type of additive, improvements in both the durability and in the costs associated with the repair and maintenance of asphalt pavements were obtained (Landi et al., 2018).

There are two approaches to adding recycled polymers to asphalt mixtures: (1) adding the polymers as additives to the complete asphalt mix so that they act as reinforcement material, and (2) adding the polymers directly to the binder to modify its properties before it comes into contact with the aggregate mixture.

### 1.2.1. Recycled polymer added by dry method

When this type of recycled polymer is added to the mixture as an additive, its interaction with the components of the mixture is mechanical and does not appreciably alter the properties of those components. The addition of the polymers is carried out by a dry process—that is, the polymers are added to the aggregate before coming into contact with the binder (Huang et al., 2007). This method creates a thin layer of plastic covering the aggregate, and once the aggregate is mixed with the binder, an excellent asphalt mixture performance is obtained (Lastra-González et al., 2016; Liang et al., 2017). The degree of interaction of the polymers with the rest of the materials depends on the softening temperature of the polymer, as well as on the time of digestion and mixing, which can vary from 2 to 15 min (Ahmadinia et al., 2012; Huang et al., 2007). Previous research into asphalt mixtures with high density polyethylene (HDPE), low density polyethylene (LDPE), polyvinyl chloride (PVC), nylon, and aramid fibers have shown increases in Marshall stability and indirect tensile strength (ITS) values, as well as a reduction in the stiffness modulus (Ahmadinia et al., 2011; Yin and Wu, 2018; Zoorob and Suparma, 2000). In addition, there was close to a 15% improvement in the conserved tensile strength ratio (TSR) and an increase in fatigue resistance (Fazaeli et al., 2016; Lastra-González et al., 2016; Modarres and Hamed, 2014). However, the results with PS were not as favourable, due to the unstable behaviour of the polymer during the production of the mixtures, which decreased its fatigue resistance and life (Lastra-González et al., 2016).

One should also consider the size of the polymer in this procedure, as the smaller the particles, the more significant the dispersal of the polymer inside the asphalt mixture. This allows the polymer to adhere better to the aggregates and the bitumen to cover the particle combination properly (Fakhri and Azami, 2017; Santagata et al., 2012). If the particle sizes or polymer types are not adequate, various problems will present themselves, resulting in premature failure of the pavement (Delongui et al., 2018; Hınıslioğlu and Açar, 2004; Montanelli and srl, 2013).

One of the most significant advantages of this process is that it does not require modifications to the mixing plants. However, the correct behaviour of the mixtures will depend on the degree of control over the processes of polymer addition, as well as the duration of mixing and digestion prior to the incorporation of the binder.

### 1.2.2. Recycled polymer added by wet method

Binder modification is the most common way to use recycled polymers in asphalt mixtures due to the creation of binders with better thermal behaviour. The addition of polymers is carried out through a wet process, whereby the recycled polymer particles are incorporated directly into the binder before being used in the production of the mixture (Huang et al., 2007). The polymers most often used to modify binders are styrene butadiene styrene (SBS),

HDPE, and crumb rubber (CR). These polymers obtain satisfactory results in all tests since the mixtures produced are less susceptible to temperature variations, with lower fatigue, higher resistance, a longer life, and less propensity to suffer permanent plastic deformations (Attaelmanan et al., 2011; González et al., 2012; Kök and Çolak, 2011; Oliviero Rossi et al., 2015).

This method has limitations, since the polymer must fulfil certain conditions to assure the creation of a suitable modified binder (Presti et al., 2014). An inadequate and incompatible polymer results in the mixture containing the bitumen being heterogeneous and without cohesion and ductility, which generally happens with polymers that have higher fusion and softening temperatures. Conversely, compatible polymers require specific treatment and mixing processes, such as high-temperature and high-speed shear mixing, to improve the properties of the asphalt binder and generate stable mixtures with better mechanical characteristics and durability (Al-Adham and Al-Abdul Wahhab, 2018; Montanelli and srl, 2013).

It should also be noted that these processes are more expensive and complicated, since complete digestion of the polymer by the binder must be achieved, and for this to happen, the modification must be carried out in specifically designed binder preparation plants. In addition, the implementation of such polymer mixes is more complicated, and not all recycled polymers have shown satisfactory behaviour during the digestion process (Fernandes et al., 2017; Lastra-González et al., 2016).

## 1.3. Considerations for the use of plastic scrap in asphalt mixtures

All the studies presented have in common that the recycled polymers added to the mixtures, in both wet and dry process, are not combined, in order to ensure control over the properties to be modified. However, the plastic scraps obtained in the recycling plants include different types of polymers in their composition. Also, all these studies used the polymers as additives for mixtures or asphalt binders, but there are no studies that include them as a binder replacement. Based on this previous information, the main goal of this research focuses on the reduction of the amount of plastic scrap currently accumulated in landfills through its use as partial substitute of binder in the production of asphalt mixtures, without compromising its durability but also reducing the amount of bitumen used. This process is developed without the need to separate the polymer types that compose it, and by adding this material by the dry method to the group of aggregates before mixing with the asphalt binder. By adding the material by dry process, possible incompatibilities that could appear in the wet process between binder and polymers are prevented, and additionally, the method of addition to the mixture is simplified.

In turn, the reduction in the amount of binder used is relevant not only from an environmental perspective but also from an economic point of view, since the binder comprises around 60% of an asphalt mix materials cost (Vila-Cortavitarre et al., 2018).

## 2. Materials and methods

Six combinations were used in this study, in which the percentage of binder and the quantity and size of polymer waste used were varied (Table 1). In order to not vary the volumetric properties of the mixtures, all the replacements were made by volume, considering the density values of both the binder and the plastic scrap. The first combination (REF) represents the reference mixture used as the basis of comparison. In this sample, the optimal percentage of the binder was previously calculated and taken as the basis for the rest of the combinations. A value of 4.7% binder referred to the mixture was obtained as the optimal percentage

**Table 1**  
Percentages of bitumen and plastic scrap.

Series	Bitumen (%)	Plastic scrap	
		Coarse (%)	Fine (%)
REF	100	–	–
REF <sub>1</sub>	90	–	–
PF <sub>1</sub>	90	–	10
PG <sub>1</sub>	90	10	–
PF <sub>2</sub>	90	–	20
PG <sub>2</sub>	90	20	–

according to the requirements for 5% of air voids in mixture, recommended filler/binder ratio, minimal voids in mineral aggregate (VMA), and minimal binder percentage of addition (General Directorate of Roads, 2002). This quantity is established as 100% of binder.

Another reference mixture (REF1) was used, which was similar to the REF standard mixture but with 10% less binder. This allowed for analysis of the behaviour change in the mixture when only 90% binder was used compared to the standard mixture (REF). This sample was taken as a basis for comparison with the other combinations that incorporated plastic scrap, enabling us to evaluate the change in behaviour generated by the addition of the two plastic scrap sizes considered in the analysis.

The rest of the combinations were based on the combination REF1. The combinations PF1 and PG1 involved a mixture with 90% binder and 10% plastic scrap in fine size and coarse size, respectively. These combinations were made to evaluate the behaviour of the mixture when 10% binder was replaced by 10% plastic scrap (replacement ratio 1:1).

Finally, combinations PF2 and PG2 were developed from the combination REF1, which involved a mixture with 90% binder and 20% plastic scrap in fine and coarse sizes, respectively. These combinations were made to evaluate the behaviour of the mixture when 10% binder was replaced by 20% plastic scrap (replacement ratio 1:2). In this way, it can be checked whether adhesive capacity improves when more significant quantities of plastic scrap are incorporated and the same percentages of binder are maintained.

## 2.1. Materials

### 2.1.1. Plastic scrap

The plastic scrap used came from the same plastic recycling plants and was supplied by the Institute of Plastic Technology (AIMPLAS), located in Valencia (Spain). The material was composed of crushed polyethylene terephthalate (PET), HDPE, and PVC, generating flakes of irregular shape. The two types analysed differ in

the size of crushed material. In the case of the coarse fraction, the crushing of the waste polymers produced flakes of 10–5 mm, while for the fine fraction, the size of the flakes was between 2 and 0.25 mm (Fig. 1).

The density of the material was calculated by the immersion method (AENOR, 2004), and a density value of 0.948 g/cm<sup>3</sup> was obtained. A calculation of the softening temperature of the fractions was also carried out, with consideration given to the fact that they incorporate different types of polymer. To do this, samples of the different fractions were placed in the oven, and the temperature was progressively increased from 60 °C until the material's consistency changed. A softening temperature of 180 °C was obtained for both materials, so it was decided to use said temperature for the heating of the aggregates and the progressive softening of the plastic scrap. In this way, the polymer flakes managed to adhere to and cover part of the aggregate.

### 2.1.2. Bitumen and aggregates

Semi-dense asphalt concrete mixture gradation AC16S (Table 2) was used as a reference mixture (AENOR, 2007). A conventional bitumen B50/70 was used with a penetration grade of 56.8·10<sup>-1</sup> mm (Table 3). The pre-heating temperatures of the bitumen and aggregates were 155 and 180 °C, respectively. The natural aggregates were crushed limestone from a local quarry in Santander (Spain). Table 4 shows the bulk specific gravity and water absorption coefficient of limestone for coarse and fine aggregates (AENOR, 2010).

The abrasion coefficient of Los Angeles (LA) obtained for limestone is 15% according to the standard. This coefficient complies with the Spanish General Technical Specifications for Roads (PG-3) (LA ≤ 25%) for heavy traffic categories. The sand equivalent (SE) of the limestone was 63%, obtained according to the standard (AENOR, 2016) for asphalt mixtures as a base course material for heavy traffic categories (greater than 55%). The flakiness index (FI) of limestone was 24%, obtained according to the standard (AENOR, 2012a) and complies with the PG-3 for heavy traffic categories (FI ≤ 20%).

**Table 2**  
Semi-dense AC16S gradation.

Sieve size [mm]	Percentage passing [%]	Percentage passing used [%]
16	90–100	100.0
8	60–75	66.1
4	35–50	42.5
2	24–38	31.0
0.5	11–21	13.5
0.25	7–15	9.4
0.063	3–7	5.3



**A**



**B**

**Fig. 1.** Plastic scrap: (a) coarse size; (b) fine size.

**Table 3**  
Characteristics of the binder.

Characteristic	Unit	Method	Requirements		Petronor 50/70
			Min	Max	
Penetration (25 °C)	Mm/10	EN 1426	50	70	57
Softening point	°C	EN 1427	46	54	51.6
Fragility point	°C	EN 12593	–	≤–8	–13
Penetration rate	–	EN 12591_Anex.A	–1.5	+0.7	–0.5
Relative density (25 °C)	g/cm <sup>3</sup>	EN 15326	–	–	1.035
T° laboratory prep.	°C	EN 12594	–	–	130

**Table 4**  
Bulk specific gravity and water absorption of the aggregates.

Size (mm)	Bulk specific density (g/cm <sup>3</sup> )	Water absorption (%)
0–2	2.690	2.716
2–4	2.672	2.707
4–8	2.639	2.680
8–16	2.625	2.685
16–22	2.602	2.684

### 2.1.3. Sample preparation

Fourteen samples were manufactured for each of the established combinations for a total of 84 samples (AENOR, 2017).

Marshall samples of 101.6 mm diameter and 63.5 mm height were used to calculate density and quantity of air voids in the mixture, Marshall stability and flow, moisture damage by indirect tensile strength (ITS), and cyclic tensile strength for cylindrical samples. Twelve prismatic samples of 410 \* 250 mm and a thickness of 50 mm were used for the rutting test.

The mixing process was carried out at a temperature of 150 °C with an automatic mixer to maintain the same mixing temperature process as a regular mixture according to the standards for a binder B50/70 and the binder data sheet recommendations (AENOR, 2017). For the reference mixture (REF), the aggregate was mixed with the bitumen for three minutes to ensure the correct coverage of the aggregate by the binder. For the mixtures modified with polymers, the aggregates and the plastic scrap were mixed for one minute at 150 °C, based on previous experiences (Fernandes et al., 2017; Lastra-González et al., 2016). At that point, the bitumen was added and mixed for three minutes at the same temperature.

For the Marshall samples, two types of compaction were performed according to the requirements of the Marshall and moisture damage tests. Twenty-four samples were compacted to 75 blows per side for the Marshall test (four samples per combination), and another 48 samples were compacted to 50 blows per side for the moisture damage test (eight samples per combination) (AENOR, 2013a). For the rutting tests, roller compaction was used on a total of 12 samples (two samples per combination) with the same bulk density and air voids as the samples used in the Marshall design (AENOR, 2008a). The temperature used in both compactations was 145 °C in order to maintain mixture workability and reach the required density (AENOR, 2017).

## 2.2. Test plan

### 2.2.1. Marshall stability and flow test

Twenty-four Marshall samples compacted to 75 blows per side were used—that is, four identical samples for each of the six combinations. The bulk density, percentage of air voids, voids in mineral aggregates (VMA), and voids filled with asphalt (VFA) of each sample were calculated using the hydrostatic method (bulk density – dry saturated surface) (AENOR, 2012a, 2006), whereby samples are dry-weighted and then saturated under water and

the bulk density is calculated using the water volume displaced. For the Marshall test, samples were then conditioned at 60 °C for 45 min according to the standard (AENOR, 2013b). Afterwards, the test samples were tested in the Marshall press, at a displacement rate of 50.8 mm/min, until reaching the maximum load. The resulting stability rate corresponds to the maximum load resisted, in kN, and the flow is the value of deformation in mm that the sample registered when reaching the maximum load value.

### 2.2.2. Moisture damage test

Forty-eight compacted Marshall samples compacted at 50 blows per side were used, according to the standard (AENOR, 2009), with eight identical samples for each of the six combinations. The eight samples available for each combination were divided into two groups for conditioning, one wet and the other dry, according to the standard (AENOR, 2009). Samples under wet conditioning underwent a period of hydrostatic vacuum with 50 mm Hg absolute pressure for 30 min, then the samples were introduced to a water bath at 40 °C for 72 h, and finally the samples remained for two hours in a water bath at a temperature of 15 °C before the test. After conditioning, all the samples were tested under indirect tensile strength, at a displacement rate of 50.8 mm/min, until reaching the maximum load. The ITS indirect tensile strength value was determined using Eq. (1):

$$ITS = \frac{2 \cdot P}{\pi \cdot h \cdot D}, \text{ [GPa]} \quad (1)$$

where *ITS* is the indirect tensile strength (GPa), *P* is the peak load (kN), and *h* and *D* are the diameter and the height of the sample (mm), respectively.

The conserved TSR value was calculated using the ratio between the ITS of wet and dry sample groups, as in Eq. (2):

$$TRS = \frac{ITS_w}{ITS_d} \cdot 100, \text{ [%]} \quad (2)$$

where *TRS* is the conserved tensile strength ratio (%), *ITS<sub>w</sub>* is the indirect tensile strength calculated for wet samples (GPa), and *ITS<sub>d</sub>* is the indirect tensile strength calculated for dry samples (GPa).

### 2.2.3. Resilient modulus test

The resilient modulus test was carried out to determine the elastic stiffness of the tested sample (AENOR, 2012b). This is a non-destructive test used to evaluate the deformation capability of the asphalt mixture in the elastic range and thus estimate the influence of the different materials in the reduction of crack appearance. The stiffness value is a relation between the applied load and the deformation suffered by the sample under that load. Forty-eight Marshall samples were used, with 24 specimens compacted at 50 blows per side and another 24 samples compacted at 75 blows per side. The test was carried out by applying a specific load haversine type during at least 15 cycles and measuring the amplitude of the horizontal deformation of the test sample during the last five cycles. The ascendant period was 124 ms, and the period of repetition of the impulses was 3.0 s. The test was carried

out at 20 °C. The resilient modulus value was calculated using Eq. (3):

$$E = \frac{F \times (v + 0,27)}{z \times h} \quad (3)$$

where  $E$  corresponds to the measured resilient modulus (in MPa),  $F$  corresponds to the maximum value of the vertical load applied (in N),  $v$  corresponds to the Poisson coefficient for asphalt mixtures,  $z$  corresponds to the range of the horizontal deformation obtained during a load cycle (in mm), and  $h$  corresponds to the average thickness of the sample (in mm).

The applied load for the test varied between 3.4 and 3.5 kN, adjusted to reach a maximum horizontal deformation of reference of 0.005% of the diameter of the samples.

#### 2.2.4. Wheel tracking test

The rutting test makes it possible to determine the resistance to permanent plastic deformations in the asphalt mixtures by applying the cycles of a loaded wheel on the surface of the samples under severe heat conditions (AENOR, 2008b). Twelve test samples of  $410 \times 250$  mm and a thickness of 50 mm were used. The conditioning and testing were carried out in the air, at a temperature of 60 °C and for a duration of 10,000 cycles. In this test, the rutting machine is set in motion and takes readings of the vertical displacement of the wheel. With these readings, the value of the wheel-tracking slope in the air ( $WTS_{air}$ ) can be obtained using Equation (4), which indicates the grade of the deformation on the track for 1000 load cycles:

$$WTS_{air} = \frac{(d_{10,000} - d_{5,000})}{5} \quad (4)$$

where  $WTS_{air}$  is the wheel-tracking slope (mm/10<sup>3</sup> load cycles), and  $d_{5,000}$  and  $d_{10,000}$  are the rut depths after 5000 load cycles or 10,000 load cycles, respectively (mm).

Additionally, the total rut depth value ( $RD_{air}$ ) is obtained. This value corresponds to the depth of the footprint in mm at the end of 10,000 load cycles.

### 3. Results and discussion

#### 3.1. Volumetric properties and Marshall stability/flow test

A preliminary analysis of the effect of the replacement of binder by plastic scrap on the volumetric properties of the mixtures was carried out. The reference mixture had an expected percentage of voids close to 5% (Fig. 2). The REF1 mixture (with 10% less than the total binder) showed an increase in the air voids but remained within the limit indicated in the regulations (4 to 6%). As the percentage of plastic scrap in the mixture increased, the percentage of air voids and VMA increased, and bulk specific gravity and VFA decreased (Table 5). This is because the polymer particles partially surround the aggregate, but the aggregate does not absorb the polymer, so the air voids generated by the reduction of the binder are still present. Also the plastic scrap has lower viscosity than the binder, which causes the aggregate particles to be separated from each other and helps to increase the air voids in the mixture. This tendency is higher when the particle size of the plastic scrap is increased. The combination of both behaviours results in an improper mixture compaction, causing the increase in air voids and VMA.

During the mixture formation process, it was possible to see that the plastic scrap had a higher affinity with the fine aggregate, forming clusters of fine aggregate and polymers that reduced the homogenisation with all of the aggregates. The increase in plastic scrap caused an increase in the dispersion of the data regarding the bulk density and percentage of air voids, which indicated a greater difficulty in controlling the process of manufacturing the mixtures.

Once the percentage of air voids and bulk density was determined, Marshall stability and flow tests were performed on the

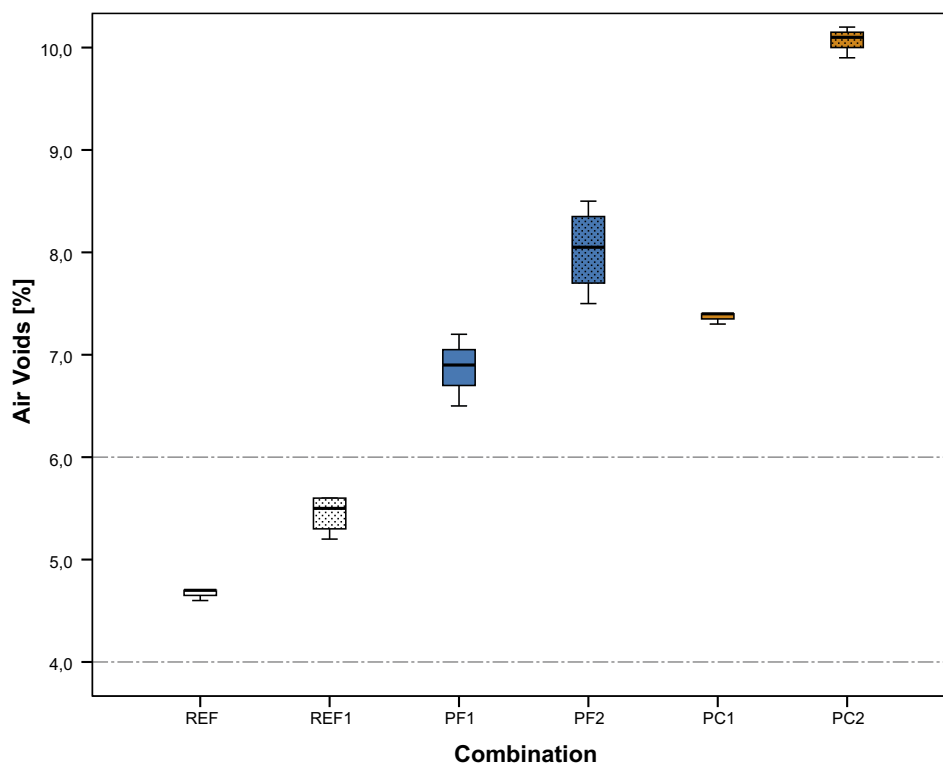


Fig. 2. Percentage of air voids.

**Table 5**  
Volumetric properties of the mixtures.

Combination	Bulk specific gravity [g/cm <sup>3</sup> ]	Voids in mineral aggregate VMA [%]	Voids filled with asphalt VFA [%]
REF	2.500	16.0	70.9
REF1	2.480	16.7	67.5
PF1	2.441	17.7	61.6
PF2	2.412	19.4	57.8
PC1	2.429	18.4	60.0
PC2	2.358	20.8	52.6

samples. All the series that incorporated plastic scrap had stability values higher than the reference mixtures REF and REF1 (Fig. 3). This is due to the higher stiffness of the plastic scrap compared to the binder at the temperature of the test (60 °C), which was based on their softening point, which caused the samples to have higher compression strength values. For fine plastic scrap, the highest result was obtained with a 1:2 ratio of binder replaced with plastic scrap (PF2), while for the coarse size the highest rate was 1:1 (PC1), which obtained the highest stability value. This is because the small material coats the aggregate more easily, acting similarly to the binder, while the coarse material acts as an aggregate attached to the natural aggregate, so if an excess of the coarse material is added, it's easier to reduce the union between particles.

These results are also related to the compaction level reached by the different combinations. While the samples with no plastic scrap particles reaches the regular level of compaction and common values of bulk density and air voids, the combinations with plastic scrap showed lower workability and compaction ability, resulting in mixtures with lower bulk density, higher air voids, and more susceptibility to recompression during the test.

The values obtained for the Marshall flow (Fig. 4) confirmed this behaviour. Logical behaviour is expected for the reference mixtures REF and REF1, because when reducing the binder content lower

flow values are obtained. With the fine size, the flow was reduced when the proportion of binder replaced by plastic scrap increased, resulting in a more rigid and less deformable mixture. With the coarse size, an increase in the proportion produced an excess of plastic scrap, causing the particles to separate easily and generate more deformation and low resistance. It should be noted that this test is carried out in moisture conditions at a temperature of 60 °C, so the plastic scrap modifies the viscoelastic property of the mixture in such a way that at higher temperatures, the mixture behaves better because the polymer needs more heat to change its physical state.

Introducing plastic scrap and reducing the amount of binder increased the dispersion of the results for both the Marshall stability and flow values, due to the random placement of polymer particles inside the mixture, the same as what happened with bulk density and air voids data. However, all the combinations obtained the minimal requirements both for Marshall (minimum 9 kN) and flow (maximum 4 mm) results usually established in the regulations (General Directorate of Roads, 2017).

### 3.2. Moisture damage test

The results obtained in the moisture damage test by ITS show that the mixtures with plastic scrap did not increase the strength in any of the cases (Fig. 5). As the percentage and size of plastic scrap rose, the ITS slightly decreased. However, differences among the combinations are negligible.

The regulations indicate that a mixture's TSR value must be equal to or greater than 85% in order for it to be used as a surface layer (General Directorate of Roads, 2002). None of the analysed combinations fulfilled that requirement; even the REF reference mixture had a value of 84%. It can be seen that when a 10% binder is reduced (REF1), the TRS value decreases to below 80%, so the product cannot be used as a base or intermediate layer either.

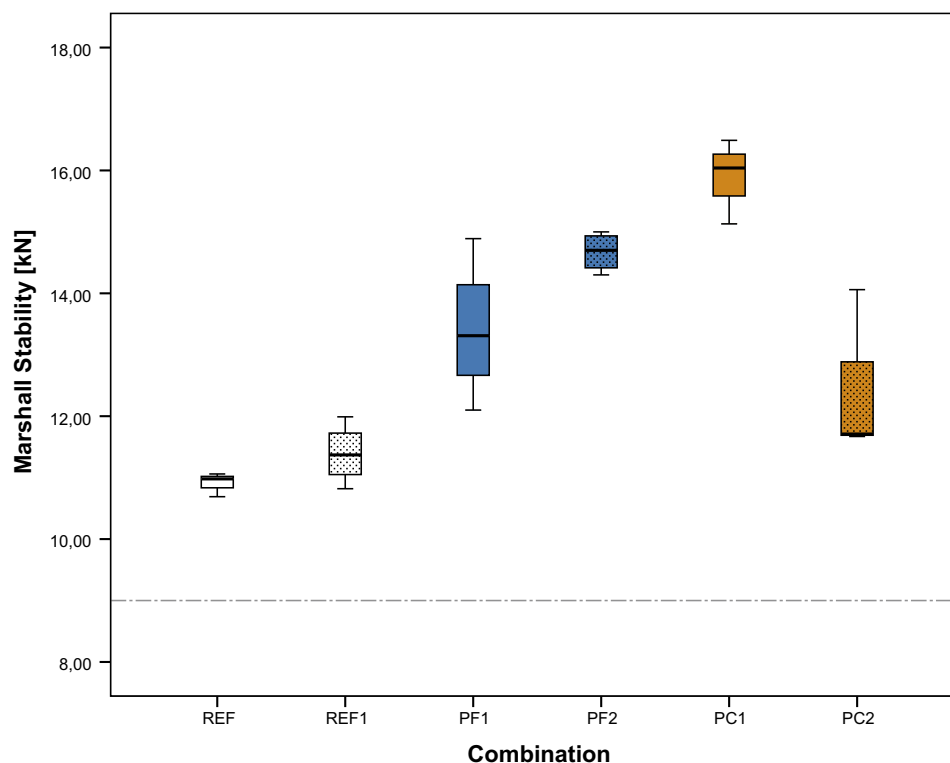


Fig. 3. Marshall stability.

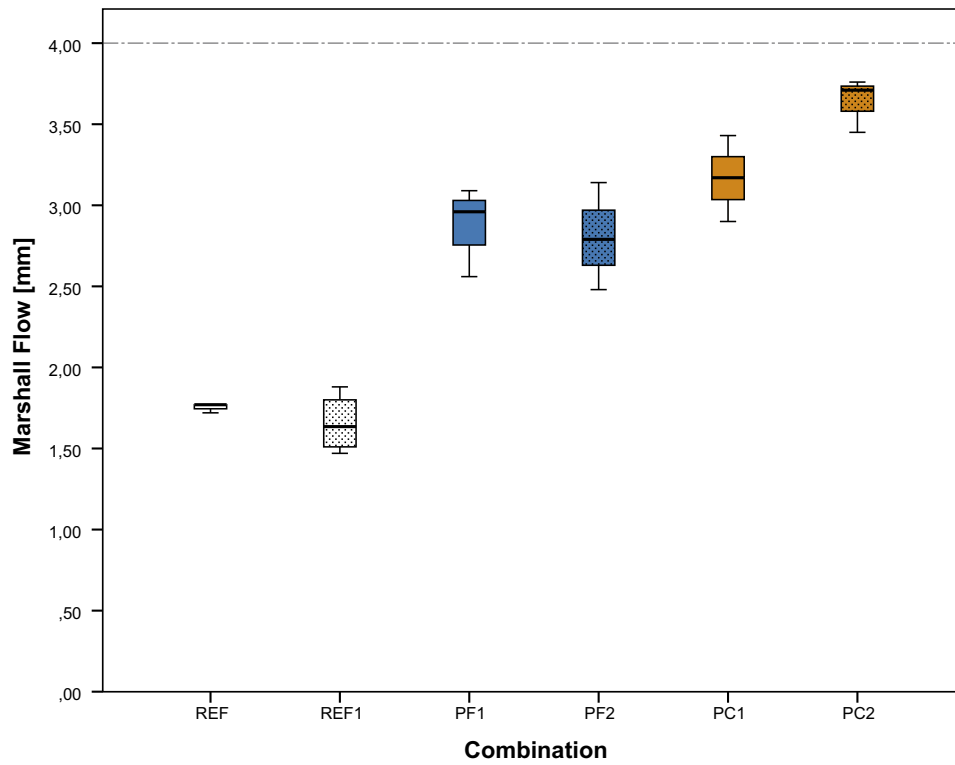


Fig. 4. Marshall flow.

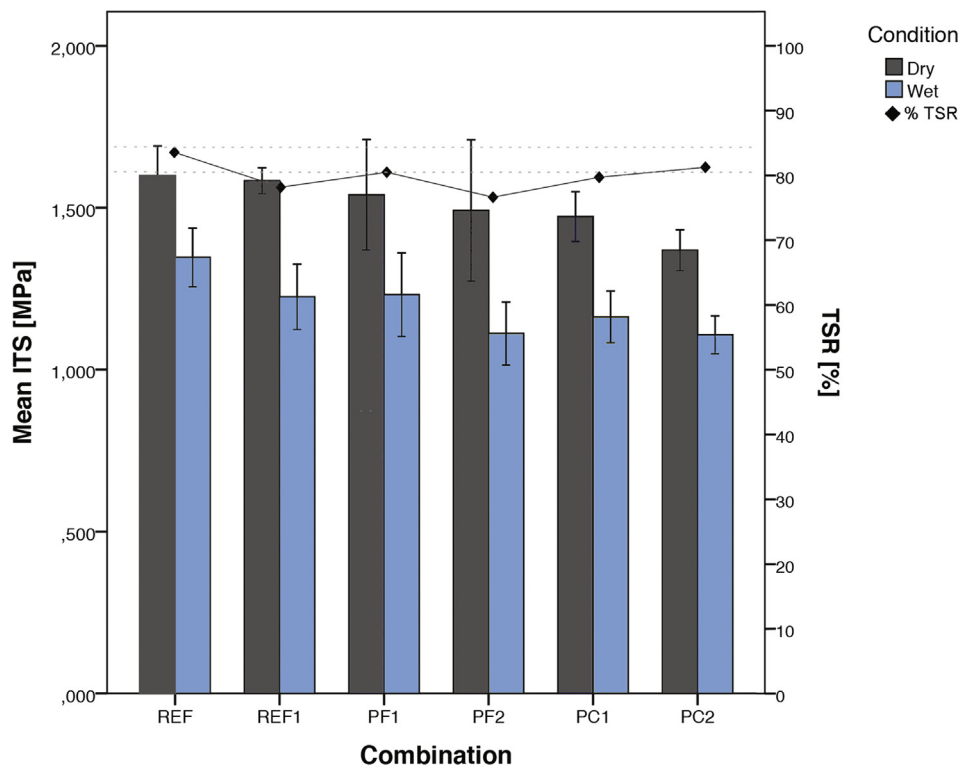


Fig. 5. ITS and TSR values (moisture damage test).

In the case of mixtures with plastic scrap, lower affinity with the aggregate was observed when compared to the binder-aggregate bonding, which makes water to generate more damage in the mixture, resulting in a loss in the strength of the wet mixtures. However,

for fine material with 1:1 replacement (PF1) and coarse material with 1:2 replacement (PC2), the TRS value increased to over 80%.

For mixtures with coarse aggregate of plastic scrap, an increase in conserved TSR is observed when the replacement ratio is

increased. Despite the theoretical improvement in the conserved strength, going from 79 to 81% of TRS, a deeper analysis of the absolute results of ITS shows that these ITS values are higher and closer to the reference mixtures when the replacement ratio is 1:1, so the overall behaviour of this combination is better than the PC2.

Although mixtures with plastic scrap did not reach the limits set by regulations for use in the surface layer, an increase in TRS was observed when compacted to the REF1 mixture. This suggests that the plastic scrap does not significantly affect strength and acts in a similar way to a binder, especially for the fine size. In this case, the biggest problem is the affinity that the aggregate has with the asphalt binder, which is the cause of the low TRS values obtained in all mixtures.

### 3.3. Resilient modulus test

Fig. 6 shows the resilient modulus obtained in each series of samples compacted with 50 and 75 blows per side. When results for samples compacted with 50 blows per side were analyzed, all the series were found to have values similar to or lower than that of the reference mixture, except for mixture with 20% fine plastic scrap (PF2). The mixture with 10% fine plastic scrap (PF1) had the value closest to that of the reference mixture, which is nearly identical. The rest of the series was less rigid, which indicates that at this compaction level, the mixture would be more deformable in its elastic state and able to recover its condition after the load disappears, thus preventing cracks in the pavement but being more susceptible to plastic deformations.

When the mixtures compacted at 75 blows per side were analysed, an increase in stiffness was observed in all combinations due to the increase in bulk gravity of the samples. However, when

increasing from 50 to 75 blows per side, the mixtures with plastic scrap showed a higher percentage increase than that obtained in the reference mixtures REF and REF1, since in this case, practically all the mixtures surpass the stiffness of the reference mixture (REF). This indicates that plastic scrap needs greater compaction energy to obtain the densities and behaviour required when it is placed on site, partly due to the previous plasticizing of the polymer during its original manufacturing process.

It was observed that at both degrees of compaction, the stiffness of mixtures with fine material (PF1 and PF2) increased when the plastic scrap ratio was also increased. In mixtures with coarse material (PC1 and PC2) the stiffness decreased, maintaining the same tendency as in the Marshall stability test. Fine plastic scrap was found to generate the highest stiffness values at both levels of compaction. The highest values were obtained with a ratio of 1:2 replacement of fine material (PF2). This is because material with this size of particle can coat the aggregate more efficiently, so the bulk density rises and better consolidates the mixture. In tests, the increase in the ratio of plastic scrap versus replaced binder caused an increase in the dispersion of the results, especially in cases where a 1:1 ratio was exceeded, suggesting that the process of production for the mixtures needs to be particularly well controlled.

### 3.4. Wheel tracking test

The results of the rutting test showed that all the mixtures with plastic scrap provided better results than the reference mixtures. The more plastic scrap used, the faster the settling and the lesser the rut depth ( $RD_{air}$ ) at 2000 and 10,000 cycles (Fig. 7). All the mixtures with plastic scrap fit the minimum requirements specified in the regulations ( $WTS_{air} \leq 0.10$ ). However, the reference mixtures

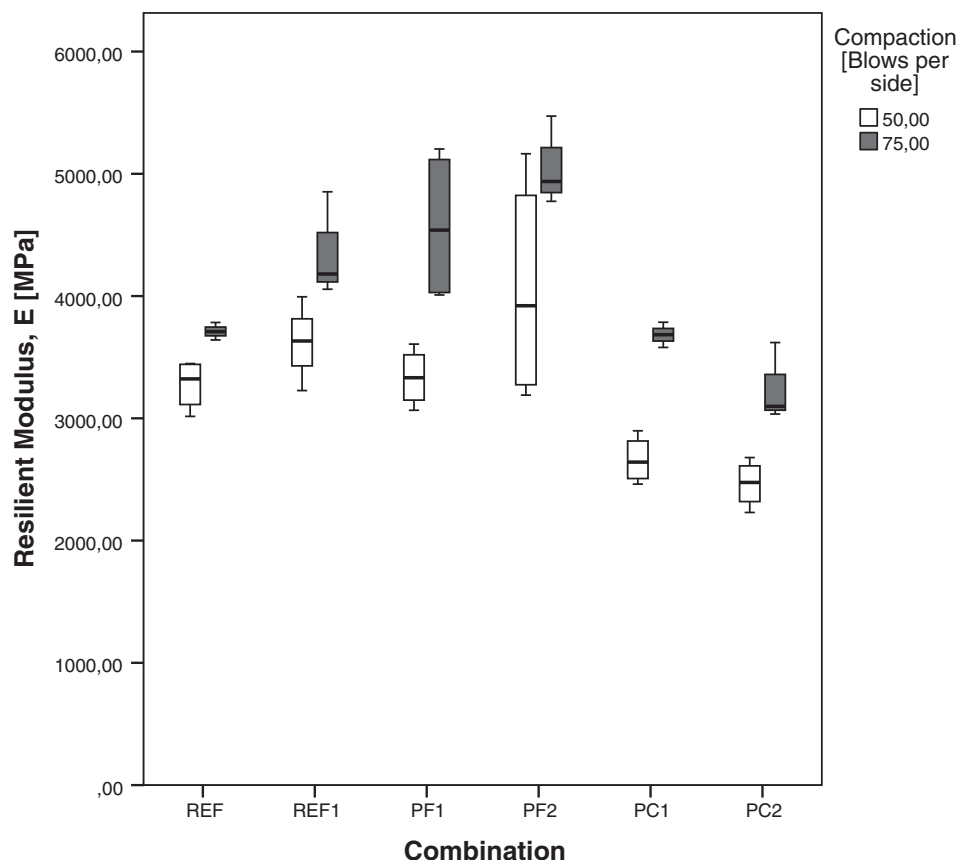


Fig. 6. Resilient modulus.



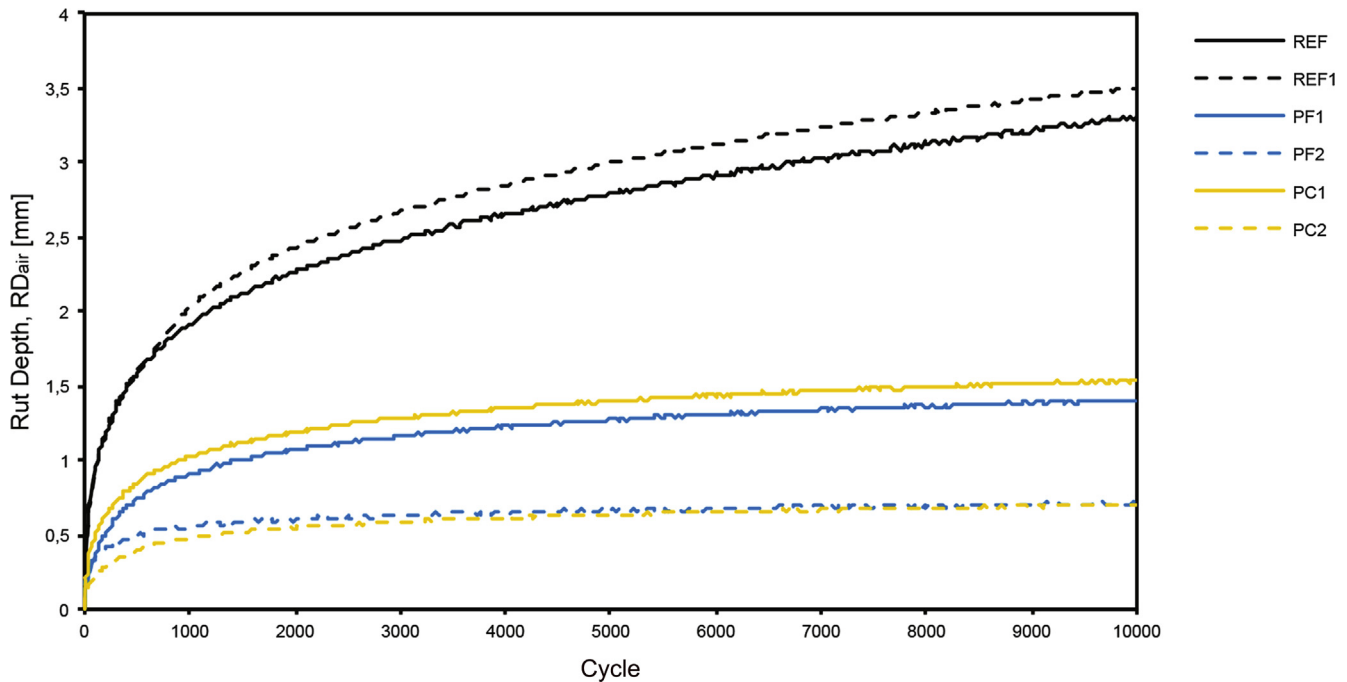


Fig. 7. Wheel tracking test.

**Table 6**  
Wheel tracking slope and rut depth.

Combination	RD <sub>air</sub> [mm]	WTS <sub>air</sub> [mm per 10 <sup>3</sup> load cycles]
REF	3.301	0.102
REF1	3.502	0.100
PF1	1.410	0.026
PF2	0.712	0.011
PC1	1.534	0.028
PC2	0.704	0.014

REF and REF1 presented higher final deformations and deformation slopes, and in the case of the REF mixture, the allowed limit was even exceeded (Table 6). The combination REF1 presented the most significant permanent deformations and rut depth (Fig. 7), which were related to the lower amount of binder included in the mixture and the low affinity of the binder with the aggregate.

The behaviour shown by the samples was complementary to that obtained in the rest of the tests. It was observed that the plastic scrap stiffens the mixture and has good affinity with the aggregate, which results in less plastic deformation.

The mixture with plastic scrap was less viscous at high temperatures. At the test temperature of 60 °C, the permanent deformations of the mixture were reduced because the polymers were more rigid than the binder. A behaviour similar to that obtained in the Marshall stability test was demonstrated. That is why the determining parameters in this test are the amount of binder included in the mixture and the ratio between the amount of plastic scrap and binder replaced. A greater proportion of replacement material produces less permanent deformation in the mixture. In this case, the particle size of the plastic scrap had no significant influence on the test results when compared to the other parameters.

#### 4. Conclusions

The following conclusions can be established on the basis of the results obtained in this study:

- The use of plastic scrap added by dry method is feasible, provided that the manufacturing process is controlled. Pre-mixing of the plastic scrap particles with the aggregates of the mixture must be carried out for at least one minute so that the polymer can partially envelop the aggregate and adhere to it. This process does not produce any incompatibilities with the rest of the materials that could affect the behaviour of the mixtures.
- Due to the way in which the plastic scrap interacts with the aggregate, the particles of this material must have a size of less than 2 mm so that they envelop the aggregates more easily and perform well in the presence of water. The index of air voids in asphalt mixes increases when plastic scrap is used as a binder replacement, since the material does not fill the voids released by the binder reduction, either in aggregate or in the mixture, but only adheres to the aggregate.
- The mixtures with plastic scrap resist compression better, showing greater energy dissipation and reduced permanent deformations. This is because this material has higher stiffness than the binder it replaces, increasing the overall stiffness of the mixture. For the same reason, these mixtures exhibit less viscosity at higher temperatures. That is why these types of mixtures perform better in climatic zones with medium and high temperatures but have a greater tendency to crack at low temperatures.
- The ratio of plastic scrap to binder replaced should not exceed 1:1 for any of the sizes analysed, since this proportion produces the best overall behaviour in the mixtures, improving their plastic properties without compromising their resistance or stiffness.

The results obtained in this study should be complemented by durability tests that allow for evaluation of how the increase in stiffness of the mixtures is affected by plastic scrap. Such evaluation can be carried out through the analysis of fatigue resistance and dynamic modulus under cyclic loads at medium and low temperatures, resistance to cracking and dissipated energy, and the assessment of the compaction energy required for installation of the material.

Based on the partial results obtained, the use of plastic scrap as a dry binder replacement can be considered feasible, allowing the use of an approximately one to two tons of plastic scrap per kilometre, assuming a 5-cm-thick paved surface layer with two lanes. The amount of asphalt binder in the manufacture of the mixture can be reduced by about one ton. The amount of plastic scrap used and binder saved per kilometre could be increased if the material is also used in lower layers of the pavement (base and binder layers), which have lower requirements for strength and moisture damage resistance and are built with greater thickness than the surface layers, generating a more significant reduction in the environmental impact of the construction of this type of pavement.

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