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MECHANICAL ANALYSIS OF ASPHALT MIXTURES PRODUCED WITH WASTE PLASTIC MODIFIED BINDERS

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ABSTRACT

This work compares the viscoelastic properties of an asphalt binder (70/100 pen) modified with different waste plastics and the mechanical properties of resultant asphalt mixtures. Two different plastic wastes were used, namely recycled HDPE and recycled EVA. Three different polymer modified binders were produced with these plastic wastes: i) 5% HDPE modified binder (P5); ii) 5% EVA modified binder (E5) and; iii) a combined modified binder with 4% of EVA and 2% HDPE (E4P2). Asphalt mixtures were produced with these modified binders, and their mechanical properties were analysed and compared with a conventional mixture produced with a30/50 pen bitumen. It was possible conclude that the recycled polymers used improve the mechanical performance of the asphalt mixtures used in road paving.

Keywords: waste plastic modified binder, asphalt mixture, mechanical performance, road pavement.

INTRODUCTION

Road pavements are very important infrastructures for the Society, but they can cause serious environmental impacts from construction to rehabilitation, thus being essential to develop solutions that promote their durability, even more in an increasingly demanding scenario. The asphalt mixture, a matrix of aggregates linked with an asphalt binder, is one of the most important materials used for road paving. The asphalt binder is the most valuable constituent and largely responsible for the asphalt mixture performance (Becker, 2001).

In order to produce mixtures with the necessary resistance to the demands resulting from climate and traffic, their asphalt binder must meet certain requirements. These requirements are mainly rheological. The binder must be fluid enough to allow homogenous coating of aggregates. At road high service temperatures the binder must be rigid enough for pavements with good rutting resistance. Paradoxically, at road low service temperatures the binder must be ductile enough for pavements with good cracking resistance (Lesueur, 2009). One way to overcome this requirement of paradoxical properties goes through extend the range of binder's use temperatures, typically by using additives or modifiers, among which stand out the polymers. However, the use of virgin polymers can even double the final price of asphalt binders and is not the best environmental solution (Kalantar, 2012).

Previous studies mentioned that the use of waste plastic can be promising for road paving (Costa, 2013a, Costa, 2013b), and that the use of recycled polymers may show a similar or improved road performance compared to the use of virgin polymers (Fuentes-Audén, 2008).There are several plastic waste mentioned in the current literature for the bitumen modification: low density polyethylene (LDPE) (García-Morales, 2006), high density polyethylene (HDPE) (Hınıslıoğlu, 2004), polypropylene (PP) (Casey, 2008), ethylene-vinyl acetate (EVA) (García-Morales, 2004, Isacsson, 1999), acrylonitrile-butadiene-styrene (ABS) (Casey, 2008), polyethylene terephthalate (PET) (Ahmadinia, 2012) and polyvinyl chloride (PVC) (Kalantar, 2012). However, not all of these polymers are suitable for bitumen modification. For example, PVC cannot be heated at high temperatures because it can cause dangerous emissions into the atmosphere, and PET has a high potential for its own recycling. Besides, it is always necessary to check if there is enough amounts of the waste plastic to be used in road pavement, in order to make each specific case study a viable solution.

In previous work, several of these waste plastics were tested, and the most promising ones that passed into this phase of the study were HDPE and EVA. Thus, the aim of this study is to evaluate the effect of adding these two different waste plastic materials on the viscoelastic properties of the asphalt binder and, consequently, in the mechanical performance of the resulting asphalt mixtures.

MATERIALS

The materials used in this study included two different penetration grade bitumens:

- a 35/50 used as control binder (being the neat bitumen typically usually used in Portugal), and;
- a 70/100 penetration grade bitumen used in the modification process.

The waste plastics used for bitumen modification were recycled HDPE and EVA, because:

- they appear as being some of the most promising in the literature review;
- the waste management company that supplied these materials had large quantities of HDPE, while EVA was selected as being the only waste plastic with some elastic properties that they are collecting during this work;
- these were the ones with best results in previous studies (Costa, 2013a, Costa, 2013b).

Thus, three modified binders were produced with these two waste plastic materials:

- P5 – 70/100 pen bitumen modified with 5% of HDPE;
- E5 – 70/100 pen bitumen modified with 5% of EVA;
- E4P2 – 70/100 pen bitumen modified with 4% of EVA and 2% of HDPE.

The modification was performed in an IKA T65 ULTRA-TURRAX disperser during 20 minutes at 160 ºC, at 3200 rpm.

Later, granite aggregates and limestone filler were used for asphalt mixtures' production. Table 1 shows the percentage of each fraction of aggregates used in the asphalt mixtures production, and Figure 1 shows additionally the detailed sieve size gradations limits for an AC14 Surf mixture used in this work, according to the Portuguese specifications.

Table 1 - Percentage of each fraction of aggregates used in the AC14 Surf mixture

Filler	Fraction 0.5/2	Fraction 2/4	Fraction 0/4	Fraction 4/6	Fraction 6/14	Fraction 10/14
2.5%	3.0%	8.0%	36.0%	11.0%	29.0%	10.5%

The binder content of each asphalt mixture produced in this study was determined using the Marshall Mix Design Methodology according to the EN 13108-1 standard and binder/bitumen content determined was 5.0%.

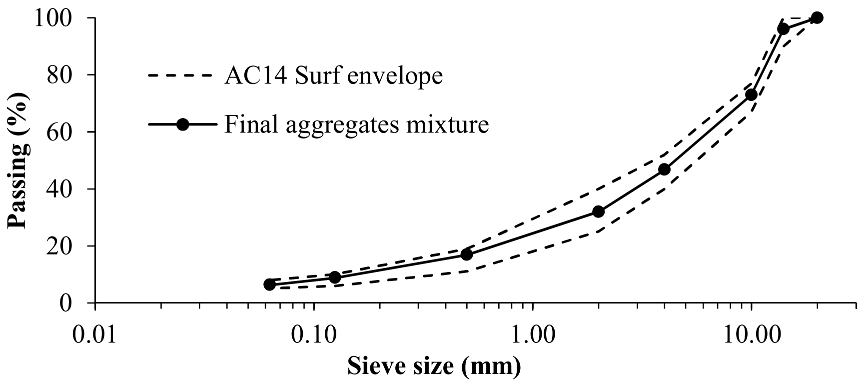

Fig. 1 - Grading curve specification limits and final aggregates mixture

METHODS

The basic asphalt binder's properties were first assessed, namely the softening point temperature according to the EN 1427 standard, the penetration value according to the EN 1426 standard, the recovery after penetration (resilience) according to the EN 13880-3 standard and the dynamic viscosity according to the EN 13 302 standard.

The asphalt binder's rheological properties were also evaluated, and the tests were performed within the material's linear viscoelastic response limits (Petersen, 1994). The dynamic measurements were carried out at 30, 45, 60, 70 and 80 ºC. Two different strain levels were used for each temperature and the overlapping results prove that the test was performed in the linear limits of the material.

For sample preparation, the asphalt binders were poured into rubberized moulds before being used for rheological testing. The rheometer used to characterize the thermal behaviour was the TA instruments AGR2 (rotational) which operates under strain control. The test geometries were plate-plate (40 mm diameter, 1 mm gap). At each test temperature, the range of frequencies tested was 100 to 0.01 Hz in order to obtain the master curves of the dynamic response of the material.

The validity of time-temperature superposition principle (TTSP) for rheological simple materials (as those evaluated in this work) facilitates the production of master curves at the reference temperature (60 ºC) by shifting the frequency sweeps measured at different temperatures along the frequency axis until they form a continuous curve.

In a second phase of this work, the mechanical properties of the asphalt mixtures produced with the binders developed in study were evaluated, namely the rutting resistance, the stiffness and the fatigue resistance.

The rutting resistance of the asphalt mixtures was assessed by means of the Wheel Tracking Test, according to the EN 12697-22 standard, using the procedure B (in air), with a standard wheel load of approximately 700 N. The test was carried at the temperature of 50 ºC, as being representative of the hotter summer days in Portugal.

The stiffness modulus test was carried out on prismatic specimens, using the four-point bending configuration (4PB-PR), according to the EN 12697-26 standard. The test was carried out at 20 ºC for a range of frequencies (0.1, 0.2, 0.5, 1, 2, 5, 8 and 10 Hz). However, EN 13108-20 establishes the temperature of 20 °C and the frequency of 8 Hz to determine and assign the stiffness modulus of one asphalt mixture. The results are represented by the stiffness modulus and the phase angle, which are the most relevant properties of viscoelastic materials such as asphalt mixtures.

Besides, it is also important to assess the stiffness modulus variation in a larger frequency range (as the assessment previously made to asphalt binders). Thus, the stiffness modulus and phase angle were also measured at 0, 10, 30 and 40 ºC, in the same range of frequencies, and based on the time-temperature superposition principle, used to relate the equivalence between frequency and temperature, it is possible to construct master curves, in this case using the test temperature of 20 ºC as reference.

The fatigue resistance of the studied mixtures was also determined using the four-point bending beam test procedure, according to the EN 12697-24 standard. The test was carried out at 20 ºC, in strain control mode, and using a frequency of 10 Hz. The fatigue resistance of the studied mixtures can be represented by Equation 1, which relates the level of extension applied in the test (ε_0) with the number of load cycles (N) that cause the test specimens failure (reduction of stiffness to half of its initial value).

$$N = a * \left(\frac{1}{\varepsilon_0}\right)^b \qquad (1)$$

Where:

N is fatigue resistance of bituminous mixture;

ε_0 is the tensile extension;

a, b are coefficients determined experimentally.

RESULTS

Characterization of the asphalt binders

The results of the asphalt binders' basic tests are presented in Figure 2. The results obtained from the empirical penetration test at 25 °C can be related with the stiffness of the asphalt binders and mixtures at in service temperatures. The results of the Ring & Ball test are usually related with the high temperature resistance or rutting resistance, as well as the resilience test results. The viscosity results are related with the flow of the binder at production temperatures, which should assure the needed workability to the asphalt mixture.

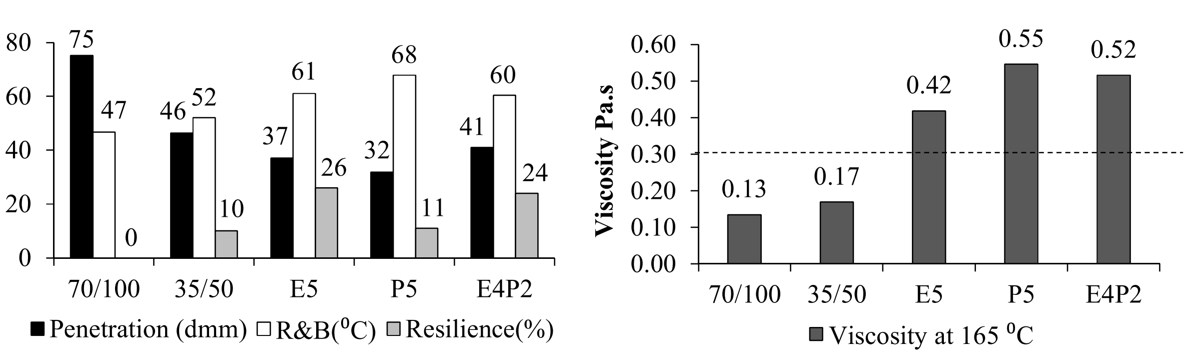

Fig. 2 - Basic properties of the unmodified and waste plastic modified asphalt binders

Looking at the variation between the properties of the 70/100 unmodified bitumen and those of the binders modified with waste plastic it could be concluded that the addition of waste plastic decreases the penetration value, being the HDPE the most effective modifier.

Moreover, the addition of waste plastic reduced the penetration of the modified binders into values below that of 35/50 control bitumen. The same tendency occurs even more sharply in the softening point results, with the modified binders presenting softening temperatures clearly higher than that of 35/50 control bitumen.

According to the resilience results the addition of waste plastic increases the recovery after penetration, being the EVA the most effective plastic waste due to its elastomeric nature.

The viscosity results were obtained at 165 ºC, which is the typical asphalt mixture production temperature for the control bitumen 35/50. The viscosity should be low enough at this temperature to allow an adequate coating of aggregates during mixture production. Looking at the results, all waste plastic materials increased the viscosity at 165 ºC, and thus the mixtures with these modified binders should be produced at higher temperatures. Among the binders produced with waste plastic, the modified with EVA was the one with best workability.

Next, the results of the rheological tests related to the complex modulus are presented in Figure 3, while those related to the phase angle are presented in Figure 4.

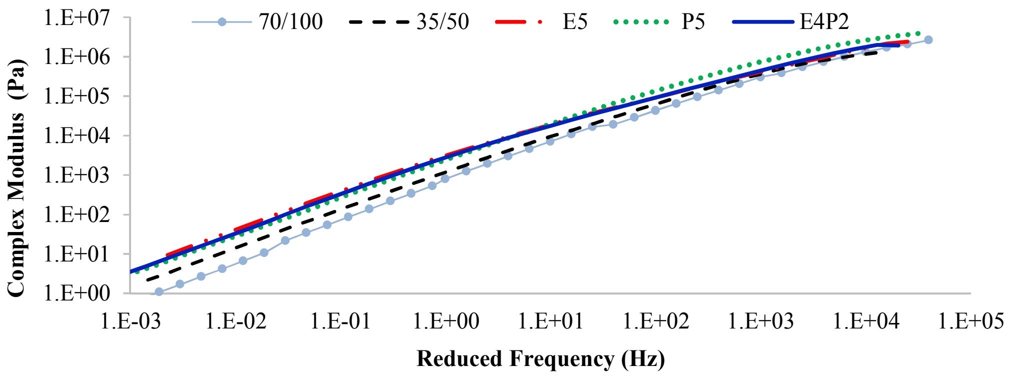

Fig. 3 - Complex modulus master curves of the unmodified and waste plastic modified asphalt binders

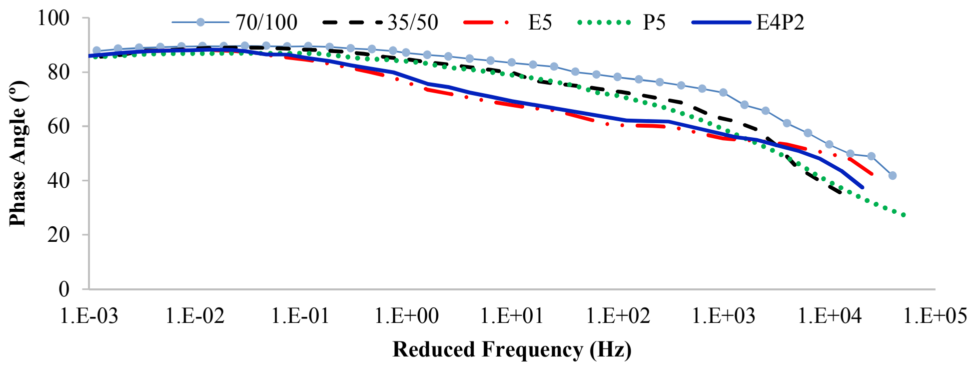

Fig. 4 - Phase angle master curves of the unmodified and waste plastic modified asphalt binders

Regarding the complex modulus at high frequencies or low temperatures, according to the TTSP, it can be seen that the binder P5 (HDPE) has a higher stiffness modulus and, therefore, the corresponding mixture is expected to have increased stiffness and reduced performance in the fatigue test. The other waste plastic modified binders, E5 (EVA) and E4P2 (mixed system), have very similar values of complex modulus at all frequencies. At low frequencies or high temperatures all modified binders have stiffness modulus higher than the control bitumen (35/50), and thus they should have better rutting resistance performance.

The phase angle shows the relationship between the elastic and viscous properties of a binder. The E5 and E4P2 binders have lower phase angle values in a wider range of frequencies and temperatures, which means that they can provide more elastic behaviour and less viscous deformation to the asphalt binder in various conditions. The control bitumen (35/50) and P5 modified binder have higher values of phase angle that result in a less elastic behaviour.

Characterization of the asphalt mixtures

The first property of the asphalt mixtures evaluated in this work was the rutting resistance, and the wheel tracking test results obtained are shown in Figure 5. The curves represent the evolution of the rut depth in the asphalt mixtures samples up to 10 000 load cycles.

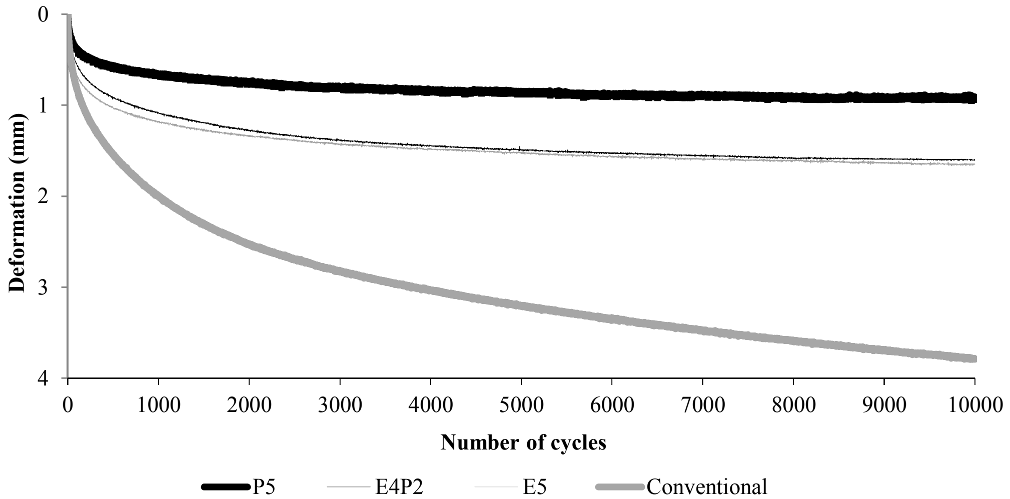

Fig. 5 - Wheel tracking test results of the conventional and waste plastic modified asphalt mixtures

As stated before, the mixtures with waste plastic modified binders presented a better performance at high temperatures than the conventional mixture with 35/50 bitumen. Among these, the mixtures using HDPE modified bitumen (the isolated system P5 and the combined system E4P2) were those with higher rutting resistance. Being HDPE a plastomer, it should increase the asphalt binder stiffness, and therefore the corresponding mixture stiffness, which is beneficial at high operating temperatures. The best rutting resistance result of the mixtures with HDPE modified binder confirms the results previously obtained in the binder's softening point test, wherein the modified HDPE binder had the best performance.

The summary of the results related to the rutting resistance test are reported in Table 2. The permanent deformation variation (WTS_{AIR}) in the test is calculated by Equation 2. The parameter PRD_{AIR} (rut proportional average depth) is calculated by Equation 3.

$$WTR_{AIR} = \frac{d_{10000} - d_{5000}}{5} \quad (2)$$

$$PRD_{AIR} = \frac{RD_{AIR}}{e} \times 100 \quad (3)$$

Where:

RD_{AIR} – average rut depth (mm);

e – specimen thickness (mm);

d_{10000} – rut depth after 10 000 cycles;

d_{5000} – rut depth after 5 000 cycles.

Table 2 - Rutting resistance parameters of the conventional and waste plastic modified asphalt mixtures

Properties	Conventional	E5	P5	E4P2
WTS_{AIR}	0.12	0.02	0.01	0.02
PRD_{AIR}	9.37	4.08	2.26	3.93

Both parameters confirm the previous observations in relation to the excellent performance of the mixtures with waste plastic modified binders in the wheel tracking test, and in particular the mixtures with HDPE. Thus, the waste plastic materials are able to increase the viscosity of the binder at 50 ºC, consequently increasing the stiffness of the resultant mixtures.

The stiffness test results of the several asphalt mixtures are represented in the Table 3. Then, the master curves of the stiffness modulus and phase angle are presented in Figure 6, where the temperature/load frequency variation susceptibility can be easily evaluated.

Table 3 - Stiffness modulus and phase angle results at 20 °C and 8 Hz for the conventional and waste plastic modified asphalt mixtures

Properties	Conventional	E5	P5	E4P2
Stiffness modulus	5973	4613	4699	5736
Phase angle	19	19	18	16

At the standard temperature of 20 °C and frequency of 8 Hz, the E4P2 and conventional mixtures are those with highest stiffness modulus, whereas the E5 and P5 mixtures have lower and very similar stiffness values. A high stiffness modulus can be favorable in terms of pavement design, reducing the total thickness of the road pavement. However, stiffer asphalt mixtures tend to have lower fatigue resistance performance. Thus, it is important to find a good balance between stiffness and flexibility in these new asphalt mixtures.

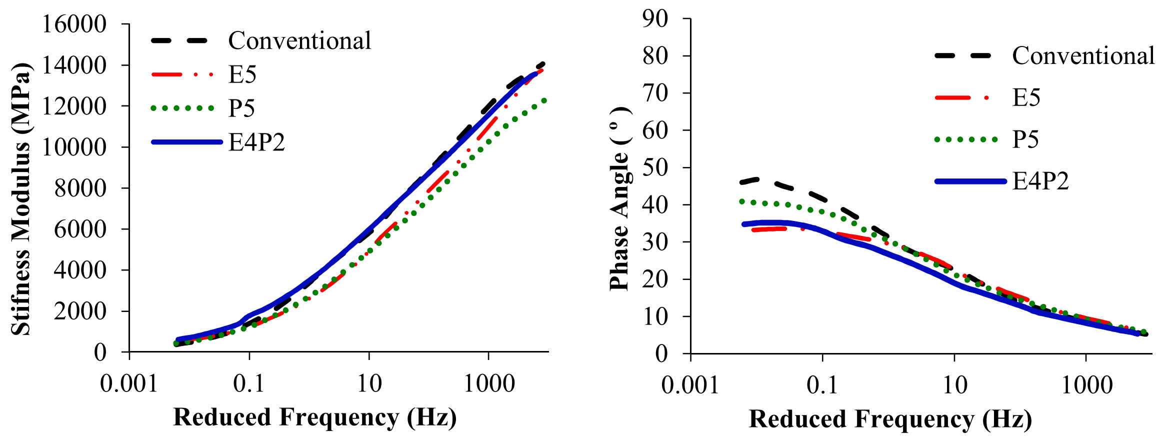

Fig. 6 - Stiffness modulus and phase angle master curves of the conventional and waste plastic modified mixtures

Analysing the stiffness modulus of the studied mixtures it was concluded that the conventional mixture shows higher stiffness values due to the use of 35/50 bitumen, which makes the mixture stiffer at 20 ºC in comparison with the mixtures using laboratory modified binders produced with a softer 70/100 base bitumen. Comparing the mixtures using binders modified with recycled polymers, it was found that the mixture E4P2 has a higher stiffness modulus due to the higher total amount of polymer (6%) used for binder modification.

The phase angle is an indicator of the elastic and viscous properties of a material. Fully elastic materials have a phase angle of 0° and fully viscous materials have a phase angle of 90°. Evaluating the phase angle of the studied mixtures, it is apparent that the conventional mixture showed higher phase angle values (being the only one that exceeds 45º) for lower frequencies or higher temperatures, at least in comparison with the modified mixtures. Thus, the conventional asphalt mixture has a higher viscous behaviour, which is consistent with the lowest rutting resistance of this unmodified mixture.

Unlike rutting deformation, the fatigue cracking phenomenon typically occurs at moderate to low service temperatures, when the loading of a significant repeating number of loads leads to a loss of asphalt mixture resistance by fatigue and to the occurrence of the fatigue cracking.

Based on the fatigue test results of several beams of each asphalt mixtures studied, it was possible to determine the corresponding fatigue laws presented in Figure 7.

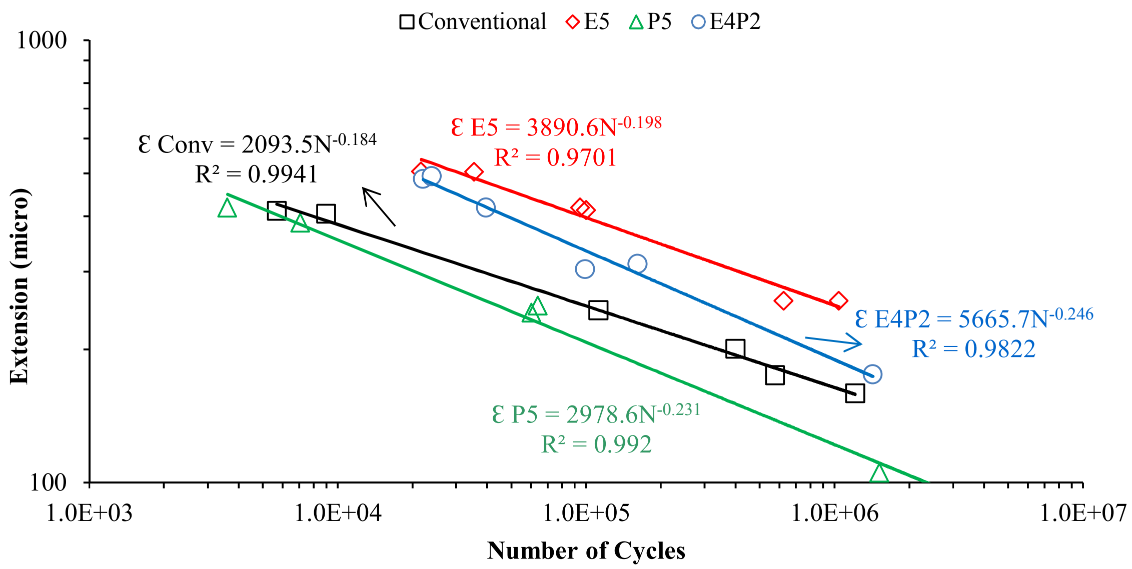

Fig. 7 - Fatigue lines of the conventional (35/50) and waste plastic modified asphalt mixtures

Based on this fatigue laws, it can be clearly observed that the mixture with EVA (E5) is the one with the best fatigue behaviour. On the other hand, HDPE mixture (P5) had the worst fatigue performance, being even worse than the conventional mixture. Yet it is interesting to observe that the mixture with the mixed system (EVA and HDPE) showed an intermediate behaviour in the fatigue test, between the good performance of EVA and the poor performance of HDPE. These results confirmed the expectations for these mixtures, and some comments previously made during the analysis of other tests.

In order to quantitatively analyse the results of the fatigue test, two parameters are typically used for a better interpretation of the results. The ε_6 parameter corresponds to the tensile strain level required to cause fatigue failure after 1 million cycles. The N_{100} parameter corresponds to the number of cycles that a mixture can withstand before fatigue failure at a strain level of 100E-6. These parameters, presented in Table 4, are computed based on the mixture's fatigue equations previously presented.

Table 4 - Fatigue resistance parameters of the conventional and waste plastic modified asphalt mixtures

Asphalt Mixture	ε_6 (micro)	N_{100}
Conventional	164.8	1.51E+07
E5	252.4	1.07E+08
P5	122.5	2.40E+06
E4P2	189.3	1.34E+07

These parameters confirmed that the E5 mixture shows optimal fatigue resistance performance due to the modification made with an elastomer (EVA) that provides elastic properties to the mixture and increases its fatigue life. As expected, P5 mixture showed the worst fatigue behaviour in both parameters (ε_6 N_{100}), because the modification with a plastomer (HDPE) makes the mixture more stiff and prone to fatigue cracking. The mixture E4P2 presents better results than the conventional mixture, thus balancing the pros and cons of using EVA and HDPE for binder modification.

CONCLUSION

The design of an asphalt road pavement means defining a structure that ensures the capacity of resisting the loads applied by vehicles and climate conditions. This depends on the mechanical properties of the asphalt mixtures used in the pavement structure, such as the rutting resistance, the stiffness modulus, the phase angle and pavement resistance to fracture mechanisms such as fatigue cracking. Moreover, several factors affect the mechanical performance of the asphalt mixtures, between which the mechanical properties of its components, and in particular the asphalt binder.

Analysing the results for the modified binders produced it was found that the waste plastic introduction in the bitumen increases the viscosity and softening point values in comparison to the base bitumen. In relation to the penetration test, the modified binders showed better results (lower penetration values) than the control 35/50 bitumen. These results indicate a higher stiffness of these binders and hence a higher stiffness of the resulting asphalt mixtures, being the HDPE waste more effective than the EVA waste. Thus, it was expected that the HDPE mixtures have better performance at high service temperatures, and that the asphalt mixtures with EVA have better fatigue performance at low service temperatures.

In fact, regarding the rutting resistance evaluation, the mixture P5 (HDPE) had the lowest rut depth among the studied mixtures, and this asphalt mixture with HDPE is the one with the best global rutting resistance performance. Overall, all polymer modified mixtures had higher performance in the wheel tracking test than the conventional mixture.

In terms fatigue cracking resistance, the mixture P5 (HDPE) showed an unsatisfactory performance, while the mixture E5 (EVA) presented the best performance. The combined system (E4P5) presented an intermediate performance between P5 and the E5.

Summing up, this study shows that the use of different waste plastics can promote substantial differences on the mechanical properties of the resultant asphalt mixtures. Thus, engineers can take advantages of their use in order to optimize the asphalt mixtures for a certain objective.

ACKNOWLEDGMENTS

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