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Waste Plastic as Potential High-Value Solution for Asphalt Road Applications

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ABSTRACT. ANAS, the main Italian road agency, manages over 30,000 km of both local and national roads. In all cases, maintenance actions involve the reconstruction of the bituminous layers that require new aggregates and binder. This aspect, together with the need of acting in compliance with the new environmental regulations that increasingly push towards the recovery of waste and/or recycled materials for the construction of new bituminous mixtures, entails the study of innovative solutions that can be considered sustainable both from an environmental, technical and economic point of view.

Among the waste materials currently available on the market (open-loop materials), the so called "light plastics" recovered from municipal solid waste (MSW) represent a potential solution still under development. Plastics constitute a large percentage of the waste material that is difficult to recycle in other fields. However, waste plastics have a high potential for recovery in bituminous mixtures since their polymeric nature could act as a modifying agent in replacement and/or integration of the synthetic polymers usually added to the bitumen. This action can significantly improve the overall mixture performance and decrease production costs.

In order to validate this potential, ANAS has developed a study on the reuse of "light plastics" in the production of hot bituminous mixtures. The study includes a preliminary laboratory analysis to verify the effects on mechanical, volumetric and durability properties. Three different pre-treated wasted plastic materials were tested in different dosages to determine the optimum mix design and the most suitable mixing process. The results described in this paper, baseline to set up full-scale trial sections, represent the kick-off step to develop efficient, innovative and sustainable technological options for the production of new bituminous mixtures both from an environmental and economic point of view.

Keywords. Waste Plastic, Hot-Mix Asphalt, Recycling.

Introduction

The management of municipal solid wastes (MSW) is one of the major concerns for European Union. In particular, the Waste Framework Directive (2018) provides that the EU members will be prepared to reuse and recycle 55%, 60% and 65% by weight of the MSW by 2025, 2030 and 2035, respectively. According to the annual report by Italian Superior Institute for Environmental Protection and Research, waste plastics represent 8.6% of the MSW. In Italy, about 1.5 million tons of waste plastics generated in 2020 and the yearly production has been increasing (ISPRA, 2021). For this reason, the identification of solutions for waste plastic recycling is currently a key target. Due to their chemical and physical properties, recent international studies highlighted the possibility to include waste plastic in hot-mix asphalt (HMA) for road applications, either as bitumen modifier or as replacement for aggregate and binder (Willis et al., 2020; Wu and Montalvo, 2021). Waste plastics may include several types of polymeric materials, such as high-density polyethylene (HDPE), low-density polyethylene (LDPE), polyethylene terephthalate (PET), linear low-density polyethylene (LLDPE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), ethyl vinyl acetate (EVA) and others. These plastics are characterised by different melting point, ranging from 80 °C to 250 °C (Ma et al., 2021), i.e. straddling around the production temperature of HMA (140-180 °C). The waste plastics with low melting points (PE, PP, EVA, PVC) can be recycled through a wet process, which consists in adding them into the hot bitumen as a modifying agent. On the other side, the dry process, which consists in the addition directly into the mixture during HMA production at the plant, is suitable for all the waste plastics. The bitumen modified with waste plastics (wet process) showed improved rutting resistance, moisture resistance, and fatigue resistance of the binder blends. However, plastics with high melting point tend to increase more viscosity but reduce more ductility of the binder blends. This reflects into two potential concerns: the phase separation between binder and plastic and the low-temperature performance of the HMA (Ma et al., 2021, Nizamuddin et al., 2021). In the dry process, waste plastics may act as aggregates substitute or bitumen modifier, according to the melting point. The great advantage of the dry processing technique lies in the easiness, as no new equipment is required at the asphalt plant. Moreover, it does not increase the amount of fumes that are released during HMA production and laying, while in the wet process the bitumen releases fumes during modification (Vasudevan et al., 2012). In terms of HMA properties, increased rutting and moisture resistance of the mix was observed when waste plastics were added through dry process (Angelone et al., 2016; Giustozzi et al., 2022; Radeef et al., 2022). Several studies have focused on the dry processing of specific plastic wastes, obtained by separation of the different materials and, in some cases, further treatment (Moghaddam et al., 2014; Lastra-Gonzalez et al., 2016; Badejo et al., 2017; Willis et al., 2020; Noor et al., 2022) but few researchers tried to recycle the non-separated waste plastic in HMA. Movilla-Quesada et al. 2019 named “plastic scrap” the non-separated plastic waste and observed that it can partially replace bitumen without penalising the mix performance. In particular, they obtained higher strength and stiffness and lower permanent deformations compared to the reference mix without plastic scrap. Dalhat et al., 2019 contemporary used selected waste plastics through wet process (binder modification) and non-separated waste plastics through dry process. They found that the combined recycling of waste plastics allowed achieving a better performance compared to a reference mix with crumb-rubber modified bitumen in terms of viscoelastic properties, resistance to rutting and fatigue. However, they did not investigate how the different materials in the non-separated plastic waste interact with the hot aggregate and bitumen during mix production. In front of the few experiences, further studies on the recyclability of non-separated plastic wastes in HMA are required.

Objective and experimental programme

The overall objective of this study was to evaluate the potential use of plastic waste into asphalt mixes for binder layer. The experimental plan was structured in two subsequent steps (hereafter indicated as Step 1 and Step 2) and involved different plastic treatments and dosages, as well as different bitumen contents. Step 1 aimed at selecting the most suitable plastic treatment for the incorporation into dense graded HMA mixtures (binder layer) via dry process. Step 2 dealt with the mechanical characterisation of the HMA produced with the plastic treatment selected in the Step 1 and including two different plastic dosages. Two additional mixtures prepared without any plastic and with neat and Styrene-Butadiene-Styrene (SBS, 3.8% by bitumen weight) modified bitumen respectively, were used as reference for comparison. In Step 2, the bitumen content of the mixtures with plastic was properly reduced in order to obtain an air voids content similar to that of the reference HMA. Volumetric and mechanical properties were assessed in terms of air voids, Indirect Tensile Strength (ITS), Cracking Tolerance (CT) index, Indirect Tensile Stiffness Modulus (ITSM) and fatigue resistance. Plastic homogeneity and melting capacity were also investigated through visual analysis of aggregate mixtures before bitumen addition and after bitumen extraction. In order to minimise the variables potentially involved in the performance development, all mixtures were prepared with the same standardised mixing process commonly applied in the laboratory to produce HMA. Aggregates and bitumen were heated in the oven at 170° C for 3 and 1 hours, respectively. Applying the same approach used in asphalt plant with mixture modifiers, plastic wastes were added directly into hot aggregate mix before bitumen inclusion.

Materials

The so-called "light plastics" recovered from municipal solid waste (MSW) were selected after three types of treatment, i.e. shredding, densification and pelletising, as coded in Figure 1. They differ in size and treatment, but are consistent in terms of chemical composition and melting point as the original waste plastic was exactly the same. The shredded plastic was put in water to eliminate the heavy elements potentially incorporated in the material, which also visually showed high heterogeneity. Only the floating fraction (around 90%) after drying was used in the HMA mixtures. The densified plastic underwent a treatment only aimed at unifying the larger pieces of plastics, whereas the pelletised plastic has a granulate texture and derived from the densified ones through extrusion. The waste plastic content ranged between 0.5% and 2% by aggregate weight.

Figure 2 depicts the aggregate distribution of the HMA dense graded mixtures for binder layers produced in this study obtained by combining limestone virgin aggregates and filler, in compliance with the technical standards of the main Italian road agencies. The neat bitumen used in the study was a 70/100 penetration bitumen with a penetration of 73 dmm and a softening point of 47 °C. The same bitumen was used to prepare the first reference mixture (coded as "Neat"). The second reference mixture (coded as "PmB") included a commercial polymer modified bitumen 45/80 characterised by a lower penetration value (53 dmm) and a higher softening point (i.e. 74 °C). The optimum bitumen content was found to be equal to 4.9% by aggregate weight for the reference mixtures without plastic, both in the case of neat and SBS modified bitumen. In the case of mixtures with plastic wastes, in Step 1 the investigated bitumen contents were 4.9% (for all the plastic dosages) and 4.2% (only for the highest plastic dosage, i.e. 2.0%) by aggregate weight. In Step 2, the bitumen content was optimised with the aim to guarantee the same volumetric properties for all the tested mixtures and varied from 4.0% to 4.9% depending on the plastic amount. The experimental plan involved the preparation of gyratory compacted specimens with standard compaction parameters (vertical pressure 600 kPa; rotation speed: 30 revolutions/min; vertical mould inclination: 1.25°). According to the Italian specifications for binder layers, 120 gyrations were applied to prepare specimens with 100 mm diameter and about 60 mm height. All the mixtures with plastic wastes (coded as "*plastic treatment_ % plastic _%bitumen*") were produced with a neat bitumen in order to better identify the potential modifying power of the plastic.

A (shredded plastic) **B (densified plastic)** **C (pelletised plastic)**

Figure 1. Waste plastics recovered from municipal solid waste (MSW).

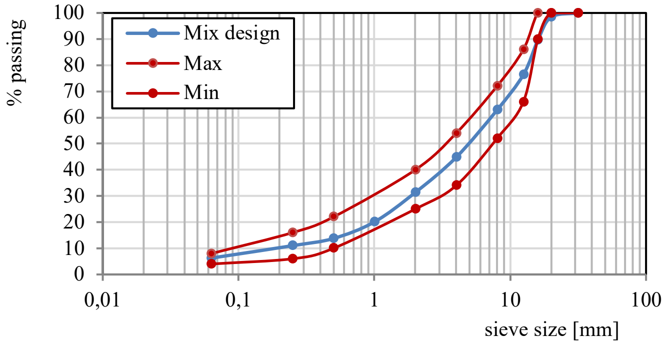

Figure 2. Aggregate gradation distribution.

Test protocols

The volumetric properties were investigated in terms of air voids content by using the maximum and bulk densities of the mixtures measured according to EN 12697-05 (procedure C). Along with the volumetric assessment, visual inspections of the aggregates with plastic before bitumen addition and after bitumen extraction were carried out to verify the capability of each treated plastic to effectively melt and homogeneously dissolve into the HMA, so demonstrating the plastic coating power of the aggregate and the potential extent of mix modification. A servo-pneumatic testing machine was used to characterise the mixtures in terms of Indirect Tensile Stiffness Modulus (ITSM) at 20 °C, according to EN 12697-26 Annex C. During the test, repeated load pulses with a rise time of 124 ms and a pulse repetition period of 3.0 s were applied. For each specimen, the load was adjusted using a closed-loop control system in order to achieve a target horizontal (diametral) deformation of 5 µm.

The Indirect Tensile Strength (ITS) was measured at the temperature of 25 °C by means of an electromechanical press, imposing a constant rate of deformation of 50 ± 2 mm/min until specimen failure occurred (EN 12697-23). According to ASTM D8225-19, from ITS test data the Cracking Tolerance (CT) Index, representing the ductile features of the HMA mixtures, was calculated as follows:

$$\text{CT-Index} = \frac{t}{62} \cdot \frac{G_f}{\frac{P}{l}} \cdot \left(\frac{l}{D}\right) \qquad (1)$$

where t and D are specimen thickness and diameter respectively; the fracture energy G_f is determined as the area under the force-displacement curve divided by the fracture surface ($t \cdot D$); l and P/l are the displacement and the slope of the load-displacement curve when the load is reduced to 75% of the peak. Generally, the lower the CT Index, the higher the material brittleness.

Cyclic indirect tension fatigue tests (ITFT) were performed for evaluating the fracture resistance due to cycling loading according to EN 12697-24 Annex E. The tests were carried out at a temperature of 20 °C in controlled stress mode, by applying a pulse load with 0.1 s loading time and 0.4 s rest time. Three horizontal stress amplitudes were fixed in order to obtain a fatigue life between one hundred and one million cycles. The fatigue failure of the specimen $N_{f=50}$ was assumed in correspondence to the number of load applications when the stiffness modulus decreased to half its initial value. All the tests provided 4 repetitions under the same conditions. Table 1 summarises the experimental programme.

Table 1. Summary of the experimental programme.

<table>
<tr><th colspan="6">Step 1</th></tr>
<tr><th>Property</th><td>Air void</td><td>ITS</td><td>CT Index</td><td>ITSM</td><td>Melting capacity</td></tr>
<tr><th>Norm</th><td>EN 12697-8</td><td>EN 12697-23</td><td>ASTM D8225</td><td>EN 12697-26</td><td>-</td></tr>
<tr><th>Tested mixes</th><td>Neat_4.9</td><td>PmB_4.9</td><td>A_1.0_4.9
A_2.0_4.2</td><td>B_0.5_4.9
B_1.0_4.9
B_2.0_4.9
B_2.0_4.2</td><td>C_0.5_4.9
C_1.0_4.9
C_2.0_4.9
C_2.0_4.2</td></tr>
<tr><th colspan="6">Step 2</th></tr>
<tr><th>Property</th><td>Air void</td><td>ITS</td><td>CT Index</td><td>ITSM</td><td>Fatigue</td></tr>
<tr><th>Norm</th><td>EN 12697-8</td><td>EN 12697-23</td><td>ASTM D8225</td><td>EN 12697-26</td><td>EN 12697-24</td></tr>
<tr><th>Tested mixes</th><td colspan="5">Neat_4.9 PmB_4.9 C_0.5_4.7 C_2.0_4.0</td></tr>
</table>

Results

Step 1

Melting capacity

One key aspect to judge the feasibility of adding plastic into a HMA is surely the plastic capability to melt and disperse into the mix to properly coat the aggregates and react with the bituminous phase. In this sense, a preliminary mixing attempt was performed using an intermediate plastic dosage (1% by aggregate weight) for all the plastic treatments. At the end of the first mixing (hot aggregates + cold plastic) it was noticed that, when shredded plastic A was used (Figure 3a), some plastic fragments did not properly melt, creating evident lumps. This negative effect significantly reduced with the densified plastic B (Figure 3b) and almost disappeared with the pelletised plastic C (Figure 3c). Anyway, it should be observed that in no case the plastic completely dissolved: some plastic residues, even if small, could be found among aggregates also when using pelletised plastic. This behaviour was confirmed by the visual inspection carried out on HMA residue after bitumen extraction (Figure 4). The aggregates recovered from HMAs prepared with plastic A showed pieces of plastic of significant dimensions (some cm). With the plastic B, the recovered aggregates were characterised by the presence of clusters composed of aggregates and plastic not completely melted. With plastic C, only residues retained at 1 mm sieve (characterised by darker colour than the limestone sand) were detected and no visible cluster or lumps were identified. Based on this preliminary analysis that showed the difficulty to properly melt the plastic particles with large size, the investigation of mixtures with shredded plastic A was limited to only one plastic dosage (1%), whereas HMAs with plastic B and C were prepared with all the three dosages originally planned.

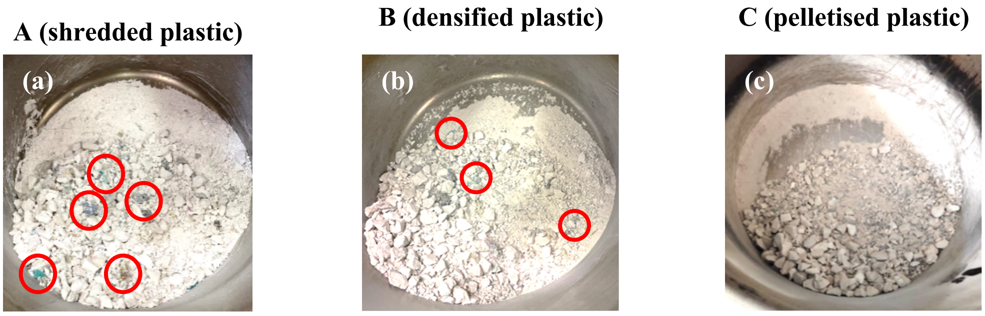
A (shredded plastic) B (densified plastic) C (pelletised plastic)

Figure 3. Melting capacity - aggregates after a first mixing @ 170 °C.

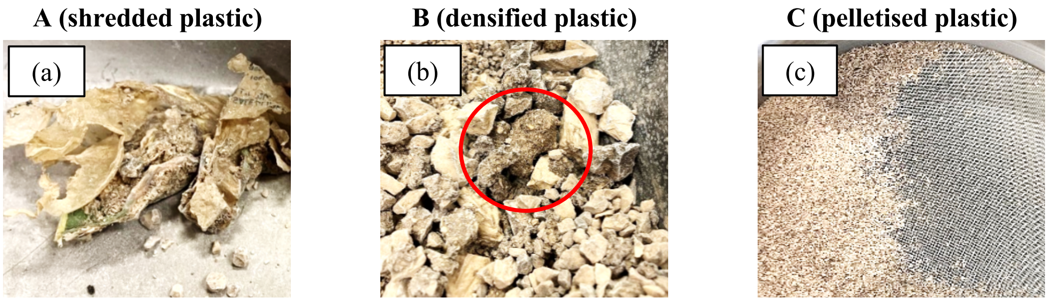
A (shredded plastic) B (densified plastic) C (pelletised plastic)

Figure 4. Melting capacity – aggregates and plastic after bitumen extraction

Volumetric properties

The air voids content (V_m) values are summarised in Figure 5. The results clearly show that the higher the plastic amount, the lower the air voids, due to a sort of lubricating effect of plastic that helps mixture workability. Air voids were significantly lower compared to both traditional and modified HMA. At the same time, no significant differences were detected as function of plastic treatment at equal plastic dosage. Lowering the bitumen percentage of the mixture at equal plastic dosage (i.e. from 4.9% to 4.2% by aggregate weight) allowed raising the air void content. In particular, the plastic C, which was able to melt almost completely in the mixture, contrarily to plastic A and B, showed lower air voids. Therefore, the plastic treatment which melts more (i.e. C) is able to affect more significantly mixture compactability when the amount of bitumen decreases, probably because the melted plastic acts as a replacement of the bitumen.

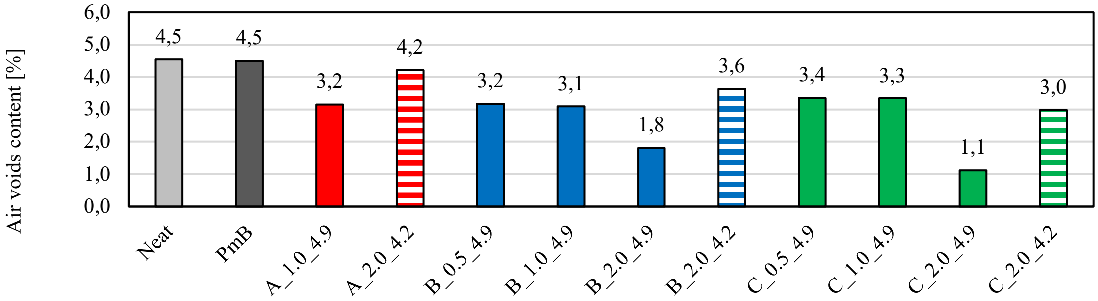

Figure 5. Phase 1: air voids content

Indirect Tensile Strength Modulus (ITSM)

Figure 6 shows mixture stiffness as function of plastic treatment and dosage and bitumen dosage. It can be observed that the waste plastic determined a significant stiffening effect compared to the reference mixtures with neat and polymer-modified bitumen. Generally, the higher the plastic amount, the higher the stiffness. Between the different waste plastic treatments, higher ITSM values were obtained for plastic A, whereas plastic C showed the lower values, under the same dosage of waste plastic and bitumen. Considering that the higher the plastic amount, the lower the air voids, the stiffening effect may partially depend on the higher density grade reached with higher plastic amounts. Moreover, the higher ITSM values obtained for the HMA with waste plastic compared to the reference mix PmB can also be due to the different polymer dosage and type (in the PmB there is 3.8% SBS by bitumen weight). It is interesting to notice that even with a lower bitumen amount, HMA mixtures were able to guarantee same stiffness performance, demonstrating that the plastic has the potential to compensate for the absence of a certain amount of bitumen as previously observed with the volumetric analysis.

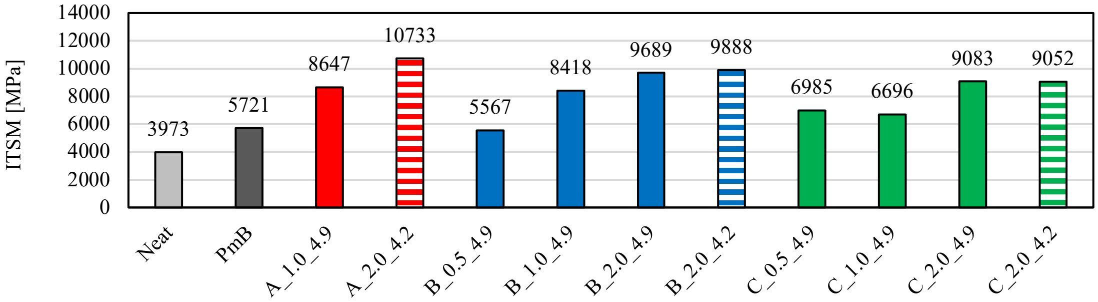

Figure 6. Phase 1: ITSM values

Indirect Tensile Strength (ITS) and Cracking Tolerance Index

In accordance with the local technical standards, the performance analysis needed for evaluating the acceptability of a mixture is primarily based on the Indirect Tensile Strength (ITS). The results are summarised in Figure 7.

Compared to the reference mixture with neat bitumen, all materials including plastic showed higher ITS values, which rose with the increase in plastic dosage. In particular, ITS similar to that of the mix with PmB were obtained with plastic dosages of 1% or 2%. This demonstrates the potential of plastic to improve the mechanical resistance of the mixture. It is worth nothing that the higher values detected were still within the limits prescribed by the Italian technical standards for binder layers regardless of the plastic treatment, which did not significantly influence the ITS.

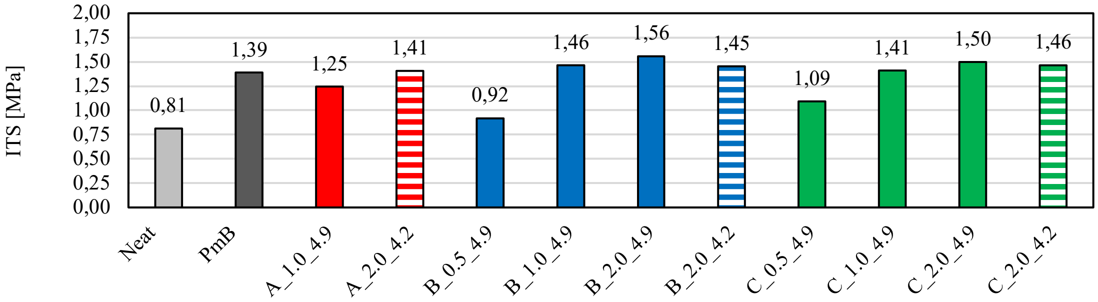

Figure 7. Phase 1: ITS values

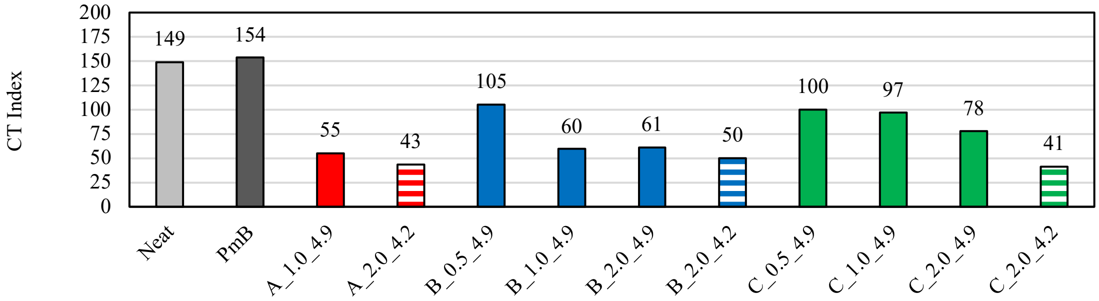

Figure 8. Phase 1: CT Index values

Analogously to what already observed in terms of ITSM, the reduction of the bitumen content in the mixture did not appear detrimental in terms of mechanical performance, as comparable ITS values were recorded for both 4.2% (striped columns) and 4.9% (full columns) bitumen contents regardless of the plastic treatment. ITS test data were also analysed in terms of CT index, which represent the ductile properties of the HMA specimens after failure (Figure 8). The analysis of the CT indexes showed higher brittleness (lower CT) for all the mixtures incorporating plastic, compared to the reference mixtures with neat or modified bitumen. Particularly, HMAs prepared with shredded plastic A showed the highest brittleness tendency. Consistently with the previous results, the higher the plastic dosage, the higher the material brittleness, although the brittleness rate tended to decrease with the increase in plastic amount and no significant difference was detected between 1 and 2% of plastic. Moreover, it can be noted that the brittleness increased with the decrease in bitumen content. This behaviour is probably a consequence of the higher impact of plastic in a lower amount of bitumen (plastic/bitumen ratio).

Step 2

Air voids and mechanical properties

In the second part of the experimental programme, as the air voids content in the HMA showed to decrease when increasing the waste plastic content (Figure 5), new mixtures including the plastic C (0.5% and 2%) were produced with reduced bitumen contents (respectively 4.7% and 4.0% by mix weight) in order to obtain air voids comparable with the reference mixtures.

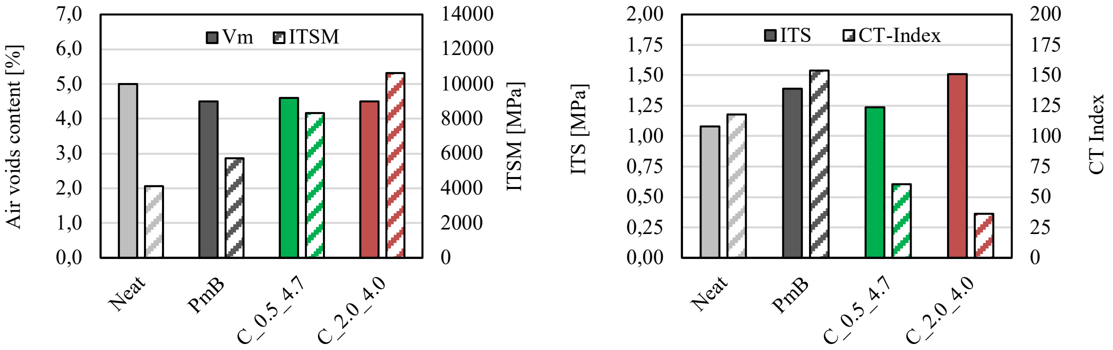

Figure 9. Phase 2: Air voids content, ITSM, ITS and CT Index values

Figure 9 shows the voids content and the mechanical properties (ITSM, ITS and CT Index) of the mixtures investigated in Step 2. From the graphs, similar air voids percentages, ranging between 4.5 and 5%, were observed. The same trend of stiffness already detected in Step 1, with an increase in the ITSM values when the plastic dosage increased, was noted. Moreover, the results show that the increase in ITS values already detected in Step 1 cannot be consequence only of the lower air void contents. In fact, the increase in the plastic content determined an increase in the mixture strength even with the same amount of air void percentage. At the same time, the CT Index decreased significantly when the plastic amount increased, confirming a brittle tendency due to the presence of plastic.

Cyclic indirect tension fatigue tests (ITFT)

The resistance to repeated loading was evaluated through the cyclic indirect tension tests. The results are plotted in Figure 11, where the number of cycles to failure is reported as a function of the initial maximum horizontal deformation ($\varepsilon_{init-horiz-max}$). It is worth noting that the regression lines drawn in Figure 11 are only indicators of the fatigue life, which is also correlated to other variables not completely taken into account in this kind of test. Particularly, the ITFT defines the crack initiation characteristics of the studied mixtures (resistance to early cracking). In this sense, the graph of Figure 11 should be analysed in correlation with the CT Index results.

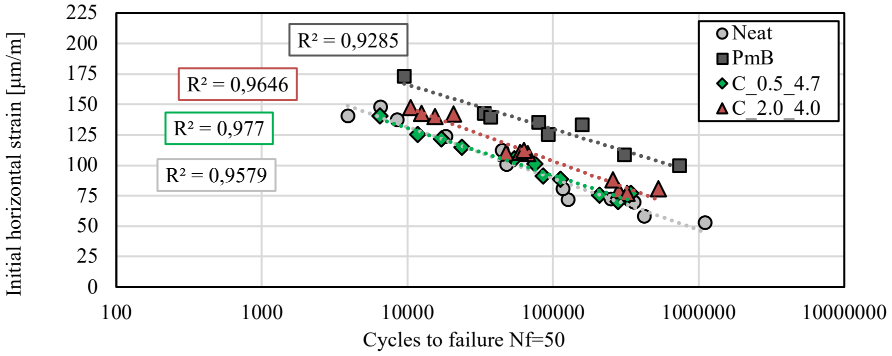

Figure 11. Phase 2: Fatigue behaviour

Although the CT Index indicated that the presence of plastic into the mixture determines a more brittle behaviour, ITFT results suggest that the presence of plastic in a certain amount (i.e. 2%) is able to delay the crack initiation compared to a traditional HMA leading to a fatigue resistance more similar to a polymer modified HMA, whereas the low plastic dosage (i.e. 0,5%) cannot provide any significant contribution. Anyway, even with the highest dosage of plastic (i.e. 2%) the performance ensured by a SBS-modified bitumen is better and associated with higher ductility and elasticity. Therefore, HMAs with a certain amount of plastic demonstrated the potential to postpone the crack formation, also due to the higher stiffness provided by the plastic, but once the crack was formed, it was observed that this fracture was associated with a sample collapse, clear symptom of the brittle behaviour of the material.

Conclusions

The present research aimed at exploring the possibility of recycling plastic from MSW in HMA without separating the several materials included in this waste. Quick and rather economic processing, i.e. shredding, densification and pelletising, were applied on the heterogeneous plastic wastes, which were included in laboratory-produced HMA in different dosages up to 2% by aggregate weight. The experimental campaign allowed observing that all the plastic types partially melt during HMA mixing, but pelletised plastic (type C) allows avoiding the formation of large aggregate-plastic clusters that can affect the mix mechanical behaviour. The presence of waste plastic determines an increase in stiffness and strength of the HMA (the higher the amount, the higher the effect), which positively influenced the resistance to crack formation in cyclic fatigue tests. However, the waste plastics also entailed a reduction of the ductile features in the post-failure behaviour. Finally, test results showed that waste plastics can act as a bitumen extender, since they allow reducing the bitumen dosage without penalising the volumetric and mechanical properties.

At the light of the promising findings, future investigations will focus on low temperature behaviour, moisture sensitivity, ageing, rheology, and surface characteristics of the HMA including waste plastics, with particular reference to the potential of plastics to improve adhesion and grip performance. Moreover, trial sections will be built in order to validate laboratory results and assess plant production, field constructability and workability.

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