Plastic waste use as aggregate and binder modifier in open-graded asphalts

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ABSTRACT: Road pavements are very important infrastructures for the Society, but they can cause serious environmental impacts during construction, operation and rehabilitation phases. Thus, it is essential to develop surface paving solutions that promote not only the durability but also a comfortable and safe use. In fact, this work aims to study the properties of new open-graded mixtures for surface layers produced with plastic wastes. First, HDPE and EVA wastes were used as bitumen modifiers, and then another plastic waste (PEX) replaced part of the aggregates. After studying the modified binders, the open-graded mixtures were designed, and then they were tested concerning their particle loss, rutting resistance, surface texture and damping effect. It was concluded that both ways of using the plastic wastes can improve the mechanical and functional properties of the open-graded mixtures related to the pavement performance.

1 INTRODUTION

The rapid urbanization growth results in higher traffic levels creating the need for roads with improved performance. However, building a road pavement requires large amounts of materials, and their extraction can lead to the devastation of natural resources and cause negative impacts on the environment.

The asphalt mixture, a matrix of aggregates linked with an asphalt binder, is one of the most important materials used for road paving. The aggregates represent approximately 90% of asphalt mixtures, and the alternative of their partial substitution by plastic wastes can be considered as a sustainable technology, since an equivalent performance can be assured (Robinson, 2004). Regarding the asphalt binder, it is the most valuable constituent and largely responsible for the asphalt mixture performance (Becker et al., 2001).

One method often used to improve the asphalt mixtures mechanical performance is the addition of polymers (Becker et al., 2001), which can be applied in asphalt mixtures by using the wet method (as asphalt binder modifier) or the dry method (when the polymers are added to the aggregates). However, the use of virgin polymers can even double the final price of asphalt binders (Kalantar et al., 2012). The use of plastic wastes, instead of virgin polymers, can be a good answer for that economic concern, being also a better environmental solution.

Besides the road mechanical performance, related to the durability and structural design of asphalt road pavements, the pavement must also provide a safe, comfortable and noiseless surface. These functional characteristics are related with the tire/pavement interaction, adhesion and noise, and the projection of water in wet weather, which in turn are related with the porosity, the surface texture, and the incorporation of polymers (usually elastomers) (Biligiri, 2013).

Open-graded and porous asphalts mixtures are frequently applied in surface layers due to their ability to reduce water splash, aquaplaning and noise, promoting the adhesion between the tires to and the pavement mainly in wet conditions. Due to the high porosity of these types of asphalt mixtures, they need to be carefully designed using modified binders with better rheological properties in order to assure a good disaggregation resistance (Arrieta & Maquilón, 2014).

Because these types of mixtures are so challenging, the objective of this study is to evaluate the performance of open-graded mixtures produced with new waste plastic modified binders, and in addition the possibility of using another plastic waste to substitute part of the aggregates.

For open-graded asphalt mixtures, the main problems caused by their high porosity are typically the low cohesion or resistance to disaggregation and the low rutting resistance, and these problems are deeply dependent on the content or type of binder used. Thus, the particles loss and the rutting resistance in the wheel tracking test will be assessed in order to evaluate the suitability of the new solution with plastic wastes for production of open-graded asphalt mixtures.

A method based on the spectra of hammer impacts on the pavement (Sandberg, 1987, Nils, 2009) may also be used to indirectly measure the asphalt pavement stiffness.

2 MATERIALS AND METHODS

2.1 *Materials*

A 70/100 penetration grade bitumen was used as a base bitumen for the production the new plastic waste modified binders. Another commercial polymer modified binder Elaster 13/60 (S) was used as control binder for comparison reasons (also during asphalt mixtures production).

The waste plastics used for bitumen modification were recycled EVA and HDPE. These two plastic wastes were selected as being those more viable for bitumen modification among several plastic wastes tested in previous studies (Costa et al., 2013a, Costa et al., 2013b).

A modified binder with elastic properties should be used to produce open-graded (OG) mixtures (Biligiri, 2013), thus justifying the inclusion of EVA wastes in both modified binders produced in this study, namely:

- a 70/100 penetration grade bitumen modified with 5% EVA (E);
- a 70/100 penetration grade bitumen modified with 4% EVA and 2% HDPE (C).

The binder modification was performed in a high speed mixer (IKA T65 ULTRA-TURRAX disperser) during 20 minutes at 160 ºC, and at 5000 rpm.

The basic asphalt binder's properties were assessed, namely the penetration value (EN 1426), the softening point or R&B temperature (EN 1427), the recovery after penetration (resilience) (EN 13880-3) and the dynamic viscosity (EN 13 302). Those properties obtained for the commercial binder and for both binders produced with plastic wastes are presented in the Figure 1.

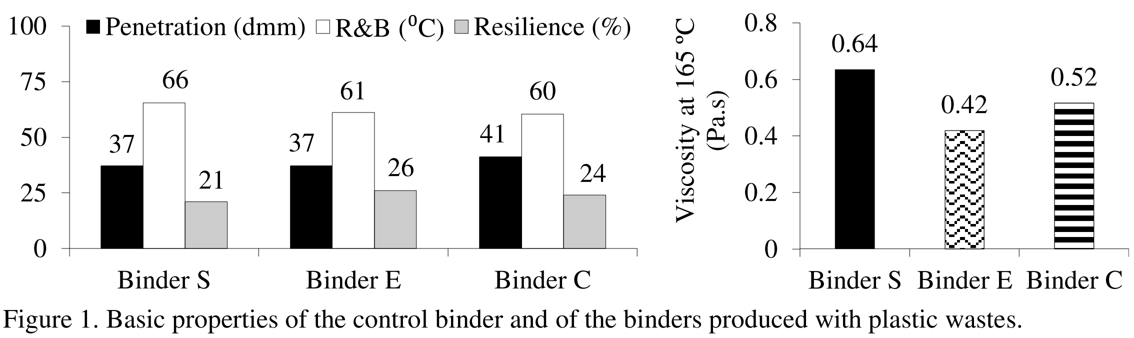

Figure 1. Basic properties of the control binder and of the binders produced with plastic wastes.

It is a valuable fact that all modified binders are in the range of a 35/50 penetration grade bitumen typically used in Portugal. Furthermore, it is expected that the commercial binder (S) would have an improved high temperature performance due to its better R&B results. The resilience of all binders is similar. Mixtures also need to be workable at high temperatures, and here the binder with EVA (E) presents best results due to its lower viscosity at 165 ºC.

Granite aggregates and limestone filler were used to obtain the aggregate matrix of the OG mixture. In addition, a crosslinked polyethylene (PEX) plastic waste partly (5.5% in volume) also substituted the aggregates used in the production of another open-graded mixture (OGP).

According to EN 12697-5, the density of PEX is 936 Kg/m^3, while the density of the stone aggregates is 2.8 times higher (nearly 2650 Kg/m^3). Taking into account that the dry methods of polymer modification typically use rates of 2% to 4% of the asphalt mixtures weight, this work was slightly conservative and selected the lowest of these values. Thus, nearly 2% of the total aggregates of OGP mixtures were substituted by PEX, corresponding to 5.5% in volume.

The possible interaction between the PEX and the binder was evaluated through the gel content of PEX (ASTM D2765-11), and it was 54.0% (cross-linked material that does not melt).

Table 1 shows the percentage of each fraction of aggregates (stone fractions, PEX fraction and filler) used for asphalt mixtures' production, in order to produce both open-graded mixtures (OG and OGP) with a maximum nominal size of 12.5.

Table 1. Percentage by volume of each fraction of aggregates used in the studied OG and OGP mixtures.

Mixture	Fraction 0/4	Fraction 4/6	Fraction 6/14	Fraction 6/12.5	PEX 0.5/4	Filler
OG	14.0%	20.0%	25.0%	40.0%	0.0%	1.0%
OGP	11.5%	17.0%	25.0%	40.0%	5.5%	1.0%

The distribution of mineral aggregates for the OGP mixtures was adjusted in the corresponding PEX fraction dimensions in order to have similar aggregate gradations for OG and OGP. Summing up, the asphalt mixtures selected for performance evaluation are the following:

- OG_S - Open-graded asphalt with commercial modified binder;
- OG_E - Open-graded asphalt with waste EVA (5%) modified binder;
- OG_C - Open-graded asphalt with combined modified binder (4% EVA and 2% HDPE);
- OGP_S - Open-graded asphalt with commercial modified binder and 5.5% PEX in volume;
- OGP_E - Open-graded asphalt with waste EVA modified binder and 5.5% PEX in volume;
- OGP_C - Open-graded asphalt with combined modified binder and 5.5% PEX in volume.

2.2 *Methods*

After defining the constituent materials, the next step of the study was the mix design of the OG mixtures, i.e. definition of the binder content. The binder content was determined by using the particle loss dry test (EN 12697-17), as suggested in the Portuguese specifications, testing five different binder contents in order to define the best binder content. The test specimens were moulded according to EN 12697-30, and tested at a temperature of 25 ºC.

As the aggregates matrix of the open-graded mixtures with PEX (OGP) is similar to that of OG mixtures, its binder content was defined as being the same previously obtained for OG mixtures. The particle loss dry test was also performed to assess the disaggregation resistance performance of the OGP mixture, but only for that optimum binder content.

The rutting resistance of the asphalt mixtures was assessed by means of the Wheel Tracking Test (WTT), according to the EN 12697-22, 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.

In order to evaluate some surface properties of the asphalt mixtures, the texture of the WTT samples was measured with laser equipment (average value per stretches of 1 meter). The results obtained were the mean profile depth (MPD) according to NP ISO13473-1.

Finally, in an attempt to assess additional mechanical properties, the mechanical impedance was measured. The mechanical impedance is a different way to evaluate the stiffness of the asphalt mixtures. In this test, the damping factor (ξ) is determined, which is directly related to the phase angle (ϕ) of the asphalt mixture (Nils, 2009), as expressed by Equation 1.

$$\xi = \tan(\phi)/2 \quad (1)$$

The test consists in exciting the material to be studied (in this case the asphalt mixtures of the WTT samples), by means of an impact hammer. Since the response of each material (damping and resonance frequency) is dependent on its shape and support conditions, it was decided to suspend the slabs and glue an accelerometer in the center of the sample with beeswax. The excitation was also produced in the center of the sample, but in the side of the slab opposite to the accelerometer. The mechanical impedance tests were performed both at 20 ºC and 30 ºC.

3 RESULTS

The binder content determination (mix design) of the OG mixtures was based on the mechanical characterization of the disaggregation resistance obtained through the Cantabro dry test. The mass or particle loss results for each OG mixture, for five different binder contents, are present in Figure 2. The binder content was selected according to the evolution of the mass loss.

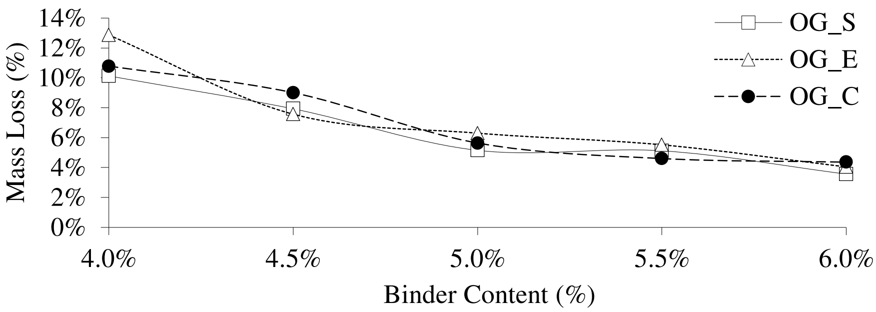

Figure 2. Influence of the binder content in the particle loss of the OG mixtures.

For all mixtures (the control mixture OG_S with commercial modified binder and both mixtures OG_E and OG_C with the new binders modified with plastic waste) it can be observed that the mass loss quickly decreases for binder contents below 5.0%. The reduction of the mass loss is much lower for higher binder contents. Thus, the value of 5.0% was selected as being the optimum binder content obtained during the mix of the studied open-graded mixtures, since it meets the mechanical and economic needs of these road materials.

The same binder content (5.0%) was adopted for the corresponding mixtures using PEX as partial substitute of the aggregates (OGP). The mass loss results of the OG and OGP mixtures, for the optimum binder content of 5.0%, are compared in Figure 3.

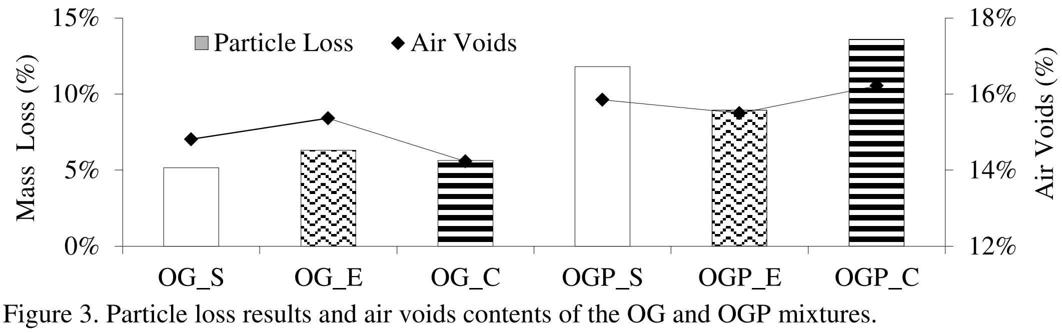

Figure 3. Particle loss results and air voids contents of the OG and OGP mixtures.

Regarding the effect of the binder on the particle loss, the new binders with EVA and HDPE presented a performance similar to that of the commercial modified binder, both in OG and OGP mixtures. In fact, the particle loss of the OGP mixture with the EVA modified binder was even lower than that of the OGP mixture produced with the commercial modified binder. Besides, when comparing the global results of OG and OGP mixtures, it can be observed that the use of PEX as aggregate increases the particle loss of the open-graded asphalt mixtures. The higher particle loss of the OGP mixtures with PEX can be related with their higher air voids contents, which in turn can be associated with the higher difficulty to compact mixtures with plastics. In fact, PEX have elastic recovery and will work like a small spring that brings additional challenges during the compaction of these mixtures. Moreover, although the particle size of OG and OGP mixtures is identical, the OGP mixtures (with PEX) may need more binder due to some interaction with PEX aggregates that are not fully cross-linked. It should also be mentioned that the lower density of PEX also reduces the volume of binder available cover the aggregates, even if the binder contents by weight of OG and OGP mixtures are the same.

Then, the WTT rutting test was used to determine the susceptibility of the asphalt mixture to deform under repeated loads at high service temperatures (Figure 4).

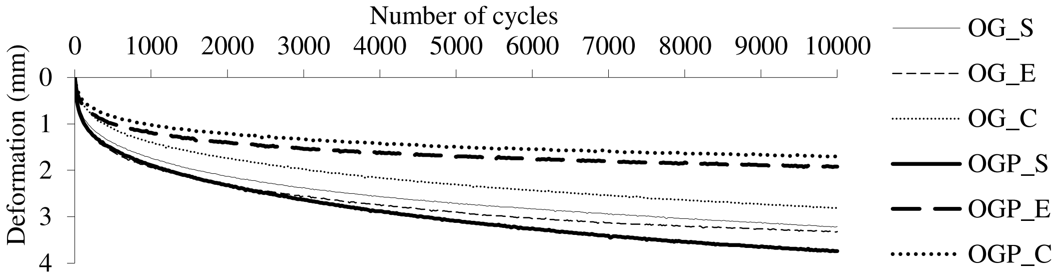

Figure 4. Wheel tracking test results for the OG and OGP mixtures.

Concerning the modified binders' rutting performance, the combined binder (EVA and HDPE) has the best deformation resistance. Besides, the use of PEX as aggregate usually improves the rutting resistance, except for the mixture with commercial binder (OGP_S). The higher deformation resistance apparently indicates that the addition of PEX increases the stiffness of the asphalt mixture at high temperatures. This result, as well as the lower density of this type of mixtures with PEX could be a very interesting advantage in some situations, allowing the production of light but rut resistant asphalt mixtures for road pavements.

The surface properties influence the tire/pavement noise production, the adhesion and the permeability. The voids content of slab samples presented in Figure 5 was similar for all the mixtures produced, but in terms of superficial properties it is also important to evaluate the surface texture of the mixtures produced, namely by computing their mean profile depth (MPD).

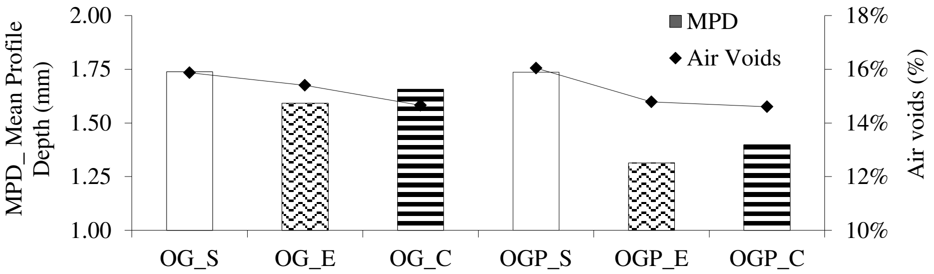

Figure 5. Surface texture evaluation through the MPD values for the OG and OGP mixtures.

The Portuguese specifications establish that the MPD should be higher than 1.25, and it was observed that all the results are similar among them and higher than that specified value.

Finally, the mechanical impedance was assessed as being a different way to evaluate the stiffness of the asphalt mixtures. In this work, only the first resonant frequency was evaluated. As the damping factor related to the phase angle, it also provides information about the stiffness of the asphalt mixture. Lower damping factors are related with a more viscous behaviour of the mixtures, while the opposite is related with an elastic behaviour. Figure 6 presents the variation of damping factors of OG and OGP mixtures with the temperature, and the corresponding first resonant frequency. The OGP mixtures present lower damping factors at each temperature, which is related to the lower phase angles and higher stiffness of these mixtures. This could indicate that PEX may have interacted somehow with the binders during the production of OGP mixtures. The damping and the resonant frequency variation with the temperature is similar for all mixtures, and thus the addition of PEX does not influence the temperature susceptibility. The less stiff mixture is OG_E, probably due to the lower viscosity of the EVA modified binder.

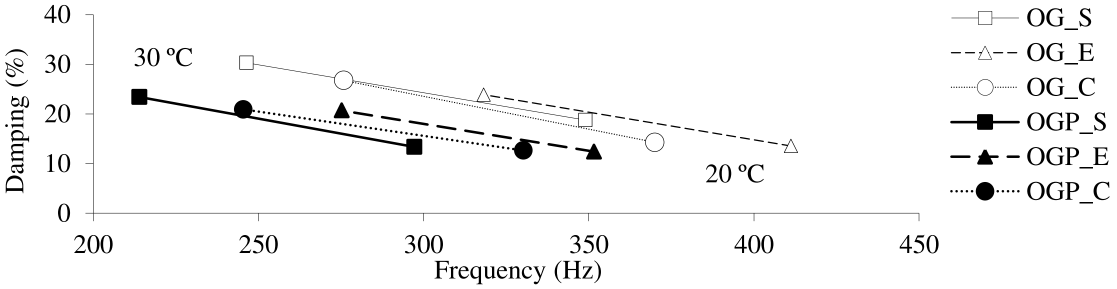

Figure 6. Damping factors for OG and OGP mixtures in the first resonant frequency.

4 CONCLUSION

It can be concluded that the binders with plastic wastes developed in this study can promote the same challenging performance in open-graded asphalt mixtures as those produced with a commercial modified binder, having additional ecological and economic advantages. The use of PEX as partial substitute of the aggregates increased the particle loss, even though this is associated with higher air voids contents. Thus, the binder content of these mixtures should be increased to avoid this problem, probably without additional costs. However, the lower density of these mixtures with PEX and their higher rutting resistance could be beneficial. In terms of rutting resistance, all the new binders with plastic wastes promoted a good performance at high temperatures. These results were confirmed in mechanical impedance tests, where the mixtures with PEX as aggregates were stiffer than those only with mineral aggregates.

5 ACKNOWLEDGMENTS

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