Construction and Building Materials 492 (2025) 143057

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Evaluation of asphalt concrete with residual aramid fibres: Mechanical simulation, abrasion test, recyclability, environmental impact and cost-benefit analysis

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ARTICLE INFO

Keywords:
Asphalt concrete
Residual fibres
Circular Road simulator
Environmental analysis
Economic analysis

ABSTRACT

The objective of this study was to improve the mechanical, environmental and economic performance of a new asphalt concrete with residual aramid fibres and conventional binder, with the aim of matching or surpassing the performance of asphalt concrete with polymer-modified binder. To achieve this goal, this research was developed in five main chapters: firstly, the mechanical performance of the mixtures was evaluated in the circular road simulator; secondly, the abrasion resistance of asphalt mixtures was studied by means of the steel brush test; thirdly, the recyclability of the experimental mixture was assessed by replacing 50 % with RAP (with residual aramid fibres) using traditional laboratory tests such as Marshall, Water Sensitivity, Wheel Tracking, Modulus and Fatigue; fourthly, an environmental impact study was conducted from a cradle-to-grave perspective; and fifthly, a cost-benefit analysis of the experimental asphalt concrete was carried out. The results indicate that, in terms of surface wear evaluated in the circular road simulator, the experimental mixture, made with 50–70 binder and residual aramid fibres, performs better than reference mixture made with 50–70 binder without fibres (typically employed in Spain), but slightly worse than reference mixture with PMB modified binder without fibres. Then, with respect to the steel-brush test, abrasion resistance seems to depend mainly on the binder type, asphalt made with polymer modified binder showing the best results. At the same time, recyclability analysis suggests that the use of 50 % RAP is feasible, although the experimental mixture shows higher stiffness and lower fatigue performance. Finally, in environmental and economic terms, asphalt concrete with recycled aramid fibres improves on the reference asphalt concrete typically used in Spain, but is still inferior to asphalt concrete made with polymer-modified binder.

1. Introduction

The use of fibres has experienced a significant expansion in order to improve the mechanical performance and environmental characteristics of asphalt pavements [1–3]. Several studies have shown that various types of fibres can increase the durability of asphalt mixtures, regardless of the type of binder used [4]. In particular, aramid fibre stands out as one of the most promising options due to its ability to improve the mechanical properties of mixtures.

At the laboratory level, aramid fibres have been found to improve the mechanical performance of mixtures [5]. However, the degree of improvement varies from one to another [6], with some authors reporting a slight improvement [7], while others report significant improvement in cracking performance [8–10], resilient modulus [11], plastic deformation [12–14,4,5] and low temperature performance [15], irrespective of the type of asphalt binder [16].

In addition, the dosage and length required for optimum performance in asphalt concretes has been studied [17,8], since the use of fibres affects the consistency of the specimens [18]. In this respect, longer fibres contribute more to the performance, but shorter fibres have a

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https://doi.org/10.1016/j.conbuildmat.2025.143057
Received 16 March 2025; Received in revised form 14 July 2025; Accepted 5 August 2025
Available online 7 August 2025

better dispersion in the mixture. Fortunately, aramid fibres have a good bond with the mastic asphalt [19] and do not significantly affect the air voids content [20].

To date, using FlexPave software, aramid fibres have been found to improve fatigue resistance and overall long-term performance [21]. However, large-scale studies are very limited, for example:

- Aramid fibres have been used to construct a full-scale section. However, the evaluation method was the traditional one, by extracting cores and evaluating them in the laboratory [22,23].
- Specimens were manufactured in a full-scale plant and tested at laboratory level. It was concluded that the specimens did not show any significant improvement in the properties of the asphalt mixtures [24]. This is contradicted by the results of the mixtures manufactured and tested in the laboratory.
- The addition of aramid fibres with sasobit wax has been studied in a laboratory and field study with positive results [25]. Unfortunately, this treatment can make the use of fibres in asphalt mixtures more expensive and less effective.
- A circular road simulator has been used to evaluate the impact of the use of aramid fibres in a porous grade asphalt. The conclusion was that the use of fibres contributes positively to the strength of the mixtures. Unfortunately, being a porous asphalt, although it is a promising result, it cannot be extrapolated to asphalt concretes [26].

These investigations present a large gap between laboratory testing and the manufacture of pilot sections. The main problem with this is that if the pilot sections do not perform as expected, they will have reduced durability and generate large amounts of waste. For this reason, this study incorporates an analysis that considers mechanical performance on a circular road simulator, as well as assessing abrasion resistance, recyclability, environmental impact and cost-benefit. This approach aims to provide a more realistic view of the impact of the use of residual aramid fibres in asphalt mixtures, optimising their application without generating unnecessary increases in costs or emissions.

Therefore, the goal of this investigation has been to achieve the mechanical, environmental and economic performance of a novel asphalt concrete with residual aramid fibres and conventional binder, aiming to bring its performance close to, equal or even exceed that of an asphalt concrete with polymer-modified binder. For this objective, this work has evaluated the feasibility of the mixtures developed and previously studied in the laboratory in [10], evaluating their performance at medium scale in a circular road simulator with the mixtures in virgin and aged state, resistance to abrasion by the brush method, recyclability by replacing 50 % of the mixture with RAP with fibres and the environmental and economic feasibility have been studied.

This research has been divided into five chapters. Firstly, the mechanical performance of the mixtures in virgin and aged state has been evaluated in a circular road simulator. In the second chapter, the abrasion resistance of asphalt concretes has been monitored by means of the brushing test. Thirdly, recyclability has been studied by traditional laboratory methods such as Marshall, water sensitivity, wheel adhesion, modulus and fatigue. Fourthly, an end-to-end environmental impact study has been carried out. Finally, in the fifth chapter, a cost-benefit study of the recycled fibre pavement has been developed.

2. Materials

For the development of this research, two types of asphalt binders typically used in Spain have been used, one of penetration grade 50/70 and the other modified with polymers of the PMB 45/80–65 type. Their properties are shown in Table 1.

For the aggregates, ophite has been used for the coarse fraction, while limestone has been used for the fine and filler fraction. Their properties are summarised in Table 2.

In addition, a residual aramid fibre has been used (Fig. 1), due to its promising results in past research [10]. This type of fibre is yellow in colour, has a density of 1.44 g/cm^3 and a length between 0.64 and 1.20 mm.

Table 1
Binder properties.

Binder type	Test	Value	Standard
50/70	Penetration (25°C, mm/10)	57	EN 1426
	Specific Gravity	1.04	EN 15326
	Softening point (°C)	51.6	EN 1427
	Ductility force (5°C, J/cm^2)	-	-
	Elastic recovery (25°C, %)	-	-
PMB 45/80–65	Penetration (25°C, mm/10)	56.00	EN 1426
	Specific Gravity	1.03	EN 15326
	Softening point (°C)	74.10	EN 1427
	Ductility force (5°C, J/cm^2)	3.11	EN 13589
	Elastic recovery (25°C, %)	88.00	EN 13398

Table 2
Aggregate properties.

Aggregate type	Property	Value	Limit	Standard
Ophite	Los Angeles coefficient	13	≤ 20	EN 1097–2
	Specific weight (g/cm^3)	2.787	-	EN 1097–6
	Polished stone value (PSV)	60	≥ 56	EN 1097–8
	Flakiness Index (%)	8	≤ 20	EN 933–3
Limestone	Los Angeles coefficient	28	-	EN 1097–2
	Specific weight (g/cm^3)	2.705	-	EN 1097–6
	Sand equivalent	78	> 55	EN 933–8
Hydrated lime	Specific weight (g/cm^3)	1.959	-	EN 1097–6

Fig. 1. Aramid residual fibre.

3. Methodology of research

In order to study the potential performance improvement of the experimental mixtures in a comprehensive manner, the structure of the manuscript has followed a logical sequence: first, the large-scale mechanical study in the CRS; then, the evaluation of abrasion resistance; and, subsequently, the analysis of recyclability. With this information, complemented by the results of a previous research [10], we have developed an environmental and economic life cycle study.

In specific, three asphalt concretes previously developed in [10] were used: two reference concretes and one experimental concrete. It should be noted that the experimental mixture corresponds to the asphalt concrete that presented the best performance in the previous research at laboratory level. Table 3 presents the description of the three mixtures considered in this study, which share the same particle size

Table 3
Detail of mixtures.

Type of mixture	Name	Bitumen		Fibres	
		Type	Dosage	Type	Dosage
Reference	Ref 1	50/70	4.4	-	-
Reference	Ref 2	PMB 45/80–65	4.4	-	-
Experimental	Exp	50/70	4.7	Aramid	0.08

distribution (Fig. 2). The mechanical performance of these mixtures at laboratory level with basic tests has already been evaluated in the laboratory and is summarised in Table 4.

The asphalt concrete specimens were manufactured according to the particular test, therefore, the explanation of the manufacturing of each mixture was described in the section of each test.

3.1. Circular road simulator test

For the mechanical evaluation in the circular road simulator (Fig. 3), the passage of a commercial vehicle was simulated at room temperature, specifically, the temperature was monitored and recorded as 22.3 ± 2°C. In this test, two 205/55 R16 tyres with a load of 450 kg each were used. In addition, In addition, 50 mm high trapezoidal specimens were manufactured (Fig. 4).

Regarding the manufacture of the specimens, they were all hot mixed according to the temperature of their binder (50/70 at 150°C and PMB 45/80–65 at 165°C). Regarding the mixing process, in the case of the experimental asphalt concrete, the fibres were mixed with the coarse and fine aggregates (dry process), then the binder was added, and finally the filler fraction was added. In the case of the reference asphalt mixtures, the same mixing process was used, except that no residual fibres were added. The compaction process for all trapezoidal specimens was carried out using an 850 kg roller compactor (Fig. 4). Importantly, the fibres were not heated or pre-processed to be added to the mixture.

Regarding the evaluation of the specimens in the circular road simulator, the specimens were tested newly manufactured and aged, because Jia [27] studied the impact of fibres with respect to ageing on a laboratory scale with promising results. The ageing process was developed according to AASHTO R30–02(2015).

In the circular road simulator, three specimens of each type of asphalt concrete were tested. In particular, the unaged specimens were tested up to 1 000 000 cycles, while the aged specimens were tested up to 500,000 cycles.

The specimens were scanned initially and every 100,000 cycles using an Ames 9500 Lt scanner to determine the profile mean depth (MDP), root mean square (RMS), skewness (Rsk) and kurtosis (Rku). For this step, the peak removal method developed by Virginia Tech [30] was used.

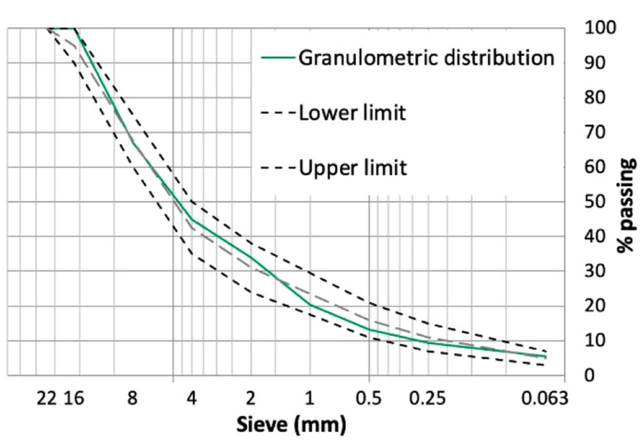

Fig. 2. Granulometric distribution.

All results were statistically evaluated with Minitab software. Student's *t*-test was used when the results showed a normal distribution and there was homogeneity of variances. Otherwise, the Mann-Whitney *U* test was used. A confidence level of 95 % was considered. The results were considered significantly different when the p-value is less than 0.05. Furthermore, with this software, the results were evaluated in order not to consider anomalous data in the analysis.

3.2. Abrasion resistance test using a steel brush

Abrasion is not a common failure in asphalt concretes. However, being an experimental mixture, an evaluation of abrasion resistance was developed to improve the understanding of fibre impact. For this, the brush abrasion test was used (Fig. 5), in the same way that [28,29]. It is important to mention that the test was carried out at room temperature, with an average test temperature of 22.4 ± 1.4°C. In this regard, this test applies a cyclic load with a steel brush with a load of 3.7 kg/cm^2. The test was performed at a rate of 21 cycles per minute, until 1000 cycles were completed.

In this test, three specimens of each type of asphalt concrete were analysed. The specimens were weighed and scanned with the Ames 9500 Lt scanner initially and every 250 cycles until the test was completed. For this step, the peak removal method developed by Virginia Tech was used [30]. In particular, the mass loss of the specimens and simultaneously the profile mean depth (MDP), root mean square (RMS), skewness (Rsk) and kurtosis (Rku) were evaluated.

The results were statistically analysed using Minitab software, with the same parameters as in the previous chapter.

3.3. Evaluation of the recyclability of experimental asphalt concrete at laboratory level

In order to evaluate the potential recyclability of the experimental asphalt concrete, the experimental asphalt mixture was aged according to AASHTO R30–02 (2015) and used as RAP. In this case, 50 % of the virgin material of the experimental asphalt concrete was replaced by RAP with residual aramid fibres.

They were evaluated according to void content (EN 12697–8), Marshall test (EN 12697–34), water sensitivity (EN 12697–12) and Wheel tracking test (EN 12697–22). In addition, dynamic testing has been carried out using the stiffness (EN 12697–26) and fatigue resistance (EN 12697–24) tests. All the tests were carried out in accordance with the standard mentioned in each case.

3.4. Cradle to grave environmental life-cycle analysis of the experimental asphalt concrete

In order to evaluate the environmental feasibility of using residual aramid fibres in asphalt concrete, a cradle to grave life cycle analysis of three road pavements incorporating ref 1, ref 2 and exp mixtures in the wearing course (Pav-ref 1, Pav-ref 2, Pav-exp), was carried out. The layers composition and thicknesses for the three pavements are shown in Table 5 and Table 6. One square meter (1 m^2) is taken for the calculations. The following stages were considered for the life cycle analysis: extraction and production of raw materials (A1), transportation of raw materials (A2), production of hot asphalt mixture at the asphalt plant (A3), transportation from the asphalt plant to the construction site (A4), paving (A5), milling and overlay of the wearing course (B), milling of the three asphalt layers (C1) and transportation of reclaimed asphalt to the asphalt plant (C2).

The Environmental Footprint 3.1 characterization method is used for selecting and quantifying the category impacts and the SIMAPRO software was used for main calculations. The study period for each alternative is set as the service life of the specific pavement and the results are annualized for comparing the different alternatives. It is important to highlight that the results of the simulation in the circular road simulator,

Table 4
Results reported in [10] for reference asphalt concretes and with residual aramid fibres.

Test	Parameters	Ref 1	Ref 2	Exp
-	Voids (%)	5.4 ± 0.3	5.4 ± 0.3	4.2 ± 0.3
Marshall	Stability (kN)	14.7 ± 1.3	18.1 ± 0.9	12.0 ± 0.5
	Deformation (mm)	3.5 ± 0.7	2.5 ± 0.4	3.1 ± 0.2
Water sensitivity	ITS Dry (kPa)	1724.5 ± 124.1	2005.8 ± 247.5	2032.5 ± 61
	ITS wet (kPa)	1594.4 ± 51.1	1906.9 ± 55.2	1639.0 ± 82
	ITS ratio (%)	92	95	81
Wheel tracking	Slope (mm/1000 cycles)	0.11 ±	0.02 ± 0.01	0.04 ± 0.01
	Rut depth (mm)	3.5 ± 0.3	1.7 ± 0.02	2.8 ± 0.3
Module	Frequency 0.1 (Hz)	757	1012	693.00
	Frequency 0.2 (Hz)	1017.25	1225.5	929.75
	Frequency 0.5 (Hz)	1520.25	1617.75	1379.5
	Frequency 1 (Hz)	2048.25	2004.5	1828.75
	Frequency 2 (Hz)	2718.00	2475.0	2436.5
	Frequency 5 (Hz)	3787.5	3270.5	3357.0
	Frequency 10 (Hz)	4788.75	4012.5	4166.75
	Frequency 20 (Hz)	5836.00	4809.75	4962.00
	Frequency 30 (Hz)	6612.25	5403.25	5568.25
Fatigue	Strain-Charact (μm/m)	177.1 ± 32.2	270.3 ± 44.9	180.8 ± 21.8
	Fatigue line	$1.364\bullet10^{-3}\bullet N^{-0.1478}$	$1.185 \bullet 10^{-3} \bullet N^{-0.1069}$	$0.659 \bullet 10^{-3} \bullet N^{-0.0936}$
	R2	0.967	0.8	0.886

Fig. 3. Circular road simulator.

Fig. 4. Trapezoidal sample and roller compact.

Fig. 5. Steel brush abrasion test.

Table 5
Reference and Experimental pavement sections.

		Pav-ref1	Pav-ref2	Pav-ref3
Wearing course	Mixture type	Ref1	Ref2	Exp
	Thickness (cm)	5	5	5
Binder course	Mixture type	AC22	AC22	AC22
	Thickness (cm)	7	7	7
Base course	Mixture type	AC32	AC32	AC32
	Thickness (cm)	8	8	8

Table 6
Formulation of reference and experimental mixtures.

	Pav. Ref 1	Pav. Ref 2	Pav. Exp	AC22	AC32
Bitumen type	B50/70	PMB 45/80–65	B50/70	B50/70	B50/70
%bitumen	4.4	4.4	4.7	4.5	4
%Coarse aggregates	63.2	63.2	62.9	60	62
%Fine aggregates	31.8	31.8	31.7	30	30
%Filler	0.57	0.57	0.57	5.5	4
% Fibre	0	0	0.08	0	0
Density (ton/m^3)	2.43	2.43	2.46	2.45	2.45

abrasion results, and the recyclability of each mixture were considered.

The data sources used for completing the Life Cycle Inventory for each process in the life cycle analysis are shown in Table 7.

3.5. Cradle to grave economic life-cycle analysis of the experimental asphalt concrete

The economic feasibility of asphalt concrete reinforced with residual aramid fibres was assessed by means of a life cycle cost assessment, by calculating the present value of all the costs throughout the life cycle of the road pavement for the three pavements under study (pav-ref 1, pav-ref 2, pav-exp). These costs include initial construction costs (C_i), maintenance costs of all the interventions (Cm_i), rehabilitation costs (Cr_i) and End-of-life costs (C_{EL}). The net present value (NPV), selected as the indicator for the life cycle cost assessment, is calculated as the sum of

Table 7
Life Cycle Inventory data sources.

Process	Data source
Bitumen	The Eurobitume Life Cycle Assessment 4.0 for bitumen
Coarse aggregate	Ecoinvent: Basalt {RER}| quarry operation | Cut-off, U
Fine aggregate	Ecoinvent: Limestone, crushed, washed {CH}| production | Cut-off, U
Filler	Ecoinvent: Lime {CH}| production, milled, loose | Cut-off, U
Residual fibre	Ecoinvent*: Nylon fibre, recycled, mechanical, post-consumer {GLO} | washing, drying, shredding, drum rotating spinning | production mix, at plant | Erec/ErecEoL, efficiency 90 % | LCI result
Transportation	Ecoinvent: Transport, freight, lorry 16–32 metric ton, EURO3 {RER}| transport, freight, lorry 16–32 metric ton, EURO3 | Cut-off, U
Energy consumption at the asphalt plant	Data given by construction company [31]
Electricity	Ecoinvent: Electricity, medium voltage {RER}| market group for | Cut-off, U
Diesel combustion	Ecoivent: Diesel, burned in building machine_nemo
Natural gas combustion	Ecoinvent: Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace > 100 kW | Cut-off, U
Paving	Comparative environmental and economic assessment of a road pavement containing multiple sustainable materials and technologies [32]
Application of tack coat	Comparative environmental and economic assessment of a road pavement containing multiple sustainable materials and technologies [32]
Milling	Comparative environmental and economic assessment of a road pavement containing multiple sustainable materials and technologies [32]

*The process for the recycling of aramid fibre is not available, so the processing of recycled nylon fibre has been used as a proxy.

all those costs and subtracting the residual value (RV) of the pavement at the end of the study period (p) (Eq. 1). Present costs of future costs are calculated based on the real discount rate (r) of the year where the maintenance activities or end-of-life activities take place. The selected study period is 30 years, in order to reflect the differences in the long-term performance among the alternatives.

$$NPV = C_I + \sum_{i=1}^{i} C_{mi}\left[\frac{1}{(1+r)^{n_i}}\right] + C_{EL} - RV\left[\frac{1}{(1+r)^{p}}\right] \quad (1)$$

The prices for the different materials and processes were collected from the Support Price Database of the General Directorate of Roads in Spain for the Year 2024 [33]. There is not information about the cost of the fibre, so a sensitivity analysis was done varying the cost of the residual aramid fibre from 0€/kg to 20 €/kg.

4. Results and discussion

4.1. Circular road simulator test

Fig. 6 and Fig. 7 shows the average results for each parameter as a function of the number of cycles. In this sense, the mixture Exp shows an intermediate degradation between those reported by Ref 1 and Ref 2, although its performance was very close to that of Ref 2 which was made with polymer modified binder. In this sense, Ref 1, typically used in Spain, shows higher depths at the end of the cycles in the circular road simulator, which may result in a surface with more irregularities, reducing the adherence to tyres in rainy conditions or water accumulations in depressions, compromising road safety. Meanwhile, Ref 2 with polymer-modified binder has a more stable surface roughness during the test, so it is likely that the service life of this type of specimen is longer and requires less maintenance costs compared to Ref 1.

On the other hand, regarding the results reported in Fig. 7, Exp mixture and Ref 2 specimens show more stable values than Ref 1, the latter having reported the highest surface wear. In all cases, between Exp mixture and Ref 2 there are no statistically significant differences, although the Exp mixture was formulated with a conventional binder, it does not incorporate the polymer modification present in the binder used in the Ref 2 mixture.

In this sense, exp is significantly better than Ref 1 in terms of MDP, RMS and Rsk (Table 8), for the case of Rku there were no statistically significant differences between all the specimens. In practical terms, these results suggest that Ref 1 may require frequent maintenance, as higher wear leads to higher MDP, together with higher RMS suggesting higher surface roughness and lower skewness and greater degradation. Therefore, Exp mixture and Ref 2 may offer greater durability with less intervention.

This result can be explained by the type and dosage of binder in each of the mixtures. In particular, the reference mixture 1 and the experimental mixture had the same particle size distribution and type of binder, but the experimental mixture had more binder due to the binder retention capacity of the residual fibres. Therefore, the improved surface stability of the experimental mixture can be explained by the higher binder content and the mechanical contribution of the residual aramid fibres. This results in improved pavement performance in repetitive loading situations, reducing the occurrence of potholes and premature deformation.

On the other hand, the experimental mixture, despite not having a polymer-modified binder, did not show statistically significant differences compared to the reference mixture 2 (manufactured with polymer-modified binder). Therefore, the use of recycled fibres is a viable option to achieve the performance of asphalt concrete made with polymer modified binder. It is important to mention, despite its excellent performance, that this binder is not usually used in this type of asphalt concrete due to its high cost.

The result of the aged specimens evaluated on the circular road simulator is shown in Fig. 8 and Table 9. In this respect, Exp mixture, with residual aramid fibres, has again reported an intermediate performance between Ref 1 and Ref 2. In Fig. 8 F, localised wear is observed, which could indicate that the strength of the material has been effective over most of the surface, but not completely uniform. In general, when studying the aged specimens, the addition of fibres seems to have reduced the magnitude of deformation compared to Ref 1, although its performance is still below Ref 2.

It is important to mention, the highest wear is reported for Ref 1, which presents the most irregular texture with deeper zones, suggesting a greater loss of material due to the passage of the tyre. Fig. 8 B shows a significant difference in height, possibly generated by plastic deformations. It is probable that the fibres actively act as reinforcement elements, helping to hold the pavement aggregates together and increasing their stability, especially when the binder has aged and loses its ability to maintain the structural integrity of the mixture. This could explain why the Ref 1 mixture showed significantly higher degradation compared to the experimental mixture with recycled fibres.

On the other hand, Ref 2 again shows the best performance, with a more uniform surface and less wear. It is evident that Ref 2 has not undergone abrupt changes nor has it shown signs of severe wear; i.e., Ref 2 has a greater capacity to retain its initial characteristics, regardless of the ageing of the mixtures. Therefore, it is likely that the polymeric matrix contributes to sustaining the properties of the binder under ageing phenomena, so that the aged pavement maintains its overall stability.

The measured parameters of the test with the aged specimens are summarised in Fig. 9. Practically all the differences in the results are statistically significant (Table 9). Initially, exp presents intermediate results, superior to those reported by Ref 1, but not matching the performance exhibited by Ref 2, which had the lowest MPD and RMS value, thus presenting lower surface deformations and better performance in

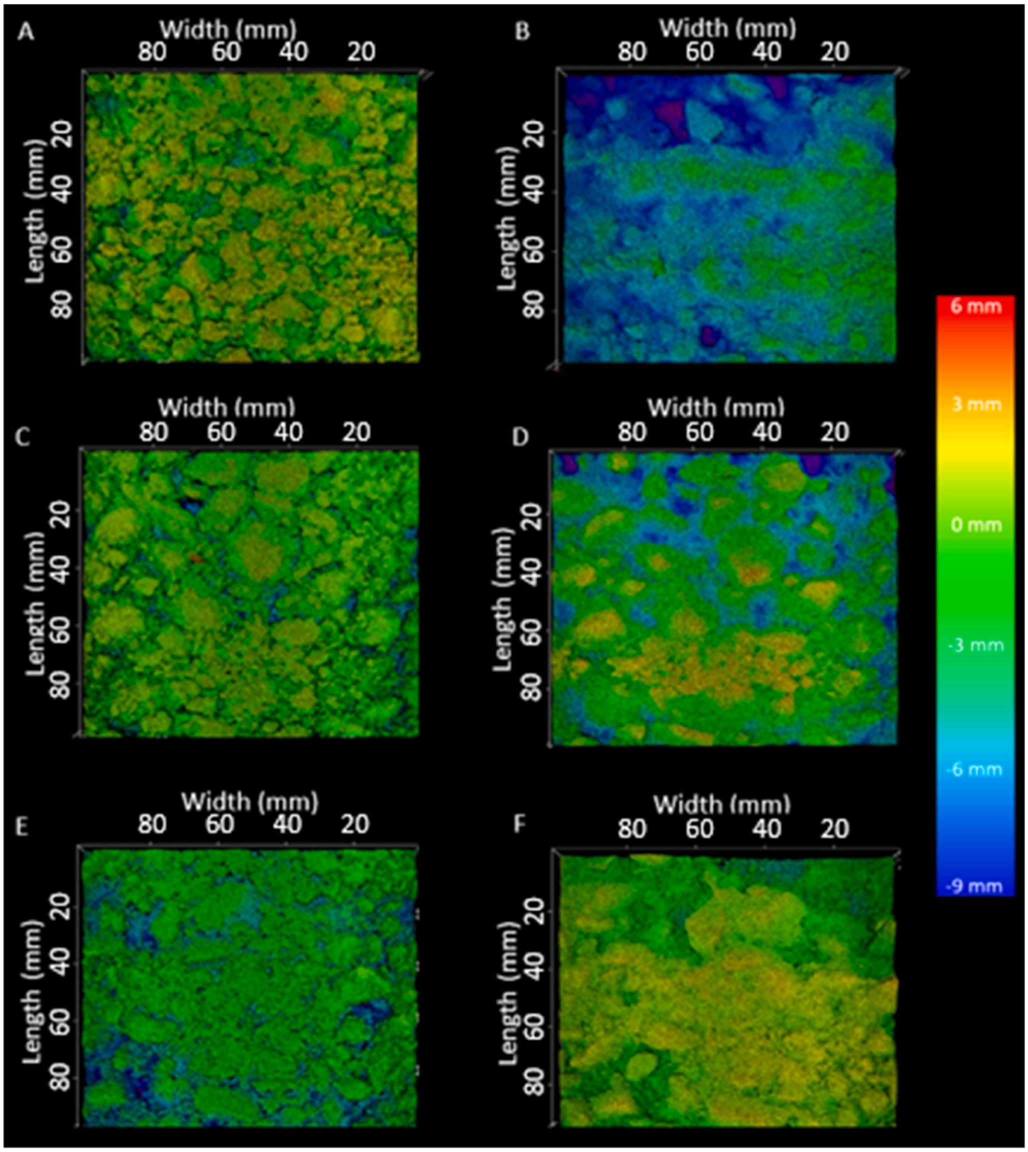

Fig. 6. Initial and final scanning of samples in a circular road simulator: (A) Initial state Ref 1; (B) Final state Ref 1; (C) Initial state Ref 2; (D) Final state Ref 2; (E) Initial state Exp and (F) Final state Exp.

terms of resistance to surface erosion. When looking at Rsk and Rku, Exp 1 and Ref 2 present more homogeneous values, suggesting that their surface is not affected by such abrupt wear peaks as Ref 1.

On the other hand, it is worth noting that Ref 1 reported the highest MPD and RMS, so it reported the highest wear and the most deteriorated surface at the end of the simulation. This is consistent with the results reported for the specimens that were not aged. In addition, the Rsk and Rku results show that Ref 1 has an irregular distribution of peaks and valleys.

4.2. Abrasion resistance test using a steel brush

With respect to particle loss (Fig. 10), there is no statistically significant difference in the performance of the mixtures (Table 10). This makes sense, because asphalt concretes do not tend to lose material. This can be explained by the nature of the internal structure of dense asphalt concretes, in which the coarse aggregates are completely enveloped by the mastic (mixture of binder and fines). This continuous film acts as an adhesive that holds the aggregates firmly together within the matrix, preventing their detachment even under cyclic loading conditions such as this test. However, the slight differences reported in the results are in line with the same trend as in the circular road simulator, Ref 1 suffers the greatest degradation with increasing abrasion cycles, indicating a lower wear resistance. In contrast, Ref 2 shows the lowest particle loss, suggesting higher cohesion of the material and better adhesion of the aggregates, possibly due to the polymer-modified binder. On the other hand, Exp shows an intermediate behaviour, indicating that the addition of fibres improves wear resistance compared to the traditional binder, although it does not reach the effectiveness of the polymer-modified binder. This result shows the asphalt concrete with residual aramid fibres will not be susceptible to raveling during its service life.

The results of the mean profile depth are strongly influenced by the type of binder used; that is, the internal structure of the pavement prevents the loss of particles, but the binder strongly influences the deformations experienced by the pavement. Specifically, the highest values were recorded for mixtures with traditional binder, having an increasingly rough surface texture. In contrast, the polymer-modified binder pavement maintains a more stable texture, which may contribute to better long-term surface preservation. Although Exp presents intermediate values, it does not present statistically significant differences with any of the reference mixtures, which indicates that the incorporation of fibres does not substantially modify the evolution of the

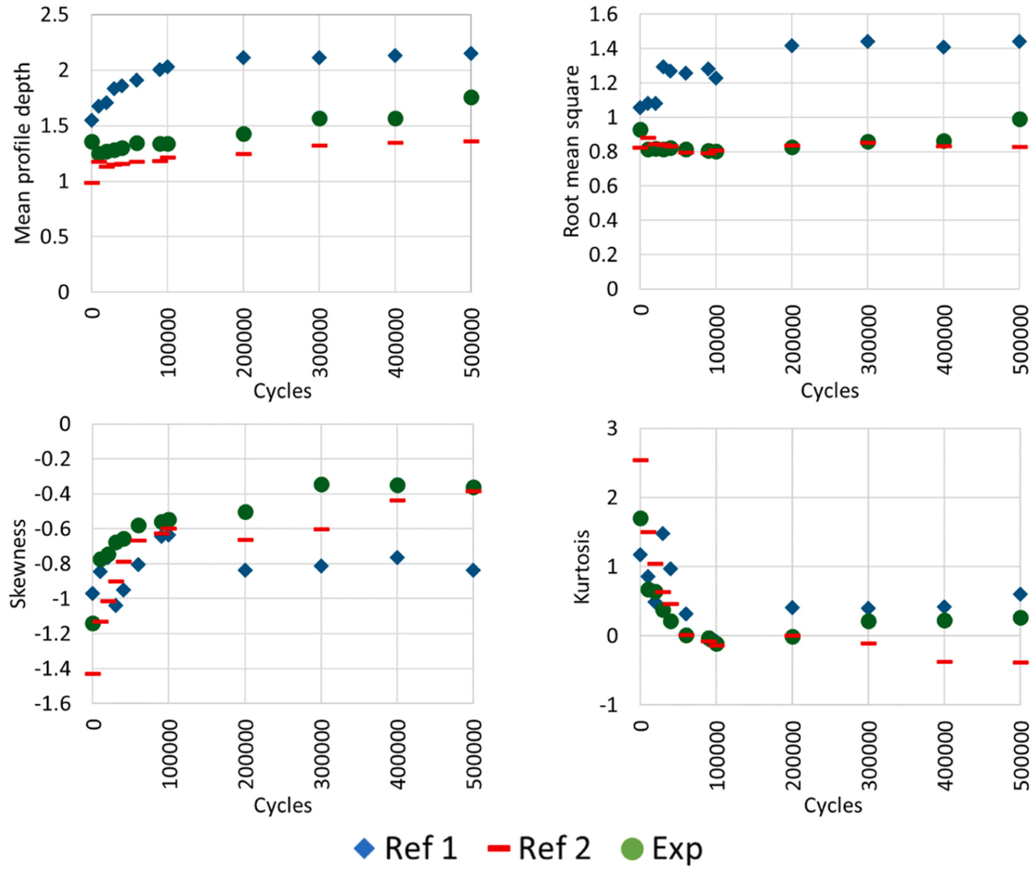

Fig. 7. Results of circular road simulator in unaged specimens.

Table 8
P- values of circular road simulator without ageing.

	P-value							
	MDP	Status	RMS	Status	Rsk	Status	Rku	Status
Ref 1 - Ref 2	0.000	Significant	0.000	Significant	0.563	Not significant	0.285	Not significant
Ref 1 - Exp	0.000	Significant	0.000	Significant	0.008	Significant	0.246	Not significant
Ref 2 - Exp	0.062	Not Significant	0.953	Not significant	0.140	Not significant	0.544	Not significant

texture with respect to conventional asphalt in terms of abrasion resistance.

There are no statistically significant differences between the mixtures with respect to skewness. Specifically, all pavements show negative values, suggesting that wear generates surface depressions rather than high peaks. However, the polymer pavement maintains values closer to zero, which means that its wear is more uniform. It will therefore have less tendency to accumulate water on its surface and cause hydroplaning.

Similarly, when kurtosis is assessed, there are no statistically significant differences between the mixtures. Initially, it is observed that all the specimens initially show more pronounced peaks on the surface, which smooth out with wear. There is quite a lot of variability in the results, which can be explained by the loss of particular particles, which caused large peaks at the surface of the mixtures.

4.3. Evaluation of the recyclability of experimental asphalt concrete at laboratory level

The use of 50 % recycled material as a replacement in the mixture shows a slight reduction in stability compared to ref 1 and 2 (Table 11). This difference is minute, so the addition of recycled fibres and reclaimed material does not compromise the strength of the mixture in terms of the Marshall test. On a full scale, this implies that the use of recycled material could be feasible without substantially affecting pavement stability, although adjustments in binder dosage may be required to optimise performance.

Then, in the water sensitivity test (Table 12), the Exp_{REC} mixture exhibits ITS values higher than those of Ref1 and comparable to those of Ref2, indicating that its resistance is similar to that achieved with a PMB. However, the ITS ratio of the experimental mixes consistently falls below that of the reference mixes, suggesting lower performance against water damage. Nevertheless, the ITSR values obtained are considered acceptable. Notably, Exp_{REC} achieved a higher ITSR than Exp, demonstrating that the inclusion of recycled material with recycled fibres enhances moisture resistance, which is an essential factor in preventing pavement failures in wet environments.

The results shown by ExpREC can be explained by the incorporation of recycled material (RAP) with recycled fibres. This recycled material with aged binder gives increased stiffness and reinforcing action of the fibres. This increases the indirect tensile strength (ITS). However, the lower ITSR of ExpRec indicates that its ability to maintain its strength in the presence of water is more limited, possibly due to the lower adhesiveness of the aged RAP binder.

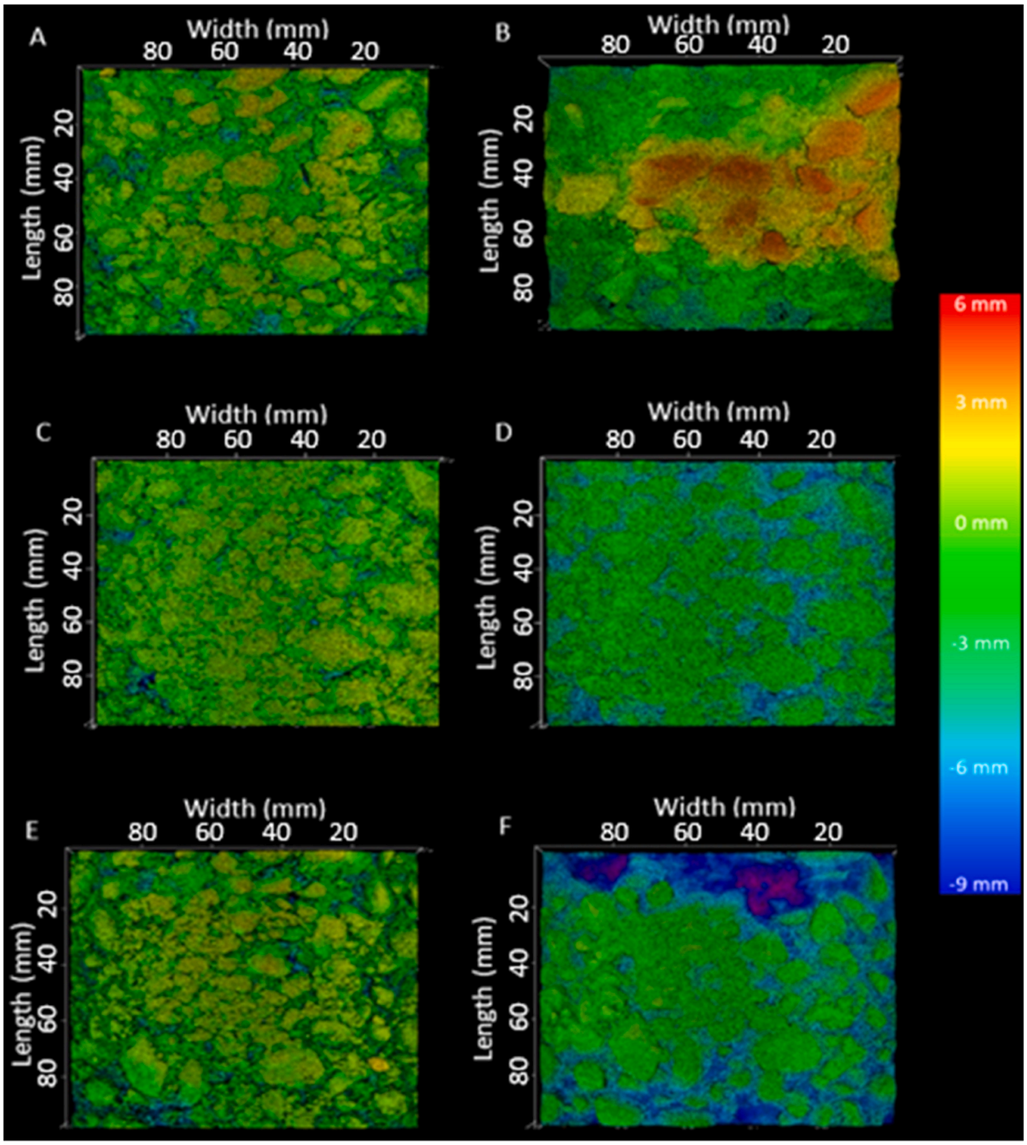

Fig. 8. Circular road simulator test: initial and final scans of aged samples: (A) Initial state Ref 1; (B) Final state Ref 1; (C) Initial state Ref 2; (D) Final state Ref 2; (E) Initial state Exp (F) and final state Exp.

Table 9
P-values circular road simulator aged.

	P-value							
	MDP	Status	RMS	Status	Rsk	Status	Rku	Status
Ref 1 - Ref 2	0.000	Significant	0.002	Significant	0.000	Significant	0.002	Significant
Ref 1 - Exp	0.000	Significant	0.003	Significant	0.002	Significant	0.002	Significant
Ref 2 - Exp	0.002	Significant	0.000	Significant	0.427	Not significant	0.014	Significant

With respect to the wheel tracking test (Table 13), the mixture Exp_{REC} presents an intermediate value, with a higher deformation compared to Ref 2, but still has a better result than that reported for Ref 1. However, there is no significant difference between the experimental specimens, so that the resistance to plastic deformation is not strongly affected by the recycled material content. This result can be attributed to the higher stiffness of the aged binder in the recycled material, since the reference mixture 1, with conventional binder in virgin state, has the highest Rut Depth, and the recycled mixture has decreased Rut Depth from 2.8 to 2.1 with respect to Exp.

However, in the dynamic modulus test (Fig. 11), the Exp_{REC} mixture exhibits a significantly higher modulus compared to the reference mixtures. This suggests that the inclusion of recycled material significantly affects the mixture under repetitive loading. In practical terms, this means that the pavement will experience less elastic deformation when subjected to traffic, which can bring both benefits and challenges to its long-term performance, e.g. it will be able to withstand higher loads but will have less capacity to dissipate energy and will have less resistance to cracking.

Finally, in the fatigue resistance test (Table 14), the mixture Exp_{REC} shows a lower performance than the references, indicating that the combination of recycled material and recycled fibres significantly affects

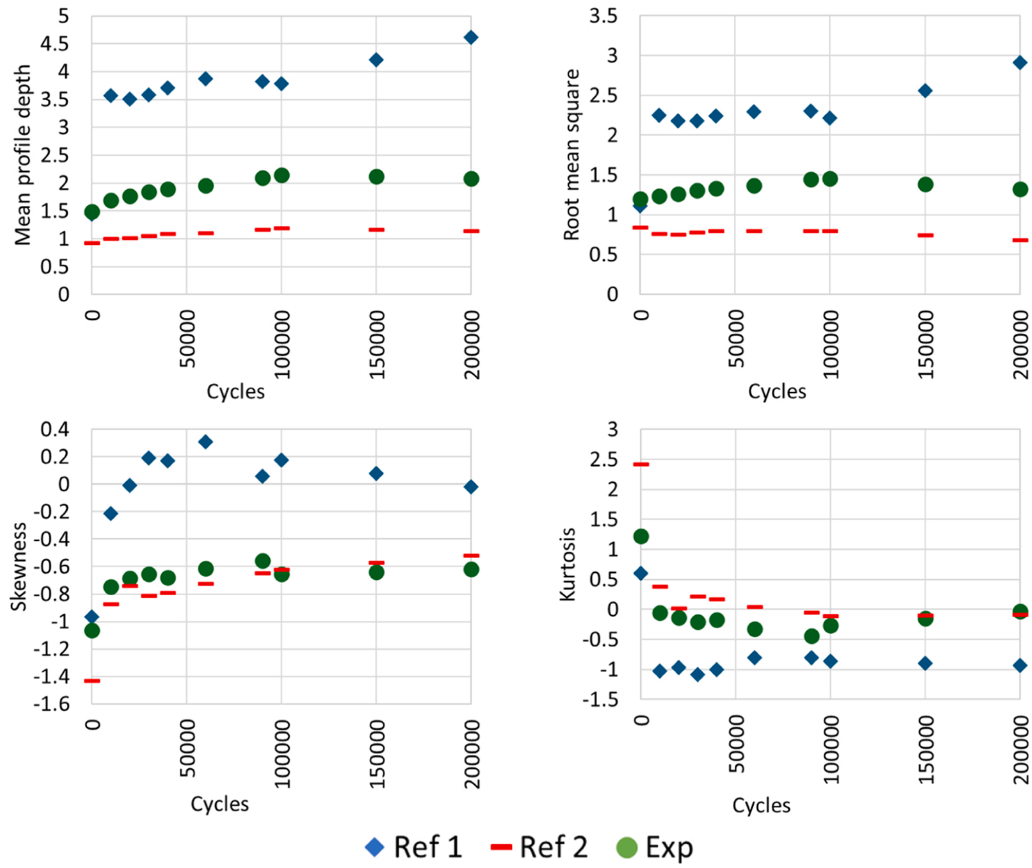

Fig. 9. Results of aged specimens in circular road simulator.

the fatigue strength. In addition, the difference in the slope of the fatigue line suggests that the deterioration rate is evidently significant, where the steepest slope is presented by Exp_{rec}. This result is significant, suggesting that the use of recycled material may produce a reduction in the durability of the Exp_{rec}.

4.4. Cradle to grave environmental life-cycle analysis of the experimental asphalt concrete

Based on the results obtained at the circular road simulator, the service life of each pavement section of Table 5 has been estimated. For ref-1, the conventional asphalt concrete, 10 years average service life is usually considered in Spain [34], while for the ref-2 that incorporates a PMB, 14 years can be a good estimation due to its higher performance. As for the experimental mixture, considering the results obtained and given that it exhibits an intermediate behavior between the conventional mix and the polymer-modified mix, an average of 12 years durability is assumed. Most relevant maintenance action for this study is the milling and overlay (M&O) of the wearing course at the end of its service life. The rehabilitation of the pavement section is done at the end of the service life of the wearing course that has already been replaced once, that is 20 years for pav-ref1, 24 years for pav-exp and 28 years for pav-ref2. The rehabilitation consists of milling the three asphalt layers and the transportation of the reclaimed asphalt to the asphalt plant. The reconstruction of the three layers is not included in the life cycle analysis since it is considered to belong to the new cycle.

Fig. 12 shows the results of the life cycle analysis carried out. In this figure, the results of the Pav-ref1 is considered the baseline with all its impact categories set at 100 %. The other alternatives are presented in the figure relative to the reference. The pavement that uses the fibre reinforced asphalt mixture (Pav-exp) improves the environmental performance of the Pav-ref1 section in all category impacts. However, the pavement section with the wearing course including a PMB presents even better results, although the difference with Pav-exp is not as significant as with Pav-ref1. The obtained results have been normalized and weighted using EF 3.1 normalization and weighting values [35,36] so a more practical single score is obtained. Similarly, the experimental pavement (Pav-exp) including the residual fibre results in a better environmental performance than the reference pavement with a conventional B50/70 bitumen but does not reach the performance of Pav-ref2 with a PMB.

4.5. Analysis cradle to grave economic life-cycle analysis of the experimental asphalt concrete

The life cycle cost assessment result for the 30 years study period is shown in Fig. 14. Both Pav-ref2 and Pav-exp are more cost-effective than Pav-ref1. The cost-efficiency of the fibre-reinforced solution depends on the cost of the residual fibre, losing its competitiveness comparing to the reference pavement (Pav-ref1) when the cost of the fibre reaches 20 €/kg, that is an approximate cost for the virgin fibre. The highest amount of bitumen that is needed for coating the fibre and the cost of fibre itself reduces the cost-effectiveness of this alternative. In the case of Pav-ref2, although the PMB is more expensive than the B50/70, the higher mechanical performance compensates it and savings can be obtained considering the life cycle of the pavement. It should be noted that the circular road simulator results have not been validated against the performance of the mixtures in real test sections. Therefore, constructing real test sections is necessary to assess the actual differences in the service life among the three surface layers and pavements.

5. Conclusions

The feasibility of using residual fibres in asphalt concrete has been

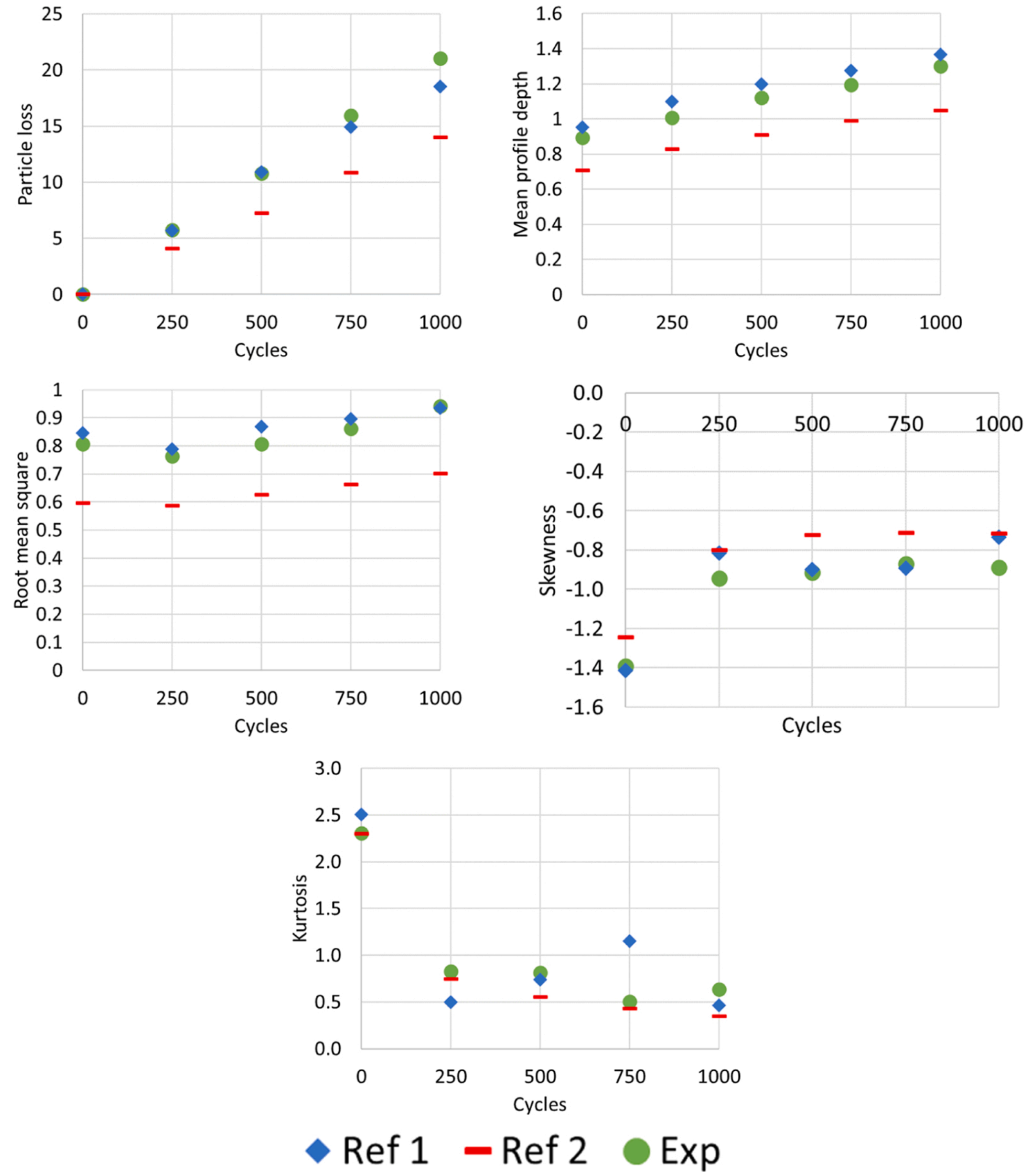

Fig. 10. Abrasion test results using steel brushes.

Table 10
P_{values} abrasion test.

	P-value									
	Particle loss	Status	MDP	Status	RMS	Status	Rsk	Status	Rku	Status
Ref 1 - Ref 2	0.370	Not significant	0.019	Significant	0.000	Significant	0.143	Not significant	0.530	Not significant
Ref 1 - Exp	0.846	Not significant	0.483	Not significant	0.468	Not significant	0.530	Not significant	0.834	Not significant
Ref 2 - Exp	0.322	Not significant	0.060	Not significant	0.001	Significant	0.094	Not significant	0.296	Not significant

Table 11
Void recyclability and Marshall test results.

Mixture	Voids (%)	Stability (kN)	deformation(mm)
Ref 1	5.4 ± 0.3	14.7 ± 1.3	3.5 ± 0.7
Ref 2	5.4 ± 0.3	18.1 ± 0.9	3.5 ± 0.4
Exp	4.2 ± 0.3	12.0 ± 0.5	3.1 ± 0.2
Exp_{REC}	4.3 ± 0.2	11.7 ± 0.5	2.8 ± 0.5

Table 12
Water sensitivity test results.

Mixture	ITS_{DRY} (kPa)	ITS_{WET} (kPa)	ITS_{RATIO} (%)
Ref 1	1724.5 ± 124.1	1594.4 ± 51.1	92
Ref 2	2005.8 ± 247.5	1906.9 ± 55.2	95
Exp	2032.5 ± 61	1639.0 ± 82	81
Exp_{REC}	2287.0 ± 15	1945.4 ± 83	85

Table 13
Results of recyclability of the wheel tracking test.

Mixture	Slope (mm/1000 cycles)	Rut Depth (mm)
Ref 1	0.11 ± 0.02	3.5 ± 0.3
Ref 2	0.02 ± 0.01	1.7 ± 0.02
Exp	0.04 ± 0.01	2.8 ± 0.3
Exp_{REC}	0.05 ± 0.01	2.1 ± 0.3

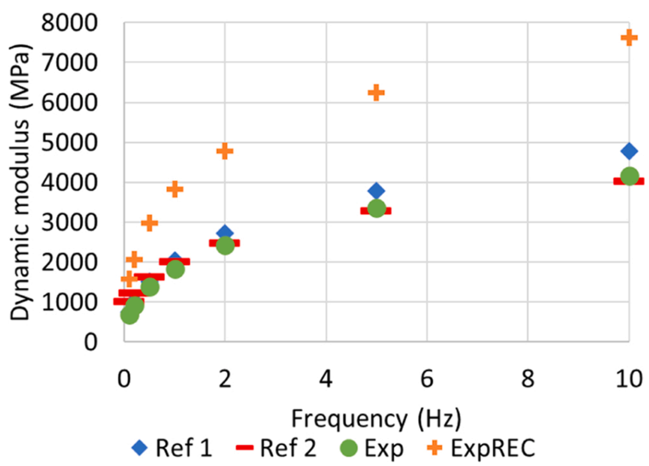

Fig. 11. Recyclability result module.

Table 14
fatigue resistance test results.

Mixture	Strain-charact (μm/m)	Fatigue Line	R^2
Ref 1	177.1 ± 32.2	$1.364 \bullet 10^{-3} \bullet N^{-0.1478}$	0.967
Ref 2	270.3 ± 44.9	$1.185 \bullet 10^{-3} \bullet N^{-0.1069}$	0.800
Exp	180.8 ± 21.8	$0.659 \bullet 10^{-3} \bullet N^{-0.0936}$	0.951
Exp_{REC}	168.4 ± 31.7	$1.524 \bullet 10^{-3} \bullet N^{-0.1594}$	0.886

studied by means of a circular road simulator, abrasion resistance, recyclability, environmental and economic impact study. In this respect, it is possible to conclude that:

1. The circular road simulator results for the unaged specimens show that Exp and Ref 2 perform statistically similar and better than Ref 1. Therefore, the incorporation of fibres seems to improve the surface stability of Exp, favouring better behaviour under repetitive loading

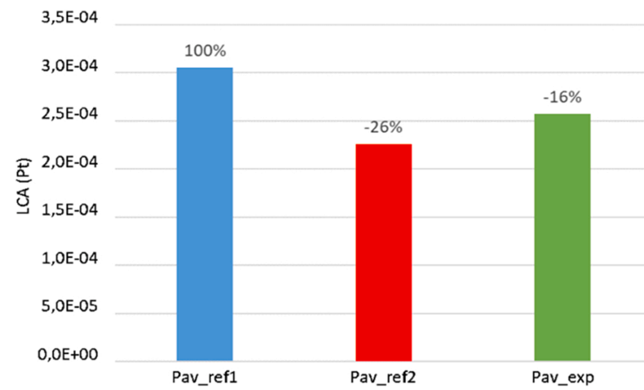

Fig. 13. Life cycle analysis results relative to Pav-ref1, PEF3.1 single score.

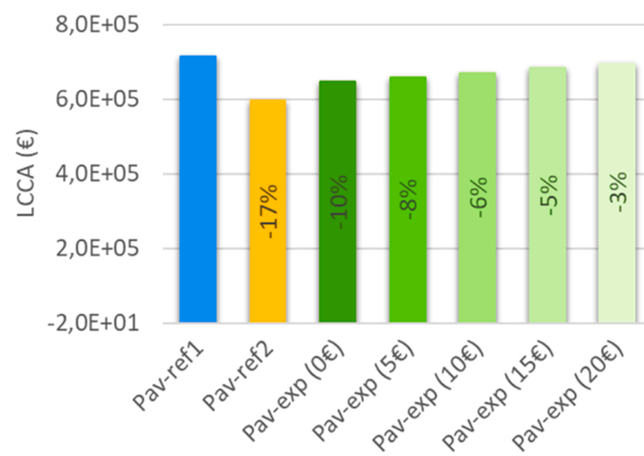

Fig. 14. Life cycle cost assessment results relative to Pav-ref1, PEF3.1 single score.

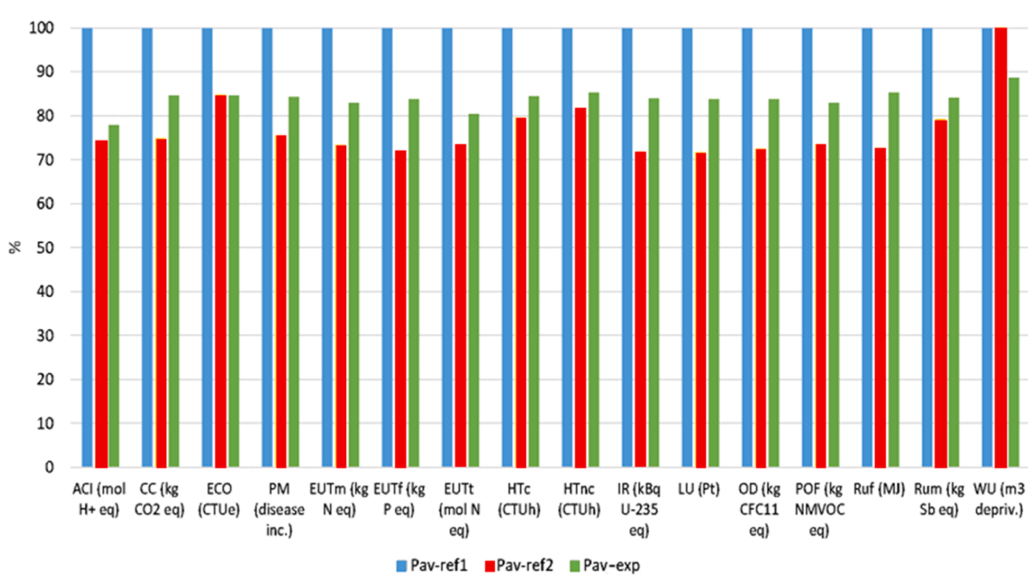

Fig. 12. Life cycle analysis results relative to Pav-ref1, PEF3.1 damage evaluation.

and reducing rutting and premature deformation without the need to use polymer-modified binder.
2. Analysis of the aged specimens in the circular road simulator shows that Exp has an intermediate performance, outperforming Ref 1 but not reaching the performance of Ref 2. This suggests that the incorporation of fibres helps to reduce wear and deformation of the asphalt concrete, but to a lesser extent than in the virgin state.
3. The results of the abrasion test suggest that the abrasion resistance depends on the type of binder, without the incorporation of fibres generating significant changes. Specifically, the experimental specimen has an intermediate behaviour, which indicates that the fibre bonding slightly improves the abrasion resistance, although without reaching the effectiveness of the polymeric binder.
4. In terms of recyclability analysis, the use of 50 % RAP in asphalt concretes is feasible without significantly compromising their mechanical performance. The experimental recycled mixture shows good resistance to moisture and plastic deformation, but a higher dynamic modulus, which could increase its stiffness and susceptibility to cracking. In addition, its fatigue performance is lower, with a higher deterioration rate.
5. It has been observed that pavement with recycled fibres improves performance in all impact categories compared to the Pav-ref1 section (without fibres and with 50–70 binder). However, the Pav-ref2 section performs even better than both previous options, demonstrating that the use of fibres to extend pavement life represents a significant advance in reducing environmental impacts. However, these advances are not yet sufficient to match the performance of the polymer modified binder section.
6. Despite the increased initial cost of manufacturing pav-exp, it is more cost effective than pav-ref 1 with 50–70 binder. However, despite the higher cost of the polymer-modified binder, pav-ref2 presents the greatest savings, as its greater durability offsets these initial costs.

The use of recycled aramid fibres to extend the life of the pavement reduces the environmental and economic impact over its life cycle compared to a pavement with the same asphalt binder, despite a higher initial cost. The extent of this improvement depends on the service life increase achieved.

In the future, efforts should be made to understand the mechanism of action of the fibres during abrasion processes at the microscopic level. At the same time, damage due to humidity and ultraviolet radiation should be studied on a scale equivalent to the circular road simulator. Also, the mechanical behaviour of the experimental mixtures at low and high temperatures should be studied at laboratory level.

In addition, tests should be carried out on the mechanical and functional performance of the experimental asphalt concrete in pilot sections.

CRediT authorship contribution statement

Daniel Castro-Fresno: Writing – review & editing, Visualization, Validation, Supervision, Project administration, Funding acquisition, Formal analysis, Conceptualization. **Helena Miera-Dominguez:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis. **Irune Indacoechea-Vega:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Felipe Ossio:** Writing – review & editing, Validation, Supervision, Project administration, Formal analysis, Data curation. **Pedro Lastra-González:** Writing – review & editing, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Christopher Delafuente-Navarro:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This publication is part of the ASFI+ project (PDC2022–133116-I00), funded by MCIN/AEI/10.13039/501100011033 and by the European Union Next Generation EU/PRTR. The authors would like to thank these institutions. The authors would like to thank also to science writer Natalia Contreras Suarez for her excellent work. At the same time, we thank Andrés Rivas Sánchez and Paula Del Rio Gandarillas, whose excellent work in the laboratory gave a fundamental added value to the development of this research.

Data Availability

Data will be made available on request.

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