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Incorporation of Waste Plastic in Asphalt Binders to Improve their Performance in the Pavement

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Abstract: With the increase in road traffic more demands are placed on pavements, and thus the structural and functional performance of road pavements needs to be improved. One method that can greatly improve the quality of the flexible pavements is the addition of polymers to the bitumen or to the asphalt mixtures. Although the modification of bitumen with virgin polymers can improve the properties of asphalt mixtures, the use of recycled plastic may also show a similar result with additional environmental advantages. This work aims to evaluate the possible advantages of modifying the bitumen with different plastic wastes, namely polyethylene (high density HDPE and low density LDPE), ethylene-vinyl acetate (EVA), acrylonitrile–butadiene-styrene (ABS) and crumb rubber, in order to improve the properties of the resulting binders for use in high performance asphalt mixtures. The performance of modified binders with recycled polymers was compared with that of the conventional bitumen and the one of a commercial modified binder (Styrelf). The results of the laboratory tests (basic characterization, dynamic viscosity, resilience and storage stability) will be used in the selection of the best plastic waste materials and production conditions that should be used in the modification of bitumen in order to optimize its behaviour, emphasizing that this study aims to promote the reuse of plastic waste in a more environmental and economic way.

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***Key words**: Asphalt binders, Bitumen performance, Modified bitumen, Production conditions, Recycled plastic.*

Introduction

Road traffic volume has been increasing worldwide, including in the European countries, and in particular the traffic volume for transportation of goods, and it is expected that this demand continues to increase sharply over the next decade [1]. Thus, in order to avoid the premature distress of the road network, the performance of flexible pavements must be improved.

One method that can greatly improve the quality of the pavements is the addition of polymers to the asphalt mixtures [2]. Although the addition of virgin polymer complies with the purpose of improving the properties of the asphalt mixture, the use of recycled polymers may show a similar performance compared to virgin polymers [3], provided that a rigorous selection of the plastic wastes and production conditions are made [4]. There are two main methods of adding polymers to the asphalt mixtures, particularly by modification of bitumen (wet process) and by addition of solid polymers to the asphalt mixtures (dry process). However, the modification of bitumen has been the process most widely applied for this purpose [5].

In fact, according to previous studies [5, 6], the modification of bitumen with polymers or plastic wastes has resulted in asphalt mixtures with improved performance, including an increased resistance to rutting deformation, higher stiffness at high temperatures and reduced susceptibility to temperature variation. In some cases, a better fatigue resistance has also been found depending on the type of polymer used, which influences the rheological properties of bitumen [7, 8].

Regarding the use of plastic wastes for bitumen modification, those mentioned in the literature are mainly the low density polyethylene (LDPE) [7], high density polyethylene (HDPE) [9], polypropylene (PP) [10], ethylene-vinyl acetate (EVA) [8, 11], acrylonitrile-butadiene-styrene (ABS) [10], polyethylene terephthalate (PET) [12] and polyvinyl chloride (PVC) [5].

According to García-Morales [8] the modification of bitumen with recycled EVA had successful results. In that work, concentrations ranging from 0 to 9% were studied, and the recycled polymer increased the binder viscosity at high service temperatures, with consequent benefits on road performance, such as in resistance to rutting. However, the bitumen viscosity at the production and application temperatures demonstrated to be sufficiently low for its adequate use in pavements even with concentrations as high as 9%.

According Fuentes-Audén [3], despite the recycled polyethylene also promotes benefits on the resistance to rutting and, in addition, on cracking and thermal fatigue, its incorporation in the bitumen should not exceed 5% (otherwise the resulting viscosity would reduce the workability of the mixture). One of the conclusions of Casey et al. [10] was that the HDPE and the LDPE were the most promising recycled wastes that can be used for bitumen modification, when compared with recycled PET, PVC, ABS and MDPE. Better results were expected to be obtained with ABS, and the authors pointed 4% as the ideal polymer (recycled HDPE and LDPE) concentration. It has been found that some of these recycled polymers improve the properties of the binder, but not all of them are suitable for bitumen modification at high temperatures. For example, heating PVC at high temperatures can cause dangerous chloride emissions to the atmosphere, and PET has a high potential for its own reuse (i.e. high valorisation in other uses).

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The current research of more sustainable materials and technologies in road paving industry is pointing out towards the increasing need to reduce the energy consumption and the emissions [13, 14] and raise the use of recycled materials [14-16], without compromising the performance of asphalt mixtures. In this context, this new study was motivated by the knowledge that there is a significant quantity of several plastic wastes in national recycling centres that are difficult to recycle, although the conclusions can be extrapolated for an international level.

At this stage, the present study aims to assess the possible advantages of modifying bitumen with different waste plastics available in order to improve the properties of the resulting modified binders for future application in asphalt mixtures. The study includes an exhaustive evaluation of the basic properties, dynamic viscosity at elevated temperatures and resilience of bitumens modified with different polymers. Moreover, the influence of the dimensions of the polymers was also evaluated. Finally, the storage stability of all the modified binders was determined. This property is critical to obtain a new product that could be used without the constraints associated with the need of modifying the bitumen in the asphalt plant.

Materials and Methods

Materials Used and Selection of the Polymers for the Study

The base bitumen used in all the study was a 35/50 penetration grade bitumen with a penetration value of 46×10-1 mm and a softening point of 52 ℃. In the future, effect of using softer bitumens in the production of modified bitumens will be evaluated, namely because the grade of the original bitumen affects the mechanical properties of the modified bitumen at low temperatures, while the used modifiers does not have statistically significant effect on stiffness at low temperature [17].

Moreover, in order to have a commercial modified bitumen to use as reference for comparison with the new modified bitumens produced in this study with different waste plastic materials, the commercial modified bitumen named Styrelf was also evaluated in this study.

Based in information given by some Portuguese companies working in plastic recycling (in particular Gintegral, which provided the recycled polymers for this study), it was possible to conclude that the higher quantities of waste plastics that can be recycled for bitumen modification are high and low-density polyethylene and ABS, and thus they were selected for evaluation.

During the literature review it was found that SBS and EVA are the polymers mostly used in the production of commercial polymer modified bitumen (PMB) [10]. Thus, this study also evaluated the modification of bitumen with these polymers in their virgin state. The EVA polymer was also obtained and used as a recycled material, thus being possible to compare the differences in the performance of binders modified with this polymer in two different stages (virgin vs. recycled). This aspect is important because the recycled polymers usually are mixed with other components (fillers, dyes, among other), which can change the efficiency of the polymer in the modification of the bitumen. So, for this particular EVA polymer, it is possible to check if there is a significant reduction of the performance of the modified bitumen when using recycled EVA instead of virgin EVA.

Finally, crumb rubber recycled from used tires was also used in this study, as being one of the recycled materials most commonly used in the modification of bitumens.

Fig. 1 summarizes schematically the polymers used in this study. In fact, bitumen was modified with virgin EVA and SBS, as well as with recycled LDPE, HDPE, ABS, EVA and tire rubber.

The various polymers, virgin or recycled, are generally provided in a granular form with a maximum dimension of approximately 4.00 mm. After observing some difficulty in the digestion of some polymers in this granular dimension, such as SBS (Fig. 2) and ABS (Fig. 3), it was necessary define an alternative solution to ensure a more effective modification of bitumen by polymers.

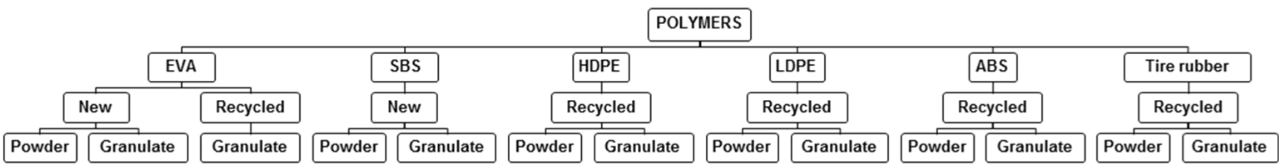

Fig. 1. Recycled and Virgin Polymers (Powder or Granules) Used in this Study.

Fig. 2. Heterogeneous Aspect of the Bitumen Modified with SBS Granules (Poor Digestion in Bitumen).

Fig. 3. Granular Particles of ABS That were not Digested Into the Bitumen (Recovered after Filtering the Modified Binder).

Thus, in a second phase of study the various polymers used in this work were converted into powder with a size below 0.45 mm. This process was carried out in a milling machine of the Department of Polymer Engineering of the University of Minho, after freezing the polymers with liquid nitrogen to ensure that the polymers did not glue with each other due the heating that occurs in the milling process, which allowed obtaining particles below the specified size.

The several polymers used in this study are shown in Fig. 4, namely the new or recycled ones (those with index R), and both dimensions in which they are mixed with bitumen (powder – left side; granulate – right side).

In the future, this study will continue evaluating alternative possibilities, other than the size reduction of polymers, for their proper digestion in the bitumen, such as using high shear mixing [18], increased temperatures and digestion times and the use of compatibility additives.

Initial Description of the Methods Used in the Study

The initial process of evaluation involved the incorporation of virgin and recycled polymers, in their initial dimensions, in the base bitumen. The objective of this study was to determine whether the dimensions of the supplied waste plastic are the most appropriate for the blending process of bitumen modification, thus eliminating costs of additional processing of the waste polymers or the need of better high shear mixers, among other.

In order to compare the modified bitumens produced with the several polymers, they were all produced using the same conditions: 5.0% of polymer per weight of bitumen and a digestion temperature/time of 180 °C for 60 minutes in a RW20 IKA mixer (stirring speed of 350 rpm), defined in order to assure a homogeneous blending of the bitumen with most of the recycled polymers.

The crumb rubber, the ABS and the SBS are not completely digested in the bitumen in their initial dimensions, resulting in a non-homogenous binder after the production period (Fig. 2). At this stage, these modified binders were filtered (Fig. 3) in order to evaluate the potential changes caused by the fraction of these polymers that has effectively melted and modified the bitumen.

The next phase of the work was the evaluation of the effectiveness of the size reduction of the polymers in order to more easily achieve their digestion, thus improving the bitumen modification. Thus, modified binders were produced with the same polymers, under the same conditions, but now using the polymers in powder (sizes lower than 0.45 mm). This procedure increases the costs of the process, but they can be justified if more homogeneous and stable binders are obtained.

Then, the characterization of the several modified bitumens was carried out in order to evaluate which polymers are the best candidates to be used in bitumen modification, particularly those obtained from waste plastic materials. The properties of the modified binders were also used to evaluate the advantages of reducing the size of the polymers (from granules to powder) before their use in bitumen modification.

The performance of the modified bitumens was measured based on several characterization tests. Initially, and in order to classify the bitumens used and produced in this study, their basic

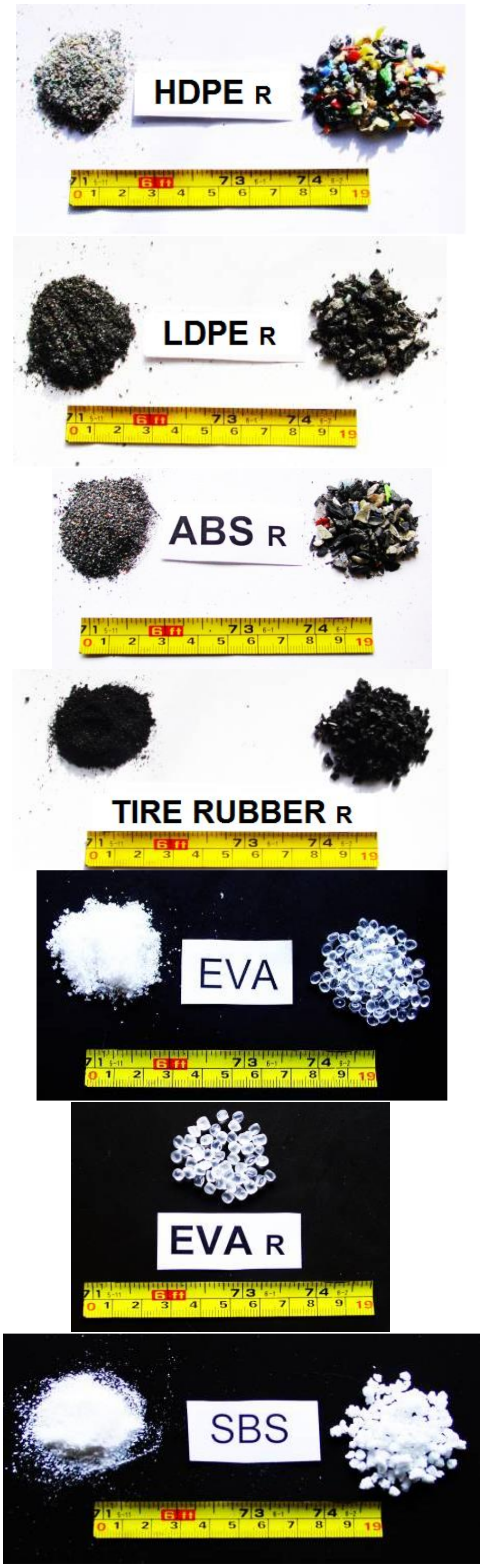

Fig. 4. Different Polymers (Powder and Granules) Used in the Study

characterization was carried out according to EN 12591. This characterization included the evaluation of the softening point of the bitumens (also known as ring and ball temperature, or R&B),

according to EN 1427, and penetration tests at 25°C, carried out according to EN 1426 standard. Other tests are also suggested in the European Specification EN 14023 in order to classify polymer modified binders. Thus, and mainly for binders modified with elastomers, resilience tests were performed to evaluate the ability of the modified bitumen to present some elastic recovery of deformation after application of a specified load. Then, the dynamic viscosity of the binders at higher production and compaction temperatures was also evaluated, mostly because some modified bitumens are very viscous in this range of temperatures and require a careful validation of the mixing conditions. Finally, the storage stability of the modified bitumens was evaluated, which is one of the most important characteristics to observe in order to create a new competitive product that can be used without the drawbacks related to the need of a binder modification unit near the asphalt plant.

Softening Point of Bitumen

The softening point test was performed according the EN 1427 standard, and it measures the temperature at which bitumen starts to flow and has a direct influence on the resistance to permanent deformation of the mixtures, i.e. indicates the maximum expected temperature that the asphalt mixture (with this bitumen) can support on the road without having propensity to quickly increase the rutting deformation. Thus, the softening point of the modified bitumen can be used to analyse improvements in the performance at high in service temperatures, after adding the polymer wastes to the base bitumen.

Penetration Value of Bitumen

The penetration value of a bitumen, assessed according the EN 1426 standard, is a measure of its consistency or stiffness at the reference in service temperature of 25°C and is the most common test for the characterization of asphalt binders in European countries. Thus, the classification of bitumens in Europe is usually made based on the value of the penetration assessed in this test. This property is mainly related to the stiffness of asphalt materials at a mean service temperature, and it can be indirectly inferred that stiffer asphalt materials will probably have a lower fatigue resistance performance.

Resilience (Penetration and Recovery) of Modified Binders

The characterization of the modified binders in this study also included resilience tests (penetration and elastic recovery) at a temperature of 25°C, according to European EN 13880-3 standard. Resilience is the capacity of material to absorb energy elastically. On removal of the load, the energy stored is released as in a spring. As fatigue failure can be characterized by a quick increase in the dissipated energy of the material, modified binders with higher resilience will have higher fatigue resistance, especially due to the ability of the elastomers to continue absorbing energy after a high number of loads applied in the pavement.

Dynamic Viscosity of Bitumen at High Temperatures

In order to evaluate the properties of the several binders, especially when they are subjected to high temperatures at which asphalt mixtures are produced and applied, its dynamic viscosity was determined using a rotational viscometer (European EN 13 302 standard). The dynamic viscosity was determined at different temperatures (130, 150 and 180°C), according to a predefined procedure [19].

Storage Stability of Modified Binders

In order to avoid the need of an expensive binder modification unit near the asphalt plant it is fundamental that the modified binder has satisfactory storage stability. The storage stability test was carried out according to EN 13399 standard. The modified binder is stable to storage when the differences between the properties of the top and base samples are low, and else it can be considered that a phase separation (polymers and bitumen) has occurred in the modified binder. Two types of phase separation were observed in the binders without good storage stability: sometimes the polymers tend to stay at the top of the tube due to their low density, lower than that of bitumen; in other cases the polymers tend to deposit on the base of the tube for the opposite motive.

Analysis and Discussion of Tests Results Performed for Bitumen Characterization

Table 1 summarizes the results of all the characterization tests carried out on the modified binders with different polymers, regarding to their basic properties (softening point and penetration value), the resilience and the dynamic viscosity at different temperatures (130, 150, and 180°C). The properties of the base bitumen used to prepare all modified binders, and those of a commercial modified bitumen (Styrelf), used as reference, are also presented in Table 1 in order to evaluate the effectiveness of the various polymers used in this study (in comparison with those known binders). In order to ease the analysis of the results, they are organized in graphics (Figs. 5 to 8).

Softening Point

Fig. 5 shows that all polymers increased the softening point of the base bitumen. The elastomers (especially the SBS powder and EVA, both virgin and recycled, granular or in powder) seem to be the most effective polymers for increasing the binder softening point. Furthermore, it was found that the EVA has excellent digestion in the bitumen, which allowed obtaining similar properties independently of the means used before it was introduced in the bitumen. On the other hand, SBS presented a difficult digestion in the bitumen and, therefore, SBS had to be filtered when it was introduced in a granular form (thus reducing its effectiveness).

As would be expected, for each group of binders modified with a specific polymer, when the polymer was used in its granular form and subsequently filtered, the resulting modified binder presented minor changes in terms of softening point compared with those binders modified with polymer powder. However, the polyethylene

Table 1. Results from Standard Tests, Resilience and Viscosity of the Binders in Study.

Binder Description	A&B [℃]	Penetration [dmm]	Resilience [%]	Viscosity [Pa.s]		
				130℃	150℃	180℃
Base Bitumen	52.2	45.9	9	0.8	0.3	0.1
Styrelf	65.5	37.2	21	3.1	1.1	0.3
EVA NEW Powder	66.4	26.4	30	3.8	1.3	0.4
EVA NEW Granulated	66.8	26.1	30	3.8	1.3	0.4
EVA R Granulated	65.2	26.0	23	3.8	1.3	0.4
SBS NEW Powder	82.1	28.1	36	5.4	1.4	0.8
SBS NEW Granulated (Filtrated)	59.2	31.5	17	2.0	0.8	0.2
HDPE R Powder	61.9	25.0	4	3.1	1.1	0.4
HDPE R Granulated	71.1	26.6	11	3.3	1.3	0.4
LDPER Powder	55.9	30.6	4	3.5	1.5	0.5
LDPER Granulated	59.5	30.7	12	2.9	1.1	0.4
ABS R Powder	61.8	37.4	6	1.1	0.4	0.1
ABS R Granulated (Filtrated)	52.3	39.6	8	0.9	0.3	0.1
Tire Rubber R Powder	57.2	30.5	19	1.4	0.5	0.1
Tire Rubber R Granulated (Filtrated)	55.1	32.1	13	1.0	0.4	0.1

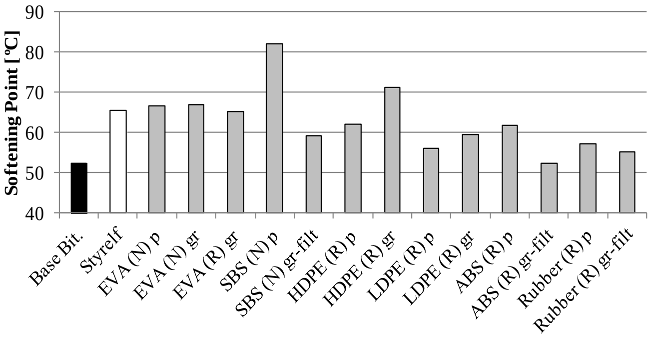

Fig. 5. Softening Point Values of the Binders Evaluated in this Study.

(HDPE, LDPE) polymers were able to be melted in the bitumen even when they were used in their granular form, and surprisingly the softening point obtained in this case is higher than that of the equivalent binder modified with polymer powder. Hypothetically, when melting PE polymers with higher grain sizes, it can be more easily formed a polymer matrix on the surface of the sample that increases the softening point. Finally, taking the polymers in powder as reference (because the binders prepared with granules sometimes were filtered), it was observed that between all the polymers studied the less effective in reducing permanent deformation were LDPE and crumb rubber from used tires.

Penetration

Regarding the effect of the different polymers on the penetration value of the base bitumen, it can be seen (in Table 1 and in Fig. 6) that in all cases the polymers have reduced the penetration value of the base bitumen. The polymers that are the most effective in reducing the penetration value are the indicated above when analysing the softening point, i.e., the HDPE and the elastomers (SBS powder and EVA). Again, the modification of binder with virgin or recycled EVA (granulate or in powder) resulted in similar characteristics in terms of penetration, which potentiate their future use as a waste material that easily melts in the bitumen.

Generally, the binders modified with the same type of polymer,

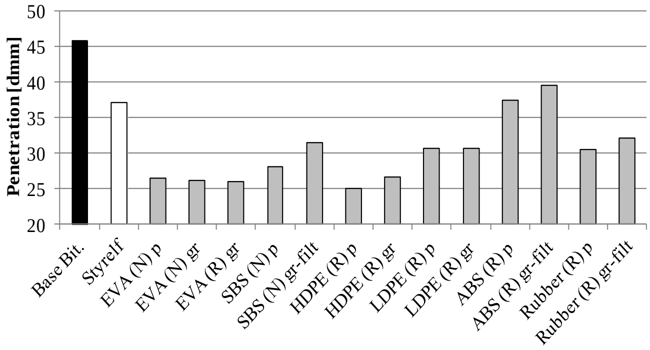

Fig. 6 . Penetration Values of the Binders Evaluated in this Study Resilience.

but introducing the polymer granulate or in powder form, showed similar penetration values. However, there is a slight difference in the case of the filtered binders (presenting higher penetration values) that, nonetheless, is not significant.

The bitumen modified with ABS powder showed the highest penetration values, demonstrating a low efficiency of this recycled polymer to change this property of the bitumen, followed by LDPE and crumb rubber from used tires. It is also confirmed that low or high density polyethylene polymers modify the bitumen in a different way. Finally, it was observed that the commercial Styrelf bitumen has a penetration value higher than all the modified bitumens produced in this work, probably because the percentage of polymer used in this study (5%) is very high, or due to the use of a high penetration grade bitumen as base bitumen, or else due to the use of stabilizers or other types of additives in Styrelf that limit the reduction of penetration.

Concerning the results of the resilience test (Table 1 and Fig. 7), which are related to the percentage of elastic recovery after penetration of the binders, the polymers that showed the best results were, as expected, the elastomers: SBS powder, followed by EVA and crumb rubber from used tyres. All these modified bitumens

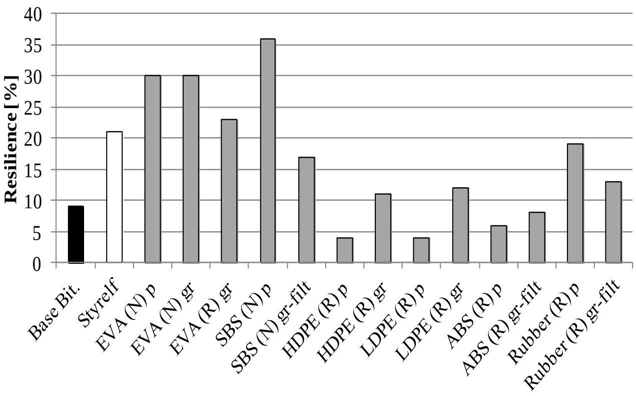

Fig. 7. Resilience of the Binders Evaluated in this Study.

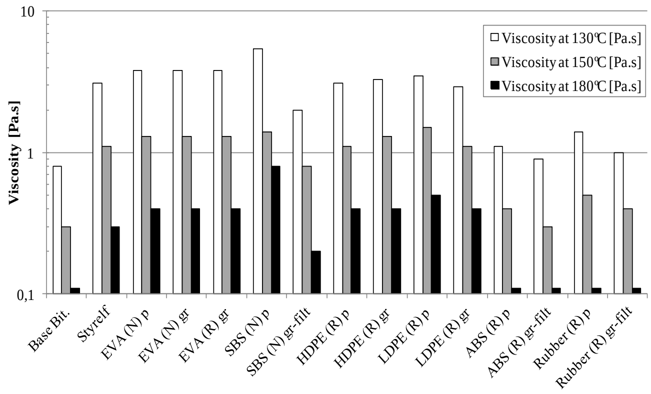

Fig. 8. Dynamic Viscosity of the Binders Evaluated in this Study.

showed resilience values similar to or greater than the commercial bitumen Styrelf, probably due to the higher percentage of polymer used (5%).

As expected, the filtered binders showed lower values of elastic recovery than those of their corresponding binders modified with polymer powder. The bitumens modified with polyethylene (HDPE and LDPE) and ABS, as well as the base bitumen, presented very low values of resilience as a consequence of their reduced capacity to recover elastically the initial deformation to which they have been subjected. Moreover, that small recovery only occurred due to the viscoelastic behaviour of the bitumen.

Dynamic Viscosity

The relationship between dynamic viscosity and temperature of the binder is very important to identify the range of temperatures for mixing/compaction of asphalt mixtures. The viscosity usually recommended for mixing is about 0.2-0.3 Pa.s and, as a consequence, the typical polymer modified binders are usually mixed at temperatures between 170 and 190 ℃. Using the data presented in Table 1, it can be concluded that almost all modified bitumens produced, excluding the ABS and crumb rubber, must use temperatures for production of asphalt mixtures equal or higher than 180 ℃. The use of ABS or crumb rubber from used tires allows the production of mixtures at temperatures lower than 180 ℃, although these materials have not shown to be the most effective in the modification of the binder, as least based on the properties already evaluated. In the other hand, the binder modified with SBS is the one with the highest viscosity, resulting in the need of using higher mixing temperatures during the production of asphalt mixtures.

It can also be seen (Fig. 8) that the Styrelf has a viscosity similar to several other modified binders. The viscosity of the elastomers is slightly higher, followed by the polyethylene group and finally, the lowest viscosities are observed for the crumb rubber, the ABS and the base bitumen.

Storage Stability

The behaviour of the modified bitumens in relation to their storage stability is a property of great importance to their commercialization and future approval by the asphalt producers, as well as the economic evaluation. Thus, the effects of the storage were evaluated in this work through the absolute difference between the properties of the base and top samples of a tube where the modified bitumen was stored for several hours at elevated temperatures (according to a standard procedure). The properties evaluated were the softening point, penetration, resilience and dynamic viscosity (Table 2 and Fig. 9).

Table 2. Storage Stability of the Modified Bitumens

Binder Description	A&B (℃)		Penetration (dmm)		Resilience (%)		Viscosity a 150℃ (Pa.s)	
	Top	Base	Top	Base	Top	Base	Top	Base
Styrelf	64.3	64.9	38.7	37.5	22	23	1.5	1.1
EVA NEW Powder	64.6	68.0	75.5	16.2	53	19	1.6	1.0
EVA NEW Granulated	64.3	69.0	79.8	15.6	52	31	2.0	1.3
EVA R Granulated	62.4	68.9	63.9	11.8	65	44	1.6	1.4
SBS NEW Powder	124.0	61.2	51.7	22.5	67	13	14.4	0.6
SBS NEW Granulated (Filtrated)	63.9	58.8	31.1	25.9	25	19	1.3	0.5
HDPE R Powder	128.1	62.2	18.2	20.7	33	11	5.3	0.6
HDPE R Granulated	127.2	62.7	17.5	19.0	33	8	5.4	0.8
LDPER Powder	117.1	64.4	25.3	19.7	22	9	5.3	0.6
LDPER Granulated	119.8	61.7	17.8	17.2	42	20	5.1	0.6
ABS R Powder	53.9	59.0	41.8	33.0	8	6	0.4	0.7
ABS R Granulated (Filtrated)	53.4	53.6	35.3	34.6	7	0	0.3	0.4
Tires Rubber R Powder	56.1	61.5	34.9	36.9	14	23	0.5	1.7
Tires Rubber R Granulated (Filtr.)	55.2	55.3	29.9	30.2	9	10	0.4	0.4

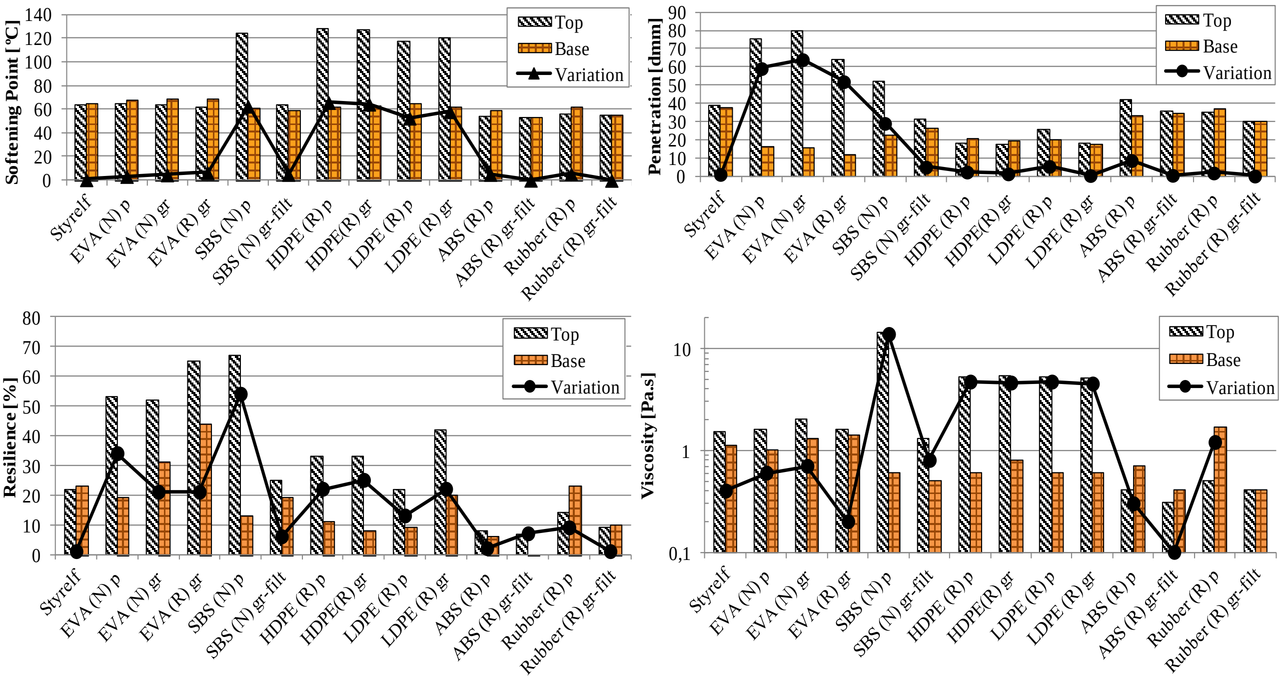

Fig. 9. Storage Stability of the Modified Bitumens.

The Portuguese specifications have limits for modified binders in terms of the difference in the R&B temperature and penetration value of the base and top samples. These limits must be fulfilled before any of these modified binders can be commercialized.

It can be seen that levels of dissociation were evident for EVA, SBS and polyethylene (LDPE and HDPE) polymers, because the differences between the properties of the samples obtained in the base and in the top of the storage tubes were significant. This is even more evident when the commercial modified bitumen Styrelf showed excellent results in terms of storage stability, being a reference in relation to this property that was not achieved by any of the polymers studied (at least those with more promising properties observed previously). This means that it is fundamental to continue this study in with plastic wastes in the future using different conditions for production of the modified binders, namely by using higher shear mixers, lower percentages of polymer and/or compatibility additives, such as polyphosphoric acid (PPA).

There are also some differences in the way that the different polymers demonstrated their low storage stability. The main differences between the properties of the base and top samples of binders produced with HDPE and LDPE polymers were observed in the softening temperature and in the viscosity at high temperatures (because these properties are more influenced by these polymers). On the other hand, the EVA polymer presented higher differences in the results of penetration and resilience. Finally, the SBS polymer presented poor storage stability for all the evaluated properties, since it was generally the polymer with higher influence in the modification of the base bitumen.

The binders that presented higher storage stability were those modified with ABS powder and with rubber from used tires in powder. However, these polymers were the ones that have caused fewer changes in the performance of the base bitumen, which can justify the minor differences found in the storage stability of these modified binders.

Thus, the first alternative to continue this study will consist in solving the problem of storage stability of SBS, EVA and polyethylene polymers, due to their good performance and bitumen modifiers. The second alternative solution will be the application of ABS or crumb rubber polymers, which have a worse performance as bitumen modifiers but appear to have good storage stability (in this case the crumb rubber would be the better choice).

Conclusions

The suitability of using different types of polymers (granulated and in powder) in the bitumen modification was evaluated in this study, in particular to assess the potential using recycled polymers in asphalt mixtures for their valorisation. The studied polymers were EVA (virgin and recycled), SBS (virgin), HDPE (recycled), LDPE (recycled), ABS (recycled) and crumb rubber from used tires (recycled). The characterization of the different bitumens modified with 5% of each one of the studied polymers demonstrated that it is possible to obtain similar properties, or even better, than those of a commercial modified bitumen. In fact, it was observed that:

- SBS, HDPE and EVA are the most promising polymers to increase the softening point of the modified binder;
- HDPE and EVA are the polymers with higher influence in the penetration test results;
- SBS, EVA and crumb rubber (elastomers) presented the best performance in relation to resilience (elastic recovery after penetration);
- All modified bitumens, excluding those with ABS and crumb rubber, only reach the proper viscosity to produce asphalt mixtures near or above 180 ºC, including the commercial bitumen;
- HDPE, LDPE and EVA have a good digestion in the bitumen,

whereas SBS, ABS and rubber are difficult to be melted in the bitumen (they should be milled to optimize their effectiveness).

The lower capacity of ABS and rubber to modify the bitumen (when using the same percentage of polymer) may justify the fact that they have presented a better performance concerning their storage stability, whereas the other polymers (EVA, SBS, HDPE and LDPE) had poor storage stability.

As a conclusion, it is considered that firstly the use the recycled polymers with improved properties (SBS, EVA, or alternatively HDPE) should be sought, namely by solving the problems of storage stability of these polymers. An alternative solution is the use of crumb rubber or ABS that appear to have good storage stability (in this case, crumb rubber the better choice).

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