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Analysis of the skid resistance and adherence between layers of Asphalt Concretes Modified by Dry Way with Polymeric Waste

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Abstract

Skid resistance is one of the most important parameters of a surface mixture due to its influence on the safety of the road. Besides, the adherence existing between the layers of a pavement makes these layers work together, which has a great impact in the useful life of the pavement. The influence on these two parameters of different polymeric waste, which have been used to modify a mixture by dry way, has been analyzed.

The polymeric waste added to an asphalt concrete by dry way are: polyethylene (PE) from micronized containers, polypropylene (PP) from ground caps, polystyrene (PS) from hangers and rubber from end-of-life tyres (ELT).

The skid resistance and the adherence between layers of the reference and the modified asphalt concretes have been evaluated separately, so their performance can be compared.

The skid resistance has been calculated with the British Pendulum Tester of the TRRL (Transport Road Research Laboratory) under two conditions: on the mixture just manufactured and on polished specimens. The adherence between layers was analyzed on

asphalt concretes with different texture (AC22 and AC16), applying a direct shear stress at constant speed in the joint junction (LCB shear test), and undergoing three-layer specimens to a dynamic shear stress (shear fatigue test designed by the Engineering School of Santander).

The results showed that the addition of residual polymers modifies the mixtures surface properties, and the performance of the asphalt concretes changes greatly depending on the polymeric waste added.

Keywords: Skid resistance; Adherence; Asphalt concrete; Polymeric waste; dry way; Modified mixture.

1. Introduction

Skid resistance and adherence between layers are two basic parameters of a road. While the first has great influence on the traffic safety (1) , the second is important when it comes to the pavement useful life (2, 3), due to the fact that adherence between layers makes it possible that they work together. Thus, this parameter should be properly considered when the pavement is designed (4).

The most important variable that characterizes this property is texture. This is divided into macrotexture, responsible for drainage and deformation that the wheel suffers when adapting to the pavement, and microtexture, which breaks the sheet of water and conditions the punctual contact between wheel and pavement (5, 6).

Macrotexture depends on the mixture properties (voids percentage, grain size analysis, aggregates properties, etc.) while microtexture, on the other hand, depends on the surface rugosity of the coarse fraction, and is especially influenced by the aggregates polishing, which wears and becomes rounded at a microscopic scale (7).

Adherence between layers is achieved using a tack coat which keeps the joint between them. Its properties depend on the type of coat employed, the materials used in the bituminous mixtures, the traffic loads, temperature, and in the case of skid, of macrotexture (3, 8-10). A good bond between the pavement layers is required to achieve a good performance. Therefore, the higher the friction between surfaces, the interlocking of the aggregates particle and the adhesion between the asphalt binder of the two layers and the applied tack coat, the better will be the adherence between layers (11).

For years, different polymers have been used to improve the bituminous mixtures properties. The rubber began to be used in the sixties to improve skid resistance due to its elasticity and capacity to break the ice on the road (12). Nowadays, rubber and plastic polymer are used basically to modify bitumen (13, 14), but their influence on these two properties, adherence between layers and skid resistance, is not well known.

This paper studies the influence that these polymeric waste have on adherence between layers and skid resistance. For this purpose, an asphalt concrete has been modified by dry way with 4 different polymers: polyethylene coming from packaging, polypropylene coming from caps, polystyrene coming from hangers, and rubber coming from end-of-life tyres. Following, the coefficient of skid resistance has been calculated with the friction pendulum of the TRRL (Transport Road Research Laboratory), and the adherence between layers has been determined through the shear stress according to the standard NLT-382/08 and also using dynamic shear test specifically designed by the Civil Engineering School of Santander (15).

2. Methodology and materials

The reference mixture that has been used is an asphalt concrete (AC22) for surface layer, with 4.8% of penetration grade bitumen (50/70) by weight of mix. The same design process was used with all the modified mixtures: 1% of aggregates was replaced by volume by each type of polymeric waste only in the filler fraction by dry way. The rubber has a low influence on the aggregates and it was mainly mixed with the bitumen, while the plastic polymers were softened by the hot aggregates and partially coated them, having this way both types of polymers (rubber and plastic polymers) an influence on the mechanical properties of the mixture (16) while modifying also its skid resistance and adherence between layers.

Four modified bituminous concretes have been manufactured, which have been called: AC22 PE, modified with polyethylene; AC22 PP, modified with polypropylene; AC22 PS, modified with polystyrene; and AC22 ELT, modified with end-of-life tyres. Besides, an asphalt concrete AC16 was designed with the same polymers added to the mixture AC22, to study the influence of the surface texture.

The particle size distribution of the polymeric waste is shown in Figure 1.

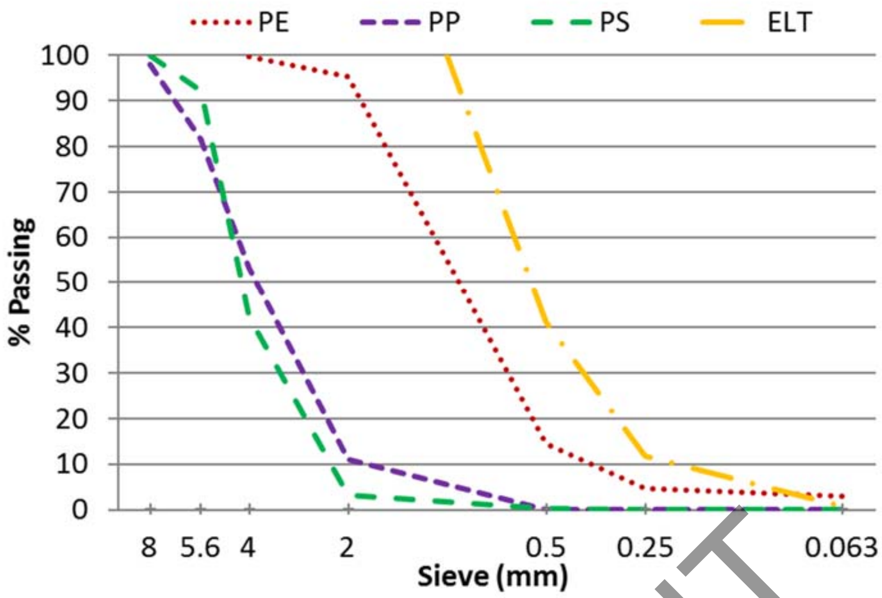

Figure 1. Particle size distribution of waste polymers (16)

2.1. Study of skid resistance

Skid resistance was evaluated in two conditions: on new samples without erosion, and on polished specimens; in this way, skid resistance was analysed in the initial and use conditions.

Skid resistance was calculated with the TRRL pendulum on track specimens, as shown in Figure 2.

Figure 2. Evaluation of skid resistance

Four samples of each type of asphalt concrete were employed. The wear procedure was carried out by abrading the wearing course surface. This procedure consisted in sanding 30 times the surface of the specimen in the same direction and sense, with sandpaper grit size 4 (17), trying to keep an even contact pressure, so that in all cases the procedure was performed by the same operator.

This procedure was aimed at achieving a similar polished to that of a road in real traffic conditions. The data obtained by the Public Works Ministry in the highway S-30 in Cantabria (Spain) were used to assess the abrasion produced on the samples. It was monitored by the Regional Road Administration between 2009 and 2014. SCRIM (Sideway-force coefficient Routine Investigation Machine) data were gathered along those years. In order to compare both measurements (the SCRIM data and the BPN), the correlation obtained by the New Zealand Transports Agency (18) was used:

$$SC = 0.0071 \cdot BPN + 0.033 \quad (1)$$

Where SC is the SCRIM Coefficient of traverse friction and BPN is the value of the British Pendulum Number, obtained by the TRRL pendulum.

This road (S-30) has a traffic category T0 (an average daily intensity of heavy vehicles between 2000 and 4000), an average daily traffic (ADT) of 20000 vehicles, a medium climate area and a rain area degree 2 (19).

2.2. Adherence between layers (shear test and fatigue to shear test)

Adherence between layers was analysed by both shear and fatigue to shear tests. For these tests, pairs of samples of identical asphalt mixtures (AC22 or AC16) were used. It means that a sample of the reference mixture was put together with a sample of the same reference mixture, a PE modified asphalt sample was coupled with other PE modified asphalt sample, etc. This way, the performance of each polymer can be analysed because the type of polymer is the only difference between the mixtures.

2.2.1. LCB Shear test

At the beginning, the layers adherence was analysed with the LCB shear test (acronym of Road Research Laboratory of Barcelona in Spanish) (20), which evaluated the adherence of two specimens by applying a direct shear stress at constant speed in the joint junction (2.5mm/min), as shown in Figure 3.

Figure 3. Test of static adherence between layers

This test is performed at 20°C with at least 7 samples for each mixture type, formed all of them by two specimens which were joined by 4.1g of conventional emulsion C69B3 ADH (what is equal to 350g/m^2 of bitumen). The tack coat used was the same in all cases.

To find out the influence that the temperature of the mixture surface and the application of an emulsion has on the adherence, the specimens are compacted at different temperatures with and without using the emulsion. This analysis is performed only with the mixture modified with PP (AC22 PP) as representative of the mixtures with polymers, and with the reference (AC22 REF). The test was done at different conditions:

i. With emulsion and mixture cold (the common situation): The test was performed compacting the first layer of the specimen and applying the emulsion when the layer is cold. Later, the second layer is compacted over the emulsion.
ii. Without emulsion and mixture cold: the same process was performed, but in this case, compacting the second layer of the specimen over the first layer without adding the emulsion; that is to say, after compacting the first layer of the specimen and leaving it to cold, the second layer was compacted directly on the clean surface of the first one. By this way, we can analyse the emulsion influence.
iii. Without emulsion and the mixture hot: in order to evaluate the temperature influence, the last procedure is repeated. The second layer is compacted over the first layer without letting the first one to cold and without applying the emulsion between them.

The compaction procedure used for each layer has been in all cases that indicated by the standard NLT 161/98.

2.2.2. Shear fatigue test

The real performance of the pavement responds to repetitive and short loads (21), so that the bituminous mixture underwent a dynamic shear fatigue test, applying a parallel load to the junction levels of the layers. In this way, we can compare the different types of mixtures in the same conditions, and analyse the adherence between layers under a static and a dynamic load.

The test was carried out at 20ºC with 4 three-layer specimens. The specimens were manufactured with the same emulsion used in the static adherence test (C69B3) and with the same amount of bitumen (350 g/m^2).

This dynamic test uses a three-layer specimen with measures of 260mm length and 205mm of width, and 50mm thickness for the central layer and 40mm thickness for the side layers. The three-layer specimen is supported in the outer layers while the central layer , on which a vertical sinusoidal load is applied with a frequency of 10Hz and a maximum value of 16KN and a minimum of 3KN (15), remains free of support. This arrangement is shown in Figure 4. The maximum shear stress reached in each junction surface is 0.22MPa, which is considered as a representative value of the real conditions (22).

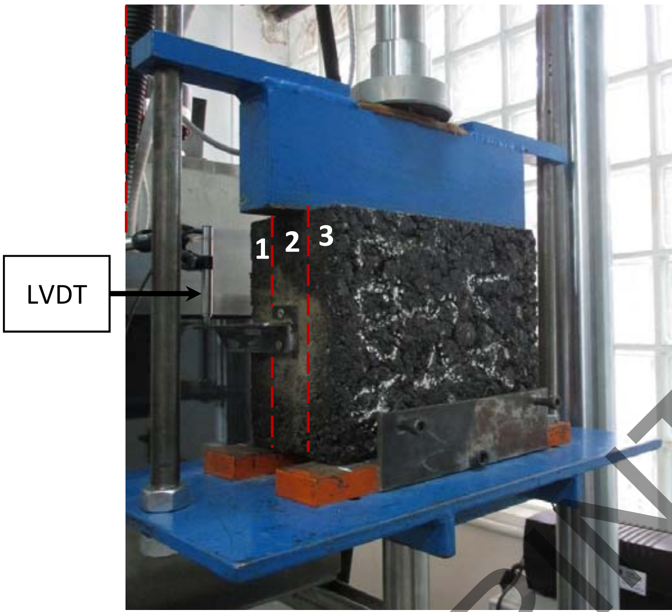

Figure 4. Shear fatigue adherence test

As starting hypothesis, it was considered that the energy applied on the central specimen produced its slip, disregarding any compression or deformation effect on it. To determine the failure moment, the vertical slip curves of the central specimen are represented in relation to the number of cycles. These curves are registered with two LVDT comparators placed in the medium point at both sides of the central specimen.

As failure criterion a maximum slip of 10mm was considered, except if any abrupt change in the slope is produced due to a rearrangement of the specimen, considering, in this case, this cycle as that of failure.

Figure 5 shows the oscillating movement of the central specimen. From this movement, and considering the amplitude associated to each cycle, and only with the aim to compare the materials, a parameter α was estimated that is related with the energy necessary to make the specimen slip. With this aim, a value of medium strength of 9.5KN (F_m) was considered.

Data were not taken for every cycle. The test was divided in intervals capturing medium values that have been considered representative:

$$\propto = \sum_{1}^{N_R} \mathrm{F}_m \cdot 2 \cdot \mathrm{A_i} \cdot \mathrm{C_i} \qquad (2)$$

Where N_R is the number of intervals until the failure is produced, A_i is the medium amplitude of each interval and C_i is the number of cycles of the interval.

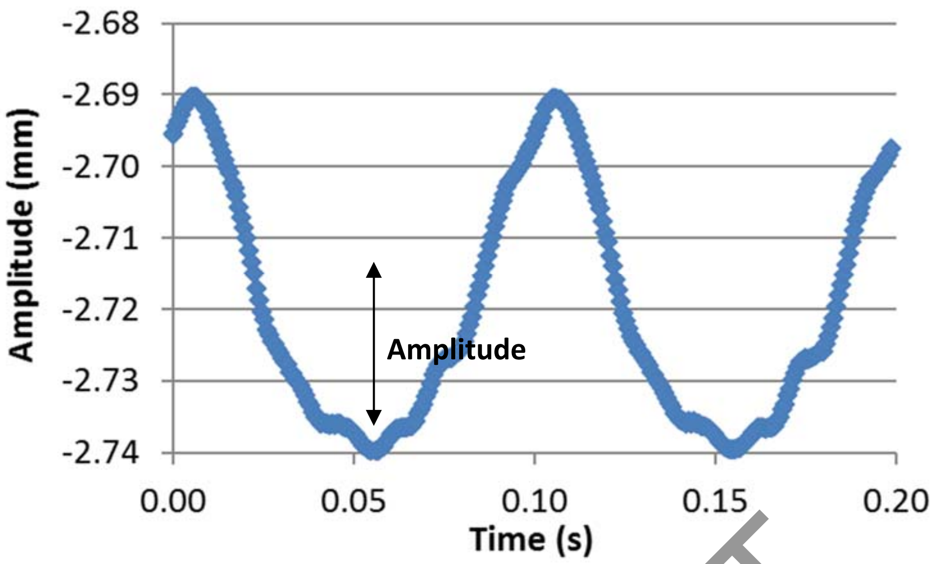

Figure 5. Amplitude of movement of the cycle 160.000 of one AC22 ELT sample

3. Statistic analysis

The statistical software IBM SPSS (Statistical Package for the Social Sciences) was used to determine if the results were significant. The confidence interval considered was 95% (p-value of 0.05). When the results fulfilled a normal distribution and there was homogeneity of variances the Scheffe test was used. However, if the results did not comply with the normal distribution or the homogeneity then, the U of Mann-Whitney test was selected.

4. Results and discussion

4.1. Evaluation of skid resistance by friction test

Figure 6 shows the values obtained by the British Pendulum Tester (BPT).

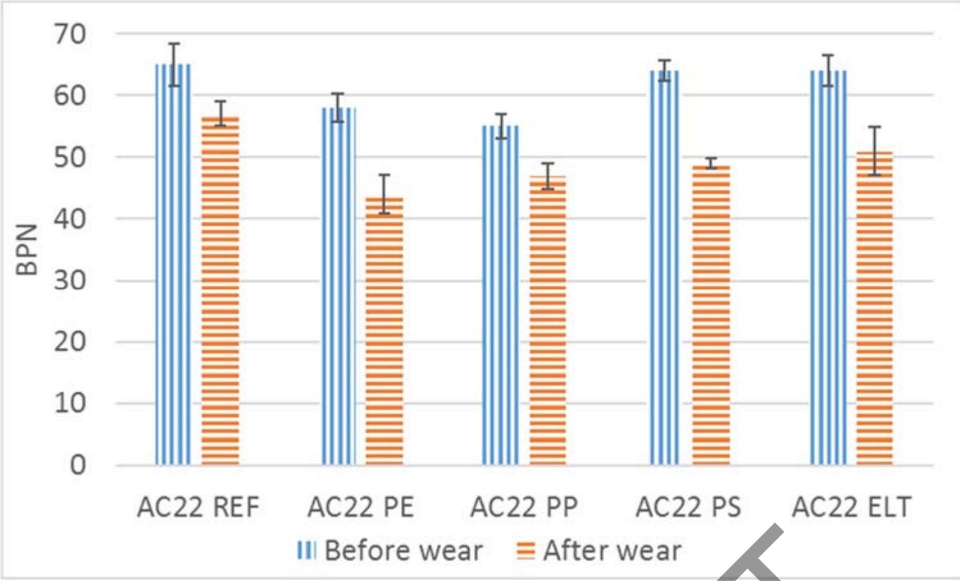

Figure 6. Skid resistance

The results adjust to a normal distribution and there is also homogeneity of variances, both before and after wearing. Table 1 presents the significances obtained.

Table 1. P-value of the skid coefficient for each type of mixture

		PE	PP	PS	ELT
REF	Before wearing	0.041	0.003	0.929	0.978
	After wearing	0.000	0.004	0.024	0.121

The skid resistance of the mixtures modified with the additives PS and ELT did not have meaningful differences with respect to the reference mixture before wear (the p-value is above that the 0.05 level of significance chosen). However, after wearing, only the ELT mixture stayed without meaningful differences regarding the reference mixture. The PE and PP reduce the skid resistance right after they are added to the mixture, while the PS does it after the mixture is polished. Rubber is the only that keeps the asphalt mixture skid resistance even after being worn down. These differences can be due to the behaviour of the rubber (it is a higher friction than plastics) (23), and the fact that it does not coat the aggregates as the plastic polymers do.

The polishing carried out on the specimens was compared with the real wear observed in the S-30 highway. For the reference mixture the wear produced would be equal to 7 years of traffic under the same conditions than the S-30. Due to the skid resistance reduction that the polymers addition causes, the same polishing procedure makes a wear equivalent to 1 year more of traffic in the case of the AC22 ELT mixture, and approximately 2.5 years in the case of the AC22 PE mixture, being these two mixtures the most extreme cases.

These results must be taken with caution. In the first place, because they are out of the range of years studied in the real road section (6 years), also because of the variability itself of the TRRL pendulum test, and finally because of the margin of error that could incorporate the correlation of results between CRT and BPN.

4.2. Evaluation of the adherence among layers by the shear test (LCB)

The results of the static adherence tests are shown on Figure 7.

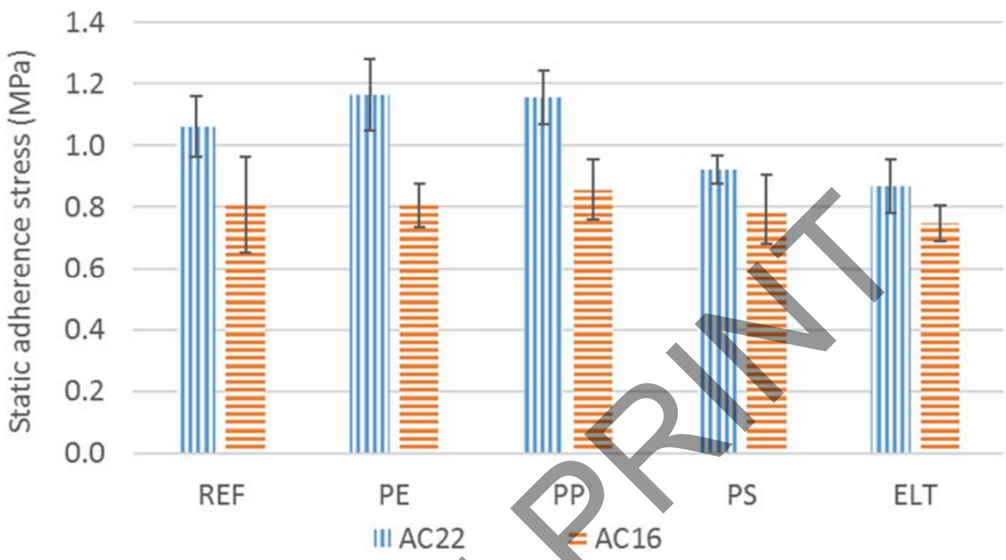

Figure 7. Adherence among layers in front of shear stress

Concerning the AC22 mixture, after verifying the normality and homoscedasticity of the results, the Scheffe test was performed for each couple of samples. The AC16 mixture did not show a normal distribution in all cases so that the U of Mann-Whitney test was applied, which showed that there were not meaningful differences between any of the mixtures. The significances are shown in Table 2.

Table 2. *P-value* of the static adherence test with a confidence interval of 95%.

		PE	PP	PS	ELT
AC22	REF	0.306	0.387	0.087	0.004
AC16	REF	0.325	0.385	0.355	0.064

According to the result, the static adherence of the AC16 reference mixtures is not modified meaningfully by any of the waste polymers. However, in the case of the AC22 mixture, the addition of rubber from ELT slightly reduces the shear resistance, obtaining a value around 80% of that of the reference.

The results were also analysed comparing the data in relation to the maximum aggregate size (AC16 vs. AC22). The results showed that the static adherence is significantly greater in the case of the AC22 mixes, confirming that the texture has influence on the adherence among the layers for all the mixtures. Table 3 summarises the significances.

Table 3. P-value for concretes of the same and different maximum size.

REF	AC16
AC22	0.008

PE	AC16
AC22	0.001

PP	AC16
AC22	0.001

PS	AC16
AC22	0.005

ELT	AC16
AC22	0.021

The influence of the temperature and the coat applied on the adherence between layers is shown in Figure 8.

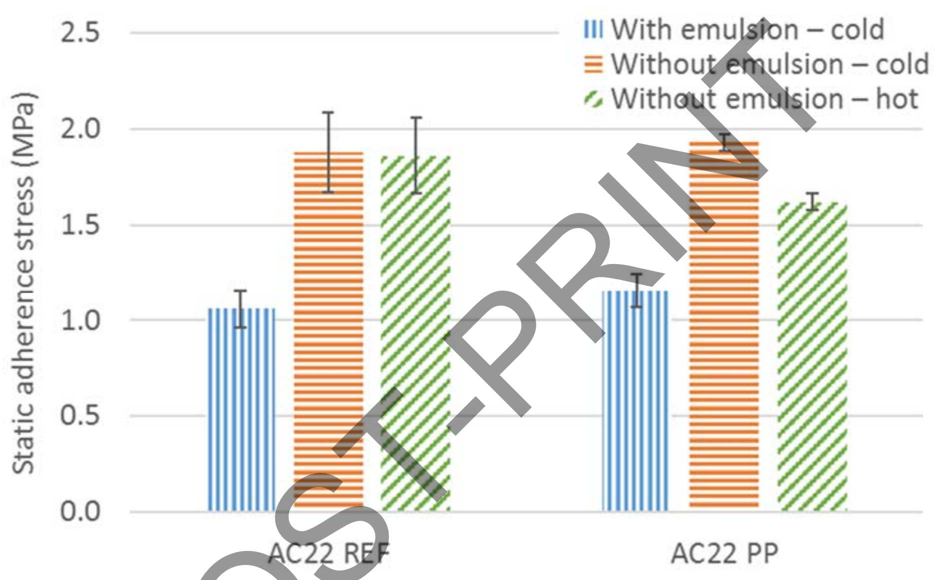

Figure 8. Shear resistance of the mixture AC22 REF and AC22 PP with and without emulsion

There has not been significant difference between the mixture with PP and the reference mixture, being the results coherent with the test previously applied (Figure 7), in which the addition of PP did not modify the static adherence. The p-values among mixtures types are shown in Table 4 below:

Table 4. P-values of the reference mixture and the modified with PP

With emulsion – cold	AC22 PP
AC22 REF	0.387

Without emulsion – cold	AC22 PP
AC22 REF	0.722

Without emulsion – hot	AC22 PP
AC22 REF	0.245

According to the results shown in Table 5, there have not been significant changes by compacting at different temperatures (p-values are above 0.05 both for the reference mixture and the PP). However, a higher shear resistance was observed when no emulsion was used. Therefore, it may be concluded that to improve the adhere between asphalt layers, the compaction of the second layer over the first layer ensuring a clean surface without emulsion is more determining than the temperature the lower layer may have.

Table 5. P-values in relation to the compaction temperature and the use of emulsion

Factor	Conditions	AC22 REF	AC22 PP
Temperature	Cold / Hot	1.000	0.081
Coat	With emulsion / without emulsion	0.019	0.019

4.3. Evaluation of the adherence among layers by the shear fatigue test

The cycles until failure of the shear fatigue test are presented for each mixture type in Figure 9.

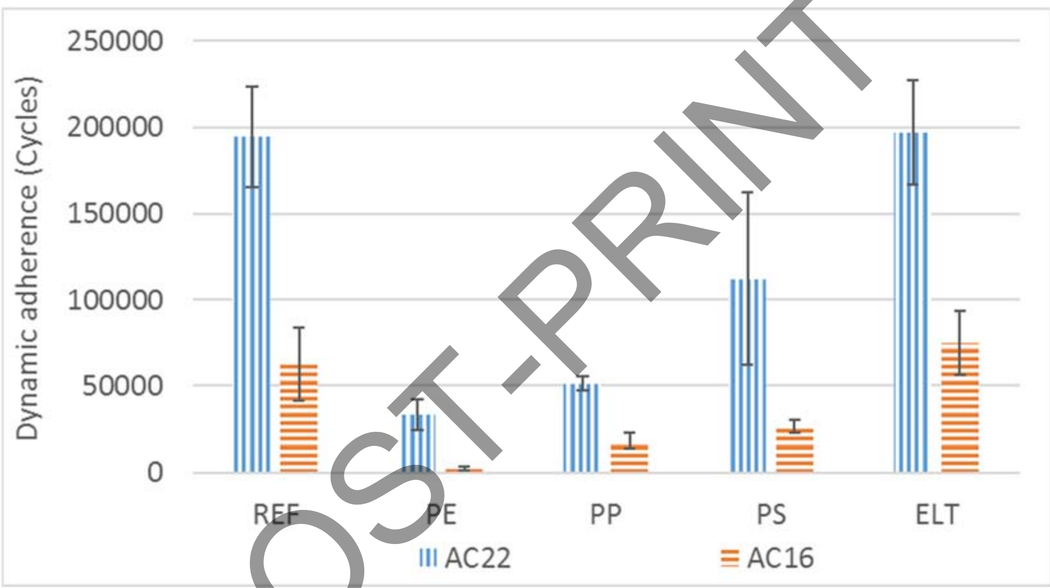

Figure 9. Cycles until failure

The texture of the mixtures becomes again a fundamental parameter, resisting the mixture AC16 a number of cycles clearly below than AC22 mixture, although the performance of the mixtures is analogous concerning the type of polymer used.

In this case, the results did not adjust to a normal distribution. With regard to the AC22 mixture, the U of Mann-Whitney test showed that there are not significant differences between the reference mixtures and those modified with PS and ELT, while the adherence reduces significantly in the case of mixtures with PE and PP. On the other hand, in the case of AC16 mixtures, only the mixture modified with ELT has a similar performance than the reference mixture, having the mixtures with PE, PP and PS a significantly lower resistance. These differences in the performance of ELT regarding the other polymers might be due to its rubbery state.

The significances for both mixtures are presented next on Table 6.

Table 6. Significances of the analysis of results of the shear fatigue adherence test.

		PE	PP	PS	ELT
AC22	REF	0.034	0.050	0.077	0.827
AC16	REF	0.021	0.021	0.034	0.386

The results of this test, unlike those of the static adherence, show a significant reduction of adherence when the polymers are added, especially in the asphalt mixes of lower texture (AC16). Only rubber has the same performance independently of the maximum aggregate size.

As in the static adherence case, it was verified that increasing the aggregate size in turn increases the shear resistance. Table 7 collects the significances in relation to size.

Table 7. Significances of the shear fatigue adherence test in relation to the maximum aggregate size.

REF	AC16
AC22	0.034

PE	AC16
AC22	0.021

PP	AC16
AC22	0.034

PS	AC16
AC22	0.034

ELT	AC16
AC22	0.034

The vertical slip of the central specimen until failure was also analyzed, studying its oscillating movement and the net slip that is produced in each cycle due to the fact that the movement amplitude is not fully recovered.

The net vertical slip is shown in Figure 10. In this figure, it is appreciated that the mixtures modified with PE and PP have a more fragile performance than the rest. The rubber modified mixture is the only one with a similar performance to that of the reference, even in the case of AC16 it increases its resistance (where the texture has a lower influence due to the smaller maximum aggregate size).

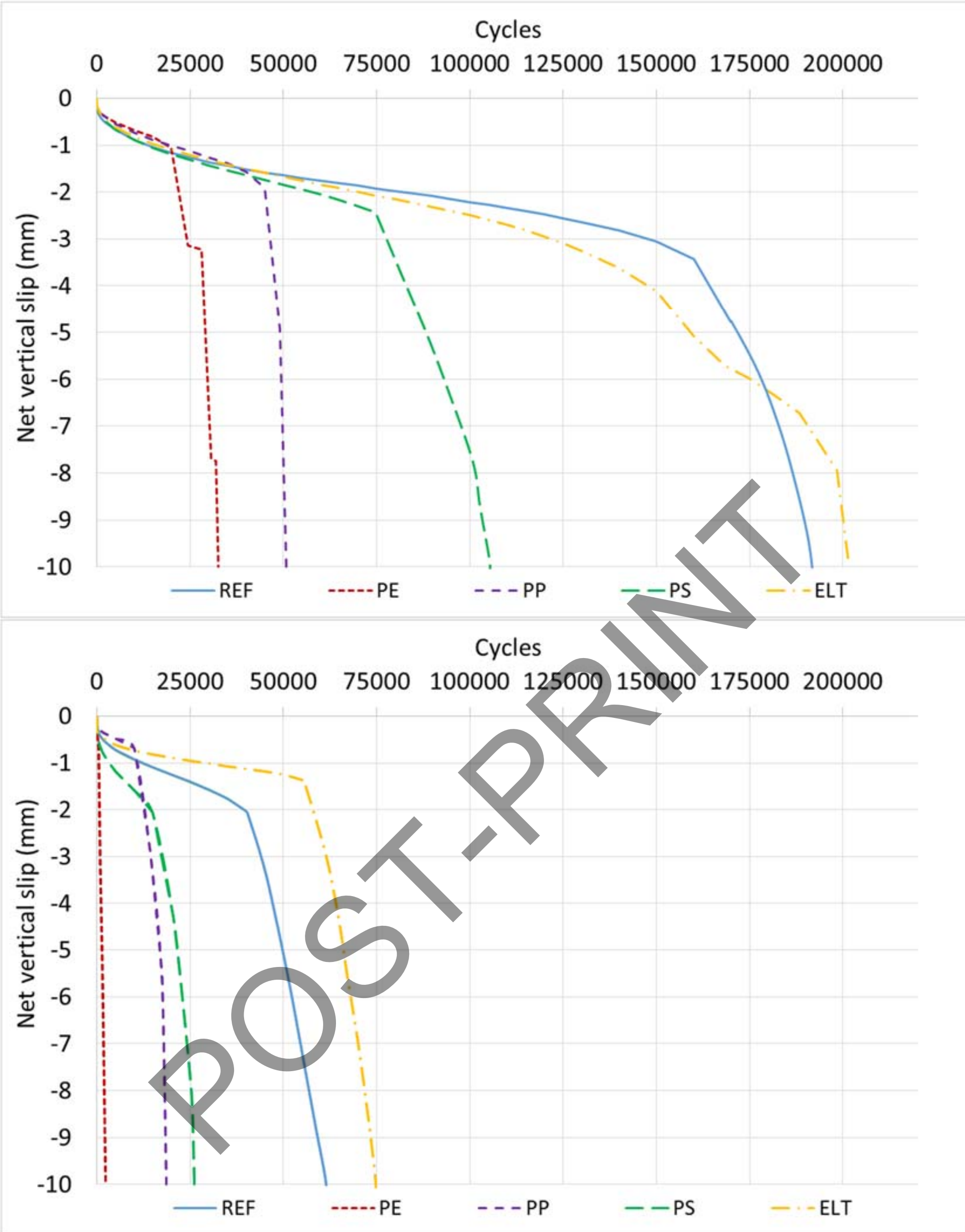

Figure 10. From top to bottom: vertical slip curves - cycles for the mixture AC22 and AC16 respectively

In Figure 11, the energy parameter α (estimated with the equation 2) is represented depending on the number of cycles.

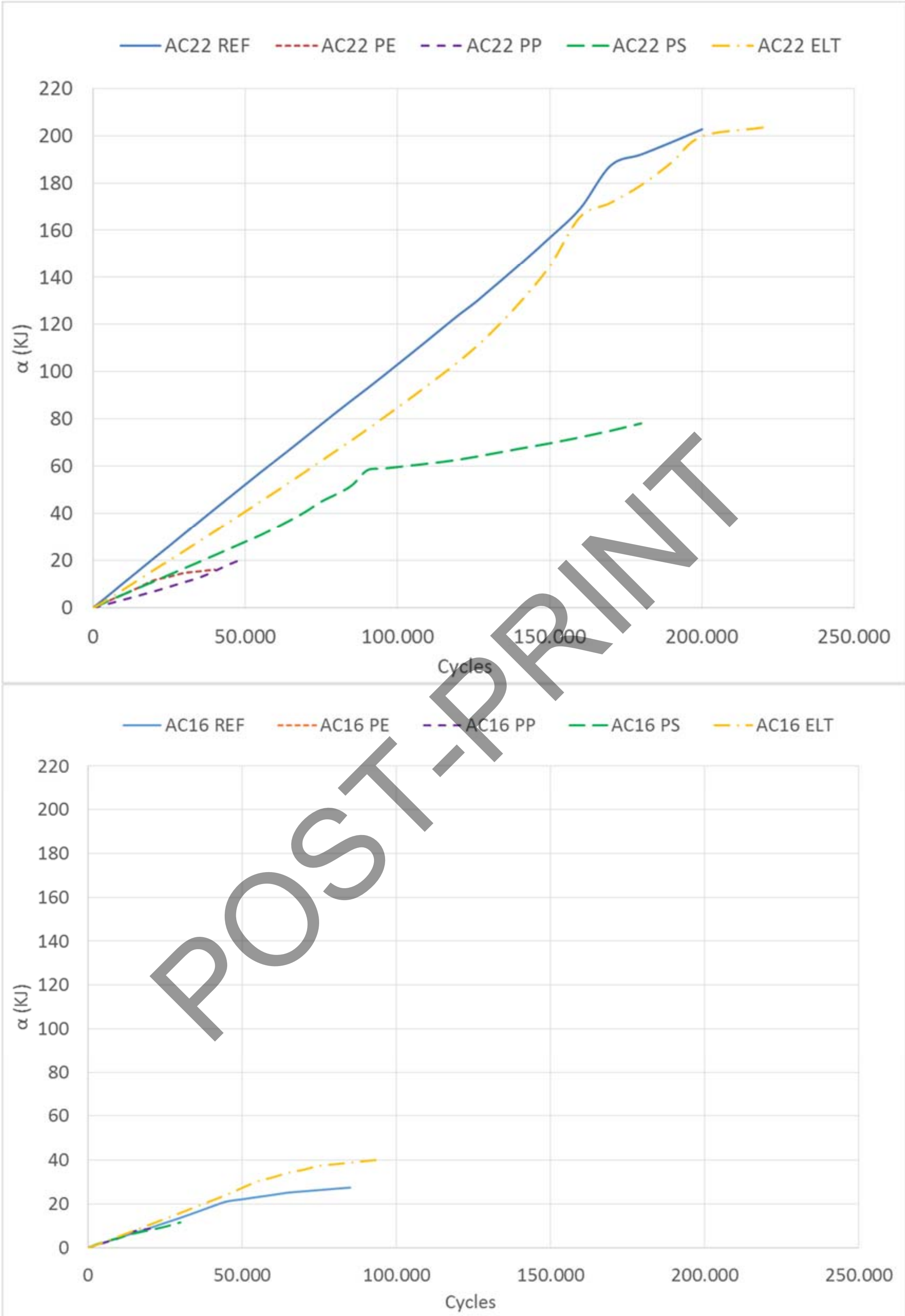

Figure 11. Parameter α for each mixture type. A) Top: AC22. B) Down: AC16.

The curves show a first lineal phase in which energy is proportional to the number of cycles. After this first phase the central specimen may slip suddenly, as in the case of the crystalline polymers (PE and PP), or rather the resistance starts to reduce in front of shear tending the curve to reduce its slope until the failure is produced. The mixtures that in this first lineal phase have a higher slope, are which achieve greater α values, and therefore, those which require higher energy until slip of the central specimen. This is coherent with the fact that a higher slope implies a more flexible performance.

In relation to the polymer used the parameter α shows great differences. The mixtures with the crystalline polymers (PE and PP) show values much smaller than the rest, with a more fragile performance. Rubber is the polymer that reaches the highest values, while PS is in an intermediate position.

These differences may be due to the fact that the emulsion is applied cold, so that the polymer is in a fully solid state and does not interact with the emulsion residual bitumen. The very composition of the polymers may be another determining factor. Rubber is the polymer that has the best performance, what is coherent if we have in mind that it is the only amorphous polymer that is above its glass transition temperature; that is to say, in rubbery state. In this way, rubber behaves in a more elastic way increasing the movement amplitude and obtaining a higher parameter α.

As before, the results are analysed in relation to the maximum aggregate size, to find out if the texture influence on the results of the α parameter was statistically significant. The results had a normal distribution but they did not show homogeneity of variances, so that the U of Mann-Whitney test was applied by couples in relation to the mixture type. The significances are shown on Table 8. The results indicate that the texture is a significant parameter for all the mixtures.

Table 8. Significances of the parameter α in relation to the aggregate maximum size.

REF	AC16
AC22	0.000

PE	AC16
AC22	0.001

PP	AC16
AC22	0.012

PS	AC16
AC22	0.000

ELT	AC16
AC22	0.001

Considering that the polymers modify the mixture surface properties, the possible relation between the shear fatigue resistance with the skid resistance of the specimens was analysed. With this aim, the results of the AC22 mixtures without sanding were used, obtaining a significant correlation among the shear fatigue resistance and the skid resistance with a significance of 0.047. This p-value, although near the limit that the confidence interval has (0.05), shows that the specimens with a higher resistance to skid also present a higher adherence in the shear fatigue test. This relation is summarized in the following equation, which obtained a coefficient of correlation of R^2=0.74.

$$Cycles_{failure} = 14982\ BPN - 799233 \quad (3)$$

5. Conclusions

The addition of residual polymers modifies the mixture's surface properties. The plastic polymers are found in the asphalt layer below their melting temperature (polyethylene and polypropylene) or glass transition temperature (polystyrene), so that they work in solid state once the mixture gets cold. However, the rubber works in the asphalt mixture above its glass transition temperature, therefore in a rubbery state, so that it is more flexible.

The polymers reduce the mixture skid resistance, except in the case of rubber. This impact is especially significant as the mixture is being polished, what is coherent with the statement that the plastic polymers modify the surface microtexture. The incorporation, therefore, of plastic polymers to a bituminous mixture in the wearing course demands the implementation of control measurements that guarantee some minimal values of skid resistance, as it may be the use of mixtures with higher texture.

Respect to adherence among layers, only the AC22 ELT mixture has its static adherence slightly affected, obtaining a value above 80% of the reference asphalt concrete. The polyethylene, polypropylene and polystyrene modified mixes withstand greater static loads until their break, than the rubber. However, in the shear fatigue test, the results differ from those obtained in the LCB shear test, being the rubber the only polymer which increases the adherence obtained by the reference mixture, while in the rest of mixtures it is considerably reduced. In both cases, adherence is also conditioned by the mixture texture, increasing its resistance with the used aggregate size.

The mixtures temperature did not seem to be a significant parameter in the LCB shear test; however, the resistance to shear increased significantly when the layers were joined without using a coat, with clean surfaces and under laboratory conditions.

With respect to the energy parameter α necessary to make slip the central specimen, the mixture with rubber is the only that exceeded the energy of the reference mixture, and depending on the texture, the energy necessary may be from 4 to 10 times higher than the requested by the mixtures with polypropylene or polyethylene.

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