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Analysis of replacing virgin bitumen by plastic waste in asphalt concrete mixtures

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Abstract

Polymers are used worldwide for their unique properties such as a light weight or chemical resistance, but which have led to an environmental challenge because of the time they need to completely decompose when buried in landfills. Complementarily, bitumen generates the second biggest environmental impact in the construction of a road. This paper analyses the mechanical, environmental and economic performance of replacing 25% of bitumen with two low-cost plastic wastes (cable plastic and the film fraction from household packaging waste) in an asphalt mixture. The results demonstrated the feasibility of the technology from the 3 viewpoints analysed. The plastic-modified mixtures achieve reductions of more than 17% and 11% in the economic and environmental impact when the analysis is focused on the wearing course.

Keywords: Asphalt mixture; Modified mixture; Plastic waste; Sustainability; Binder replacement

1. Introduction

Polymers are used worldwide to provide unique properties such as, for instance, light weight, chemical resistance or thermal and electrical insulation at a very affordable cost (American Chemistry Council). According to the Association of Plastic Manufacturers in Europe, their utilization has increased 40% in the last decade, around 359 million tons having been produced in 2018 (Plastics Europe 2019). This industry produces multiple social and economic benefits given that, just in Europe, it contributes close to 30 billion Euros to public finances and provides over 1.6 million jobs (Plastics Europe 2018). However, the proliferation of plastic has also caused an environmental challenge because of the time it needs to completely decompose when buried in landfills (American Chemistry Council). In 2018, around 7.2 million tons of waste plastic were sent to landfill in Europe, which represents 24.9% of the amount collected. Most of it (42.6%) was used to produce energy and only 32.5% was recycled (Plastics Europe 2018). To increase the recycling rate, some countries such as Switzerland, Austria or Germany have established thresholds for the amount of plastic which can be discarded. Nevertheless, this measure requires new applications to be found for plastic scrap.

Complementarily, the production of virgin bitumen generates the second biggest environmental impact in the construction of roads, despite accounting for around 5% in the asphalt mixture dosage (Lizasoain-Arteaga et al. 2019; Stripple 2001; Huang, Bird, and Heidrich 2009). In addition to the energy consumption and emissions generated during the cracking of petroleum, bitumen requires heat during the manufacture of the asphalt mixture to achieve an adequate workability. Consequently, small differences in the percentage of bitumen can substantially affect the total energy consumed to produce an asphalt mixture (Zapata and Gambatese 2005). Furthermore, bitumen not only is decisive for the environmental impact, but also for the economic impact, representing around 60% of the total cost of the mixture (Vila-Cortavitarte et al. 2018).

Some researchers have explored the idea of replacing bitumen with plastic wastes and very promising results have been obtained so far. Motlagh et al. (Motlagh et al. 2012) performed Marshall tests on asphalt mixtures modified with polystyrene disposable dishes. Replacing 10% of bitumen by a dry process was found to be the best option, achieving a better Marshall stability than the control sample. Vasudevan et al. (Vasudevan et al. 2012) corroborated these results when analysing the addition of polyethylene, polypropylene and polystyrene coming from packing at lab and field level. When replacing 10% of the bitumen of the mixture, the Marshall stability and the load-bearing capacity increased. Vila-Cortavitarte et al. (Vila-Cortavitarte et al. 2018) explored the possibility of replacing 25% of bitumen with different types of polystyrene. The mixtures were found to perform at least as well as conventional mixtures, even improving some characteristics like rutting resistance. However, the cost effectiveness was compromised by the price of the recycled materials employed.

Despite the good technical results achieved in these projects, this technique has not been implemented due to the lack of comprehensive studies using affordable recycled materials. The aim of this paper is to analyse the mechanical, environmental and economic performance of two low-cost plastic wastes employed to replace a fraction of the binder of an asphalt mixture.

2. Materials and methodology

2.1. Materials

Plastic waste is the only alternative material used in this work, the rest of materials were those usually employed to manufacture asphalt mixtures. To select the most suitable plastic waste, a comprehensive analysis was carried out to check technical (such as cleanliness, size or maintaining a relatively homogeneity of the waste composition over time) and economic requirements (considering an average cost of 500 €/tn of bitumen, 250 – 300 €/tn was established as the maximum admissible value for plastic waste).

Based on these criteria, two plastic wastes were selected: Polyethylene from copper cables (Pe - Cu) and the flexible packaging from the yellow container (film). The former comes from the company Recuperación Materiales Diversos S.A. (RMD), located in León (Spain), and is currently being burned to recover energy. It mainly consists of Polyethylene (95%) and has a specific weight of 0.906 g/cm3. The latter was supplied by Ecoembes, coming from a recovery company in the Community of Madrid (Spain). Composed of different types of polyethylene with a specific weight of 0.90 g/cm3 and separated by optical processes, it undergoes several steps to clean and homogenize the material. However, the material was extracted before the extrusion step, reducing considerably the cost. Figure 1 shows the materials as they were supplied.

Figure 1. Left: Pe-Cu Plastic waste. Right: Film plastic waste

Conventional materials were also used for the asphalt concrete mix design. Ophite and limestone were used as aggregates. Their properties are included in Table 1. The binder used was a 40/60 penetration grade bitumen, with the properties shown in Table 2.

Table 1. Properties of aggregates.

Properties	**Result**	**Limits**	**Standard**
Ophite (Coarse aggregate)			
Los Angeles coefficient	16	≤ 20	EN 1097-2
Specific weight (g/cm^3)	2.937	-	EN 1097-6
Polished stone value (PSV)	> 56	≥ 50	EN 1097-8
Flakiness Index (%)	8	≤ 20	EN 933-3
Limestone (Fine aggregate and filler)			
Los Angeles coefficient	28	< 25	EN 1097-2
Specific weight (g/cm^3)	2.725	-	EN 1097-6
Sand equivalent	78	> 55	EN 933-8

Table 2. Binder properties.

Binder	**Result**	**Standard**
Penetration at 25 °C (dmm)	44	EN 1426
Softening point (°C)	51.6	EN 1427
Density (g/cm^3)	1.026	EN 15326

2.2. Testing program

The addition process was optimized and the feasibility of manufacturing asphalt mixtures with these plastic wastes was evaluated using the following tests: air void content (EN 12697-8), Marshall test (EN 12697 – 34) and water sensitivity test (EN 12697-12). For this purpose, an initial percentage of 15% of the bitumen was replaced by the alternative materials selected, which were incorporated at ambient temperature in two stages of the manufacturing process: adding them to the coarse fraction (coarse fr) and right after the binder (aft binder) (Figure 2). The replacement of binder with the plastic waste was made by volume to ensure that no significant differences would occur due to their different specific weight. In this way, the impact of plastics when they work as an alternative binder or embedded within the mortar was studied.

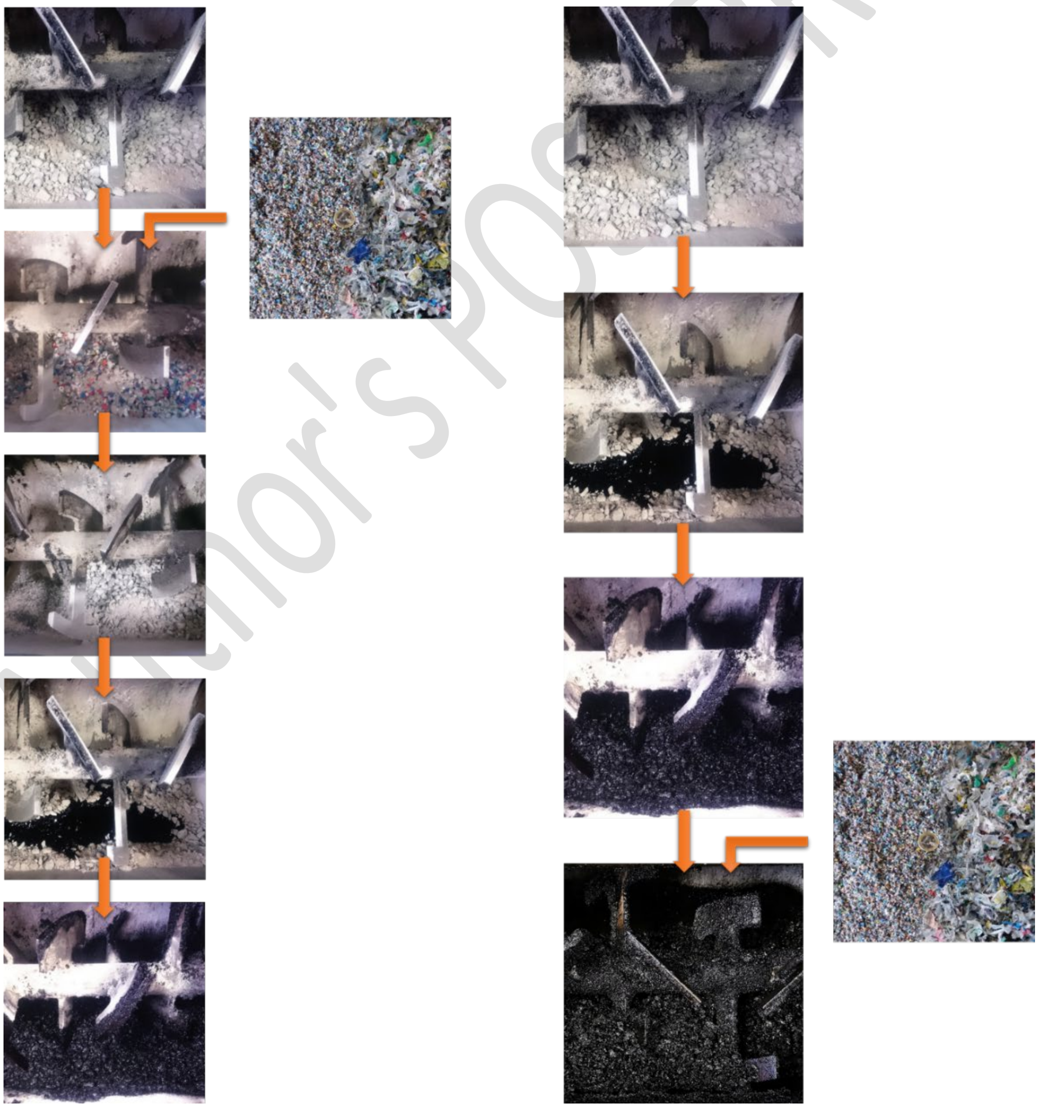

Figure 2. Plastic waste added into the coarse fraction (left) and after binder (right).

After selecting the addition process and due to the good results achieved previously, the final mixes were designed by replacing 25% of the bitumen with the plastic wastes. Given that plastics were proven to significantly increase the percentage of voids of the mixtures, two compaction energies were applied during the manufacturing of the mixtures: conventional (applying the same energy as the reference mixture) and overcompacted (doubling the compacting energy normally used). This would imply a modification in the traditional laying process of this type of mixture. In this phase, in addition to the mechanical tests mentioned before, the plastic deformation of the mixtures was evaluated with the wheel tracking test (EN 12697 – 22) and, since the increase of void proportion could compromise the cohesion of the experimental mixtures, the particle loss was evaluated with the Cantabro test (EN 12697 - 17). Furthermore, the compaction energy of each mixture per unit mass (W) was calculated according to Eq.(1) (del Río Prat 2011) performing the compactability test in a gyratory compactor. This energy was analysed considering the density of each mixture and the compaction energy, which is the density per cycle divided by the reference density obtained in the void test.

$$W / m = \sum_{1}^{N} Wi / m = (2 \cdot \pi \cdot \alpha \cdot A / m) \sum_{1}^{N} h_i \cdot S_i \qquad (1)$$

Where Si (KN/m2) is the shear stress measured in each cycle i, hi (m) is the specimen height in each cycle I, m (kg) is the mass, A (m2) is the transverse specimen area, α (rad) is the inclination angle of the cylindrical sample and N is the number of cycles.

Finally, the stiffness (EN 12697-26) and fatigue resistance (EN 12697-24) were evaluated by performing the four-point bending test at 20ºC to completely characterize mechanical performance of the asphalt mixtures.

The results were statistically analysed with Minitab software applying a 95% confidence interval. The T-Student test was employed when a normal distribution of the results and homogeneity of the variances were observed, and the Mann-Whitney U test was used otherwise.

2.3. Specimen preparation

A reference AC 16 mixture was designed with an optimum binder content of 4.5% and the particle size distribution is shown in Figure 3.

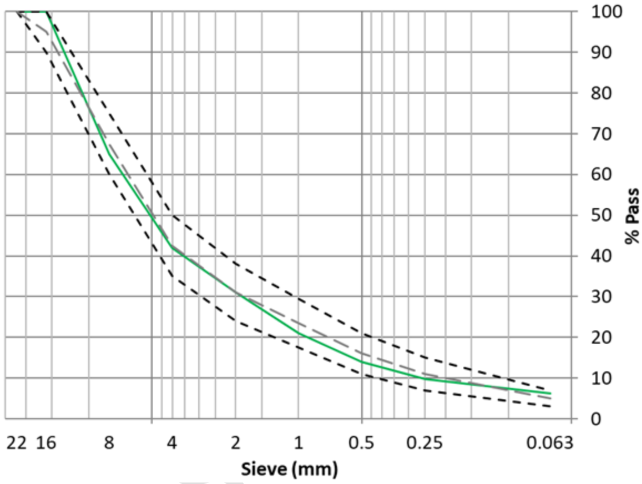

Figure 3. Particle size distribution of asphalt mixtures.

The asphalt samples were produced trying to replicate as much as possible the traditional manufacturing process. The manufacturing temperature of the reference mixture (150ºC for the bitumen and 175ºC for aggregates) was also applied in the alternative mixtures. The compaction temperature was 145ºC for every mixture. However, to achieve an adequate diffusion of plastics, the mixing time was increased by one minute. Moreover, plastics were used as supplied in order to simplify the process and minimise costs.

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

LCA is a methodology that calculates the potential environmental impact of a product throughout its life cycle. Regulated by the standards ISO 14040:2006 and 14044:2006, the LCA methodology consists of 4 interrelated stages: goal and scope definition, inventory analysis, impact assessment and interpretation of the results.

The main goal of this analysis was to evaluate the environmental sustainability of replacing 25% of virgin bitumen by plastic wastes in an asphalt mixture. The functional unit was a 1-km lane with a width of 3.5 m. Regarding the thickness, only the wearing course is normally analysed when the other layers of the pavement remain unaltered. However, the characteristics of every layer affect the durability of the whole pavement. Therefore, this research considers both approaches, the wearing, binder and base layers having 4, 10 and 10 cm thickness each.

The selection of the system boundaries was based on the stages defined in the standard UNE-EN 15804:2012. However, only the material, construction, maintenance and end-of life stages were included due to the variability of the results from the existing rolling resistance models (Trupia et al. 2017). These stages, as well as the inventory, are extensively explained in a previous work (Lizasoain-Arteaga et al. 2019). Nevertheless, some aspects need more consideration:

- The energy consumed by the Pe-Cu plastic was calculated using Eldan Recycling AS machinery catalogue, 111.63 MJ being necessary to recover 1 ton of plastic. In those processes shared by both plastic and copper, an impact allocation based on the economic profit was applied.
- Pe-Cu plastic is currently burned to produce energy, what also generates atmospheric emissions. Therefore, to determine whether their use in asphalt mixtures is better than their burning, the impact of producing the energy that is currently being obtained from the plastics and the credit for the avoided impact should be added to the 111.63 MJ/tn.

- Film plastic needs to be grinded, washed and dried, consuming 186 MJ/tn (Herbold Mecksheim). However, no environmental burden from the waste separation process was assigned and no credit was considered since the material is neither burned nor buried.
- The distance travelled by plastics from the producers to the asphalt plant was assumed to be 100 km.
- The diesel needed to construct the road was assumed to be 1.56, 1.80 and 1.59 l/tn for the reference, Pe-Cu and Film mixture, respectively. These values were obtained by correlating the 1.56 l/tn consumed by a conventional mixture (Lizasoain-Arteaga et al. 2019) with the results of the compactability test.
- The reference is supposed to have a life expectancy of about 15 years (EAPA 2007) (Nicholls et al. 2012). Nevertheless, different assumptions were made regarding the alternative mixtures' durability to determine when the same impact as the conventional mix is produced.
- The recyclability of the mixtures was assumed. In other words, the RAP achieved by milling the road was assumed to be used to produce another asphalt mix. Therefore, the transportation of the RAP to the recovery centre was included within the system boundaries. However, no credit was given.

Emissions detected during the inventory analysis were transferred into impacts by using the ReCiPe 2016 characterization method. This method, developed by the University of Leiden, 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). Once calculated, the impacts were annualized (dividing them by the road service life) to achieve a fair comparison.

LCCA is an equivalent methodology but focused on the economic aspects. It normally evaluates agency and user costs but, this analysis considers only the agency cost because of the boundaries defined above. The economic data used in this analysis, as well as the sources are shown in Table 3. A 4% discount rate was applied to take into account the time value of money (European Commission 2014).

Table 3. Costs database.

Material/process	**Units**	**Costs**	**Source**
Bitumen	€/tn	440.00	(M. de Fomento 2016)
Limestone aggregates	€/tn	7.50	Provider
Ophitic aggregates	€/tn	19.00	Provider
Filler	€/tn	41.36	(CYPE Ingenieros 2019)
Pe-Cu plastic	€/tn	40.00	Provider
Ecoembes plastic	€/tn	300.00	Estimated
Construction	€/tn	4.74	(CYPE Ingenieros 2019)
Milling	€/tn	29.30	(CYPE Ingenieros 2019)
Transportation	€/(tn*km)	0.10	(CYPE Ingenieros 2019)

Finally, as the sustainability results are highly dependent on the service life of the road, a simulation of the pavement performance was carried out. For this, two software packages (Alize and 3-D Move) were used assuming only a fatigue failure since rutting was considered unlikely based on the test results (Table 8). Alize is a software developed by the French organization LCPC and SETRA which calculates the pavement's response to truck loads considering an isotropic linear elastic behaviour (LCPC 2011). In contrast, 3D-Move software uses a continuum-based finite layer approach assuming a viscoelastic performance of the layers (University of Nevada 2013). The same single axle dual tyre was selected in both cases to load the pavement with: tyre pressure of 900 kPa, tyre load of 32 KN, tyre radius of 0.106 m and centre-to-centre tyre spacing of 0.3192 m. An annual average daily traffic of 1,400 vehicles with 2% traffic growth was simulated.

3. Results and discussion

3.1. Plastic addition process

The addition of plastic waste results in a significant increase of the percentage of voids independently from the process and plastic used (see Table 4). When the plastic makes contact with the hot aggregate it softens, but it is unable to flow as bitumen does. Therefore, when the plastic coats the aggregate it sticks to it and makes compaction more difficult. This problem could be solved with a higher temperature, but it is not recommended since the bitumen could age and the plastic could produce unhealthy fumes (Vasudevan et al. 2012). However, despite this increase in voids, experimental mixtures with film and Pe-Cu polymers show greater stability than the reference mixture, however, this is only statistically significant in the case of film plastic waste (see Table 5). Furthermore, although there is no significant difference in the deformation of the samples, slightly less deformation is obtained when plastics are added to the coarse fraction.

Moreover, the water sensitivity test (see Table 4) showed that incorporating plastics after the binder improves the resistance of the dry specimens, especially those of Pe-Cu mixture. However, their performance under wet conditions worsen as water damage increases.

In consequence, and despite the differences being small, the addition of plastics to the coarse aggregate fraction was selected for the rest of the work.

Table 4. Mechanical performance. Analysis of the plastic addition process.

Results	**Ref**	**Film Coarse fr**	**Film Aft binder**	**Pe-Cu Coarse fr**	**Pe-CU Aft binder**
		Void test (EN 12697-8)			
Binder content (%)	4.5	3.8	3.8	3.8	3.8
Density (g/cm^3)	2.466	2.401	2.411	2.383	2.394
Voids in mixture (%)	4.2	7.8	7.4	8.4	8.0

Voids in aggregates (%)	15.0	16.6	16.3	17.2	16.9
Marshall test (EN 12697 – 34)					
Stability (kN)	13.6	15.5	15.9	15.4	15.0
Deformation (mm)	2.9	3.2	3.7	3.4	3.5
Water sensitivity test (EN 12697-12)					
ITS (KPa) (Dry specimens)	2,686	2,666	2,912	2,685	3,004
ITS (KPa) (Wet specimens)	2,275	2,390	2,362	2,238	2,195
ITSR (%)	85	90	81	83	73

Table 5. P-values of experimental mixtures compared to the reference mixture. Analysis of the plastic addition process.

P values (Ref)	Film Coarse fr	Film Aft binder	Pe-Cu Coarse fr	Pe-CU Aft binder
Voids in mixture	0.000	0.000	0.000	0.000
Stability	0.004	0.019	0.180	0.133
Deformation	0.629	0.129	0.365	0.160
ITS (Dry specimens)	0.909	0.079	0.985	0.043
ITS (Wet specimens)	0.252	0.587	0.505	0.184

3.2. Final mixture dosage

Once the addition process was selected, the final mixtures were designed by replacing 25% of the binder and applying two compaction energies.

When a conventional compaction energy was applied, a direct relationship between the amount of plastic and the percentage of voids was observed (see Table 6). In the previous step, when the addition process was being analysed by replacing 15% of the binder, 7.8% and 8.4% of voids were achieved in the Film and Pe-Cu mixtures respectively. However, the air void content increased significantly in this step reaching 10.2% and 11.1%. The p-values of these experimental mixtures compared to the reference are shown in Table 7.

Table 6. Mechanical performance of the final dosages conventionally compacted.

Results	Ref	Film	Pe-Cu	Standard
Void test (EN 12697-8)				

Binder content (%)	4.5	3.4	3.4	-
Density (g/cm^3)	2.466	2.352	2.328	-
Voids in mixture (%)	4.2	10.2	11.1	4 – 6
Voids in aggregates (%)	15.0	18.0	18.8	≥ 15
Geometric density (g/cm^3)	2.361	2.255	2.228	-
Geometric voids (%)	8.3	13.9	14.9	-
Marshall test (EN 12697 – 34)				
Stability (kN)	13.6	15.3	16.2	> 12.5 [a]
Deformation (mm)	2.9	4.5	4.6	2 – 3.5 [a]
Water sensitivity test (EN 12697-12)				
ITS (KPa) (Dry specimens)	2,686	2,222	1,895	-
ITS (KPa) (Wet specimens)	2,275	1,641	1,473	-
ITSR (%)	85	74	78	≥ 85
Wheel tracking test (EN 12697 – 22)				
Slope (mm/1000 cycles)	0.13	0.02	0.03	≤ 0.15
Rut depth (mm)	4.6	1.1	1.6	-
Rut depth$^{5000\ cycles}$ (%)	1.3	0.2	0.3	< 5
Particle loss test (EN 12697 – 12)				
Particle loss (%)	5.9	16.0	21.8	< 20

[a] Limits established for the NLT 159/00 Standard

Table 7. P-values of experimental mixtures compared to the reference mixture.

P values (Ref)	Voids	Stability	Deformation	ITS Dry	ITS Wet	Wheel tracking	Cantabro
Film	0.000	0.040	0.103	0.030	0.000	0.000	0.000
Pe-Cu	0.000	0.007	0.049	0.030	0.007	0.004	0.001

To look in more depth at the compaction energy of the mixtures, the compactability test was carried out with a gyratory compactor (see Figure 4) and the geometric density of the mixtures was calculated. Results showed that the energy required to reach the same density in all the mixtures is higher when incorporating the plastics, especially in the Pe-Cu samples, which corroborates the void test results. However, each mixture works at a different density and percentage of voids, the density of the experimental mixtures being lower than the density of the reference mixture. Therefore, considering the compaction percentage, both experimental mixtures require less energy than the reference to reach 100% of their density. The key point is to determine whether these experimental mixtures will be able to perform well with those percentages of voids.

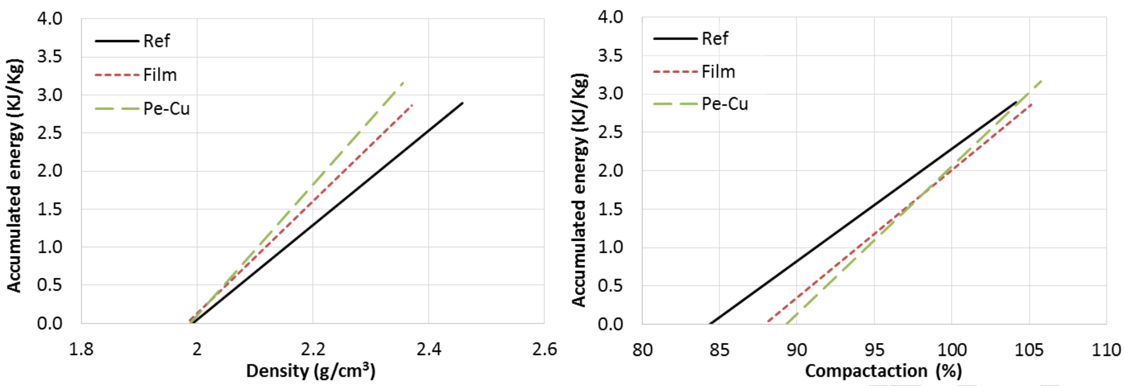

Figure 4. Compaction energy. Final dosage. Conventionally compacted.

The Marshall test was then employed to evaluate whether the addition of a higher percentage of plastic results in an increment in the stability and deformation, as observed before in the previous step (see Table 6). Results showed that although the percentage of voids increased compared to the mixture with 15% of plastic waste, the stability is significantly higher. This shows that the links created between the polymer waste and the aggregates improve the resistance of the mixtures. However, this increase in voids also produced a higher deformation that is only statistically significant in the case of Pe-Cu plastic (see Table 7). Furthermore, the negative impact of voids was also reflected in the water sensitivity test (see Table 6). When compared with the previous step, the damage caused by the saturation of the specimens increased by 16% and 5% in the Film and Pe-Cu mixes, respectively, and the resistances (both dry and wet) are reduced between 17% and 34%. This decrease is significant under both dry and wet conditions for both experimental mixtures, so the reference mixture achieves better results in this regard. It seems that the links provided by plastic do not compensate for the increase in void percentage in terms of the indirect tensile strength.

Regarding plastic deformation, the contribution of plastic wastes was very significant, clearly increasing the asphalt mixture’s resistance when the wheel tracking test was carried out (see Table 6). This good behaviour achieved despite the high percentage of voids is probably caused by the high temperature at which the test was carried out (60ºC), since plastics remain practically unaltered while the bitumen softens.

Given the high percentage of voids and the decrease in the resistances in the water sensitivity test, the lack of cohesion of the experimental mixtures was considered to be one of their major potential drawbacks. In consequence, the Cantabro test was also carried out despite usually being applied only to porous asphalt mixtures (see Table 6). Results clearly show that the particle loss due to lack of cohesion is the most influential property of the experimental mixtures. In fact, the Pe-Cu mixture surpasses the Spanish standard limit for porous asphalt mixtures (in the most restrictive conditions).

The compaction energy was doubled to analyse the mechanical properties of the experimental mixtures depending on the percentage of voids (see Table 8). The p-values of the alternative mixtures compared to the reference mixture can be seen in Table 9.

By increasing the compaction energy, the percentage of voids in the experimental mixtures was significantly reduced, although they did not reach the values of the reference mixture. This reduction in voids resulted in an increased stability and a reduction in deformation, thus improving the results obtained.

Due to the decrease in voids, the experimental mixtures notably increased their indirect tensile resistance, the Film mixture even surpassing the reference mixture. Moreover, damage due to specimen saturation was also minimized (from 74% and 78% in Film and Pe-Cu mixtures to 85%), thus obtaining the same values as the reference mixture despite the higher percentage of voids. In fact, no significant differences among mixtures were observed except for the tests performed to Pe-Cu samples under wet conditions. Therefore, the overcompaction of experimental mixtures seems to be a good method to increase the cohesion and improve the behaviour.

When performing the wheel tracking test, the resistance contribution is again very significant. In fact, the results obtained in the test can be considered as optimal. It seems that the links created by plastic stiffen the mixtures and made them more resistant at high temperatures.

Void reduction also has a positive effect on the particle loss test, which enables experimental mixtures with plastic film to reach values similar to those of the reference mix. However, the differences between the mixtures are still statistically significant. Regarding Pe-Cu mixtures, although they obtain a higher particle loss than the Film mixture, this value is far from that obtained previously and is below the limit established for porous mixtures under the most restrictive conditions.

Table 8. Mechanical performance of the final dosages overcompacted.

Results	**Ref**	**Film**	**Pe-Cu**	**Standard**
Void test (EN 12697-8)				
Binder content (%)	4.5	3.4	3.4	-
Density (g/cm^3)	2.466	2.392	2.390	-
Voids in mixture (%)	4.2	8.7	8.8	4 – 6
Voids in aggregates (%)	15.0	16.6	16.7	≥ 15
Geometric density (g/cm^3)	2.361	2.298	2.294	-
Geometric voids (%)	8.3	12.3	12.4	-
Marshall test (EN 12697 – 34)				
Stability (kN)	13,6	20,4	21,1	> 12,5 [a]
Deformation (mm)	2,9	3,0	3,4	2 – 3,5 [a]
Water sensitivity test (EN 12697-12)				
ITS (KPa) (Dry specimens)	2,686	2,704	2,512	-
ITS(KPa) (Wet specimens)	2,275	2,285	2,125	-
ITSR (%)	85	85	85	≥ 85
Wheel tracking test (EN 12697 – 22)				
Slope (mm/1000 cycles)	0.13	0.01	0.02	≤ 0.15
Rut depth (mm)	4.6	0.7	1.4	-
Rut depth$^{5000\ cycles}$ (%)	1.3	0.1	0.2	< 5
Particle loss test (EN 12697 – 12)				
Particle loss (%)	5.9	8.0	12.4	< 20

[a] Limits established for the NLT 159/00 Standard

Table 9. P-values of experimental mixtures in relation to reference overcompacted.

P values (Ref)	Voids	Stability	Deformation	ITS Dry	ITS Wet	Wheel tracking	Cantabro
Film	0.000	0.000	0.616	0.845	0.897	0.003	0.019
Pe-Cu	0.000	0.000	0.065	0.148	0.010	0.003	0.000

Dynamic tests (both stiffness and fatigue tests) are crucial for evaluating the pavement behaviour since they influence the transmission of loads and their service life. Furthermore, they must be analysed simultaneously since the stiffness of a bituminous mixture is directly related to its deformation and, therefore, to its fatigue damage. Table 10 presents the modulus test results for each mix.

Table 10. Stiffness test of the final dosages overcompacted.

Frequency	Ref		Film		Pe-Cu	
(Hz)	Dynamic modulus (MPa)	Phase angle (°)	Dynamic modulus (MPa)	Phase angle (°)	Dynamic modulus (MPa)	Phase angle (°)
0.1	751	54.9	2,002	34.3	1,656	42.0
0.2	1,107	52.7	2,468	32.4	2,139	39.9
0.5	1,800	48.2	3,240	29.9	2,813	36.1
1	2,509	44.6	3,936	27.6	3,495	33.4
2	3,390	40.6	4,692	25.4	4,553	30.1
5	4,842	35.1	5,868	22.4	5,877	26.1
8	5,709	32.2	6,509	20.9	6,704	24.1
10	6,135	31.0	6,846	20.1	7,113	23.0
20	7,658	26.3	8,553	16.5	8,949	20.3
30	8,591	25.2	9,194	16.3	10,633	17.7

The increase in dynamic modulus indicates that the addition of the polymers stiffens the reference mixture, which is more significant at low frequencies. These results are consistent with the resistance increase obtained previously in the wheel tracking test at high temperatures and with the reduction in the phase angle detected. Therefore, the experimental mixtures have greater elastic behaviour, especially when using film. Moreover, Pe-Cu shows the highest stiffness variability with lower values than Film under 5Hz, but higher stiffness over this frequency.

Fatigue test results are shown in Figure 5 and Table 11. It can be observed that replacing bitumen with residual plastics reduces fatigue resistance, especially for high deformation. This is reasonable considering that the mixtures are stiffer. However, as they need a higher load to undergo the same deformation as the reference, this reduction does not imply that the pavement will withstand a lower number of cycles. Furthermore, although this test is crucial to know the behaviour of the experimental mixtures, as they were designed to be used as surface layer, the tensile stress produced due to the axle of vehicles will be small as long as it works with adhesion between layers.

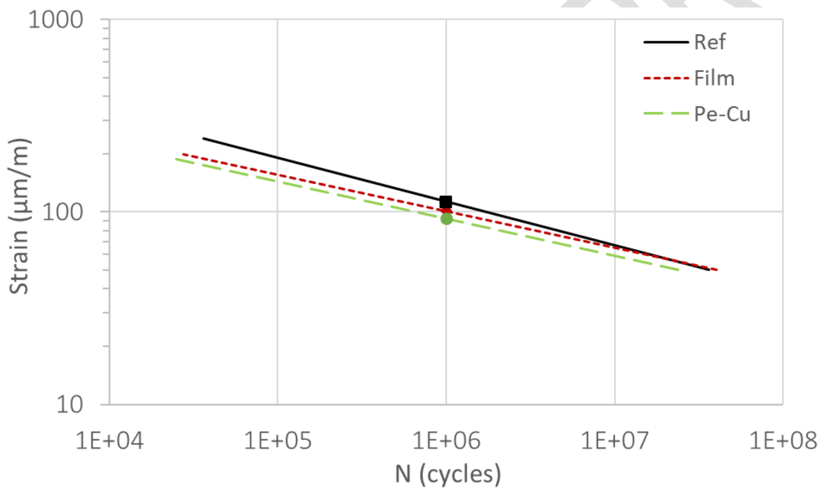

Figure 5. Fatigue test results of the final dosages overcompacted.

Table 11. Fatigue test of the final dosages overcompacted.

Mixture	**strain-characteristic* (µm/m)**	**Fatigue line**	**R^2**
Ref	113.0	$\varepsilon\ (m/m) = 2.607 \cdot 10^{-3} \cdot N^{-0.2272}$	0.94
Film	101.0	$\varepsilon\ (m/m) = 1.400 \cdot 10^{-3} \cdot N^{-0.1903}$	0.90
Pe-Cu	92.4	$\varepsilon\ (m/m) = 1.338 \cdot 10^{-3} \cdot N^{-0.1935}$	0.77

*10^6 cycles

3.3. Sustainability results

Results achieved after comparing the LCA and LCCA of the alternative mixtures when overcompaction is applied are shown in Figure 6. As expected, the greater the service life extension, the better the economic and environmental results.

When the analysis is performed in a simplified way by considering only the wearing course, a big difference between the mixtures is seen. RA is the impact that obtains greatest benefit from reducing the percentage of bitumen in the Film mixture. In fact, if the alternative mixture had the same durability as the conventional mixture, almost 20% impact reduction could be achieved. Regarding the other environmental impacts (HH and ED), not noticeable differences among them are appreciated. The Film mixture could reduce its service life by up to 7.3% and 6.2% according to the HH and ED impacts but still obtain improvements over the conventional mixture. However, the economic impact is the most restrictive aspect. In this sense, Film mixture would be better than a conventional mixture as long as it does not decrease its durability more than 3.7%.

Regarding the Pe-Cu mixture, better results than with the Film mixture were achieved except for the RA impact. As Pe-Cu plastic is currently burned to produce energy, replacing bitumen with Pe-Cu plastic decreases the HH and ED impacts by more than 19% when 0% service life increment is considered. However, fossil fuels are used to produce the energy that is obtained from plastic. This explains why RA impact is reduced 15.5% instead of the 19.7% achieved with the film plastic. Moreover, the economic aspect is again more restrictive than the environmental impacts, Pe-Cu obtaining benefits as long as the durability of the mixture does not decrease more than 6.3%.

When the analysis is performed on the whole pavement section, a reduction in the differences between the mixtures and also between the impacts is observed. It should be noted that the replacement of bitumen only takes place in the wearing course, the other two layers only benefiting from the service life extension. Therefore, although the advantages in absolute value are greater when including the whole pavement section within the system boundaries than when the analysis performed only on the wearing course, the percentage value decreases. Consequently, LCCA impact is still the most restrictive aspect in both alternative mixtures, but in this case, the durability of the Pe-Cu and Film pavements can only decrease 1.2% and 1.9%, respectively, while being considered sustainable.

As the sustainability results are highly dependent on the service life of the road, a simulation of the pavement performance was carried out. When a pavement fails due to fatigue, a bottom up crack is normally developed, so the wearing course is not normally affected by the tensile stresses generated by passing vehicles. However, if only the mechanical behaviour of the wearing course is simulated with the selected program packages, the software would subject it to both tensile and compressive stresses. Therefore, considering that the alternative mixtures studied in this work have a higher dynamic modulus than the reference mixture and lower fatigue resistance, their durability would be underestimated. Consequently, the durability was calculated by including the whole pavement section in the software and assuming that all the layers undergo the same percentage of life extension. The durability calculated with Alize and 3D-Move can be seen in Table 12. Pavement durability.Table 12.

Table 12. Pavement durability.

Mix	**Alize (static)**		**3D-MOVE Analysis**								**Static (mean)**	**Dynamic (mean)**
			Static		**20 km/h**		**60 km/h**		**100 km/h**			
	Years	**Δ(%)**	**Years**	**Δ(%)**	**Years**	**Δ(%)**	**Years**	**Δ(%)**	**Years**	**Δ(%)**	**Δ(%)**	**Δ(%)**
Ref	14.01	0%	18.14	0%	17.1	0%	29.2	0%	35.7	0%	0%	0%
Film	14.40	3%	18.60	3%	17.5	2%	29.5	1%	36.0	1%	3%	1%
Pe-Cu	14.53	4%	18.76	3%	17.6	2%	29.8	2%	36.4	2%	4%	2%

Comparing the service life calculated with the different software packages, important variations in the results can be seen because of the characteristics of the software itself when a static analysis is applied and because of the effect of the vehicle speed on the dynamic analysis. However, when the service life extension is compared as a percentage, the differences are not so great. For this reason, the Film mixture was considered to increase its service life 3% and 1% with static and dynamic analysis, respectively, and the Pe-Cu mixture 4% and 2%. Thus, focusing on the most conservative scenario (the dynamic analysis), Film mixture reduces the HH, ED, RA and LCCA impacts 8.6%, 7.5%, 20.7% and 6.8% when only the wearing course is considered. Nevertheless, as mentioned before, these results decrease when including the whole pavement section within the system boundaries, the RA impact reaching the highest impact reduction with 7.1%.

Greater benefits are achieved using the Pe-Cu plastic. A reduction in the environmental impact between 17.2% and 20.9% can be obtained by replacing 25% of bitumen with this plastic, 11.1% economic profit also being possible. However, evaluating the whole pavement section reduces these values reaching between 6.6% and 7.6% reduction in the environmental impacts and 5.0% in the economic impacts.

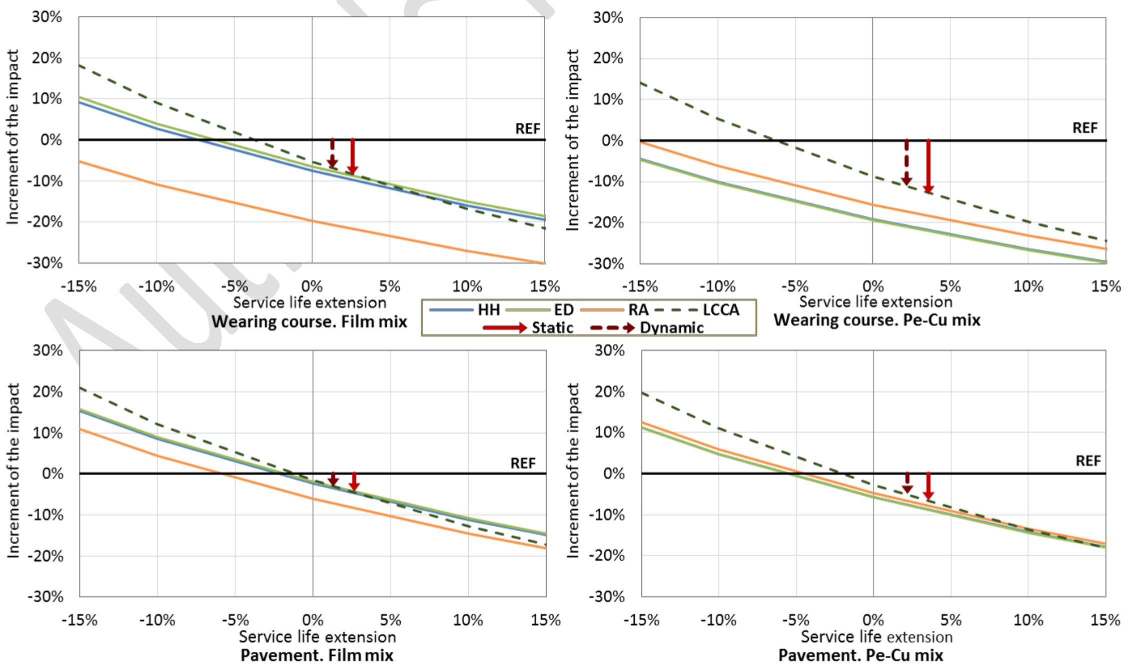

Figure 6. LCA and LCCA result comparison.

4. Conclusions

Two experimental asphalt mixtures were designed in this study replacing 25% of bitumen with two types of plastic waste: film and Pe-Cu. After analysing the mechanical, environmental and economic performance, the following conclusions were drawn:

- The feasibility of incorporating low-cost residual polymers as an alternative binder to replace virgin bitumen was demonstrated from the mechanical, economic and environmental points of view.
- The mechanical performance of the plastic-modified mixtures is similar to that of the reference mix despite their higher percentage of voids. In fact, the greatest difference between them is the increase in the plastic deformation resistance, the rest of the properties being similar or slightly better. Regarding the dynamic performance, the addition of plastic tends to increase the mixture stiffness and decrease the fatigue resistance.
- The modification does not require special technology or significant changes in the construction process. The main change with respect to the reference mix is the increase in the compaction energy to limit a possible lack of cohesion. This overcompaction is highly recommended due to the great improvement achieved in the mechanical performance of the mixtures.
- Both alternative mixtures show environmental and economic advantages. Despite the Film mixture performing slightly better than Pe-Cu from the mechanical point of view, Pe-Cu is the material that provides the greatest benefits. In fact, 17% reduction in environmental impact and 11% in economic impact can be achieved when the wearing course is analysed. However, as the

binder replacement technology is only applied in this layer, the advantages decrease when the whole pavement is evaluated.

- Even when the LCA and LCCA are performed only for the wearing course, the durability calculation tools have to be applied to the entire pavement to simulate the real stresses that the layer will suffer. Furthermore, neither the software used for the static simulation nor the speed for the dynamic one seems to affect the results too much as long as the service life increase is calculated as a percentage.
- Although its utilization as a wearing course is feasible for any road, this type of mixture seems to be particularly suitable for urban roads, since these are the areas where a larger amount of waste is generated.
- There are still properties such as the mixtures' ageing, their recyclability or the effect of plastic waste on skid resistance that should be analysed.

5. Future lines

Based on all the activities and results analysed throughout the project, the following future lines of action were identified to give continuity to this research:

- Analyse the experimental mixtures at aged state. The increase in air voids and the impact of residual plastics could negatively affect their aging resistance.
- Study some functional properties as the skid resistance, which could determine if this mixture is useful for surface layer or only to base and binder layer.
- Compare the mixtures at the same level of voids, modifying factors such as the particle size distribution of aggregates or the compaction process, among other.
- Adapt the method applied to the polymer basic properties. Tests like Melt Flow Index (MFI), molecular weight (Mw), or thermogravimetric analysis (TGA)

would be useful to improve the knowledge on this technique.

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