1  **USE OF PLASTIC SCRAP IN ASPHALT MIXTURES ADDED BY DRY METHOD**

2  **AS A PARTIAL SUBSTITUTE FOR BITUMEN**

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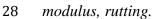
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10  **ABSTRACT**

11  In recent decades, the generation of plastic waste has increased substantially worldwide, with

12  the result that more of such waste is introduced into the environment. Currently, most

13  polymers (polyethylene terephthalate, polyethylene, polyvinyl chloride, and others) are

14  recycled. However, some are rejected for recycling in the primary separation processes due to

15  their physical condition, contamination, or size. These materials are called plastic scrap.

16  In this research, the use of plastic scrap added by dry method was evaluated as a

17  replacement for bitumen in asphalt mixtures. Two sizes of plastic scrap, coarse and fine,

18  were considered. An AC16S semi-dense mixture was designed for this purpose, with a 10%

19  reduction in binder, and 10% and 20% of plastic scrap binder was added in coarse and fine

20  sizes.

21    The results obtained in the Marshall stability and flow test showed reduced moisture

22    damage, greater indirect tensile strength, higher air void content, and a 2% decrease in the

23    conserved tensile strength ratio while the same usage field as the conventional mixture was

24    maintained. Meanwhile, significant decreases in plastic deformations, as compared to

25    traditional values, were obtained from resilient modulus and rutting tests.

26

27    **Keywords:** *Plastic scrap, asphalt mixtures, Marshall test, moisture damage, resilient*

28    *modulus, rutting.*

## 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

52  vehicle's weight is high. On the other hand, given temperatures lower than 0ºC, along with

53  repetitive vehicular traffic loads and high traffic speeds, more solid, elastic characteristics

54  are exhibited, which can create cracks in the pavement (Bera & Babadagli, 2015; Köfteci et

55  al., 2014). Because the binder has the same origin as the polymers, most of them have an

56  adequate affinity with aggregate and asphalt binders, complementing the original properties

57  of asphalt mixtures. In this way, the range of temperatures in which the mixture maintains

58  stability is extended.

59

60  **1.2. Use of recycled polymers in asphalt mixtures**

61      There are previous studies in which recycled polymer has been used as an additive

62  in the manufacture of asphalt mixtures, resulting in behaviour similar to that of mixtures

63  with modified binders (Polacco et al., 2015). Through the use of this type of additive,

64  improvements in both the durability and in the costs associated with the repair and

65  maintenance of asphalt pavements were obtained (Landi et al., 2018).

66      There are two approaches to adding recycled polymers to asphalt mixtures: (1)

67  adding the polymers as additives to the complete asphalt mix so that they act as

68  reinforcement material, and (2) adding the polymers directly to the binder to modify its

69  properties before it comes into contact with the aggregate mixture.

70

71  *1.2.1. Recycled polymer added by dry method*

72      When this type of recycled polymer is added to the mixture as an additive, its

73  interaction with the components of the mixture is mechanical and does not appreciably alter

74  the properties of those components. The addition of the polymers is carried out by a dry

4

75  process—that is, the polymers are added to the aggregate before coming into contact with

76  the binder (Huang et al., 2007). This method creates a thin layer of plastic covering the

77  aggregate, and once the aggregate is mixed with the binder, an excellent asphalt mixture

78  performance is obtained (Lastra-González et al., 2016; Liang et al., 2017). The degree of

79  interaction of the polymers with the rest of the materials depends on the softening

80  temperature of the polymer, as well as on the time of digestion and mixing, which can vary

81  from 2 to 15 minutes (Ahmadinia et al., 2012; Huang et al., 2007). Previous research into

82  asphalt mixtures with high density polyethylene (HDPE), low density polyethylene

83  (LDPE), polyvinyl chloride (PVC), nylon, and aramid fibers have shown increases in

84  Marshall stability and indirect tensile strength (ITS) values, as well as a reduction in the

85  stiffness modulus (Ahmadinia et al., 2011; Yin & Wu, 2018; Zoorob & Suparma, 2000). In

86  addition, there was close to a 15% improvement in the conserved tensile strength ratio

87  (TSR) and an increase in fatigue resistance (Fazaeli et al., 2016; Lastra-González et al.,

88  2016; Modarres & Hamedi, 2014). However, the results with PS were not as favourable,

89  due to the unstable behaviour of the polymer during the production of the mixtures, which

90  decreased its fatigue resistance and life (Lastra-González et al., 2016).

91      One should also consider the size of the polymer in this procedure, as the smaller

92  the particles, the more significant the dispersal of the polymer inside the asphalt mixture.

93  This allows the polymer to adhere better to the aggregates and the bitumen to cover the

94  particle combination properly (Fakhri & Azami, 2017; Santagata et al., 2012). If the

95  particle sizes or polymer types are not adequate, various problems will present themselves,

96  resulting in premature failure of the pavement (Delongui et al., 2018; Hınıslıoğlu & Ağar,

97  2004; Montanelli & srl, 2013).

98      One of the most significant advantages of this process is that it does not require

99  modifications to the mixing plants. However, the correct behaviour of the mixtures will

100 depend on the degree of control over the processes of polymer addition, as well as the

101 duration of mixing and digestion prior to the incorporation of the binder.

102

103 *1.2.1. Recycled polymer added by wet method*

104     Binder modification is the most common way to use recycled polymers in asphalt

105 mixtures due to the creation of binders with better thermal behaviour. The addition of

106 polymers is carried out through a wet process, whereby the recycled polymer particles are

107 incorporated directly into the binder before being used in the production of the mixture

108 (Huang et al., 2007). The polymers most often used to modify binders are styrene butadiene

109 styrene (SBS), HDPE, and crumb rubber (CR). These polymers obtain satisfactory results

110 in all tests since the mixtures produced are less susceptible to temperature variations, with

111 lower fatigue, higher resistance, a longer life, and less propensity to suffer permanent

112 plastic deformations (Attaelmanan et al., 2011; González et al., 2012; Kök & Çolak, 2011;

113 Rossi et al., 2015).

114     This method has limitations, since the polymer must fulfil certain conditions to

115 assure the creation of a suitable modified binder (Presti et al., 2014). An inadequate and

116 incompatible polymer results in the mixture containing the bitumen being heterogeneous

117 and without cohesion and ductility, which generally happens with polymers that have

118 higher fusion and softening temperatures. Conversely, compatible polymers require specific

119 treatment and mixing processes, such as high-temperature and high-speed shear mixing, to

120 improve the properties of the asphalt binder and generate stable mixtures with better

121 mechanical characteristics and durability (Al-Adham & Al-Abdul Wahhab, 2018;

122 Montanelli & srl, 2013).

123 It should also be noted that these processes are more expensive and complicated,

124 since complete digestion of the polymer by the binder must be achieved, and for this to

125 happen, the modification must be carried out in specifically designed binder preparation

126 plants. In addition, the implementation of such polymer mixes is more complicated, and not

127 all recycled polymers have shown satisfactory behaviour during the digestion process

128 (Fernandes et al., 2017; Lastra-González et al., 2016).

129

130 **1.3. Considerations for the use of plastic scrap in asphalt mixtures**

131 All the studies presented have in common that the recycled polymers added to the

132 mixtures, in both wet and dry process, are not combined, in order to ensure control over the

133 properties to be modified. However, the plastic scraps obtained in the recycling plants

134 include different types of polymers in their composition. Also, all these studies used the

135 polymers as additives for mixtures or asphalt binders, but there are no studies that include

136 them as a binder replacement. Based on this previous information, the main goal of this

137 research focuses on the reduction of the amount of plastic scrap currently accumulated in

138 landfills through its use as partial substitute of binder in the production of asphalt mixtures,

139 without compromising its durability but also reducing the amount of bitumen used. This

140 process is developed without the need to separate the polymer types that compose it, and by

141 adding this material by the dry method to the group of aggregates before mixing with the

142 asphalt binder. By adding the material by dry process, possible incompatibilities that could

143 appear in the wet process between binder and polymers are prevented, and additionally, the

144 method of addition to the mixture is simplified.

145   In turn, the reduction in the amount of binder used is relevant not only from an

146 environmental perspective but also from an economic point of view, since the binder

147 comprises around 60% of an asphalt mix materials cost (Vila-Cortavitarte et al., 2018).

148

149 **2. MATERIALS AND METHODS**

150   Six combinations were used in this study, in which the percentage of binder and the

151 quantity and size of polymer waste used were varied (Table 1). In order to not vary the

152 volumetric properties of the mixtures, all the replacements were made by volume,

153 considering the density values of both the binder and the plastic scrap. The first

154 combination (REF) represents the reference mixture used as the basis of comparison. In this

155 sample, the optimal percentage of the binder was previously calculated and taken as the

156 basis for the rest of the combinations. A value of 4.7% binder referred to the mixture was

157 obtained as the optimal percentage according to the requirements for 5% of air voids in

158 mixture, recommended filler/binder ratio, minimal voids in mineral aggregate (VMA), and

159 minimal binder percentage of addition (General Directorate of Roads, 2002). This quantity

160 is established as 100% of binder.

161   Another reference mixture (REF1) was used, which was similar to the REF standard

162 mixture but with 10% less binder. This allowed for analysis of the behaviour change in the

163 mixture when only 90% binder was used compared to the standard mixture (REF). This

164 sample was taken as a basis for comparison with the other combinations that incorporated

165 plastic scrap, enabling us to evaluate the change in behaviour generated by the addition of

166 the two plastic scrap sizes considered in the analysis.

167     The rest of the combinations were based on the combination REF1. The

168 combinations PF1 and PG1 involved a mixture with 90% binder and 10% plastic scrap in

169 fine size and coarse size, respectively. These combinations were made to evaluate the

170 behaviour of the mixture when 10% binder was replaced by 10% plastic scrap (replacement

171 ratio 1:1).

172     Finally, combinations PF2 and PG2 were developed from the combination REF1,

173 which involved a mixture with 90% binder and 20% plastic scrap in fine and coarse sizes,

174 respectively. These combinations were made to evaluate the behaviour of the mixture when

175 10% binder was replaced by 20% plastic scrap (replacement ratio 1:2). In this way, it can

176 be checked whether adhesive capacity improves when more significant quantities of plastic

177 scrap are incorporated and the same percentages of binder are maintained.

178

179 *2.1. Materials*

180 *2.1.1. Plastic scrap*

181     The plastic scrap used came from the same plastic recycling plants and was supplied

182 by the Institute of Plastic Technology (AIMPLAS), located in Valencia (Spain). The

183 material was composed of crushed polyethylene terephthalate (PET), HDPE, and PVC,

184 generating flakes of irregular shape. The two types analysed differ in the size of crushed

185 material. In the case of the coarse fraction, the crushing of the waste polymers produced

186 flakes of 10 to 5 mm, while for the fine fraction, the size of the flakes was between 2 and

187 0.25 mm (Fig. 1).

188    The density of the material was calculated by the immersion method (AENOR,

189    2004), and a density value of 0.948 g/cm$^3$ was obtained. A calculation of the softening

190    temperature of the fractions was also carried out, with consideration given to the fact that

191    they incorporate different types of polymer. To do this, samples of the different fractions

192    were placed in the oven, and the temperature was progressively increased from 60 ºC until

193    the material's consistency changed. A softening temperature of 180 ºC was obtained for

194    both materials, so it was decided to use said temperature for the heating of the aggregates

195    and the progressive softening of the plastic scrap. In this way, the polymer flakes managed

196    to adhere to and cover part of the aggregate.

197

198    *2.1.2. Bitumen and aggregates*

199    Semi-dense asphalt concrete mixture gradation AC16S (Table 2) was used as a

200    reference mixture (AENOR, 2007). A conventional bitumen B50/70 was used with a

201    penetration grade of 56.8·10-1 mm (Table 3). The pre-heating temperatures of the bitumen

202    and aggregates were 155 and 180ºC, respectively. The natural aggregates were crushed

203    limestone from a local quarry in Santander (Spain). Table 4 shows the bulk specific gravity

204    and water absorption coefficient of limestone for coarse and fine aggregates (AENOR,

205    2010).

206    The abrasion coefficient of Los Angeles (LA) obtained for limestone is 15%

207    according to the standard. This coefficient complies with the Spanish General Technical

208    Specifications for Roads (PG-3) (LA ≤ 25%) for heavy traffic categories. The sand

209    equivalent (SE) of the limestone was 63%, obtained according to the standard (AENOR,

210    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%).

*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

233   compacted to 75 blows per side for the Marshall test (four samples per combination), and

234   another 48 samples were compacted to 50 blows per side for the moisture damage test

235   (eight samples per combination) (AENOR, 2013a). For the rutting tests, roller compaction

236   was used on a total of 12 samples (two samples per combination) with the same bulk

237   density and air voids as the samples used in the Marshall design (AENOR, 2008a). The

238   temperature used in both compactions was 145ºC in order to maintain mixture workability

239   and reach the required density (AENOR, 2017).

240

241   ***2.2. Test plan***

242   *2.2.1. Marshall stability and flow test*

243       Twenty-four Marshall samples compacted to 75 blows per side were used—that is,

244   four identical samples for each of the six combinations. The bulk density, percentage of air

245   voids, voids in mineral aggregates (VMA), and voids filled with asphalt (VFA) of each

246   sample were calculated using the hydrostatic method (bulk density – dry saturated surface)

247   (AENOR, 2012a, 2006), whereby samples are dry-weighted and then saturated under water

248   and the bulk density is calculated using the water volume displaced. For the Marshall test,

249   samples were then conditioned at 60ºC for 45 minutes according to the standard (AENOR,

250   2013b). Afterwards, the test samples were tested in the Marshall press, at a displacement

251   rate of 50.8 mm/min, until reaching the maximum load. The resulting stability rate

252   corresponds to the maximum load resisted, in kN, and the flow is the value of deformation

253   in mm that the sample registered when reaching the maximum load value.

254

255 *2.2.2. Moisture damage test*

256    Forty-eight compacted Marshall samples compacted at 50 blows per side were used,

257 according to the standard (AENOR, 2009), with eight identical samples for each of the six

258 combinations. The eight samples available for each combination were divided into two

259 groups for conditioning, one wet and the other dry, according to the standard (AENOR,

260 2009). Samples under wet conditioning underwent a period of hydrostatic vacuum with 50

261 mm Hg absolute pressure for 30 minutes, then the samples were introduced to a water bath

262 at 40ºC for 72 hours, and finally the samples remained for two hours in a water bath at a

263 temperature of 15ºC before the test. After conditioning, all the samples were tested under

264 indirect tensile strength, at a displacement rate of 50.8 mm/min, until reaching the

265 maximum load. The ITS indirect tensile strength value was determined using Equation 1:

266

267 $$ITS = \frac{2 \cdot P}{\pi \cdot h \cdot D}, [GPa], \tag{1}$$

268

269 where *ITS* is the indirect tensile strength (GPa), *P* is the peak load (kN), and *h* and *D* are the

270 diameter and the height of the sample (mm), respectively.

271    The conserved TSR value was calculated using the ratio between the ITS of wet and

272 dry sample groups, as in Equation 2:

273

274 $$TRS = \frac{ITS_w}{ITS_d} \cdot 100, [\%], \tag{2}$$

275

276 where *TRS* is the conserved tensile strength ratio (%), *ITS*$_w$ is the indirect tensile strength

277 calculated for wet samples (GPa), and *ITS*$_d$ is the indirect tensile strength calculated for dry

278 samples (GPa).

279

280 *2.2.3. Resilient modulus test*

281 The resilient modulus test was carried out to determine the elastic stiffness of the

282 tested sample (AENOR, 2012b). This is a non-destructive test used to evaluate the

283 deformation capability of the asphalt mixture in the elastic range and thus estimate the

284 influence of the different materials in the reduction of crack appearance. The stiffness value

285 is a relation between the applied load and the deformation suffered by the sample under that

286 load. Forty-eight Marshall samples were used, with 24 specimens compacted at 50 blows

287 per side and another 24 samples compacted at 75 blows per side. The test was carried out

288 by applying a specific load haversine type during at least 15 cycles and measuring the

289 amplitude of the horizontal deformation of the test sample during the last five cycles. The

290 ascendant period was 124 ms, and the period of repetition of the impulses was 3.0 s. The

291 test was carried out at 20ºC. The resilient modulus value was calculated using Equation 3:

292

293 $$E = \frac{F \times (v + 0,27)}{z \times h},$$ (3)

294

295 where *E* corresponds to the measured resilient modulus (in MPa), *F* corresponds to the

296 maximum value of the vertical load applied (in N), *ν* corresponds to the Poisson coefficient

297 for asphalt mixtures, *z* corresponds to the range of the horizontal deformation obtained

298    during a load cycle (in mm), and *h* corresponds to the average thickness of the sample (in

299    mm).

300    The applied load for the test varied between 3.4 and 3.5 kN, adjusted to reach a

301    maximum horizontal deformation of reference of 0.005% of the diameter of the samples.

302

303    *2.2.4. Wheel tracking test*

304    The rutting test makes it possible to determine the resistance to permanent plastic

305    deformations in the asphalt mixtures by applying the cycles of a loaded wheel on the

306    surface of the samples under severe heat conditions (AENOR, 2008b). Twelve test samples

307    of 410x250 mm and a thickness of 50 mm were used. The conditioning and testing were

308    carried out in the air, at a temperature of 60 °C and for a duration of 10,000 cycles. In this

309    test, the rutting machine is set in motion and takes readings of the vertical displacement of

310    the wheel. With these readings, the value of the wheel-tracking slope in the air ($WTS_{air}$) can

311    be obtained using Equation 4, which indicates the grade of the deformation on the track for

312    1,000 load cycles:

313

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

315

316    where $WTS_{air}$ is the wheel-tracking slope (mm/$10^3$ load cycles), and $d_{5,000}$ and $d_{10,000}$ are the

317    rut depths after 5,000 load cycles or 10,000 load cycles, respectively (mm).

318    Additionally, the total rut depth value ($RD_{air}$) is obtained. This value corresponds to

319    the depth of the footprint in mm at the end of 10,000 load cycles.

320

## 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.

342    Once the percentage of air voids and bulk density was determined, Marshall

343    stability and flow tests were performed on the samples. All the series that incorporated

344    plastic scrap had stability values higher than the reference mixtures REF and REF1 (Fig. 3).

345    This is due to the higher stiffness of the plastic scrap compared to the binder at the

346    temperature of the test (60ºC), which was based on their softening point, which caused the

347    samples to have higher compression strength values. For fine plastic scrap, the highest

348    result was obtained with a 1:2 ratio of binder replaced with plastic scrap (PF2), while for

349    the coarse size the highest rate was 1:1 (PC1), which obtained the highest stability value.

350    This is because the small material coats the aggregate more easily, acting similarly to the

351    binder, while the coarse material acts as an aggregate attached to the natural aggregate, so if

352    an excess of the coarse material is added, it's easier to reduce the union between particles.

353    These results are also related to the compaction level reached by the different

354    combinations. While the samples with no plastic scrap particles reaches the regular level of

355    compaction and common values of bulk density and air voids, the combinations with

356    plastic scrap showed lower workability and compaction ability, resulting in mixtures with

357    lower bulk density, higher air voids, and more susceptibility to recompression during the

358    test.

359    The values obtained for the Marshall flow (Fig. 4) confirmed this behaviour.

360    Logical behaviour is expected for the reference mixtures REF and REF1, because when

361    reducing the binder content lower flow values are obtained. With the fine size, the flow was

362    reduced when the proportion of binder replaced by plastic scrap increased, resulting in a

363    more rigid and less deformable mixture. With the coarse size, an increase in the proportion

364    produced an excess of plastic scrap, causing the particles to separate easily and generate

365 more deformation and low resistance. It should be noted that this test is carried out in

366 moisture conditions at a temperature of 60°C, so the plastic scrap modifies the viscoelastic

367 property of the mixture in such a way that at higher temperatures, the mixture behaves

368 better because the polymer needs more heat to change its physical state.

369       Introducing plastic scrap and reducing the amount of binder increased the dispersion

370 of the results for both the Marshall stability and flow values, due to the random placement

371 of polymer particles inside the mixture, the same as what happened with bulk density and

372 air voids data. However, all the combinations obtained the minimal requirements both for

373 Marshall (minimum 9 kN) and flow (maximum 4 mm) results usually established in the

374 regulations (General Directorate of Roads, 2017).

375

376 *3.2. Moisture damage test*

377       The results obtained in the moisture damage test by ITS show that the mixtures with

378 plastic scrap did not increase the strength in any of the cases (Fig. 5). As the percentage and

379 size of plastic scrap rose, the ITS slightly decreased. However, differences among the

380 combinations are negligible.

381       The regulations indicate that a mixture's TSR value must be equal to or greater than

382 85% in order for it to be used as a surface layer (General Directorate of Roads, 2002). None

383 of the analysed combinations fulfilled that requirement; even the REF reference mixture

384 had a value of 84%. It can be seen that when a 10% binder is reduced (REF1), the TRS

385 value decreases to below 80%, so the product cannot be used as a base or intermediate layer

386 either.

387    In the case of mixtures with plastic scrap, lower affinity with the aggregate was

388    observed when compared to the binder-aggregate bonding, which makes water to generate

389    more damage in the mixture, resulting in a loss in the strength of the wet mixtures.

390    However, for fine material with 1:1 replacement (PF1) and coarse material with 1:2

391    replacement (PC2), the TRS value increased to over 80%.

392    For mixtures with coarse aggregate of plastic scrap, an increase in conserved TSR is

393    observed when the replacement ratio is increased. Despite the theoretical improvement in

394    the conserved strength, going from 79 to 81% of TRS, a deeper analysis of the absolute

395    results of ITS shows that these ITS values are higher and closer to the reference mixtures

396    when the replacement ratio is 1:1, so the overall behaviour of this combination is better

397    than the PC2.

398    Although mixtures with plastic scrap did not reach the limits set by regulations for

399    use in the surface layer, an increase in TRS was observed when compacted to the REF1

400    mixture. This suggests that the plastic scrap does not significantly affect strength and acts

401    in a similar way to a binder, especially for the fine size. In this case, the biggest problem is

402    the affinity that the aggregate has with the asphalt binder, which is the cause of the low

403    TRS values obtained in all mixtures.

404

405    *3.3. Resilient modulus test*

406    Figure 6 shows the resilient modulus obtained in each series of samples compacted

407    with 50 and 75 blows per side. When results for samples compacted with 50 blows per side

408    were analyzed, all the series were found to have values similar to or lower than that of the

409    reference mixture, except for mixture with 20% fine plastic scrap (PF2). The mixture with

410 10% fine plastic scrap (PF1) had the value closest to that of the reference mixture, which is

411 nearly identical. The rest of the series was less rigid, which indicates that at this compaction

412 level, the mixture would be more deformable in its elastic state and able to recover its

413 condition after the load disappears, thus preventing cracks in the pavement but being more

414 susceptible to plastic deformations.

415    When the mixtures compacted at 75 blows per side were analysed, an increase in

416 stiffness was observed in all combinations due to the increase in bulk gravity of the

417 samples. However, when increasing from 50 to 75 blows per side, the mixtures with plastic

418 scrap showed a higher percentage increase than that obtained in the reference mixtures REF

419 and REF1, since in this case, practically all the mixtures surpass the stiffness of the

420 reference mixture (REF). This indicates that plastic scrap needs greater compaction energy

421 to obtain the densities and behaviour required when it is placed on site, partly due to the

422 previous plasticizing of the polymer during its original manufacturing process.

423    It was observed that at both degrees of compaction, the stiffness of mixtures with

424 fine material (PF1 and PF2) increased when the plastic scrap ratio was also increased. In

425 mixtures with coarse material (PC1 and PC2) the stiffness decreased, maintaining the same

426 tendency as in the Marshall stability test. Fine plastic scrap was found to generate the

427 highest stiffness values at both levels of compaction. The highest values were obtained with

428 a ratio of 1:2 replacement of fine material (PF2). This is because material with this size of

429 particle can coat the aggregate more efficiently, so the bulk density rises and better

430 consolidates the mixture. In tests, the increase in the ratio of plastic scrap versus replaced

431 binder caused an increase in the dispersion of the results, especially in cases where a 1:1

432    ratio was exceeded, suggesting that the process of production for the mixtures needs to be

433    particularly well controlled.

434

435    *3.3. Wheel tracking test*

436         The results of the rutting test showed that all the mixtures with plastic scrap

437    provided better results than the reference mixtures. The more plastic scrap used, the faster

438    the settling and the lesser the rut depth ($RD_{air}$) at 2,000 and 10,000 cycles (Fig. 7). All the

439    mixtures with plastic scrap fit the minimum requirements specified in the regulations

440    ($WTS_{air} \leq 0.10$). However, the reference mixtures REF and REF1 presented higher final

441    deformations and deformation slopes, and in the case of the REF mixture, the allowed limit

442    was even exceeded (Table 6). The combination REF1 presented the most significant

443    permanent deformations and rut depth (Fig. 7), which were related to the lower amount of

444    binder included in the mixture and the low affinity of the binder with the aggregate.

445         The behaviour shown by the samples was complementary to that obtained in the rest

446    of the tests. It was observed that the plastic scrap stiffens the mixture and has good affinity

447    with the aggregate, which results in less plastic deformation.

448         The mixture with plastic scrap was less viscous at high temperatures. At the test

449    temperature of 60 °C, the permanent deformations of the mixture were reduced because the

450    polymers were more rigid than the binder. A behaviour similar to that obtained in the

451    Marshall stability test was demonstrated. That is why the determining parameters in this

452    test are the amount of binder included in the mixture and the ratio between the amount of

453    plastic scrap and binder replaced. A greater proportion of replacement material produces

21

454 less permanent deformation in the mixture. In this case, the particle size of the plastic scrap

455 had no significant influence on the test results when compared to the other parameters.

456

457 **4. CONCLUSIONS**

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

459 study:

460

461 - The use of plastic scrap added by dry method is feasible, provided that the

462     manufacturing process is controlled. Pre-mixing of the plastic scrap particles with the

463     aggregates of the mixture must be carried out for at least one minute so that the polymer

464     can partially envelop the aggregate and adhere to it. This process does not produce any

465     incompatibilities with the rest of the materials that could affect the behaviour of the

466     mixtures.

467 - Due to the way in which the plastic scrap interacts with the aggregate, the particles of

468     this material must have a size of less than 2 mm so that they envelop the aggregates

469     more easily and perform well in the presence of water. The index of air voids in asphalt

470     mixes increases when plastic scrap is used as a binder replacement, since the material

471     does not fill the voids released by the binder reduction, either in aggregate or in the

472     mixture, but only adheres to the aggregate.

473 - The mixtures with plastic scrap resist compression better, showing greater energy

474     dissipation and reduced permanent deformations. This is because this material has

475     higher stiffness than the binder it replaces, increasing the overall stiffness of the

476     mixture. For the same reason, these mixtures exhibit less viscosity at higher

477      temperatures. That is why these types of mixtures perform better in climatic zones with

478      medium and high temperatures but have a greater tendency to crack at low

479      temperatures.

480    -   The ratio of plastic scrap to binder replaced should not exceed 1:1 for any of the sizes

481      analysed, since this proportion produces the best overall behaviour in the mixtures,

482      improving their plastic properties without compromising their resistance or stiffness.

483

484      The results obtained in this study should be complemented by durability tests that

485    allow for evaluation of how the increase in stiffness of the mixtures is affected by plastic

486    scrap. Such evaluation can be carried out through the analysis of fatigue resistance and

487    dynamic modulus under cyclic loads at medium and low temperatures, resistance to

488    cracking and dissipated energy, and the assessment of the compaction energy required for

489    installation of the material.

490      Based on the partial results obtained, the use of plastic scrap as a dry binder

491    replacement can be considered feasible, allowing the use of an approximately one to two

492    tons of plastic scrap per kilometre, assuming a 5-cm-thick paved surface layer with two

493    lanes. The amount of asphalt binder in the manufacture of the mixture can be reduced by

494    about one ton. The amount of plastic scrap used and binder saved per kilometre could be

495    increased if the material is also used in lower layers of the pavement (base and binder

496    layers), which have lower requirements for strength and moisture damage resistance and

497    are built with greater thickness than the surface layers, generating a more significant

498    reduction in the environmental impact of the construction of this type of pavement.

499

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646

647    **FIGURE CAPTION**

648    Figure 1. Plastic scrap: a) coarse size; b) fine size

649    Figure 2. Percentage of air voids

650    Figure 3. Marshall stability

651    Figure 4. Marshall flow

652    Figure 5. ITS and TSR values (moisture damage test)

653    Figure 6. Resilient modulus

654    Figure 7. Wheel tracking test

655 **TABLES**

656 Table 1. Percentages of bitumen and plastic scrap

657 Table 2. Semi-dense AC16S gradation

658 Table 3. Characteristics of the binder

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

660 Table 5. Volumetric properties of the mixtures

661 Table 6. Wheel Tracking Slope and Rut depth

**Table**

Table 1. Percentages of bitumen and plastic scrap

| Series | Bitumen (%) | Plastic scrap | |
|---|---|---|---|
| | | Coarse (%) | Fine (%) |
| REF | 100 | - | - |
| REF$_1$ | 90 | - | - |
| PF1 | 90 | - | 10 |
| PG$_1$ | 90 | 10 | - |
| PF$_2$ | 90 | - | 20 |
| PG$_2$ | 90 | 20 | - |

**Table**

**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 |

**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/cm³ | EN 15326 | - | - | 1.035 |
| T° laboratory prep. | °C | EN 12594 | | | 130 |

**Table**

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

| Size (mm) | Bulk Specific Density (g/cm³) | 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 |

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

| Combination | Bulk Specific Gravity [g/cm$^3$] | 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 |

**Table 6.** Wheel Tracking Slope and Rut depth

| Combination | $RD_{air}$ [mm] | $WTS_{air}$ [mm per $10^3$ 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 |

**Figure 1**



A                                                                                    B

**Figure 2**

**Figure 3**

**Figure 4**

**Figure 5**

**Figure 6**

**Figure 7**