Developments in the Built Environment 18 (2024) 100435

Contents lists available at ScienceDirect

Developments in the Built Environment

journal homepage: www.sciencedirect.com/journal/developments-in-the-built-environment

Evaluation of the mechanical performance of AC mixtures with recycled fibres.

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ARTICLE INFO

Keywords:
Asphalt mixture
Recycled fibres
Polymer-modified mixture
Aramid

ABSTRACT

Based on the positive results of most of the studies using virgin fibres to reinforce asphalt mixes, this work proposes the use of recycled fibres in order to go a step further in terms of environmental impact and cost-efficiency. Different experimental asphalt concrete (AC) mixtures are proposed, incorporating three types of recycled fibres. Mechanical performance is assessed through the Marshall, water sensitivity and wheel tracking tests, as well as stiffness and fatigue tests to assess dynamic performance. The results obtained from the different tests performed are analysed by means of a multi-criteria analysis to obtain the asphalt mix with the best performance. The results show that all the tested fibres are suitable for the reinforcement of asphalt mixtures, as the values obtained improved those of the reference mixture, although without reaching the behaviour of a mixture with polymer modified bitumen (PMB). The recycled aramid fibres showed the best results.

1. Introduction

In recent years, roads have been exposed to increasing loads as well as constant temperature changes induced by global warming. As a result of these traffic and climatic loads, the asphalt concrete (AC) mixture is prone to various types of failure, including fatigue cracking, rutting and moisture damage. To deal with this, science and engineering are constantly working to improve the properties of asphalt mixtures and the addition of fibres has emerged as an alternative to boost mechanical performance. In this sense, fibre-reinforced asphalt mixtures (FRAM) have emerged as a feasible alternative to extend the durability of road pavements (Slebi-Acevedo et al., 2019a; Abtahi et al., 2010).

So far, the use of fibres in hot mix asphalts is mostly limited to virgin fibres of different types: steel, organic (e.g. cellulose), mineral (e.g. basalt) and synthetic (e.g. aramid). In addition to improving the mechanical properties of a mixture, recycled fibres can also reduce costs, increase sustainability, and help promote the circular economy needed to mitigate climate change. Moreover, other advantages of the technology are that the fibres can be easily added without increasing the temperature and almost with the same productivity, since the amount of fibres is generally low, and that no specialised plant equipment is needed for the production, storage or transport of FRAM, which favours its feasibly on a large scale (Qiu et al., 2023; Eskandarsefat et al., 2018).

Previous studies (Kim et al., 2018; Elias Kaloush et al., 2010; Park et al., 2015; Serin et al., 2012) have investigated the capacity for reinforcement of different virgin fibres in AC mixtures. Several tests were carried out and the results concluded that most of the experimental mixtures provided better mechanical performance than conventional mixtures. Fibre reinforcement acts as a barrier to prevent crack formation and propagation and good results have been obtained in terms of rutting, cracking, moisture sensitivity and tensile strength (Kim et al., 2018; Park et al., 2015; Bueno and Poulikakos, 2020). In contrast, there is hardly any literature on the use of recycled fibres from industrial processes in bituminous mixtures, and it is practically limited to the use of synthetic fibres, such as nylon, polyester or rubber (Yin and Wu, 2018; Moghaddam et al., 2014; Eskandarsefat et al., 2019).

Since the optimal selection is a complex task due to the high number of variables, the multicriteria analysis has demonstrated to be an effective tool to properly compare the different mixtures and highlight the most promising fibres (Slebi-Acevedo et al., 2019b, 2020a, 2021).

The aim of this paper is to evaluate the technical feasibility of using recycled fibres from different industrial sectors for the fibre-reinforcement of AC mixtures, instead of other type of virgin fibres more expensive and with potentially higher environmental impact. To

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https://doi.org/10.1016/j.dibe.2024.100435
Received 23 January 2024; Received in revised form 13 March 2024; Accepted 6 April 2024
Available online 10 April 2024

do so, the mechanical performance of different FRAM formulations is compared with that of AC mixtures with penetration grade bitumen and with polymer modified bitumen, being the latter, currently in the market, the technology with the best results in extending the service life of asphalt mixtures, and therefore the main competitor of FRAM.

2. Materials and methods

2.1. Materials

A conventional 50/70 penetration grade bituminous binder was used for preparing the experimental and one of the two reference mixtures, while the other control mixture was designed with a polymer modified bitumen PMB 45/80-65. All the mixtures included ophite (a porphyry igneous rock) in the coarse fraction, and limestone in the fine and filler fractions. The properties of the aggregates and bitumen are provided in Table 1 and Table 2, respectively. The particle size distribution of all the mixtures was the same (Fig. 1).

Furthermore, three different types of recycled fibres were used: a recycled fibre from the textile production (TEX) provided by a local company, a recycled fibre composed by a blend of cellulose and recycled polymers (ECO) developed by the company Iterchimica and a pulp-shape recycled aramid fibre (PUL) provided by the company Teijin Aramid B.V. The physical properties and an image of these fibres are shown in Table 3 and Fig. 2, respectively.

2.2. Mixture design

Eleven mixtures have been produced. Two reference mixtures, one with a conventional penetration grade bitumen (REF) and one with a PMB (CONTROL), and nine experimental mixtures in which the amount and type of the recycle fibre and the amount of bitumen were varied. The target is to take advantage of the different characteristics of the fibres, from their ability to retain the binder until the possible increase in mortar strength. The nomenclature of the different designs was defined based on the type (TEX, ECO or PUL) and amount of fibre (0.05–0.4) in the mixture and the bitumen content (4.4 or 4.7). Additionally, in order to limit the length of the names, the fibre type was shortened to its first letter (T, E, P). Thus, the designed mixture T0.05/4.4 corresponds to an AC mixture with 0.05% TEX fibre and 4.4% bitumen content by weight of mixture. Table 4 details the different designs.

Based on previous experience (Slebi-Acevedo et al., 2020a, 2020b) and the data provided by the suppliers, different ratios of fibres were tested: in the case of the TEX and PUL fibres, the research was focused on trying to increase the strength of the mortar (although they also collaborate to retain the binder), while in the case of the ECO, the target was to increase their capacity to retain the binder (although they also collaborate to modify the properties of the bitumen because they contain different types of polymers). In order to do this, the mixtures designed with the same percentage of binder than the reference mixture are intended to analyse whether the fibres increase the resistance of the mortar, while the mixtures with a higher amount of bitumen are aimed at studying the binder retention capacity of the fibres. The control mixture represents the highest performance level due to the use of a PMB.

Table 1
Properties of aggregates.

Characteristics	Value	Standard
Ophite		
Specific Weight (g/cm3)	2.794	EN 1097-6
Los Angeles abrasion (%)	15	EN 1097-2
Flakiness Index (%)	<1%	EN 933-3
Polishing Value	60	EN 1097-8
Limestone		
Specific Weight (g/cm3)	2.724	EN 1097-6
Sand Equivalent	78	EN 933-8

Table 2
Properties of bitumen.

Characteristics	Value		Standard
	50/70	PMB 45/80-65	
Specific weight (g/cm3)	1.035	1.028	EN 15326
Penetration at 25 °C	57	55	EN 1426
Softening point (°C)	51.6	74.1	EN 1427
Fraass brittle point (°C)	−13	−16	EN 12593
Elastic recovery at 25 °C (%)	-	92	EN 13398

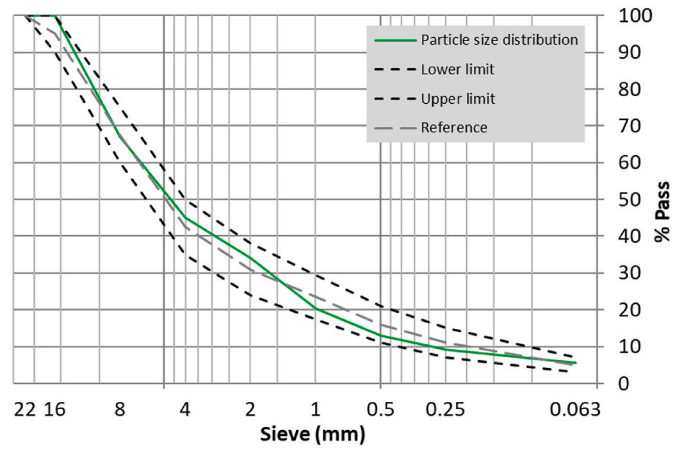

Fig. 1. Particle size distribution of the mixtures.

Table 3
Characteristics and properties of recycled fibres.

Fibre	Colour	Density (g/cm3)	Length (mm)	Diameter (mm)
TEX	Blue	1.24	9.93	0.16
ECO	Brown to black	0.25–0.45	4–12	4–6
PUL	Yellow	1.44	0.64–1.20	–

2.3. Sample preparation

FRAM are manufactured in a similar way to conventional mixtures except for the addition of fibres. Based on previous results (Slebi-Acevedo et al., 2022), the fibres are added at room temperature and directly to the mixing drum together with the aggregate fraction (dry-way). In the case of ECO fibres, the supplier itself specified the method of incorporation into the mix, which involved shredding the fibres before pouring them into the coarse aggregate fraction. However, in the case of TEX and PUL, this was not considered necessary. The aggregates and the fibres are mixed to get a homogeneous distribution of the fibres. From this point on, the process is the same in all the mixtures (reference and experimental): the fine fraction is added before the bitumen and the filler is added at the end. The manufacturing temperature was selected based on the specification of the bitumen: 150 °C for the mixture incorporating the 50/70 penetration grade bitumen and 165 °C for the mixtures with PMB. The mixing time for the production of FRAM was increased approximately in 2 min to ensure that no lumps were formed, which was visually checked.

3. Experimental work plan

Fig. 3 shows the methodology followed in this study. First, several mechanical properties were evaluated whose results fed a multi-criteria analysis, from which the best formulation was selected. A complete

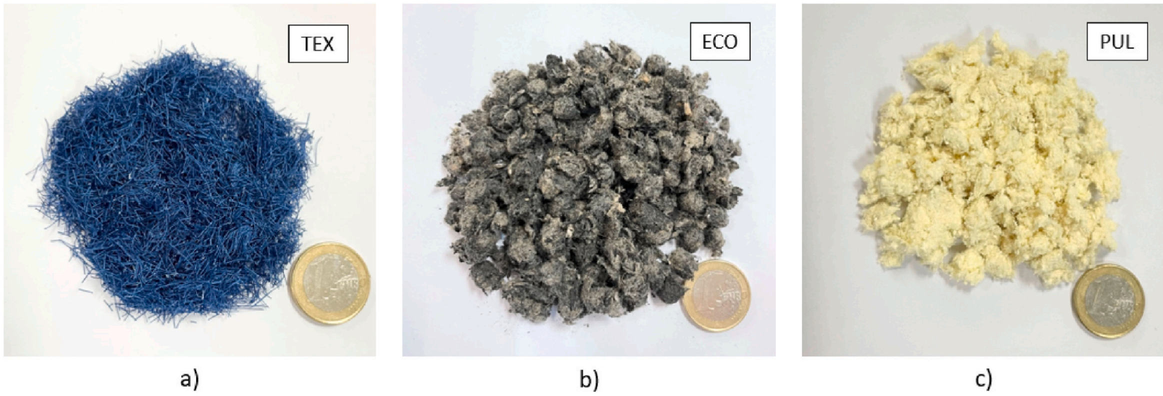

Fig. 2. Fibres used in the study: (a) Textil (TEX); (b) Ecofibra (ECO); (c) Aramid pulp (PUL).

Table 4
AC mixtures designs.

ID. Nº	Mixture design	Fibres		Bitumen	
		Type	Dosage (% b/w of mix)	Type	Dosage (% b/w of mix)
1	REF	–	–	50/70	4.4
2	CONTROL	–	–	45/80-65	4.3
3	T0.05/4.4	TEX	0.05	50/70	4.4
4	T0.08/4.4	TEX	0.08	50/70	4.4
5	T0.08/4.7	TEX	0.08	50/70	4.7
6	E0.2/4.4	ECO	0.20	50/70	4.4
7	E0.4/4.4	ECO	0.40	50/70	4.4
8	E0.4/4.7	ECO	0.40	50/70	4.7
9	P0.05/4.4	PUL	0.05	50/70	4.4
10	P0.08/4.4	PUL	0.08	50/70	4.4
11	P0.08/4.7	PUL	0.08	50/70	4.7

characterization of the selected formula was carried out next. All the results have been statistically analysed using Minitab and applying a 95% confidence interval (p-value 0.05). Depending on whether the distribution is normal and on the homogeneity of variances, T-student or Mann-Whitney tests were used.

3.1. *Mechanical properties tests*

The mechanical performance of the 11 formulas presented in Table 4 was assessed by conducting material property tests, namely void content (EN 12697-8), Marshall (EN 12697-34), wheel tracking test (EN 12697-22) and water sensitivity (EN 12697-12). For the first two tests, four cylindrical specimens (around 63.5 mm depth and 101.6 mm diameter) were compacted with 75 blows per side, according to the standard EN 12697-30. After measuring the voids and bulk density, they were placed in a water bath at 60 °C for 30 min to carry out the Marshall test. For the water sensitivity test, indirect tensile strength was measured at 15 °C in dry and wet conditions (8 specimens in total) by loading the specimens at a constant rate of 50 mm/min and measuring the peak strength to failure. Wet conditions were obtained by immersing the specimens in a water bath at 40 °C for 72 h prior to testing. In addition, cracking energy was evaluated via the indirect tensile strength test (EN 12697-23) in which the area under the curve formed by the Indirect Tensile Strength and the strain is measured (Fig. 4). The Fracture Energy (FE) (i.e. area until the peak) represents the cracking resistance, the Post-cracking Energy (PE) (area after the peak) is related to the crack propagation resistance and the total Cracking Toughness (CT) is the sum of both (Park et al., 2015; Slebi-Acevedo et al., 2020c). Finally, for the rutting test, two slabs (410 mm × 260 mm x 50 mm height) were compacted with the roller compactor and conditioned at 60 °C, the same temperature at which the test was carried out.

3.2. *Multi-criteria decision*

A multi-criteria decision-making was applied, in order to identify the best performing formula based on the results obtained in the different mechanical tests. Calculating and weighting the criteria is one of the most critical steps to get a meaningful result. To this end, the Entropy Weighting Method (EWM) based on objective weighting was applied, eliminating human intervention and overcoming the limitations of subjectivity (Wang et al., 2017) (Wang and Zhan, 2012). As for the MCDM method, the Weighted Aggregated Sum Product Assessment

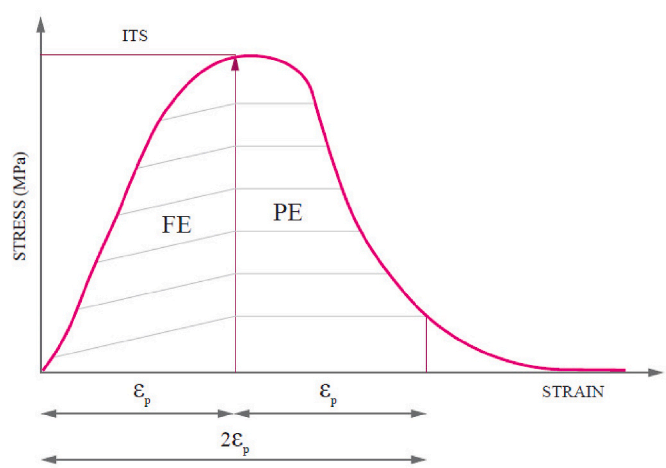

Fig. 4. Stress-strain curve recorded from ITS.

Fig. 3. Methodology followed for this study.

(WASPAS) (Zavadskas et al., 2012) that combines the Weighted Product Model (WPM) and the Weighted Sum Model (WSM) was used.

3.3. Complete characterization of the best mixture

Finally, the best performing formula was further assessed in terms of stiffness (UNE-EN 12697-26 – Annex B), fatigue resistance (UNE-EN 12697-24 – Annex D) and compactability (EN 12697-10). The compactability test was performed to analyse whether the addition of fibres requires higher levels of energy compaction. Consequently, three cylindrical specimens of 100 mm of diameter were manufactured using the gyratory machine. The stiffness modulus and fatigue strength were assessed using the four-point bending test in accordance with the above standards. A total of eight specimens per mixture were tested, each measuring 410 mm × 60 mm x 60 mm. The stiffness test was conducted at 20 °C under strain-controlled mode with a strain amplitude of 50 μm/m and the fatigue test at 20 °C using a frequency of 30 Hz in controlled strain mode, varying in a range of 100–350 μm/m the strain amplitude. These tests provide a complete picture of the mechanical performance of the residual fibre-reinforced asphalt mixture under the effect of dynamic loads.

4. Results and discussion

4.1. Mechanical properties tests

Bulk density, air void content and Marshall test results are shown in Table 5. The percentage of voids ranges 4–6% and, as expected, decreases with the addition of fibres and the increase in bitumen content. Based on this and on the results of Table 6, it seems that the addition of fibres does not excessively hinder the compaction of the samples while it significantly modifies the structure of the mixes when compared with the reference and control mixtures. The compaction is later verified with the compactability test done on the final mixture. Regarding the Marshall tests, no significant differences have been found on the strain values (Table 6) of the tested formulas. Apparently, the addition of the residual fibres and the increase in the binder content do not affect this parameter, which could indicate that the residual fibres are able to retain bitumen as all the mixtures have the same amount of filler and fine aggregates. However, there is a general tendency for stability to decrease with increasing fibre and bitumen content, especially in the case of ECO and PUL fibres. Likely, the coarse aggregates exhibit lower interlocking due to the addition of these materials. Comparing with the control mixtures with PMB, both the reference and experimental mixtures present a lower performance.

Table 5
Void content and Marshall test results.

Mixtures	Density [g/cm3]	Voids mixture [%]	Voids aggregates [%]	Stability [kN]	Flow [mm]
REF	2.431 ± 0.005	5.4 ± 0.2	15.7 ± 0.2	14.7 ± 1.4	3.5 ± 0.8
CONTROL	2.443 ± 0.008	5.4 ± 0.3	15.6 ± 0.3	18.1 ± 0.9	3.5 ± 0.4
T0.05/4.4	2.439 ± 0.012	5.1 ± 0.5	15.5 ± 0.4	13.9 ± 0.9	3.6 ± 0.7
T0.08/4.4	2.462 ± 0.007	4.2 ± 0.3	14.7 ± 0.2	12.8 ± 0.5	3.2 ± 0.4
T0.08/4.7	2.464 ± 0.007	3.8 ± 0.3	14.9 ± 0.2	14.0 ± 0.4	3.6 ± 0.9
E0.2/4.4	2.437 ± 0.011	5.2 ± 0.4	15.6 ± 0.4	13.6 ± 0.6	4.2 ± 1.6
E0.4/4.4	2.443 ± 0.004	5.1 ± 0.2	15.4 ± 0.2	12.2 ± 0.9	3.4 ± 0.7
E0.4/4.7	2.442 ± 0.006	4.7 ± 0.2	15.6 ± 0.2	12.4 ± 0.1	3.3 ± 0.6
P0.05/4.4	2.454 ± 0.009	4.5 ± 0.4	15.0 ± 0.3	14.1 ± 0.5	3.2 ± 0.3
P0.08/4.4	2.438 ± 0.007	5.1 ± 0.3	15.5 ± 0.2	16.0 ± 0.5	3.8 ± 0.5
P0.08/4.7	2.455 ± 0.007	4.2 ± 0.3	15.2 ± 0.3	12.0 ± 0.5	3.1 ± 0.2

Table 6
p-values from void content and Marshall test.

Mixtures	Voids mixture		Stability		Strain	
	REF	Control	REF	Control	Ref	Control
T0.05/4.4	0.67	0.40	0.39	0.00	0.42	0.90
T0.08/4.4	0.00	0.00	0.08	0.00	0.64	0.29
T0.08/4.7	0.00	0.00	0.31	0.00	0.84	0.90
E0.2/4.4	0.89	0.54	0.21	0.00	0.25	0.46
E0.4/4.4	0.04	0.12	0.03	0.00	0.49	0.82
E0.4/4.7	0.00	0.01	0.04	0.00	0.67	0.47
P0.05/4.4	0.01	0.01	0.47	0.00	0.65	0.23
P0.08/4.4	0.16	0.26	0.18	0.01	0.32	0.48
P0.08/4.7	0.00	0.00	0.03	0.00	0.72	0.12

Table 7 presents the Indirect Tensile Strength (ITS) results in both, dry and wet conditions, as well as the Indirect Tensile Strength Ratio (ITSR). Two experimental mixtures with ECO fibre present the best results with a similar performance than the control mixture with PMB in both, dry and wet conditions, with no statistical differences according to Table 8. As for the rest, in most cases, the incorporation of the residual fibre significantly improves the ITS and water sensitivity when comparing to the reference mixture with conventional bitumen, suggesting a positive effect of the residual fibres on these parameters. Finally, it is worth noting the performance of the T0.08/4.7, with an ITSR value lower than 80%, which a priori may seem a bad result. However, analysing individually the dry and wet ITS values in Tables 7 and 8 and it is observed that both are significantly better than those of the reference mixture. Therefore, despite its higher water sensitivity, the mix shows a good cohesion in both dry and wet conditions, being the low ITSR value attributable to the remarkable ITS value obtained in dry conditions.

Concerning the fracture properties, the FE, PE and CT results for all the mixtures are shown in dry and wet conditions in Fig. 5a and b, respectively. Generally speaking, the experimental mixtures reinforced with residual fibres outperform the reference mixture with conventional penetration grad bitumen in terms of FE, PE and CT. Significant differences in the performance of the experimental mixtures are obtained for all the mixtures with TEX and ECO fibres in terms of PE (see statistical analysis in Table 9). As for FE, only those mixtures with more bitumen and higher fibre content (and therefore a lower void content) present significant differences comparing to the reference mixture. Moreover, in the case of the TEX and ECO fibres, the addition of the fibre and the increase in the bitumen content present similar FE, PE and CT values than the control mixture with PMB both at dry and wet conditions, with no significant differences found in those mixtures with the highest fibre

Table 7
Water sensitivity test results.

Mixtures	ITS ^{Dry} [kPa]	ITS ^{Wet} [kPa]	ITRS [%]
REF	1725 ± 113	1594 ± 41	92
CONTROL	2006 ± 248	1907 ± 55	95
T0.05/4.4	1764 ± 36	1662 ± 121	94
T0.08/4.4	1993 ± 107	1725 ± 100	87
T0.08/4.7	2476 ± 119	1856 ± 88	75
E0.2/4.4	1860 ± 37	1730 ± 129	93
E0.4/4.4	1861 ± 63	1861 ± 46	100
E0.4/4.7	2042 ± 140	1893 ± 74	93
P0.05/4.4	1945 ± 101	1693 ± 18	87
P0.08/4.4	1829 ± 121	1785 ± 69	98
P0.08/4.7	2033 ± 61	1639 ± 82	81

Table 8
p-values from water sensitivity test.

Mixtures	ITS ^{Dry}		ITS ^{Wet}	
	Ref	Control	Ref	Control
T0.05/4.4	0.56	0.06	0.37	0.02
T0.08/4.4	0.02	1.00	0.09	0.03
T0.08/4.7	0.00	0.03	0.01	0.37
E0.2/4.4	0.11	1.00	0.14	0.07
E0.4/4.4	0.11	1.00	0.00	0.29
E0.4/4.7	0.02	0.81	0.00	0.77
P0.05/4.4	0.03	1.00	0.01	0.01
P0.08/4.4	0.26	0.31	0.01	0.04
P0.08/4.7	0.01	1.00	0.39	0.00

dosage shown in Table 9. Concerning this property, the addition of these waste fibres seems an alternative to PMB mixes. As for PUL fibres, the experimental mixtures outperform the reference mixture in the dry and wet conditions; however, the performance of the control mixture with PMB is not reached. Although the positive impact of the fibres addition is observed for both FE and PE, the improvement of the post-cracking energy is more evident, indicating a better resistance against the propagation of cracks. These results are consistent with previous researches (Abtahi et al., 2010; Saliani et al., 2021) suggesting that fibres give ductility to the mix, act as a barrier and prevent crack initiation and propagation.

Wheel tracking test results and their statistical significance are presented in Fig. 6 and Table 10, respectively. The addition of the residual fibres (TEX, ECO and PUL) improves the resistance to plastic deformation, comparing to the reference mixture in almost all the cases,

Fig. 5. Fracture properties. Dry conditions (a); wet conditions (b).

Table 9
p-values from energy properties.

Mixtures	Dry conditions				Wet conditions			
	Ref		Control		Ref		Control	
	FE	PE	FE	PE	FE	PE	FE	PE
T0.05/4.4	0.424	0.046	0.010	0.248	0.848	0.110	0.049	0.014
T0.08/4.4	0.003	0.001	0.197	0.649	0.001	0.009	0.344	0.863
T0.08/4.7	0.020	0.000	0.129	0.007	0.032	0.012	0.863	0.779
E0.2/4.4	0.525	0.037	0.005	0.002	0.036	0.939	0.022	0.000
E0.4/4.4	0.126	0.051	0.163	0.454	0.286	0.077	0.446	0.041
E0.4/4.7	0.008	0.005	0.100	0.212	0.004	0.005	0.599	0.135
P0.05/4.4	0.734	0.182	0.008	0.424	0.387	0.068	0.033	0.000
P0.08/4.4	0.882	0.106	0.003	0.092	0.508	0.463	0.036	0.001
P0.08/4.7	0.021	0.004	0.031	0.056	0.034	0.086	0.084	0.078

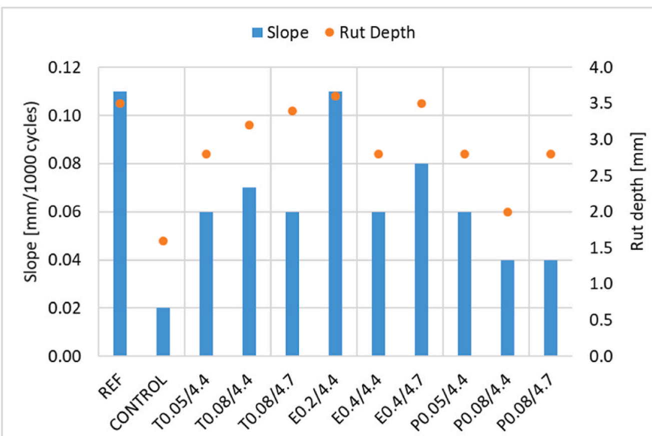

Fig. 6. Wheel tracking test results.

Table 10
p-values from wheel tracking test.

Mixtures	Slope	
	Ref	Control
T0.05/4.4	0.04	0.00
T0.08/4.4	0.08	0.03
T0.08/4.7	0.02	0.02
E0.2/4.4	0.56	0.00
E0.4/4.4	0.04	0.02
E0.4/4.7	0.11	0.00
P0.05/4.4	0.05	0.00
P0.08/4.4	0.02	0.06
P0.08/4.7	0.01	0.09

especially in those formulas with the highest fibre content. Particularly significant is the increase of the resistance to plastic deformation achieved by the mixtures incorporating PUL fibres. The two mixtures with the highest fibre content (0.08) reach similar results to the control mixture with PMB, since no significant differences in the results are obtained, according to Table 10. It has been suggested by other researchers (Kim et al., 2018; Slebi-Acevedo et al., 2022; Klinsky et al., 2018; Xu et al., 2010) that fibres stabilise mixtures at high temperatures, preventing the fluidity of the bitumen.

4.2. Selection of the best fibres according to multi-criteria analysis

Since the ranking of the tested formulas differs depending on the assessed mechanical property, for the selection of the best performed composition a multicriteria decision making method is recommended. The first step to apply the MCDM method is to determine the weights for the different criteria. The entropy weight method allows the weight of each of the criteria used in the decision-making process to be calculated objectively. Table 11 shows the criteria and the assigned weights based on the EWM. Based on this table, the criteria "slope" related to the resistance to plastic deformation is the one assigned with the highest weight. This is consistent with the fact that the introduction of fibres has a greater effect on resistance to plastic deformation than other properties. The criteria "Energy parameters" and "Marshall stability" follow "slope" in relevance, although with considerably lower weights. As for the "ITS" and "ITSR" criteria, their relative importance in the decision making is low since similar results are obtained by all the mixtures with no significant differences among them.

Once the weights are assigned, the next step is the ranking and the Joint Performance Score (JPS) determination with the WASPAS method (Fig. 7). The alternative with the highest JPS value is considered the optimal combination among all the experiments carried out in this study. According to the ranking in Fig. 7, all the waste fibre-reinforced asphalt mixtures fall between the reference and the control mixtures, meaning that the experimental mixtures present a better mechanical performance than the reference mixture with penetration grade bitumen but none of them reaches the performance of the mixture with PMB. Looking at the first 5 positions, the three fibres (T, E, P) are included. This means that the three analysed fibres could indistinctly be used to improve the mechanical behaviour of AC mixes. Nevertheless, the formulas P0.08/4.7 and P0.08/4.4 top the ranking of the fibre-reinforced asphalt mixtures, thanks to their outstanding results on the wheel tracking test. They are followed by the mixtures T0.08/4.7 and E0.4/4.4 both with high energy values which are related to a higher resistance to cracking and crack propagation. In addition, their resistance to plastic deformation is also fairly good, halving the slope compared to the reference mixture.

4.3. Compactness and dynamic performance

The purpose of this compactness test is to determine whether additional effort would be required to achieve the target density on site. Both the control mixture with PMB and the P0.08/4.7, with very similar results, require more energy to reach the same density as the reference mix (see Fig. 8). As mentioned before, other researcher (Kim et al., 2018; Slebi-Acevedo et al., 2022; Klinsky et al., 2018; Xu et al., 2010) indicated that fibres prevent the fluidity of the bitumen at high temperatures, which might be related to the slightly higher compaction energy needed by the experimental mixtures. On the other hand, the increase in the energy is limited, probably due to the higher bitumen content of the

Table 11
Weights assigned to each criterion.

Stability	Slope	ITS_{Dry}	ITS_{Wet}	ITRS	FE_{Dry}	PE_{Dry}	FE_{Wet}	PE_{Wet}
0.05	0.58	0.03	0.01	0.02	0.06	0.08	0.07	0.11

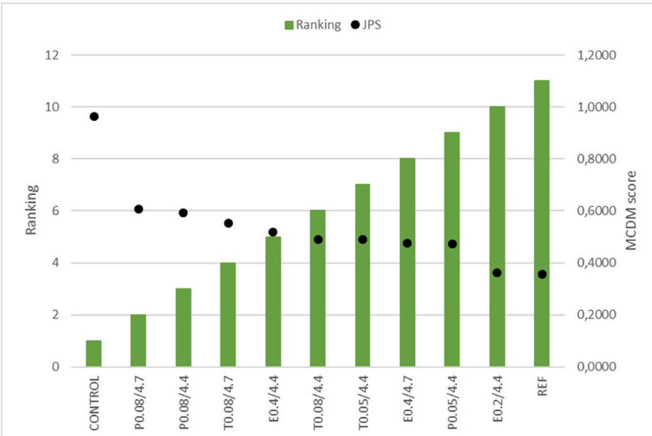

Fig. 7. Results and ranking of the alternatives with WASPAS method.

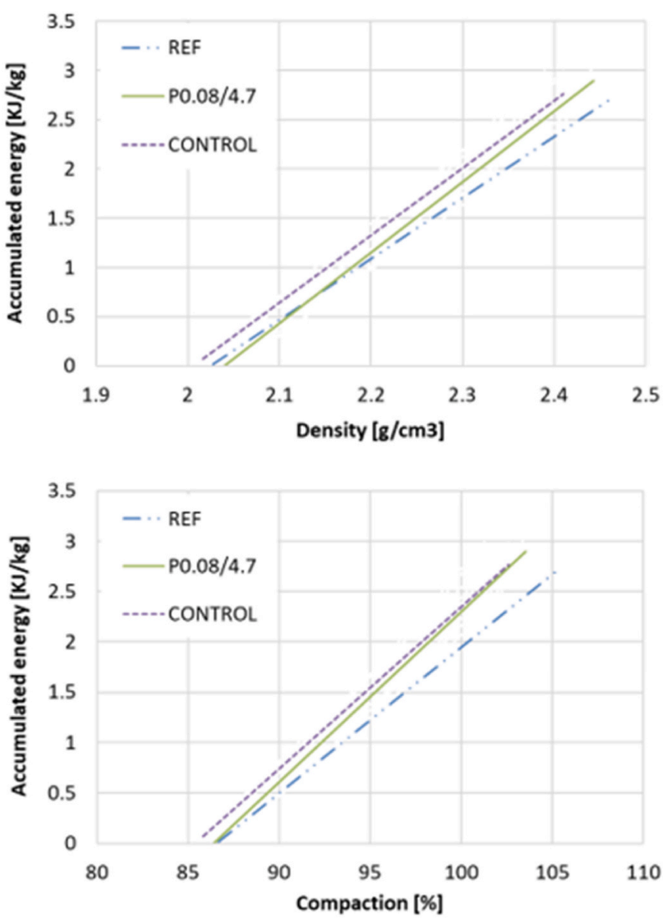

Fig. 8. Compaction energy of the final mixtures.

mixture and the small size of the PUL fibre which is well distributed throughout the mortar.

Once the mixture P0.08/4.7 was chosen through the MCDM, it was fully characterised by carrying out the compactness test and the stiffness and fatigue tests, whose results are shown below.

The dynamic performance in this work includes the evaluation of stiffness and the resistance to fatigue. These tests are key to understand the performance of the mixtures during their service life since these properties influence the transmission of loads among the pavement layers. In addition, both are simultaneously analysed because of the influence the stiffness has on the deformation and the fatigue damage in the mixture. The results of the dynamic modulus are shown in Table 12. FRAM with PUL fibre present slightly lower dynamic modulus and phase angle than the reference mixture probably because of the higher bitumen content that results in a less rigid mixture. Comparing the results with the control mixture with PMB, the dynamic modulus is substantially lower at frequencies lower to 1Hz and similar results are obtained at higher frequencies. As for the phase angle, the control mixture with PMB presents lower values at frequencies lower than 2Hz which is coherent with the higher elasticity of PMB.

Fatigue test results are shown in Fig. 9 and Table 13. In these tests, the failure criterion was defined as the cycle in which the dynamic module reaches half of its initial value. According to the results, the reinforcement of asphalt mixtures with PUL fibres does not improve their fatigue resistance. In this case, the impact of the fibres in terms of fracture energy or the higher amount of bitumen does not seem to correlate with the fatigue resistance. In any case, the fatigue resistance of both mixtures is satisfactory although it does not reach the performance of the control mixture with PMB, with a significantly higher fatigue resistance. These results are in good agreement with (Call 2017 New Materials FIBRA, 2021), in which the reinforcement of asphalt mixtures with fibres is evaluated in depth.

5. Conclusions

In this work, the reinforcing effect of three different types of recycled fibres in an AC mixture has been evaluated. After analysing the impact of the recycled fibres on the mechanical performance of the mixtures by performing different mechanical and dynamic tests, the following conclusions have been obtained:

- The feasibility of incorporating recycled fibres as an additive was demonstrated from the mechanical point of view. Based on the results, the best recycled fibre was 0.08% PUL, with the best mechanical performance.
- In general, the waste-fibre reinforced mixtures have better mechanical performance than the reference mixture, in some cases even reaching the performance of a control mixture. The main improvement is related to the increase in the resistance against plastic deformation.
- In terms of dynamic performance, the addition of recycled fibres to the asphalt mixture apparently does not result in any improvement in terms of stiffness and fatigue resistance.
- The incorporation of the recycled fibres does not require special technology or significant changes in the production process. However, to avoid the potential formation of clusters, the increase of the mixing time of the fibres with the aggregates is highly recommended.

This study advances in the analysis of the mechanical and dynamic performance of asphalt mixtures reinforced with recycled fibres. However, more research is needed to investigate their resistance to aging throughout their service life and their recyclability at the end of it. In addition, the economic and environmental feasibility, including the stable supply of the waste fibres must be ensured since they are key to support the future market of this technology as it is the mechanical performance assessed in this paper.

CRediT authorship contribution statement

Helena Miera-Dominguez: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Pedro Lastra-González:** Investigation, Formal analysis, Conceptualization, Methodology, Supervision, Writing – review & editing. **Irune Indacoechea-Vega:** Supervision, Project administration, Methodology, Writing – review & editing, Conceptualization. **Daniel Castro-Fresno:** Funding acquisition, Project administration, Supervision, Writing – review &

Table 12
Stiffness of the final mixtures.

Frequency (Hz)	REF		CONTROL		P0.08/4.7	
	Dynamic modulus (MPa)	Phase angle (°)	Dynamic modulus (MPa)	Phase angle (°)	Dynamic modulus (MPa)	Phase angle (°)
0.1	757	41.1	1012	29.5	693	40.0
0.2	1017	40.4	1226	29.4	930	38.8
0.5	1520	37.8	1618	29.1	1380	36.2
1	2048	36.3	2005	28.6	1829	35.5
2	2718	33.6	2475	27.8	2437	33.2
5	3788	29.5	3271	26.0	3357	25.0
10	4789	25.4	4013	24.3	4167	21.6

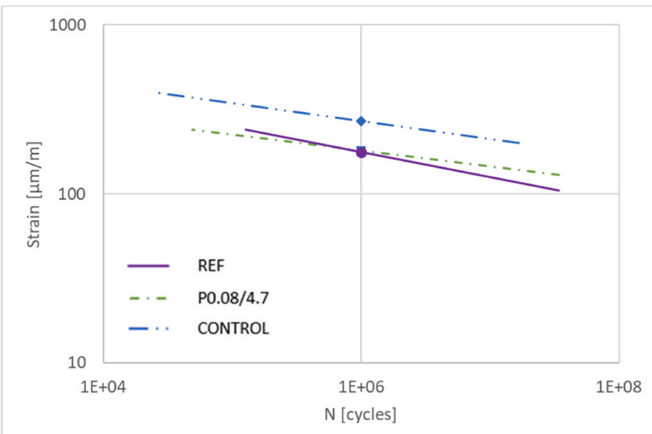

Fig. 9. Fatigue test results of the final designs.

Table 13
Fatigue laws of the asphalt concrete mixtures.

Mixture	Strain at 10^6 cycles	Fatigue line	R^2
REF	177.1	$\varepsilon\ (m/m) = 1.36\cdot10^{-3}\cdot N^{-0.148}$	0.97
P0.08/4.7	180.8	$\varepsilon\ (m/m) = 0.66\cdot10^{-3}\cdot N^{-0.094}$	0.95
CONTROL	270.3	$\varepsilon\ (m/m) = 1.19\cdot10^{-3}\cdot N^{-0.107}$	0.80

editing.

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.

Data availability

Data will be made available on request.

Fundings

This publication is part of the I+D+i project ASFIPLUS (PDC2022-133116-I00), financed by MICIU/AEI/10.13039/501100011033 and by the European Union Next Generation EU/PRTR. Also, this publication is part of the I+D+i project ASFIVAL (PID2019-110797RB-I00) funded by MICIU/AEI/10.13039/501100011033.

PRE2020-093516 assistance financed by MICIU/AEI/10.13039/501100011033 and FSE “FSE invests in your future”.

Acknowledgement

The authors gratefully acknowledge the support of CEPSA for providing the bitumen, Iterchimica S.p.A. for supplying the ecofibra and to Teijin Aramid B.V. for supplying the aramid pulp.

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