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Original citation & hyperlink:
Rodríguez-Fernández, I, Lastra-González, P, Indacoechea-Vega, I & Castro-Fresno, D 2019, 'Recyclability potential of asphalt mixes containing reclaimed asphalt pavement and industrial by-products' Construction and Building Materials, vol. 195, pp. 148-155.
https://dx.doi.org/10.1016/j.conbuildmat.2018.11.069

DOI 10.1016/j.conbuildmat.2018.11.069
ISSN 0950-0618
ESSN 1879-0526

Publisher: Elsevier

Author's post-print: Rodríguez-Fernández, I., Lastra-González, P., Indacoechea-Vega, I., & Castro-Fresno, D. (2019). Recyclability potential of asphalt mixes containing reclaimed asphalt pavement and industrial by-products. Construction and Building Materials, 195, 148-155. doi:10.1016/j.conbuildmat.2018.11.069

Recyclability potential of asphalt mixes containing reclaimed asphalt pavement and industrial by-products

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Abstract

The aim of this study was the evaluation and validation of the recyclability potential of asphalt mixtures that incorporate high proportions of by-products (electric arc furnace slag and foundry sand) and reclaimed asphalt pavement in their composition. In a first stage, the performance of these asphalt mixes was assessed using mechanical tests as Marshall, water sensitivity, wheel tracking, stiffness and resistance to fatigue. Then, the samples underwent thermal aging treatment in order to be used as RAP in the manufacturing of new samples. Two rejuvenators were studied to check their effectiveness for the purpose of achieving this aim. Finally, the mechanical performance of these new mixes was evaluated. The results demonstrated a suitable technical performance and a good recyclability of the asphalt mixes used to replace practically all conventional aggregates. However, appropriate design and evaluation of the mixes is required, assessing the binder properties and the mechanical performance of the asphalt mix as well as evaluating its fatigue performance.

Keywords

Asphalt; Recycled materials; Reclaimed asphalt pavement; EAF slag; Waste foundry sand; Rejuvenators.

1. Introduction.

The use of recycled materials in road construction is becoming an increasingly common practice. The main objective pursued is the reduction of environmental impact, in this case, looking for alternatives that reduce the exploitation of natural resources such as mineral aggregates and binder. To do so, common practice is to turn to by-products or waste materials with characteristics suitable for use in the composition of asphalt mixtures, thus producing a twofold benefit for the environment by reducing the amount of waste taken to landfills [1,2] as well.

One of the most widely studied alternatives is the use of reclaimed asphalt pavement (RAP). Increasing the percentage of RAP in the composition of new mixes has been one of the main lines of research in this field [3–8]. In fact, there are research works that endorse the use of 100% recycled mixes [9–11]. This is reported to offer huge advantages in terms of sustainability and savings in costs [12,13]. For instance, by reusing the materials for the same purpose for which they were originally designed, an important reduction is achieved in the emissions produced in these asphalt mixtures, mainly associated with the process of production of new materials [9].

Nevertheless, there are some restrictions when incorporating high dosages of RAP including; deficiencies in the blending between virgin binder and residual binder, an excess of aggregates in the fine fraction caused by the milling process or the aging degree of the binder, which can affect the final performance of the asphalt mix [5]. There are additional shortcomings related to the production process of these mixes, such as the restrictions found in the asphalt plants to the incorporation of high RAP dosages or the need to adopt a new design methodology [9].

Reducing the amount of virgin binder used is one of the biggest challenges. The use of RAP is the most feasible alternative but the effect of aging on binders makes it necessary to use additives that restore the properties that have been lost over time. Aging causes changes in the distribution of malthenes and asphaltenes that increase the rigidity and viscosity and reduce the ductility of binders. To recover these properties, two different additives are normally used: fluxing agents and rejuvenators. Fluxing agents act mainly by reducing the viscosity while rejuvenators aim at restoring the physical and chemical properties of the aged binder. There are commercial products on the market that perform these functions but other wastes have also been considered as possible alternatives, for instance: Waste Vegetable Oil, Waste Vegetable Grease, Organic Oil, Waste Engine Oil or Distilled Tall Oil [14–16]. Another option to reduce the amount of virgin binder is to totally or partially replace it by non-petroleum-based asphalts. Materials such as bio oil, polymers, rubber or wastes such as cooking oil, among others, have been assessed in different studies as alternatives to reduce the amount of virgin binder used [2,17–23].

Finally, as an alternative to natural aggregates there are studies on the use of industrial by-products, such as slags or waste foundry sands, construction and demolition wastes, the recycled asphalt already mentioned and to a lesser extent recycled concrete aggregate (RCA) [24–29]. There are also studies with other materials such as ceramic waste, urban waste, wood or plastic [1,30–32]. The metallurgical industry generates a great volume of waste in the processes of iron and steel manufacturing. In 2010, 48% of the slag generated in Europe was reused as aggregate in road construction [33], including unbound layers and pavements., Some slags have been successfully used in asphalt layers in the last years. One example is the slag resulting from steel manufacture in electric arc furnaces (EAF slag), whose characteristics make it suitable for its use even in wearing courses, showing great resistance to polishing and a low Los Angeles coefficient [34–39]. There are other alternatives that have been evaluated such as the slag generated in copper manufacture or the slag generated in iron manufacture in basic oxygen furnaces (BOF slag) [40–42].

The study presented in this paper is framed in the project ALTERPAVE. This project aims to demonstrate an innovative and integrated approach for the sustainable construction of roads considering the whole life cycle of the infrastructure. Several actions are considered: enhancing the efficiency of resource use and cost of alternative materials, ensuring the recyclability of the roads developed with alternative green materials and implementing a "circular economy approach" by taking advantage of modern by-products and waste produced by local industry. In this paper, the study of the recyclability of asphalt mixes incorporating industrial by-products and RAP in high proportions is presented. The aim is to verify that the use of these materials in the manufacture of asphalt mixes does not hinder their future recyclability, so enabling their reuse.

In this sense, most recent studies attempt to characterise the effect that age has on the performance of these asphalt mixes, not to assess their reuse once the end of their useful life is reached [43–48].

To carry out this study, the performance of different asphalt mixes was assessed incorporating alternative materials. Afterwards, the mixes underwent thermal aging treatment in order to be used as RAP in the manufacturing of new samples. Finally, the mechanical performance of the recycled mix is compared to the performance of the original mix and a reference mix with no alternative materials.

2. Materials

Two industrial by-products were used as aggregates. For the coarse fraction (particle size greater than 2mm), EAF slag aggregate generated in a local company in Santander (Spain) was selected. This material is subjected to a thermal treatment which is divided is two phases: first, the hot slag is submerged in a pool, when it has been cooled the slag is laid and water is sprayed above it. This process guarantees the absence of any environmental (i.e. leaching) or technical (i.e. expansiveness) problem in the final product. The mechanical properties of this material are shown in table 1.

Test	Standard	Results	Specification*
Los Angeles Abrasion	EN 1097-2	18%	≤ 20%
Specific weight	EN 1097-6	3.735 g/cm^3	-
Polished stone value	EN 1097-8	59	≥ 56
Flakiness index	EN 933-3	2	≤ 20

*Spanish standard for pavement design [49]. Limits for the most restrictive category of heavy traffic.

Table 1. Properties of EAF slag

For the fine fraction, waste foundry sand (also called molding sand) was selected as an alternative material. Foundry sand is used for making molds within the ferrous and nonferrous metal casting industry. When the sand cannot be further reused, it is called waste foundry sand. The waste foundry sand selected employs a chemical product as a binding agent to pack the sand and hold the mold shape. The use of this material does not cause environmental or expansiveness problems in the asphalt mix. The principal properties of this material are shown in table 2.

Test	Standard	Results	Specification*
Specific weight	EN 1097-6	2.689 g/cm^3	-
Sand equivalent	EN 933-8	90	≥ 55

*Spanish standard for pavement design [49].

Table 2. Properties of foundry sand

Reclaimed asphalt pavement (RAP) is another important component in the experimental asphalt mix composition. The material selected was generated in a car park located in Santander (Spain). In order to characterize the RAP, the binder content was determined according to the standard EN 12697-1, using trichloroethylene to dissolve the bitumen and a centrifuge to separate the solution from the aggregate. Next, the residual bitumen was recovered from the solvent using a rotary evaporator, according to the methodology proposed by the standard ASTM D5404. The main properties and particle size distribution of the RAP are shown in table 3 and figure 1 respectively.

Test	Standard	Result
Specific weight	EN 1097-6	2.535 g/cm^3
Specific weight (recovered aggregate)	EN 1097-6	2.698 g/cm^3
Residual binder (above mix)	EN 12697-39	4.2%
Softening point of residual binder	EN 1427	70.8°C
Penetration of residual binder	EN 1426	10 (0.1mm)

Table 3. RAP properties

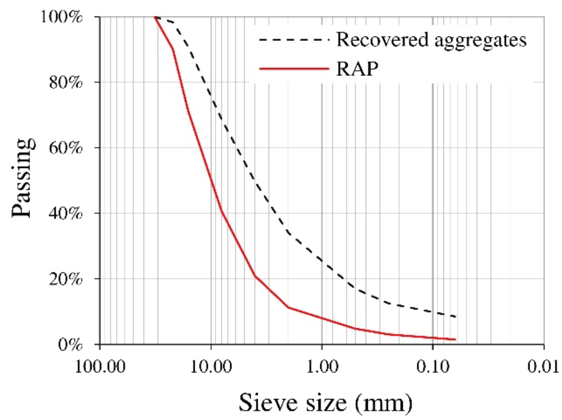

Figure 1. Particle size distribution of the RAP

The conventional materials employed in this study as aggregates were limestone for the fine fraction and ophite for the coarse fraction. These two materials comply with the requirements of the current Spanish regulation [49] for their use in asphalt concrete. Their main properties are shown in table 4.

Test	Standard	Ophite	Limestone	Specification*
Los Angeles Abrasion	EN 1097-2	16%	-	≤ 20%

Specific weight	EN 1097-6	2.937 g/cm^3	2.725 g/cm^3	-
Polished stone value	EN 1097-8	>56	-	≥ 56
Flakiness index	EN 933-3	8	-	≤ 20
Sand equivalent	EN 933-8	-	78	≥ 55

*Specifications for the most restrictive climate and traffic conditions.

Table 4. Properties of conventional materials

Finally, a conventional 50/70 penetration grade binder is used. The penetration index of this binder is 56 (25°C) and the softening point is 52.3°C. The compaction temperature was fixed at 140°C for this binder. Two different additives were used in order to improve the properties of the aged binder contained in the RAP. The first (henceforth A1) was a bio-based additive from pine chemistry. The second (henceforth A2), was a commercial bio-based fluxing agent. Both are in liquid state at room temperature and are incorporated by spraying onto the preheated RAP at 110°C.

3. Methods

3.1. Asphalt mix manufacture and characterization

The asphalt mix selected was an asphalt concrete (AC) with nominal maximum aggregate size of 16mm. This mix was intended for use in the surface layer. In this project, one asphalt mix formula was studied. For this formula, samples with A1 (henceforth mix 1) and A2 (henceforth mix 2) were produced.

In terms of volumetric properties, an air void content between 4 and 6% was considered adequate for this type of mixes. In this study, the air void content was determined using specimens prepared according to the Marshall design method. Thus, cylindrical specimens of 101,6mm diameter and 63,5mm height were compacted with the Marshall Hammer, with 75 blows on each side. Given that the compaction energy is fixed by the design method, three main variables determine the air void content of the mixture: the particle size distribution (aggregate composition), the binder content and the compaction temperature.

The aggregates of the experimental mixes are composed of 98.1% alternative materials (w/w), using only 1.9% of conventional materials (limestone) to complete the filler fraction. The RAP content is 35.5% (w/w). As a reference, an asphalt mix produced entirely with non-waste materials was also studied. The mixes composition and the particle size distribution are shown in table 5 and figure 2.

Mix	Rejuvenator	EAF slag	Ophite	RAP	Foundry sand	Limestone
Mix 1	A1	50.5%	-	35.5%	12.1%	1.9%
Mix 2	A2	50.5%	-	35.5%	12.1%	1.9%
Reference	-	-	66.5%	-	-	33.5%

Table 5. Asphalt mix composition (percentages by weight)

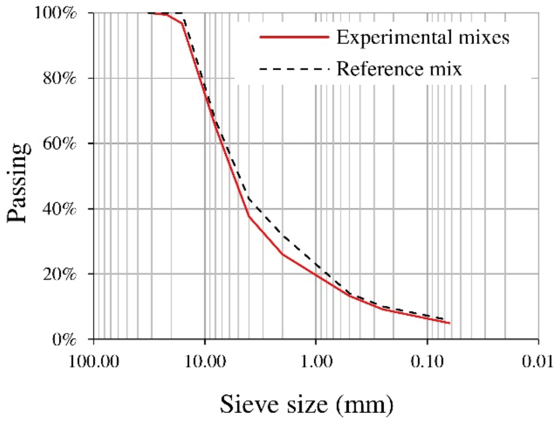

Figure 2. Particle size distribution of asphalt mixes (percentage by weight)

The difference between the experimental mixes and the reference mix in the particle size distribution is related to the different specific weight of the aggregates employed. The particle size distribution calculated in volume percentage is exactly the same for the reference and experimental mixes.

The additive content, for both A1 and A2, was fixed at 2.5% of the residual binder weight. To check the asphalt mix performance, the following laboratory tests were carried out: volumetric properties (EN 12697-5; EN 12697-6; EN 12697-8), Marshall (EN 12697-34), water sensitivity (EN 12697-12), wheel tracking (EN 12697-22), stiffness (EN 12697-26) and resistance to fatigue (EN 12697-24).

3.2. Evaluation of recyclability potential

To evaluate the recyclability potential, the first step is accelerated aging of the asphalt mixes. The method selected for short-term aging the mixes was SHRP short-term oven aging (STOA) and the accelerated method selected for long-term aging the mixes was SHRP long-term oven aging (LTOA). The STOA method establishes that loose mix should be placed in the oven at 135°C for 4h. After STOA, the LTOA method establishes that the compacted specimens should be placed in the oven at 85°C for 120h. The parameters used for LTOA are meant to represent 15 years of field ageing in a Wet-No-Freeze climate and 7 years in a Dry-Freeze climate [50].

In order to evaluate the aging effect, the penetration (EN 1426) and softening point (EN 1427) properties of the binder in mix 1 were determined before and after the aging process. Then, the content of additive A1 needed to restore the properties of the aged binder from mix 1 was determined experimentally. Thus, three dosages of A1 (2.5, 5.0 and 7.5%) were added to a combination of 70% of virgin binder and 30% of mix 1 aged binder (proportion in the original asphalt mixes). The extraction of the binder was carried out following the same procedure explained before for the RAP binder recovery (see section 2). The penetration and softening point of all the combinations were determined, the final dosage selected being the one with the highest recovery capacity in binder properties. The same quantity, here determined, is used for A2.

Once the rejuvenator content was defined, two new asphalt mixes were manufactured. The same methodology was used as with the original mixes. Concerning the aggregates, the same source, percentage and particle size distribution were used with as the original mixes, except for the RAP, which, as described before, was obtained from the artificial aging of mix 1 and mix 2. The composition of these new mixes (henceforth "recycled mix 1" and "recycled mix 2") are shown in table 6.

Mix	Rejuvenator	EAF slag	RAP	Foundry sand	Limestone
Recycled mix 1	A1	47.5%	35.0% (Aged A1)	14.3%	3.2%
Recycled mix 2	A2	47.5%	35.0% (Aged A2)	14.3%	3.2%

Table 6. Recycled asphalt mixes composition (percentages by weight)

Likewise, for the determination of the optimum binder content, the same methodology as for the original mixes was followed. The same laboratory tests as in the previous section were performed to evaluate the mechanical performance of the new mixes (see section 3.1).

4. Results and discussion.

The study done to determinate the rejuvenator content in the recycled mixes is presented following, after this, the results of the original and recycled mixes are shown.

The recyclability potential of the experimental mixes was evaluated by artificially aging both mixes and using the product obtained as RAP in new asphalt mixes. In figure 3, the penetration and softening point of the binder of the mix 1 before and after aging and of the different combinations of virgin binder (70%), aged binder (30%) and rejuvenator A1 are presented.

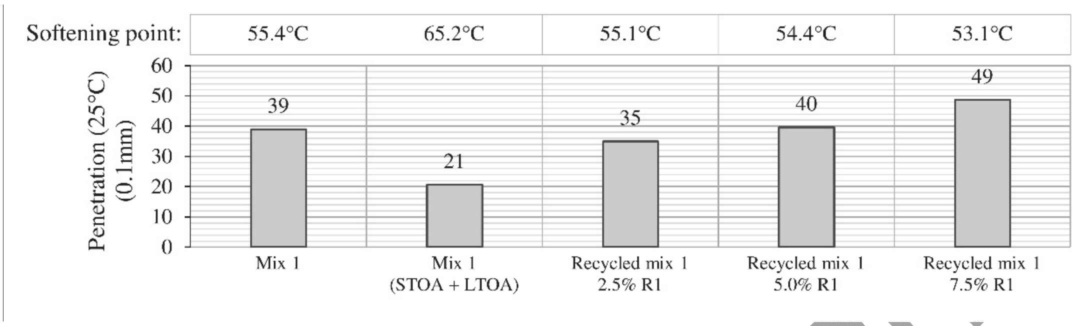

Figure 3. Softening point and penetration test results

The content of rejuvenator selected for the recycled mixes was 5%. Although the addition of 2.5% of rejuvenator almost restored the properties of the original binder, especially in terms of softening point, the 5% content was finally chosen. This increment in the rejuvenator content looks for reducing the binder content and the stiffness of the recycled mixes in comparison with the original mixes, trying to obtain results more similar to the reference mix. The same rejuvenator content (5%) was selected for the design of recycled mix 2.

Focus on the results, the total binder content for each mix and the corresponding amount of virgin and old binder are shown in table 7. The high specific weight of the EAF slag results in a high bulk density of the experimental mixes. Therefore, for a fairer assessment between the different mixes, the binder content is calculated in volume percentage.

	Mix 1	Recycled mix 1	Mix 2	Recycled mix 2	Reference
Rejuvenator	A1	A1	A2	A2	-
Total binder (% w/w)	4.6	3.9	4.6	3.9	4.3
Total binder (% v/v)	12.5	10.9	12.5	10.9	10.5
Virgin Binder (% v/v)	8.6	6.4	8.6	6.4	10.5
RAP Binder (% v/v)	3.9	4.5	3.9	4.5	-

Table 7. Binder content of asphalt mixes

According to these results, the original mixes require a significantly higher amount of binder than the reference one. Despite this, the virgin binder employed was 18% less than in the reference mix. The recycled mixes requires 13% less binder than in the original mixes, showing values close to the reference mix. In addition, the recycled mixes have a higher residual/virgin binder ratio, the virgin binder reduction being of around 25% and 40% when compared to the original and reference mix respectively.

This virgin bitumen reduction has a significant influence in the performance of the recycled mixtures. The original mixtures were composed of 70% and 30% of virgin and aged bitumen respectively, and the same ratio was used in the assessment of the rejuvenators (penetration and softening point). The recycled mixtures were composed of 59% and 41% of virgin and aged bitumen respectively, and it should be noted that 31% of the aged binder has been aged twice and this fact should be taken into account during the discussion of the results later on. The first aging occurred naturally during the service life of the RAP used on the original mixtures and the second one was performed at the laboratory according to the artificial aging procedure explained before (STOA and LTOA). The volumetric properties of the asphalt mixes are directly related with the binder content. In table 8 the bulk density, the maximum density and the air voids content for each mix are presented.

	Mix 1	Recycled mix 1	Mix 2	Recycled mix 2	Reference
Rejuvenator	A1	A1	A2	A2	-
Max. density (Mg/m^3)	2.942	3.061	2.942	3.061	2.660
Bulk density (Mg/m^3)	2.805	2.884	2.759	2.894	2.522
Air void content (%)	4.7	5.8	6.2	5.5	5.2

Table 8. Volumetric properties of asphalt mixes

As said before, and increment in the bulk and maximum density of the experimental asphalt mixes (both original and recycled) is caused by the use of the EAF slag. In the recycled mixes, the already high bulk density of the original mixes used as RAP, together with the use of EAF slag in the coarse fraction, cause a slight increase in the bulk and maximum density with respect to the original mixes.

The differences found in the air void content should be considered in the discussion of the results. However, in order to check if these differences are statistically significant, a statistical analysis has been done. The t-test method was used to do this analysis and the differences between mixtures was determined through the P-values and the 95% confidence interval.

Regarding the original mixtures, mix 1 and mix 2 are the mixes with the lowest and highest air void content respectively. The statistical analysis (t-test) resulted in a P-value of 0.012, supporting the hypothesis that the difference between these two mixes is statistically significant. Although the difference in the air void content could have been reduced by modifying the amount of virgin bitumen in the mixes, their composition were kept constant to evaluate the effect of the type of rejuvenator on both the volumetric properties and mechanical performance.

On the other hand, when the same analysis is done on the recycled mixtures, the differences in the air void contents resulted not statistically significant with a P-value of 0.453. Therefore, it cannot be concluded that there are differences between both rejuvenators in terms of mix workability. Actually, these differences in the air void content of the original mixtures could be attributed to the use of RAP, since the intrinsic variability of the material could introduce some differences in the particle size distribution and binder content, and therefore, in the volumetric properties.

The results of the Marshall test, the water sensitivity test and the wheel tracking test on the asphalt mixes are summarized in table 9.

	Mix 1	Recycled mix 1	Mix 2	Recycled mix 2	Reference
Rejuvenator	A1	A1	A2	A2	-
Marshall Flow (mm)	3.1	2.1	2.4	2.2	2.4
Marshall stability (kN)	18.8	18.9	16.3	18.6	14.1
MQ (kN/mm)	6.1	9.0	6.8	8.5	5.8
$ITS_{Unconditioned}$ (kPa)	2,125	2,079	1,720	2,433	1,576
$ITS_{Conditioned}$ (kPa)	1,934	2,005	1,544	2,357	1,466
ITSR (%)	91.0	96.4	89.8	96.9	93.0
WTS (mm/10^3 cycles)	0.02	0.04	0.02	0.03	0.08

Table 9. Laboratory test results of asphalt mixes

Concerning resistance to permanent deformation, the experimental mixes (both original and recycled) show high performance level in view of the results obtained in the wheel tracking test, significantly better than those obtained by the reference mixture. These results could indicate that the binder in the experimental mixes could be stiffer than the virgin binder due to the hardening effect of the binder from RAP, especially considering that all the mixtures have high quality coarse aggregates and the same percentage of filler.

Comparing original and recycled mixes, the recycled mixes present a slightly worse result. This could be due to the effect of the rejuvenator. In any case, the resistance of every experimental mixture is very high and the differences small.

Regarding Marshall Test, the experimental mixes showed higher values of Marshall stability, especially mix 1 and both recycled mixes. The lower value in the Marshall stability showed by mix 2 in comparison with mix 1 could be related with the high air void content of this mix. Likewise, mix 1 also showed higher values than the rest of the mixes in terms of Marshall flow, these latter with similar results. Therefore, the ratio of stability to flow, stated as the Marshall quotient (MQ), showed higher values in the experimental mixes. The MQ indicates how stiff the mix is. Therefore, high MQ values indicate a high stiffness mix with a greater ability to transmit the applied load and good resistance to creep deformation [51]. In agreement with the wheel tracking test, the Marshall test results also suggest that the binder contained in the experimental mixes could be harder than the binder contained in the reference mix. Analysing original and recycled mixes, the MQ is higher in the recycled mixes. These results are not in accordance with the wheel tracking test results, suggesting that the recycled mixes could have higher resistance against permanent deformation. However, more variables could be affecting these results.

Regarding the water sensitivity test, the experimental mixes showed significant differences between original and recycled mixes. The original mixes showed slightly lower ITSR values than the reference mix, but in any case adequate for this test. The recycled mixes present values of ITSR greater than 96%, significant better than the reference and original mixes, showing a low susceptibility to the effect of water. Analysing the ITS values, the results are in accordance with the Marshall stability results. The experimental mixes showed higher values of ITS, especially mix 1 and both recycled mixes. Mix 2 showed intermediate values between the reference mix and the rest of the experimental mixes. As said for the Marshall stability, this reduction in the ITS values could be related with the higher air void content of the mix 2. These results highlight the great level of adhesion of the alternative aggregates and binder.

Concerning the rejuvenators effect, the use of these additives allows to reach similar volumetric properties in asphalt mixtures with 40% of RAP (recycled mixtures) using the same total binder content, but reducing the amount of virgin binder used. Related with mechanical performance, the use of these additives seems to increase the mixture cohesion (higher ITS values), However, other variables could be affecting these results. There were no significant differences between the mixes with different rejuvenator. The only differences found were in the Marshall stability and in the ITS values of the original mixes. However, as said before, these differences could be related with the differences in the air void content. In fact, this phenomena is not shown in the recycled mixes, both with similar volumetric properties and similar performance for all the tests, and in this case, with higher values of ITS in the mix with rejuvenator R2. Said this, it is not possible to extract any conclusion beyond the good performance of the mixes independently of the rejuvenator used. Finally, regarding the mechanical tests, it is possible to conclude that all the mixes showed notable results in all the tests done, similar or even better than the reference.

In order to complete the study, the dynamic performance of the asphalt mixes was assessed. Firstly, the dynamic modulus of all mixes was determined and the results obtained are presented in figure 4 and figure 5. According to the results, the dynamic modulus of the original mixes was similar but significantly higher than that of the reference mixture. The higher stiffness and lower phase angle indicate more elastic behaviour than the reference. Again, the results tend to highlight that the binder in these mixes is harder than the binder in the reference mixture. However, the recycled mixes have lower stiffness values compared to the original mixes, especially recycled mix 1. In fact, this mix has a similar dynamic modulus to the reference mix at all frequencies. This behaviour could be justified by the increment in the rejuvenator content, resulting in a softer binder in the recycled mixes, more similar to the bitumen of the reference mixture and in accordance with the results obtained in the wheel-tracking test.

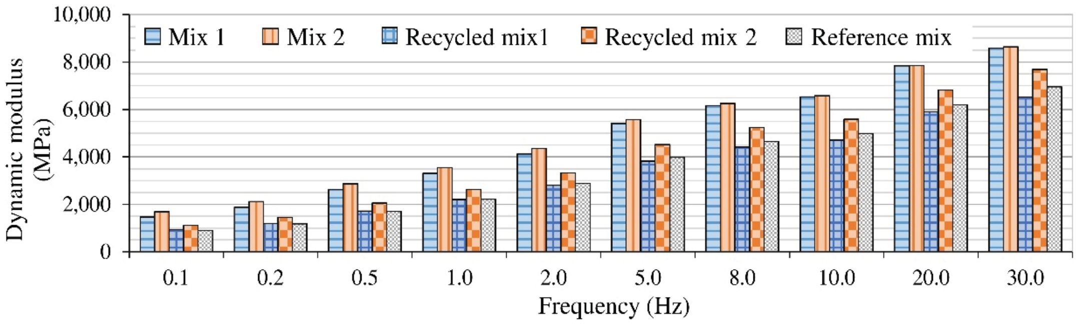

Figure 4. Dynamic modulus test results. Dynamic modulus

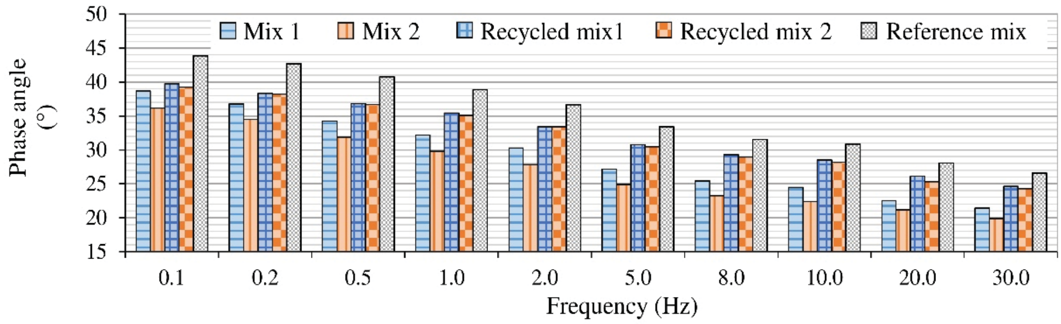

Figure 5. Dynamic modulus test results. Phase angle

Following with the dynamic characterization, the resistance to fatigue of the asphalt mixes was evaluated. The results are shown in table 10 and figure 6. In table 10, the strain related to 1 million cycles to failure (strain characteristic) and the number of cycles to failure when the strain is fixed at 100 microstrain (N_{100}) are presented. These two parameters are usually considered as indicators of the fatigue performance. The R^2 values and the fatigue law parameters ($\ln[N]=P_1-P_2\times\ln[\varepsilon]$) are also presented. It should be noted that the fatigue test is done under strain-controlled conditions, meaning that for the same strain level, the mixes that present higher stiffness are subjected to higher loads. Therefore, although this test provides a good indicator of the fatigue performance of the mixes, the comparison between the asphalt mixes should take into account the differences found in their stiffness.

	Mix 1	Recycled mix A1	Mix 2	Recycled mix A2	Reference
Rejuvenator	A1	A1	A2	A2	-
Strain characteristic (μm/m)	130.8	120.3	148.3	114.3	154.5
N_{100}	4.15E+06	3.01E+06	1.60E+07	1.90E+06	2.08E+07
P_1	39.7	42.4	49.0	36.7	48.9
P_2	5.30	5.97	7.04	4.83	6.97
R^2 (18 specimens)	0.763	0.872	0.863	0.971	0.947

Table 10. Fatigue test results

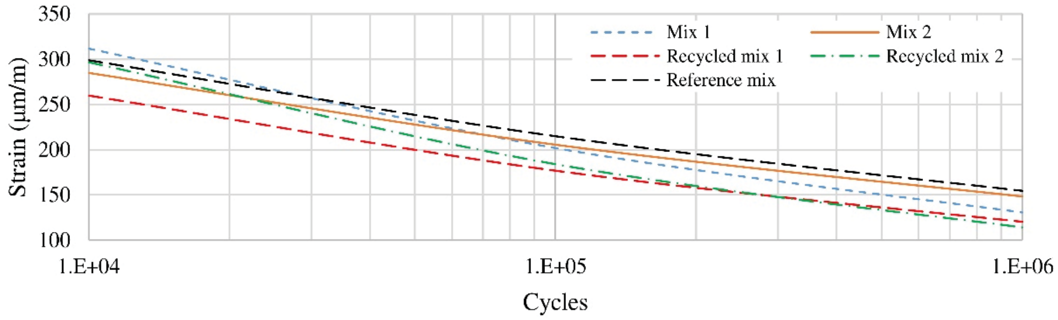

Figure 6. Fatigue test results

Based on the results obtained, it is possible to conclude that original mix 2 displays good fatigue performance, similar to the reference mix. The strain characteristics of both mixes are similar and their N_{100} values are of the same order of magnitude. Moreover, as shown in Figure 7, the curve corresponding to mix 2 is almost parallel to the curve of the reference mix. On the contrary, mix 1 presents different behaviour depending on the strain magnitude, good fatigue performance being obtained for high strains but this getting worse as the strain decreases, the strain characteristic of mix 1 being significantly lower and N_{100} one order of magnitude smaller than the reference and mix 2. In any case, both mixes show a very good fatigue performance, taking into account the higher stiffness of these mixes in comparison with the reference mix.

A lower fatigue resistance is observed for the recycled mixes compared to the original mixes. In general, a lower strain characteristic and N_{100} values are obtained for the recycled mixes, although the differences are higher between mix 2 and recycled mix 2 than between mix 1 and its recycled counterpart. However, comparing the curves, recycled mix 1 and mix 1 are almost parallel while in the case of recycled mix 2, the curve intersects with the original mix at 250µm/m, the fatigue performance above this strain being similar to the original mix and getting worse as the strain decreases.

In this case, the effect of the rejuvenators did not achieve the performance of the original mixtures. Probably, the lower virgin binder content (40% less than the reference mix) could have influenced the results. To increase the binder content or to decrease the percentage of RAP of the recycled mixtures is proposed to achieve the same performance against fatigue as the reference mix.

5. Conclusions.

In this study, the recyclability potential of asphalt mixes incorporating large amounts of alternative materials has been evaluated. The alternative materials used are EAF slags, waste foundry sand, RAP and non-oil-based rejuvenators to restore the properties of the RAP's old binder. The findings are summarized as follows:

- The use of RAP and rejuvenators resulted in a significant virgin binder reduction. The original mixes used 18% less virgin binder than the reference mix and the recycled mixes, with a higher rejuvenator content, used 40% less binder than the reference mix. This decrease shows that the rejuvenators work properly, besides this reduction of the required virgin binder is clear environmental advantage, which could mean a significant reduction of the environmental impact of the asphalt concrete mixtures.
- The use of EAF slags provides a good alternative to conventional aggregates in the coarse fraction. This material shows great resistance to polishing, a low Los Angeles coefficient and the mixes that incorporate it in the coarse fraction have a good resistance to permanent deformation. The high specific weight of the EAF slag should be taken into account during the manufacture of the asphalt mixes, it being recommendable to determine the particle size distribution by volume percentage instead of by weight.
- The waste foundry sand employed in this study provided a good alternative to conventional aggregates for the fine fraction. As for the EAF slag, its mechanical properties should be evaluated before use. It is also necessary to guarantee the absence of environmental and expansiveness problems.
- The suitable technical performance of asphalt mixes with alternative materials replacing practically all conventional aggregates has been demonstrated at laboratory level. These mixes showed adequate dynamic performance, with a slightly higher stiffness in comparison to a conventional mix and with satisfactory fatigue performance.
- The results obtained in this study demonstrate the recyclability of the experimental asphalt mixes. However, proper design and evaluation of the mixes is required. Assessing

the binder properties and the mechanical performance of the asphalt mix is necessary and the evaluation of the fatigue performance of the asphalt mix is recommended.

Acknowledgements

This study is framed within the ALTERPAVE project. This project was carried out by a consortium coordinated by GITECO (Construction Technology Applied Research Group, University of Cantabria) and integrated by ACCIONA Infrastructuras (Spain), I. Bacchi (Italy), Statens väg-och transportforskningsinstitut VTI (Sweden) and Western Research Institute (USA). The authors wish to acknowledge and especially thank Emilio Blas Galindo (ACCIONA), Matteo Bacchi (I. Bacchi), Livio Trussardi (I. Bacchi), Dina Kuttah (VTI) and Jean-Pascal Planche (WRI) for their collaboration.

ALTERPAVE is co-funded by Funding Partners of the ERA-NET Plus Infravation and the European Commission. The Funding Partners of the Infravation 2014 Call are: Ministerie van Infrastructuur en Milieu, Rijkswaterstaat, Bundesministerium für Verkehr, Bau und Stadtentwicklung, Danish Road Directorate, Statens Vegvesen Vegdirektoratet, Trafickverket-TRV, Vegagerdin, Ministere de l'Ecologie du Developpement Durable et de l'Energie, Centro para el Desarrollo Tecnológico Industrial, Anas S.P.S, Netivei Israel – National Transport Infrastructure Company LTD and Federal Highway Administration USDOT.

This work was supported by the European Union's Seventh Framework Programme for research, technological development and demonstration [grant numbers 1109806.0006]; and the FPU Programme of the Spanish Ministry of Education, Culture and Sport [grant number FPU-14/06997].

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