Post-print versión: Rodríguez-Fernández, I.; Lizasoain-Arteaga, E.; Lastra-González, P.; Castro-Fresno, D.; Mechanical, environmental and economic feasibility of highly sustainable porous asphalt mixtures. Construction and Building Materials, 251, 118982. https://doi.org/10.1016/j.conbuildmat.2020.118982

Title

Mechanical, environmental and economic feasibility of highly sustainable porous asphalt mixtures

Authors

Rodríguez-Fernández, Israel[1]; Lizasoain-Arteaga, Esther[1]; Lastra-González, Pedro[1]; Castro-Fresno, Daniel[1]*

Affiliations

[1]GITECO Research Group, University of Cantabria, Santander, Spain;

Email addresses

israel.rodriguez@unican.es (I. Rodriguez-Fernández); lizasoaine@unican.es (E. Lizasoain-Arteaga); pedro.lastragonzalez@unican.es (P. Lastra-González); castrod@unican.es (D. Castro-Fresno)

*Corresponding author. Tel +34942201753; Fax: +34942201703

Total words 6208

Abstract:

Road infrastructure plays a crucial role in the social and economic development of nations but also generates several environmental problems. To deal with these, three technologies were combined to produce highly sustainable porous asphalt mixtures: namely replacement of natural aggregates, reduction in manufacturing temperature and use of a nano-modified binder. The feasibility of the mixtures was evaluated by applying mechanical tests and performing a life-cycle assessment (LCA) and life-cycle cost analysis (LCCA). The results demonstrated the good behaviour of these sustainable mixes, enabling more than 12% and 15% reduction in the environmental and economic impacts of the road.

Keywords

Carbon black; Evotherm; Porous asphalt; Electric arc furnace slag; Reclaimed asphalt

1. Introduction.

Road infrastructure is vital for social and economic development of nations by enabling the transportation of valuable resources such as wood, minerals and petroleum and also by boosting trade between regions. However, it also generates several environmental problems which worsen as the transport network grows. The length of roads is expected to increase by at least 25 million kilometres by 2050 (60% more traffic than in 2010), thus affecting areas with exceptional biodiversity [1]. Therefore, there is a need to implement new technologies that reduce the impact of these infrastructures.

One of the main technologies used to reduce the environmental impact of roads is the replacement of natural aggregates by wastes and by-products [1–5]. For instance, slags generated during steel production, and in particular, those generated in electric arc furnaces (EAF) are a very promising material for use in asphalt pavements due to their good behaviour regarding plastic deformation, durability, stiffness and fatigue resistance [6]. They are especially suitable as coarse aggregates, given that they form a very stable mineral skeleton [7]. Furthermore, their resistance to polishing and abrasion and their toughness make EAF slags an appropriate material for use in surface layers [8].

Another alternative for replacement of natural aggregates is the use of by-products generated by the construction industry, reclaimed asphalt pavement (RAP) being the most common material. Traditionally, RAP has been treated as a black rock, meaning that the binder linked to the aggregates was supposed not to mix with the new binder, and therefore, no savings of virgin binder were considered. However, several authors state that the residual bitumen blends, so both materials (aggregates and binder) can be recovered [9,10]. Consequently, when RAP is used in unbound layers (a common practice nowadays), the full potential of the material is not reached.

In addition to the replacement of natural aggregates, warm mix asphalt technology (WMA) is also a good option to palliate the environmental impact produced by roads. The WMA concept relies on reducing the hot mix asphalt's (HMA) manufacturing temperature by 20-40°C while maintaining a similar mechanical performance [11]. To achieve this temperature reduction, the binder viscosity has to be modified by using, among other methods, additives (organic or chemical) and foamed binder. Considering that around 48% of the energy consumed during the materials' production and road construction occurs in the asphalt plant, several benefits (such as the reduction in the CO2 emissions, energy consumption or costs) can be achieved by using these asphalt mixtures [12].

Recently, researchers have also focused on increasing the durability of the pavements to amortize the environmental impacts and cost incurred during the production of asphalt mixtures [13–15]. In this sense, there is a trend toward incorporating nano-materials such as carbon black (CB) or graphite as additives to modify the binder, trying to improve its thermal properties, plastic deformation or elasticity [16,17].

The aim of this paper is to attempt to reduce as far as possible the environmental impact of asphalt mixtures without compromising their economic and mechanical performance. With this in mind, this research entirely replaced the natural aggregates commonly used in asphalt mixtures by adding RAP and EAF slag. Then, the effect of incorporating a temperature reduction additive and also using a new nano-modified binder instead of traditional polymer-modified bitumen (PMB) was analysed. The feasibility of combining all the technologies to produce highly sustainable asphalt mixtures was evaluated by applying mechanical tests and life-cycle assessment (LCA) and life-cycle cost analysis (LCCA) methodologies.

2. Materials and methodology

2.1. Experimental design

Three mixtures were developed to evaluate the technical, economic and environmental feasibility of applying three technologies (replacement of virgin materials, warm mix asphalt and nano-modified binder) in a porous asphalt (PA) mixture. This type of mixture already has some advantages over asphalt concrete (AC) mixtures since its high void content (more than 20%) improves the water runoff, heat island effect and noise pollution of roads [14]. However, its impact could be even smaller after applying the aforementioned measures. With this in mind, the mixtures were developed introducing changes sequentially: firstly, a HMA was designed containing EAF and RAP and using a PMB 45/80-65 bitumen; then, a WMA was manufactured incorporating Evotherm into the previous mix to reduce the production temperature; and finally, a nano-modified binder (NB) developed by ACCIONA Infrastructure [16] containing carbon black (CB) and styrene-butadiene-styrene (SBS) was used instead of the PMB to produce another WMA. It should be noted that the percentages of EAF slag, RAP and binder content remain unaltered in the different stages of the mix design. Furthermore, the mixes only employed conventional aggregates (limestone) in the filler fraction since the filler contained in the RAP was not enough to accomplish the requirements of this type of mixes.

As mentioned previously in the introduction, EAF slags present good characteristics for use as coarse aggregates, as is demonstrated by several studies. The properties of both EAF slag and conventional aggregates are summarized in Table 1.

Table 1. Aggregate properties

Test	Standard	EAF slag	Limestone
Specific weight (g/cm^3)	EN 1097-6	3.735	2.725
Los Angeles coefficient	EN 1097-2	18	-
Flakiness index	EN 933-3	2	-
Polished stone value	EN 1097-8	> 59	-
Sand equivalent	EN 933-8	-	78
Maximum particle size (mm)	-	16	2
Minimum particle size (mm)	-	2	< 0.063

The RAP used in this study comes from a road located in Cantabria (Spain) and no information regarding its original properties is available. Therefore, in order to characterize it, basic laboratory tests were done. The RAP binder content was determined according to the standard EN 12697-1 and the residual binder content was recovered following the methodology proposed by the standard ASTM D5404. In **Table 2**, the main properties of the RAP aggregates and binder are shown, while the particle size distributions of the RAP and the recovered aggregates can be verified in Figure 1.

Table 2. RAP properties

Test	Standard	Result
Specific weight	EN 1097-6	2.502 g/cm^3
Los Angeles coefficient (recovered aggregate)	EN 1097-2	24
Flakiness index (recovered aggregate)	EN 933-3	11
Residual binder content (from mass of mixture)	EN 12697-39	4.0%
Softening point of residual binder	EN 1427	76.1°C
Penetration of residual binder	EN 1426	13 (0.1mm)
Penetration index	EN 12591	0.9

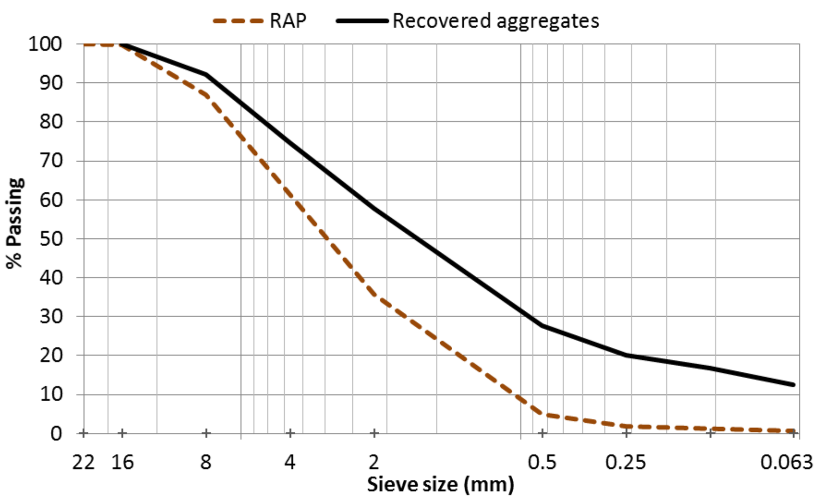

Figure 1. Particle size distribution of RAP

The two binders selected for this study are a polymeric modified binder (PMB 45/80-65) and a nano-modified binder produced by mixing carbon black (CB) and styrene-butadiene-styrene (SBS) [16]. The basic properties of these binders are shown in the Table 3.

Table 3. Binder properties

Test	Standard	PMB 45/80-65	NB
Softening point	EN 1427	74.1°C	71.0°C
Penetration at 25°C	EN 1426	55 (0.1mm)	45.3 (0.1mm)
Fraass breaking point (ºC)	EN 12593	-13	-12
Elastic recovery	EN 13398	92%	91%

Once the materials were selected, the next step was the asphalt mixture design. The specimens were compacted with 50 blows on each side, following the indications of the Spanish standard [18]. Given that the compaction energy is fixed, there are three main variables which determine the volumetric properties of the mixture: the particle size distribution, the binder content and the compaction temperature.

The particle size distribution of the PA mixture (see Figure 2b) was defined considering the limits established by the Spanish regulation for pavement design [18]. However, in this study the passing percentages were specified by volume instead of by weight due to the high specific weight of EAF slags. In this way, the same volumetric characteristics for all the mixtures' aggregates was ensured, and as a result, the asphalt mixture aggregate composition shown in Figure 2a was obtained.

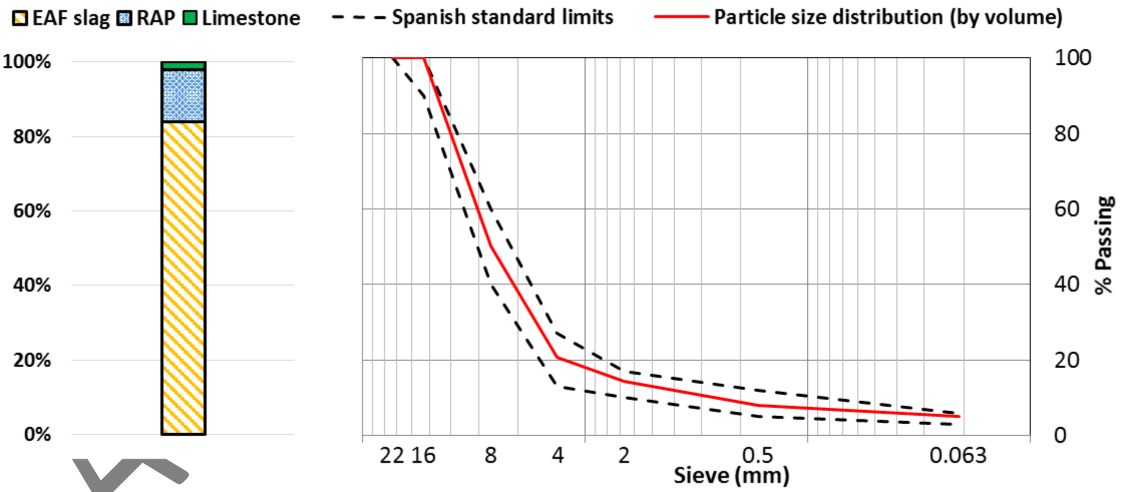

Figure 2. a) Aggregate composition (%w/w); b) Particle size distribution (%v/v)

The binder content employed in the mixtures was determined based on the air void content, which was fixed, in turn, according to the Spanish regulation for pavement design [18]. This standard stipulates the minimum air void content that every type of mixture should have: 20% regarding the PA mix. However, a maximum value is not specified. Taking these requirements into account, the binder content (expressed by weight) selected is shown in Table 4. It should be noted that the residual binder of RAP was assumed to blend and mix with the virgin binder. Therefore, the total amount of binder is the combination of both binders.

Table 4. Binder content of PA mix (%w/w)

Virgin Binder	RAP Binder	Total binder
3.55%	0.55%	4.10%

To achieve the temperature reduction in the WMA, the commercial additive Evotherm was used following the indications of the manufacturer, who stated that a 0.5% of additive by weight of virgin binder was needed due to the characteristics of the binder. This additive, which is in liquid state at room temperature, was added to the preheated virgin binder at mixing temperature and was then blended at 5,000 rpm during 5 min using a high shear mixer.

Regarding the manufacturing temperatures, HMA samples were mixed at around 165°C and compacted at 155°C, following the indications of the binder manufacturer. Once the temperature and the particle size distribution were fixed, the optimum binder content was obtained by testing different quantities of bitumen until the desired percentage of air void content was achieved. In contrast, WMA was designed using the same binder content as the HMA but varying the manufacturing and compaction temperatures until the same air void content as the HMA mixture was reached. Table 5 shows the temperatures used for each phase.

Table 5. Manufacturing temperatures (°C)

Mix	Mixing Temp	Compaction Temp	Aggregates Temp	Binder Temp	RAP Temp
HMA – PMB	165	155	195	165	110
WMA – PMB	145	135	175	145	110
WMA – NB	155	145	185	155	110

Once the asphalt mixtures' composition was defined, the mechanical performance of the mixtures was evaluated using the mechanical tests required by the European standards: Maximum density (EN 12697-5 procedure C), bulk density (EN 12697-6 procedure D), air void content (EN 12697-8), Particle loss test (EN 12697-17), water sensitivity test (EN 12697-12) and indirect traction test EN 12697-23. Dynamic tests were also conducted: stiffness test (EN 12697-26) and the resistance to fatigue test (EN 12697-24).

The results were statistically analysed and interpreted with Minitab statistical software. Firstly, the Shapiro-Wilk normality test was performed. Secondly, the One-Way Analysis of Variance (ANOVA) was carried out since a normal distribution was observed in all the samples analysed. The Tukey test was used to determine the differences between the asphalt mixtures' means. In all cases, the influence of the different factors has been determined applying a 95% confidence interval, thus the results are significantly different when the p-value is less than 0.05.

2.2. Life cycle assessment (LCA) and life cycle cost analysis (LCCA)

LCA is a methodology which enables the calculation of the potential environmental impact of a product throughout its life cycle. Standardised by the ISO 14040:2006 [19] and 14044:2006 [20], the LCA methodology consists in the application of 4 interrelated stages: goal and scope definition, inventory analysis, impact assessment and interpretation of the results.

As mentioned before, the main goal of this paper is to attempt to reduce as far as possible the environmental impact of asphalt mixtures without compromising their economic and mechanical performance, consequently achieving more sustainable infrastructures. With this in mind, the analysis was performed considering as a reference unit a 1-km lane with a width of 3.5 m and a pavement thickness of 25 cm (5 cm wearing course, 10 cm binder course and 10 cm base layer).

The selection of the system boundaries was based on the stages defined in the standard UNE-EN 15804:2012 [21]. In this sense, the material, construction, maintenance, use (leaching) and end-of life stages were included in the analysis and the inventory defined in a previous work [22] was also used here. However, the following aspects need to be specified:

- The production of CB was obtained from the database available in Gabi.
- The nano-modified binder developed by ACCIONA Infrastructure was calculated by combining the inventory of a polymer-modified bitumen [23] and CB.
- The environmental impact of producing Evotherm was excluded due to the lack of data and the little amount added to the mixture (0.018%) [21]. However, it was considered in the economic analysis.
- The impact of generating slags includes the valorisation process described by Arenal (2016) [24].
- Slags and Evotherm were assumed to be transported 30 km and 100 km, respectively, from the factory to the asphalt plant.
- WMA-PMB and WMA-NB were assumed to reduce 8.8% and 4.4%, respectively, the manufacturing energy of a HMA according to the model developed by Peinado *et al.* (2011) [25] despite reducing the temperature 12% and 6%. It should be noted that a certain amount of energy is consumed drying the aggregates.
- Although a mixture containing slag leaches less than the slag itself due to the impermeability provided by the bitumen, in this case, the same leaching rate has been assumed.
- The analysis was performed considering different service life extensions for the WMA-PMB and WMA-NB pavements.

Impacts were calculated using the ReCiPe 2016 characterization method. Developed by the University of Leiden, this method enables the calculation of the damage caused by a product to the three protection areas: human health (HH), ecosystem diversity (ED) and resource availability (RA). However, to compare the results when different service life extensions are assumed, results need to be annualized dividing them by the road service life. LCCA is a similar methodology but applying an economic point of view, that is to say, quantifying agency and user cost. The former includes the expenditures that the owner of the road bears whereas the latter refers to the cost that the road users incur. It should be noted that the value of money does not remain constant over time, thus, a discount rate needs to be applied to calculate the present value of future costs [26]. In this analysis, only the agency costs were considered due to the boundaries defined above and the 4% discount rate recommended by the European commission was selected. The cost data employed in the analysis as well as the sources are shown in Table 6.

Table 6. Costs database

Material/process	Units	Costs	Source
PMB	€/tn	540.00	[27]
NB	€/tn	704.00	Calculated
Coarse and fine aggregates	€/tn	7.50	Provider
RAP	€/tn	4.65	PaLaTe v2.0
Slags	€/tn	10.00	Waste manager
Filler	€/tn	41.36	[28]
Evotherm	€/tn	6,200.00	ACCIONA Infrastructure
Asphalt plant HMA	€/tn	8.16	[28]
Asphalt plant WMA-PMB	€/tn	7.56	Calculated
Asphalt plant WMA-NB	€/tn	7.86	Calculated
Construction	€/tn	4.74	[28]
Milling	€/tn	29.30	[28]
Transportation	€/(tn*km)	0.10	[28]

Finally, as the sustainability results are highly dependent on the service life of the road, a simulation of the pavement performance was carried out. The main failure mechanism of the binder and base layers is fatigue damage and ravelling is the most common failure of porous mixtures. The Cantabro test can shed light on the particle loss that a porous mixture could undergo in the future. However, a direct correlation between the laboratory test results and the durability of the mixture does not exist. Therefore, the pavement was assumed to fail by fatigue cracking and it was simulated using two software packages: Alize and 3D-Move. Alize is software developed by the French organization LCPC and SETRA, which calculates the response of a pavement to truck loads considering an isotropic linear elastic behaviour [29]. In contrast, 3D-Move uses a continuum-based finite layer approach accounting for a viscoelastic performance of the layers [30]. In both cases, a single axle dual tire was selected to load the pavement: tire pressure of 900 kPa, tire load of 32 KN, tire radius of 0.106 m and centre to centre tyre spacing of 0.3192 m.

3. Results and discussion.

3.1. Mechanical results

The volumetric properties of the three PA mixtures are shown in Table 7. 4 samples were used for each test, except for the water sensitivity test, where 4 samples for each condition (wet and dry) were employed.

Table 7. Mechanical properties of PA mixes

Results		HMA - PMB	WMA - PMB	WMA - NB
Voids test (EN 12697 – 8)				
Total binder (%)		4.1	4.1	4.1
Raw binder (%)		3.55	3.55	3.55
Bulk density (g/cm^3)		2.554	2.555	2.539
Voids (%)		20.8	20.7	21.1
Particle loss test (EN 12697-17)				
Loss particle (%)		15.5	12.1	18.3
Water sensitivity test (EN 12697 – 12)				
I.T.S.	Dry (KPa)	1022.6	1502.6	1203.9
	Wet (KPa)	896.6	1408.3	1197.5
I.T.S.R. (%)		88	94	99

As can be observed, all the mixtures have very similar volumetric characteristics and the minimum air void content of 20% considered as adequate for porous asphalt mixes was accomplished. In fact, the differences among the mixtures on this point are not statically significant according to the statistical analysis performed at 95% confidence level (Table 8). This is reasonable considering that it was a requirement decided during the mixtures' design.

Table 8. Mechanical properties. Statistical analysis

Difference of Levels	Difference of means	95% CI	Adjusted P-Value
Voids test (EN 12697 – 8)			
WMA-PMB – HMA-PMB	0.0016	-0.0247; 0.0280	0.987
WMA-NB – HMA-PMB	-0.0146	-0.0409; 0.0117	0.374
WMA-NB – WMA-PMB	-0.0162	-0.0435; 0.0111	0.324
Particle loss test (EN 12697-17)			
WMA-PMB – HMA-PMB	-3.4	-7.7; 0.9	0.121
WMA-NB – HMA-PMB	2.8	-1.4; 7.1	0.212
WMA-NB – WMA-PMB	6.2	1.9; 10.5	0.007

ITS values for unconditioned samples (kPa)			
WMA-PMB – HMA-PMB	479.9	286.0; 673.8	0.000
WMA-NB – HMA-PMB	181.3	-12.6; 375.2	0.066
WMA-NB – WMA-PMB	-298.6	-478.1; -119.1	0.004
ITS values for conditioned samples (kPa)			
WMA-PMB – HMA-PMB	511.7	352.2; 671.1	0.000
WMA-NB – HMA-PMB	300.9	151.7; 450.0	0.001
WMA-NB – WMA-PMB	-210.8	-360.0; -61.6	0.010

Even though achieving a very similar air void content in all the mixtures seems to indicate that no differences exist among the compaction energies required by each mix, the workability test (EN 12697-31) was carried out to 2 samples to corroborate this. The relationship between the air void content and the number of gyrations applied was analysed (Figure 3). These results agree with the values obtained above for the volumetric properties. The temperature reduction in WMA mixtures does not affect the mix's workability, the three asphalt mixtures demonstrating very similar results in this test.

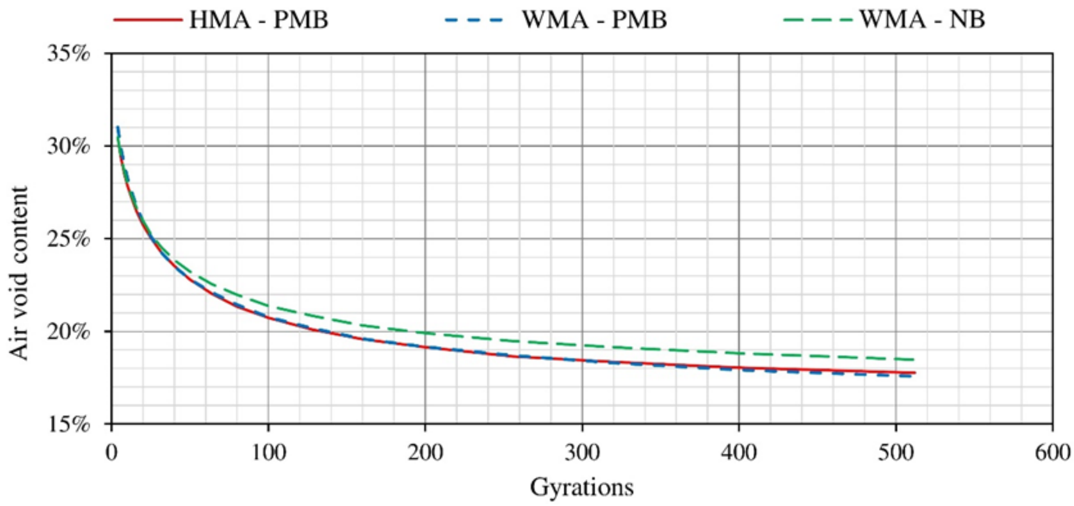

Figure 3. Workability test results

As raveling is the main failure mechanism of porous mixtures, the cohesion of the three mixtures under study needs to be analysed by means of the Cantabro test (EN 12697-17) (Table 7).

To evaluate whether the results are adequate or not, the limit established by the Spanish regulation for pavement design [18] can be considered. This standard establishes a maximum value for particle loss of 20%. Therefore, it is possible to state that all the mixtures show an adequate performance. However, some conclusions can be drawn by comparing the different mixtures.

Firstly, the use of the experimental NB leads to lower mixture cohesion. This fact is clearly shown when comparing the two WMAs, which only differ in the type of binder and production temperature. In this sense, the WMA with NB undergoes more particle loss than the mixture with PMB. However, no significant differences are observed when the mixture is compared to the HMA mix (see Table 8).

Another conclusion is related to the use of Evotherm, or in other words, with the temperature reduction. Comparing the WMA and the HMA, both with the PMB, it can be stated that using Evotherm does not produce any problem in terms of mixture cohesion. In fact, the WMA results are slightly better than HMA results although these differences are not statistically significant.

The moisture susceptibility of the asphalt mixes was evaluated by performing the water sensitivity test (EN 12697-12). This test provides a good indicator of the adhesiveness between binder and aggregates in an asphalt mix. The ITS values of both conditioned and unconditioned groups of specimens as well as the Indirect Tensile Strength Ratio (ITSR) are shown in Table 7 and the statistical analysis is shown in Table 8.

The good performance of the three mixtures regarding indirect traction can be observed when analysing the results. In this sense, the addition of Evotherm produces a significant increment in the ITS values (whether unconditioned or conditioned), WMA-PMB surpassing the HMA results by more than 50%. These results corroborate other studies' findings which concluded that using Evotherm has a positive effect on the moisture performance of the mixtures [31,32].

On the other hand, when the NB is used instead of the PMB, a median value between the other two mixtures is observed, what implies a 25% increment in the HMA results. Furthermore, WMA-NB reaches 99% in the ITSR and therefore, it undergoes less damage due to moisture effects.

The dynamic performance of the PA mixes was evaluated through the stiffness (EN 12697-26) and resistance to fatigue (EN 12697-24) tests. 3 and 12 samples were used, respectively, in this case. The dynamic modulus of the three asphalt mixtures at different frequencies are shown in Figure 4 and 2 examples of the statistical analysis can be seen in Table 9.

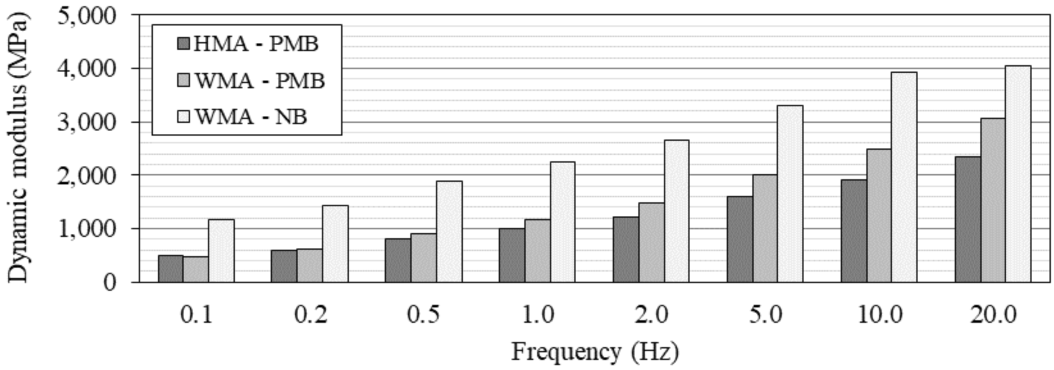

Figure 4. Dynamic modulus test results of PA mixtures

The WMA with NB shows higher stiffness at all frequencies in comparison with the rest of the mixtures. In fact, the higher the frequency, the higher the difference between the dynamic modulus of the WMA-NB and the other two mixes, especially when compared to the HMA. Therefore, it seems that NB could be stiffer than the conventional polymeric modified binder.

Regarding the WMA-PMB, its behaviour is very similar to the HMA mix in the lower range of the graph. However, over 2 Hz the difference between WMA-PMB and the HMA mix becomes significant, demonstrating the capability of Evotherm to increase the mixture stiffness.

Table 9. Dynamic modulus (MPa). Statistical analysis

Difference of Levels	Difference of means	95% CI	Adjusted P-Value
	0.1 Hz		
WMA-PMB – HMA-PMB	-2.3	-137.0; 132.5	0.999
WMA-NB – HMA-PMB	673.9	529.9; 818.0	0.000
WMA-NB – WMA-PMB	676.2	541.5; 810.9	0.000
	20 Hz		
WMA-PMB – HMA-PMB	714	359; 1068	0.001
WMA-NB – HMA-PMB	1695	1316; 2074	0.000
WMA-NB – WMA-PMB	981	626; 1335	0.000

Fatigue test results, expressed using the two most common parameters, are shown in Table 10 and Figure 5. The strain characteristic represents the strain which causes the mixture failure after a million cycles while N_{100} indicates the number of cycles at which a mixture fails when a strain of 100 microstrains is fixed.

The results obtained during the development of the fatigue test are coherent with the stiffness values. The two mixtures that uses PMB show a very similar stress-cycle (S-N) curve. However, the higher stiffness of the WMA mixture displaces the fatigue law trace downwards, WMA suffering a higher stress under the same strain conditions.

Regarding the WMA-NB, it presents a similar performance to the WMA-PMB at high strain levels (350-500µm/m). However, as the deformation decreases the performance of this mixture gets worse.

It is important to mention that the real fatigue performance is directly influenced by the material stiffness. For the same traffic loads, the response of the pavement will be different depending on the stiffness of the materials used for each layer. In this case, the differences shown in the fatigue test between the WMA-NB and the rest of the mixtures will be reduced under real pavement conditions due to the positive effect caused by the higher stiffness of the new binder. Finally, it is necessary to consider that these types of mixtures are usually employed in surface layers, where the damage caused by fatigue is not as important as in the bottom layers. In any case, the results obtained in terms of dynamic performance are adequate for this type of asphalt mixtures.

Table 10. Fatigue test results of PA mixes

Mix	Binder	Strain characteristic (µm/m)	N_{100} (cycles)	Fatigue law	R^2
HMA	PMB 45/80-65	222.1	1.02E+08	ln(N)=45.1 -5.79×ln(ε)	0.90
WMA	PMB 45/80-65	185.7	3.03E+07	ln(N)=42.6 -5.51×ln(ε)	0.88
WMA	NB	126.4	1.89E+06	ln(N)=30.7 -3.54×ln(ε)	0.92

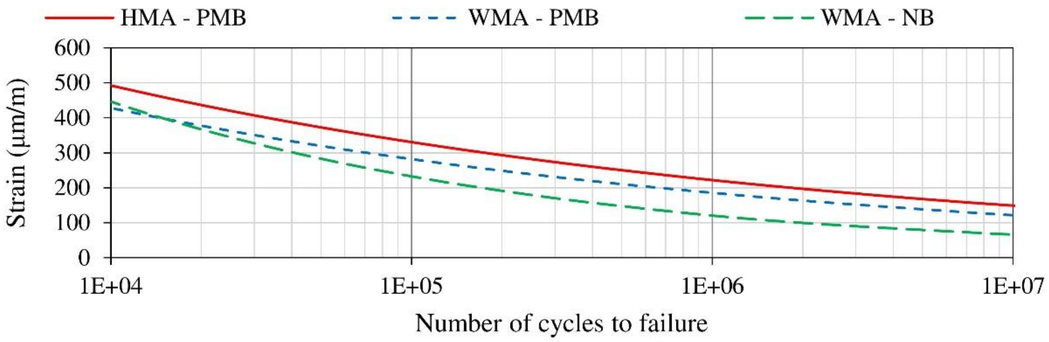

Figure 5. Fatigue test results of PA mixes

3.2. LCA and LCCA results

Results after comparing the LCA and LCCA of both WMA with the HMA are shown in Figure 6 and Figure 7. As is obvious, the greater the service life of the road, the smaller the economic and environmental impacts.

When the analysis is performed considering only the wearing course (Figure 6), the differences between the mixtures are more obvious. The 20ºC reduction in the manufacturing temperature of the WMA-PMB leads to a decrease of 1.0%, 2.9% and 3.3% in the RA, HH and ED impacts, respectively when no service life extension is considered. However, the addition of Evotherm increases the cost of the mixture, WMA-PMB needing 0.5% life extension to equalize the HMA cost.

Regarding WMA-NB, the addition of nano-technology results in a higher environmental and economic impact if no service life extension takes place. Again, the economic impact is the most restrictive one with 8.8% higher cost than the HMA. This impact is followed by HH, which is 4.6% higher than in the HMA, RA having the lowest impact with an increment of 0.5%. Nevertheless, as calculating the durability of porous asphalt mixtures is not possible with the tools that are currently available (at least at laboratory level), the analysis was performed applying the LCA and LCCA methodology to the whole pavement assuming fatigue failure.

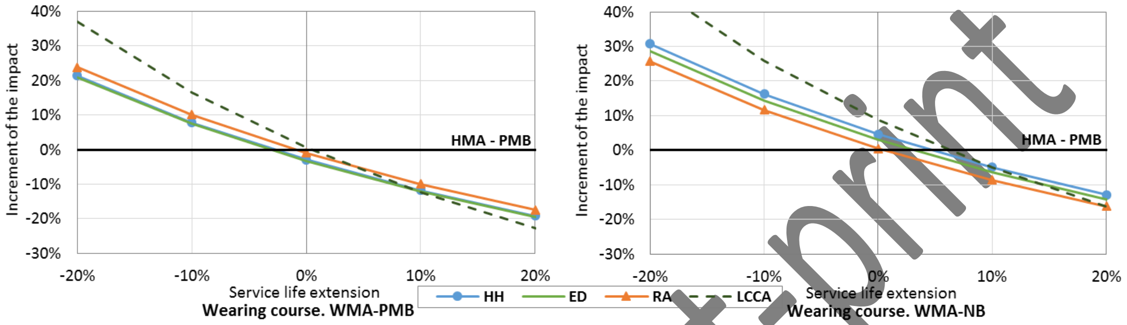

Figure 6. LCA and LCCA result comparison. Wearing course.

The durability of the asphalt pavements calculated with Alize and 3D-Move as well as their relationship (in percentage) can be seen in Table 11. When a static approach is applied, Alize provides more conservative results than 3D-Moves due to intrinsic variables of the software (such as the adherence between the layers). However, the relationship between the mixtures durability is very similar whichever software is used. In this sense, WMA-PMB and WMA-NB increase the durability of HMA by around 5% and 17%. On the other hand, the effect of vehicle speed on the pavement deterioration can be clearly observed when the dynamic analysis is carried out: the lower the speed, the greater the damage. Nevertheless, as the relationship between the mixtures' durability is barely affected by the speed selected, the service life increase of the WMA-PMB and WMA-MB is 4% and 11%. Therefore, smaller increments in the service life are calculated when performing a dynamic analysis.

Table 11. PA mixture durability

Mix	**Alize Static**	**3D-MOVE**					**Static (mean**	**Dynamic (mean)**
		Static	**10 km/h**	**20 km/h**	**60 km/h**	**100 km/h**		
Absolute value (years)								
HMA-PMB	11.8	15.3	10.0	14.2	23.8	29.2	-	-
WMA-PMB	12.5	16.1	10.3	14.8	24.9	30.5	-	-
WMA-NB	13.9	17.8	11.1	15.9	26.4	32.2	-	-
Durability increase compared to the HMA-PMB mix (%)								
HMA-PMB	0%	0%	0%	0%	0%	0%	0%	0%
WMA-PMB	6%	5%	3%	4%	5%	5%	5%	4%
WMA-NB	17%	16%	12%	12%	11%	11%	17%	11%

When the whole pavement section is included in the LCA and LCCA system boundaries (see Figure 7), the effect of the technology is attenuated. In this sense, the economic aspect is still the most restrictive impact, WMA-PMB needing 0.2% service life extensions to be considered as profitable, whereas the WMA-NB needs at least a 3.0% increase. On the other hand, when the environmental point of view is taken into account, the benefits of using WMA-PMB technology can be observed even when the pavement lasts 1.4% less than the HMA pavement, the pavement needing -0.3% life extension to improve the three environmental impacts. However, WMA-NB starts showing benefits when 0.2% service life increase is achieved and requires 2.3% increase to be considered as environmentally friendly due to the HH impact generated during the CB production.

Considering the service life extension calculated with the software, significant improvements are obtained with both mixes. WMA-PMB, achieving a smaller increment in the service life, enables a reduction between 5.2% and 6.3% in the environmental impact when the static approach is applied and between 4.1% and 5.2% with the dynamic analysis. Bigger improvements are achieved with the nano-modified binder. When the dynamic analysis is carried out, reductions of 8.2%, 8.9 and 10.0% in the HH, ED and RA impacts are possible. Furthermore, if the static analysis is performed, these three environmental impacts can be reduced 12.3%, 13.0% and 14.0% respectively.

Economic advantages are also obtained with these technologies and again, WMA-NB is the most profitable pavement. When an optimistic service life extension is assumed, WMA-NB achieves 15.0% cost reduction while WMA-PMB achieves 5.9%. Considering a more conservative scenario, WMA-NB can reduce 9.8% the agency costs whereas WMA-PMB only reduces them 4.5%.

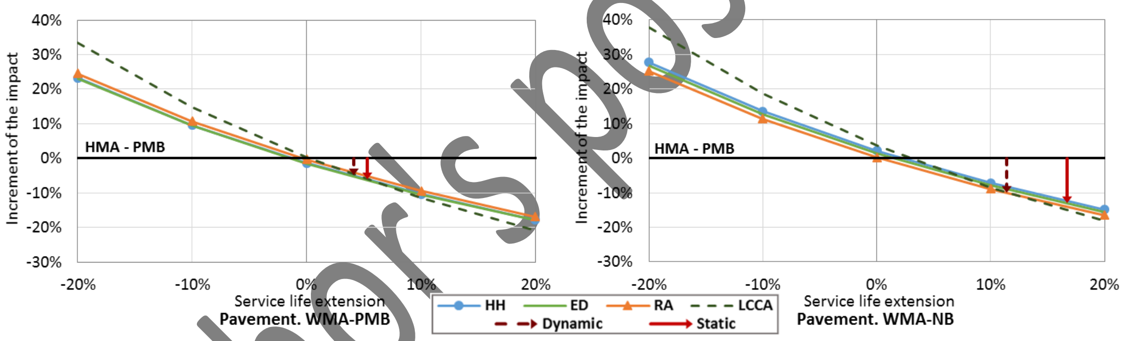

Figure 7. LCA and LCCA result comparison. Pavement.

4. Conclusions.

Three porous asphalt mixtures which combine the most common techniques to reduce the environmental impact of roads (the replacement of natural aggregates, the reduction of the manufacturing temperature and the use of a nano-modified binder) were designed in this paper. All the mixtures were dosed using EAF slag (80.4%) and RAP (14.0%), the addition of limestone (natural aggregates) being necessary in the filler fraction (2.0%). Evotherm was used as the additive to reduce the WMA temperature and CB was used by ACCIONA Infrastructure to develop a nano-modified bitumen.

After performing several mechanical tests in the laboratory as well as applying the LCA and LCCA methodologies, several conclusions can be drawn:

- The technical feasibility of producing highly sustainable PA mixtures which combine the three technologies was demonstrated at laboratory level.

- Evotherm ends up being a good additive to produce WMA. Adding 5% of Evotherm by weight of virgin binder leads to a decrease of 20ºC in the manufacturing temperature in porous asphalt mixes without affecting the compaction energy.
- Using Evotherm has a positive influence on the mechanical performance of the mixtures. WMA-PMB presents less particle loss than HMA and achieves the highest values of ITS. Furthermore, Evotherm tends to increase the stiffness of the mixture.
- The mixtures with the experimental binder show the lowest water susceptibility. In contrast, despite accomplishing the standards and the differences not being statistically significant, WMA-NB presents the worst results in the particle loss test. In terms of dynamic performance, WMA-NB shows worse fatigue performance than the mixture with PMB. However, its higher dynamic modulus would reduce the differences between the mixtures' behaviour under real pavement conditions.
- In general, static simulations provide more conservative results than dynamic analysis when they are expressed in absolute terms. However, comparing the durability of the pavements percentage-wise, static simulations calculates larger service life increases.
- Alize and 3D-Move can be used interchangeable to calculate the relationship between the pavements durability in a static way. However, the absolute value is different due to intrinsic characteristics of the software. This is also observed in the dynamic analysis when several traffic speeds are simulated. Although the absolute values of durability differ, any speed can be selected as long as the analysis is being performed for comparative purposes.
- Both WMA technologies improve the environmental and economic impacts. Nevertheless, using nano-modified binder provides the most promising results. When the best durability scenario is considered, more than 12% and 15% reductions in the environmental and economic impacts can be achieved.
- The incorporation of the whole pavement within the system boundaries when the technology is only applied in the wearing course attenuates the LCA and LCCA results. However, there is a need to develop tools which enable the prediction of porous asphalt mixture service life.
- The experimental binder shows an adequate performance for use in PA mixes. However, considering the failure mechanism of this type of mixtures and the behaviour detected during this research, the benefits of this NB could be maximized by its application in asphalt concrete mixes.

Acknowledgements

This work was supported by the European Union's Seventh Framework Programme for research, technological development and demonstration [Grant Agreement n° 605404], the FPU Programme of the Spanish Ministry of Education, Culture and Sport [grant number FPU-1/06997] and the doctoral studentship programme of the University of Cantabria, co-financed by the Government of Cantabria.

References

[1] W.F. Laurance, G.R. Clements, S. Sloan, C.S. O'Connell, N.D. Mueller, M. Goosem, O. Venter, D.P. Edwards, B. Phalan, A. Balmford, R. Van Der Ree, I.B. Arrea, A global strategy for road building, Nature. 513 (2014) 229–232. https://doi.org/10.1038/nature13717.

[2] P. Ahmedzade, B. Sengoz, Evaluation of steel slag coarse aggregate in hot mix asphalt concrete, J. Hazard. Mater. 165 (2009) 300–305. https://doi.org/10.1016/J.JHAZMAT.2008.09.105.

[3] S. Sorlini, A. Sanzeni, L. Rondi, Reuse of steel slag in bituminous paving mixtures, J. Hazard. Mater. 209–210 (2012) 84–91. https://doi.org/https://doi.org/10.1016/j.jhazmat.2011.12.066.

[4] M. Ameri, S. Hesami, H. Goli, Laboratory evaluation of warm mix asphalt mixtures containing electric arc furnace (EAF) steel slag, Constr. Build. Mater. 49 (2013) 611–617. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2013.08.034.

[5] D. Movilla-Quesada, A.C. Raposeiras, O. Muñoz, D. Castro-Fresno, Reduction in the use of mineral aggregate by recycling cellulose ashes to decrease the aging of hot asphalt mixtures, Constr. Build. Mater. 143 (2017) 547–557. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2017.03.154.

[6] M. Pasetto, N. Baldo, Experimental evaluation of high performance base course and road base asphalt concrete with electric arc furnace steel slags, J. Hazard. Mater. 181 (2010) 938–948. https://doi.org/https://doi.org/10.1016/j.jhazmat.2010.05.104.

[7] A. Behnood, M. Ameri, Experimental investigation of stone matrix asphalt mixtures containing steel slag, Sci. Iran. 19 (2012) 1214–1219. https://doi.org/10.1016/j.scient.2012.07.007.

[8] M. Skaf, J.M. Manso, Á. Aragón, J.A. Fuente-Alonso, V. Ortega-López, EAF slag in asphalt mixes: A brief review of its possible re-use, Resour. Conserv. Recycl. 120 (2017) 176–185. https://doi.org/10.1016/j.resconrec.2016.12.009.

[9] H.M.R.D. Silva, J.R.M. Oliveira, C.M.G. Jesus, Are totally recycled hot mix asphalts a sustainable alternative for road paving?, Resour. Conserv. Recycl. 60 (2012) 38–48. https://doi.org/10.1016/J.RESCONREC.2011.11.013.

[10] M. Zaumanis, R.B. Mallick, R. Frank, 100% recycled hot mix asphalt: A review and analysis, Resour. Conserv. Recycl. 92 (2014) 230–245. https://doi.org/10.1016/J.RESCONREC.2014.07.007.

[11] M.C. Rubio, G. Martínez, L. Baena, F. Moreno, Warm Mix Asphalt: An overview, J. Clean. Prod. 24 (2012) 76–84. https://doi.org/10.1016/j.jclepro.2011.11.053.

[12] A. Almeida-Costa, A. Benta, Economic and environmental impact study of warm mix asphalt compared to hot mix asphalt, J. Clean. Prod. 112 (2016) 2308–2317. https://doi.org/10.1016/j.jclepro.2015.10.077.

[13] H. Ajam, P. Lastra-González, B. Gómez-Meijide, G. Airey, A. Garcia, Self-healing of dense asphalt concrete by two different approaches: Electromagnetic induction and infrared radiation, J. Test. Eval. 45 (2017). https://doi.org/10.1520/JTE20160612.

[14] C.J. Slebi-Acevedo, P. Lastra-González, I. Indacoechea-Vega, D. Castro-Fresno, Laboratory assessment of porous asphalt mixtures reinforced with synthetic fibers, Constr. Build. Mater. 234 (2020) 117224. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2019.117224.

[15] S. Eskandarsefat, G. Dondi, C. Sangiorgi, Recycled and rubberized SMA modified mixtures: A comparison between polymer modified bitumen and modified fibres, Constr. Build. Mater. 202 (2019) 681–691. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2019.01.045.

[16] R. Casado-Barrasa, P. Lastra-González, I. Indacoechea-Vega, D. Castro-Fresno, Assessment of carbon black modified binder in a sustainable asphalt concrete mixture, Constr. Build. Mater. 211 (2019) 363–370. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2019.03.255.

[17] F. Moreno-Navarro, M. Sol-Sánchez, F. Gámiz, M.C. Rubio-Gámez, Mechanical and thermal properties of graphene modified asphalt binders, Constr. Build. Mater. 180 (2018) 265–274. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2018.05.259.

[18] Dirección General de Carreteras, Pliego de Prescripciones Técnicas Generales para Obras de Carreteras y Puentes (PG-3) (Spanish General Technical Specifications for Roads and Bridge Works, PG-3), 2017. https://fomento.gob.es/NR/rdonlyres/7E090150-7354-4F83-8D4E-E4BA2BE70717/141045/PG3_PARTE_5.pdf.

[19] ISO, ISO 14040: Environmental Management - Life Cycle Assessment - Principles and Framework, 2 nd. International Organization for Standardization, 2006.

[20] ISO, ISO 14044: Environmental Management - Life Cycle Assessment - Requirements and Guidelines, 1 edn. International Organization for Standardization, 2006.

[21] UNE-EN, UNE-EN 15804:2012+A1:2013. Sustainability of construction works. Environmental product declarations. Core rules for the product category of construction products, 2012.

[22] E. Lizasoain-Arteaga, I. Indacoechea-Vega, P. Pascual-Muñoz, D. Castro-Fresno, Environmental impact assessment of induction-healed asphalt mixtures, J. Clean. Prod. 208 (2019). https://doi.org/10.1016/j.jclepro.2018.10.223.

[23] Eurobitume, The bitumen industry in Europe, (2012). http://www.eurobitume.eu/bitumen/industry/ (accessed December 30, 2017).

[24] J.R. Arenal, Estudio, análisis y diseño de aplicaciones de áridos procedentes de la valorización de residuos industriales : firmes de carreteras y hormigones, 2016. https://repositorio.unican.es/xmlui/handle/10902/8293.

[25] D. Peinado, M. de Vega, N. García-Hernando, C. Marugán-Cruz, Energy and exergy analysis in an asphalt plant's rotary dryer, Appl. Therm. Eng. 31 (2011) 1039–1049. https://doi.org/https://doi.org/10.1016/j.applthermaleng.2010.11.029.

[26] European Commission, Guide to Cost-Benefit Analysis of Investment Projects, 2014.

[27] M. de Fomento, Ordin Circular 37/2016. Base de precios de referencia de la Dirección General de Carreteras., 2016.

[28] CYPE Ingenieros, Generador de Precios. España, (2019). http://www.generadordeprecios.info/.

[29] LCPC, Alize-LCPC Software. Version 1.3. User manual, 2011. http://www.alize-lcpc.com/documents/ALIZE-MU-V130-GB.pdf.

[30] University of Nevada, 3D-Move Analysis, (2013). http://www.arc.unr.edu/Software.html.

[31] D.X. Lu, M. Saleh, Laboratory evaluation of warm mix asphalt incorporating high RAP proportion by using evotherm and sylvaroad additives, Constr. Build. Mater. 114 (2016) 580–587. https://doi.org/10.1016/J.CONBUILDMAT.2016.03.200.

[32] A. Kusam, H. Malladi, A.A. Ayebali, N.P. Khosla, Laboratory Evaluation of Workability and Moisture Susceptibility of Warm-Mix Asphalt Mixtures Containing Recycled Asphalt Pavements, J. Mater. Civ. Eng. 29 (2017) 1–8. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001825.