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Experimental evaluation and recyclability potential of asphalt concrete mixtures with polyacrylonitrile fibers

Carlos J. Slebi-Acevedo [a], Pedro Lastra-González [a], Daniel Castro-Fresno [a,*], Ángel Vega-Zamanillo [b]

[a] GITECO Research Group, Universidad de Cantabria, Avda. de Los Castros s/n., 39005 Santander, Spain
[b] GCS Research Group, Universidad de Cantabria, Avda. de Los Castros s/n., 39005 Santander, Spain

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ABSTRACT

Recently, the use of fibers has become an attractive option to be implemented as reinforcement in Asphalt Concrete (AC) mixtures. Nonetheless, few studies have been carried out to evaluate the recyclability potential of AC mixtures incorporating fibers. In this study, the reinforcing effect of polyacrylonitrile (PAN) fibers in AC mixtures is investigated. Air voids, Marshall stability, indirect tensile strength (ITS), moisture sensitivity, compactability, rutting, stiffness, and fatigue were the tests taken into consideration. In addition, bituminous mixtures manufactured with higher quantities of artificial reclaimed asphalt pavement containing PAN fibers (PANRAP) were evaluated experimentally. The results indicate that PAN fibers significantly increased the resistance to permanent deformation of the AC mixture. Improvements in ITS, moisture sensitivity and stiffness keeping the same fatigue life were also observed. In addition, a suitable performance was found in mixtures incorporating PANRAP in relation to control mix and remarkable increases in ITS, rutting, and stiffness were noted. The present investigation provides technical evidence of recycling AC mixtures with fibers up to 50% without the presence of rejuvenators.

1. Introduction

Flexible pavements play a crucial role in the social and economic development of any country since it facilitates the trade of goods and the transport of people. These infrastructures are popularly used in highways, airfield runways, and roads with low, medium, and high traffic providing safety and comfort to road users. Asphalt concrete (AC), which comprises binder, aggregates, and filler, is one of the most preferred bituminous mixtures to be used as a wearing course and designed to withstand the traffic loads generated by the passage of vehicles. However, given that each year the demand for higher and different load configurations increases as well as the constant temperature changes induced by global warming, this mixture is prone to present various types of failures, among the most mentioned fatigue cracking, rutting and moisture damage.

To deal with these distresses, many additives or modifiers, including polymers and polymer modified binders PMBs (e.g., styrene–butadienestyrene, styrene-butadiene rubber, and polybutadiene) have been implemented in AC mixtures to improve their durability properties. PMBs have gained attention since they improve the viscoelastic properties of the mixture [1,2]. Some polymers (elastomers) provide greater elasticity to the mixture, enhancing the fatigue resistance while others (plastomers) stiffen the mixture, enhancing the resistance to plastic deformations [3,4]. However, despite these benefits, the cost of these modifiers turns out to be so high that it makes them less attractive. Other drawbacks include higher mixing temperature releasing more pollutants to the environment, and segregation problems between the asphalt-polymer phases during high-temperature static storage or during transport to the pavement site [1].

Fibers appear as an alternative solution to improve the mechanical performance of AC mixtures [5,6]. In other construction materials such as reinforced Portland concrete, fibers act as a reinforcement replacing steel reinforcement bars [7]. In AC mixtures, the addition of fibers dates to 1970 [8]. Different types of fibers such as steel, organics (e.g., cellulose, sisal, jute), mineral (e.g., basalt), and synthetic fibers (e.g., aramid, polyester, polypropylene, carbon) have been used in hot mix

* Corresponding author.
E-mail addresses: carlosjose.slebi@unican.es (C.J. Slebi-Acevedo), lastragp@unican.es (P. Lastra-González), castrod@unican.es (D. Castro-Fresno), angel.vega@unican.es (Á. Vega-Zamanillo).

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asphalt [5]. Among the advantages of adding fibers, they are set mostly by dry method in the mix without the need to preheat them; therefore, no additional energy consumption is required. Besides, no specialized equipment in the plant is necessary for the production, storage, transportation or laying of the mixture. The amount of fibers added to the mix is generally low in comparison to the raw materials necessary for manufacturing traditional AC mixtures, moreover, large amounts could cause clustering. The main objective of adding fibers is to provide the mix with more tensile resistance and to bring more toughness increasing the strain energy during the processes of fatigue and fracture [9]. In another report it was observed that fiber reinforcement acts a barrier avoiding the formation and propagation of cracks [10]. Due to the above, outstanding benefits in terms of other properties such as rutting, cracking, moisture sensitivity, and tensile strength have been reported [10-13]. For instance, Park et al. [10] evaluate the reinforcing effect of adding steel fibers in AC mixtures through the indirect tensile test (ITT) experimentally. Indirect tensile strength and fracture parameters such as fracture energy, post-cracking energy, and toughness were calculated from the tests. Based on their experimental results, the authors reported significant improvements in the cracking resistance of fiber reinforced asphalt concrete (FRAC) mixtures at low temperatures adding the optimal content of steel fibers. Serin et al. [8] also analyzed the reinforcing effect of steel fibers in AC mixtures employing the Marshall stability test. The authors concluded that the best results were attained with an optimal binder content of 5.5% and 0.75% of steel fibers. In a broader study, Kim et al. [12] investigated the reinforcing efficiency of adding different types of synthetic fibers (i.e., Nylon, Polyester, Polypropylene, Carbon) in AC mixtures. Various tests, including Marshall Stability, voids, indirect tensile strength, moisture sensitivity, dynamic stability, and flexural strength, were performed. According to results, the authors reported that 0.1% of 12 mm long nylon fibers improve the mechanical performance of the mixture for all test parameters except for the dynamic stability. In a similar study Xu et al. [14] added polyester, polyacrylonitrile, lignin, and asbestos fiber additives to the AC mixture. A fiber concentration of 0.3% was kept as constant in the reinforced specimens with the different types of fibers. Fiber-reinforced AC mixtures with synthetic fibers (polyester and polyacrylonitrile) showed more outstanding performance in tensile strength, rutting and fatigue cracking than lignin and asbestos fibers. Due to the remarkable networking effect, synthetic fibers are more recommended as a reinforcement while organic fibers are suggested to stabilize binder due to the greatest surface area of the fiber [14]. At the asphalt binder scale, the use of the same fibers was also studied. Chen and Xu [15], based on their experiments, concluded that fibers improve the asphalt binder properties such as dynamic shear modulus, rutting, and resistance to flow. In the same way, lignin and asbestos fibers have more significant asphalt absorption function while polymer fibers show greater networking function. Experimental results carried out by Liyang et al. [16] in dynamic shear rheometer indicated that polyacrylonitrile fibers might increase the stability of asphalt binders at high temperatures. In hot mix asphalt, better improvements in resistance to water damage were reported adding PAN fibers instead of methylcellulose fibers. Kaloush et al. [13] assessed the mechanical properties of a modified AC mixture with a set of synthetic fibers (i.e. Polyolefin and aramid). Stiffness, permanent deformation, tensile strength, fracture energy and cracking test parameters were recorded. Based on their experimental results, the authors indicate that fiber reinforced AC mixture presented an increment of 25–50% and 50–75% for the tensile strength and fracture energy, respectively. In porous asphalt and stone matrix asphalt mixtures, cellulose organic fibers work very well as good binder drain down inhibitors [17]. These fibers are commonly used due to their low relative cost, wide availability in the market, biodegradability and because they are not a threat to human health [18].

Polyacrylonitrile fiber belongs to the group of synthetic fibers whose synthesis is done by the polymerization of acrylonitrile [19]. In the scientific literature, PAN fiber (as it is also known) is popular for being the main precursor of high-performance carbon fibers [20]. PAN fibers have high tensile modulus, high chemical resistivity, high thermal resistance, and low density, and hence they are a desirable material in many industries like automotive and aerospace applications [21]. In pavement engineering, there are still gaps in the literature concerning the use of polyacrylonitrile fibers in bituminous mixtures. Therefore, in this research, a complete experimental plan was developed to evaluate the mechanical properties of polyacrylonitrile fibers as reinforcement of asphalt concrete mixtures. Accordingly, different parameters, including Marshall Stability, voids, indirect tensile strength, fracture properties, moisture sensitivity, modulus, permanent deformation, and fatigue life, were calculated.

In addition, hot mix asphalt recycling goes one step further in the development of sustainable pavements structures. The use of novel additives in the asphalt concrete will become a normal practice and, as a result, the evaluation of the potential recyclability of these modified mixes is necessary. Recently, some studies have analyzed the performance of hot mix asphalt incorporating reclaimed asphalt pavement (RAP), warm mix asphalt additives, rejuvenators and even fibers as a reinforcement [22-26]. However, few research efforts have been made in the evaluation of the recyclability potential of FRAC mixtures. It is well understood that the recycling of asphalt pavements is becoming increasingly important in the sustainable and economic development of the countries. In that sense, the incorporation of high percentages of RAP in new bituminous mixtures supposes a decrease in the consumption of virgin natural resources and savings in the costs related to the transportation of raw materials to the plant sites [27]. A reduction of energy, gas emissions, carbon footprint, and fuel consumption during the utilization of new natural aggregates and virgin asphalt as well as the reduction in the extraction of nonrenewable resources are other benefits from the environmental point of view [23,27,28]. Therefore, as a complement of this study, control and a reinforced AC concrete mixture with a high percentage of recycled FRAC mixtures (50%) were also experimentally tested and analyzed. Thus, it is being verified that the use of these auspicious composite mixtures in the production of new mixtures can be potentially recycled and so, that they may be reused. Finally, a comparative analysis regarding the mechanical properties among all the mixture was carried out.

2. Materials and methods

2.1. Raw materials

Conventional 50/70 penetration grade bituminous binder was used for the preparation of AC mixtures. The main physical characteristics according to provider are shown in Table 1. Ophite (porphyry igneous rock) with a maximum nominal size of 16 mm was used as coarse aggregate fraction while limestone was utilized as filler and fine aggregate fraction. The main physical characteristics and the limits of the Spanish standard for the highest traffic level are given in Table 2. Fig. 1 presents the particle size distribution used in this study which is commonly applied as wearing course in Spain.

Polyacrylonitrile, also known as PAN fibers, as said before, was added to the AC mixture as a reinforcement. A detailed description of the basic physical characteristics and an illustration of the appearance of these fibers can be observed in Table 3 and Fig. 2**,** respectively.

Table 1
Main physical characteristics of 50/70 penetration graded binder.

Characteristic	Standard	Value	Limits
Specific weight (g/cm^3)	EN 15,326	1.035	–
Penetration at 25 °C (dmm)	EN 1426	57	50–70
Softening point (°C)	EN 1427	51.6	46–54
Fraass breaking point (°C)	EN 12,593	−13	≤ − 8

Table 2
Main physical characteristics of aggregates.

Characteristic	Value	Standard	Limits
Coarse Aggregate			
Specific Weight (g/cm^3)	2.794	EN 1097-6	–
Water absorption (%)	0.60	EN 1097-6	< 1%
L.A abrasion (%)	15	EN 1097-2	≤ 15%
Slab Index (%)	< 1%	EN 933-3	≤ 20%
Polishing Stone Value	60	EN 1097-8	≥ 50
Fine Aggregate			
Specific Weight (g/cm^3)	2.724	EN 1097-6	–
Sand Equivalent	78	EN 933-8	> 55

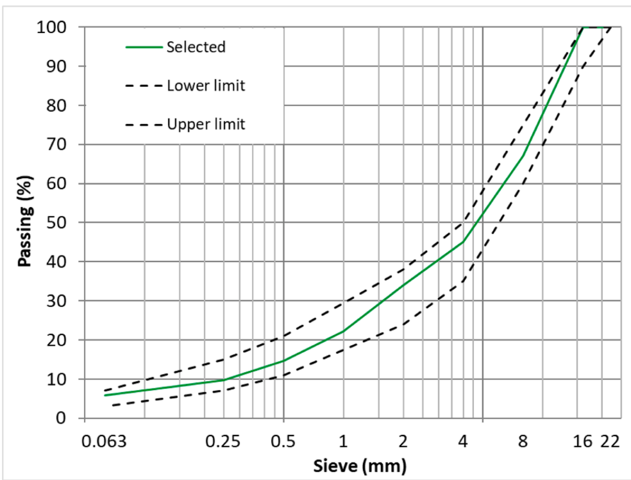

Fig. 1. Particle size distribution of the AC mixtures.

Table 3
Basic physical characteristics of PAN fibers.

Fiber	Polyacrylonitrile
Form	Staple fibers
Color	Bright straw-yellow gold
Density (g/cm3)	1.18
Length (mm)	4
Tenacity (MPa)	> 708
Elastic modulus (MPa)	16,500
Elongation at break (%)	< 13
Diameter (mm)	0.0127

Fig. 2. PAN fibers.

2.2. Artificial RAP

To analyze the potential recyclability of FRAC mixtures, artificial RAP with PAN fibers (PANRAP) was manufactured. To this purpose, a modification of the AASHTO R30 standard was carried out. According to the standard, the loose mixture is initially placed in the oven at 135 °C for 4 h to simulate the short-term oven aging (STOA). Then the mixture is compacted and placed in the oven for 120 h at 85 °C to simulate the long-term oven aging performance (LTOA). However, in this study, the LTOA procedure was also performed with the loose mixture stirring the mix twice daily. The grading and the percentage of asphalt binder on the artificial RAP was the same one that was used to produce the control and FRAC mixtures. To evaluate the aging effect of the binder, part of the bitumen was extracted by centrifuge device and rotary evaporator (EN 12697 – 3) and subjected to penetration (EN 1426) and softening point (EN 1427). The properties of the residual binder can be seen in Table 4.

In bituminous mixtures with high RAP contents, the use of rejuvenators contributes to recover the initial properties of the aged binder by restoring their chemical components as the maltenes, mainly [27]. In the same way, these products facilitate the blending process between the aged bitumen and the new virgin bitumen added to the mix [28]. However, in this research, to avoid adding more control variables and try to apply the simplest process, a softer 70/100 penetration grade binder with penetration and softening point of 73 dmm and 48.5 °C, respectively, was chosen to be mixed with the residual mixture. Previous researches suggest the possibility to compensate the chemical components of the stiffen binder by the aging, combining with a softer bitumen [29].

2.3. Mixture designs and sample preparation

Control AC mixture was prepared in accordance with the technical specifications listed in the general technical prescription manual for roadways of Spain [30]. The optimum asphalt content for control mixture was determined at 4.30% by weight of mixture with a voids content of 5.10%. For AC mixtures a range of voids between 4.00 and 6.00% is appropriate to be used as wearing course. The fiber modified asphalt concrete mixture was obtained by adding 0.15% of PAN fibers by total weight of the mixture. The binder content was kept as a constant with the intention to analyze the reinforcing effect of the fiber. Previous investigations have suggested that in FRAC mixtures it is necessary to increase the optimal binder content given the absorption rate that fibers have [15]. Therefore, in this research, another experimental FRAC mixture was performed with a binder content of 4.60%. To produce the mixtures, 4 mm long PAN fibers were added to the mix by dry method. In that sense, fibers were added to hot aggregates previously heated at 175 °C and mixed thoroughly until a good dispersion of the fibers in the aggregates was achieved. Then, the binder was kept at 150 °C and mixed continuously until the set was properly covered by the binder.

To prepare AC mixtures with 50% of recycled FRAC mixtures, first, artificial RAP with fibers (PANRAP) was heated in the oven at 110 °C for 2 h prior to the mixing process. Meanwhile, the remaining 50% of the new mixture was prepared as described in the previous paragraph. However, in this case a softer 70/100 penetration grade binder was used instead of the 50/70 penetration grade binder. Finally, both sets of mixtures (i.e., 50% of artificial RAP and 50% of new mixture) were mixed together at 145 °C until a completely homogeneous mixture was achieved. A total of five experimental designs were developed in this study. To clarify better all mixtures, the summary of the five designs is

Table 4
Characteristics of the aged binder in the PANRAP.

Characteristic	Standard	Value
Penetration at 25 °C (dmm)	EN 1426	18
Softening point (°C)	EN 1427	71.4

Table 5
Experimental designs.

Mixtures ID	Natural RAP-aggregates distribution (%)		Fiber percentage contribution (%)		Type of binder used		Asphalt content (%)	
	Natural	PANRAP	New	PANRAP	Virgin	PANRAP	Virgin	PANRAP
Control	100	–	–	–	50/70	–	4.30	–
FRAC1	100	–	0.15	–	50/70	–	4.30	–
FRAC2	100	–	0.15	–	50/70	–	4.60	–
Control-PANRAP	50	50	0	0.075	70/100	50/70	2.50	2.15
FRAC-PANRAP	50	50	0.075	0.075	70/100	50/70	2.50	2.15

given in Table 5.

2.4. Experimental tests

2.4.1. Air voids and Marshall Stability

Marshall cylindrical specimens were compacted by applying 75 blows per side following the European standard EN 12697 – 30. After twelve hours of cooling, the bulk density and air voids were determined according to European standard EN 12697 – 8 [31]. Then, the samples were placed in a water bath at 60 °C during 30 min, and the flow and Marshall Stability parameters were also recorded. Four replicates per each experimental design were done.

2.4.2. Indirect tensile strength and moisture sensitivity

To evaluate the sensitivity characteristics of the AC mixtures to water damage, the water sensitivity test was performed following the European standards EN 12697 – 12 [32]. First, the indirect tensile strength (ITS) was measured in both dry and wet conditions (ITS_{dry} and ITS_{wet}) by loading the specimens diametrically across the circular cross-section at a constant rate of 50 mm/min and measuring the peak strength to the failure. To prepare the mixtures in wet conditions, the samples were immersed in a water bath at 40 °C for 72 h before carrying out the test. The moisture susceptibility is assessed by calculating the indirect tensile strength ratio (ITSR) using the following formula. The ITS of both groups of samples was performed at 15 °C.

$$ITSR(\%) = \frac{ITS_{wet}}{ITS_{dry}} \times 100\% \quad (1)$$

In the same way, the stress–strain curves of each one of the specimens in both dry and wet conditions were recorded as shown in Fig. 3. The test was performed until the strain achieved at the peak of maximum stress was achieved twice ($2\varepsilon_p$) or until the specimens were completely split in two pieces. Fracture energy (FE); post-cracking energy (PE) and toughness as the sum of FE and PE were calculated from the graph (see Fig. 3). Previous investigations argue that FE is a good indicator of the cracking resistance prior to the failure while PE gives an idea of the ductility of the mixture and the resistance to crack propagation [33]. For this test, a total of eight cylindrical specimens compacted by 50 impacts on each side were prepared for each mixture design. Four of them were tested in dry conditions while the remaining four underwent wet conditions.

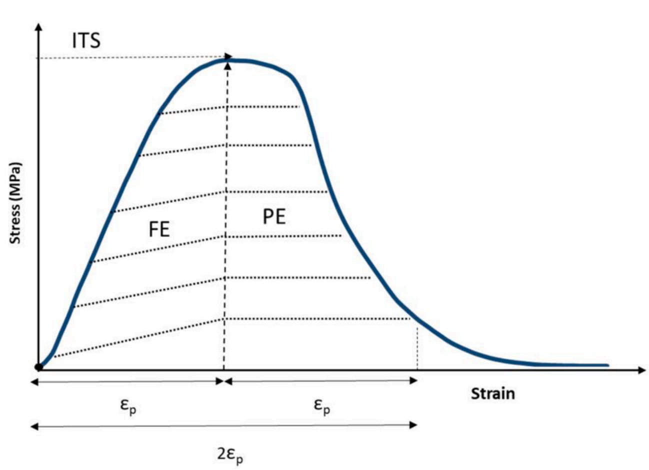

Fig. 3. Stress–strain curve recorded from ITS.

2.4.3. Rutting resistance

The wheel tracking test was adopted to evaluate the rutting resistance of the AC mixtures following the European Standards EN 12697 – 22 [34]. The rolling compacting machine was chosen to compact the specimens. A total of three replicates of rutting slabs (410 mm × 260 mm × 50 mm height) were manufactured per bituminous mixture. According to the standard protocol, the conditioning of the sample as well as the test temperature are performed at 60 °C.

2.4.4. Energy of compaction

Following the European Standard EN 12697 – 10 [35], the compactability test was performed to analyze whether the addition of fibers or artificial RAP requires higher levels of energy compaction. Therefore, cylindrical specimens of 100 mm of diameter were manufactured using the gyratory machine. The test was done in three replicates per experimental design applying a load pressure of 600 kPa, inclination angle of 0.82°, and a rotation speed of 30 rpm. The following equation proposed by del Rio [36] was used to calculate the accumulated energy:

$$\frac{\frac{W}{m} = \sum_{1}^{N} \frac{W_i}{m} = 2 \cdot \pi \cdot \alpha \cdot A}{m \sum_{1}^{N} h_i \cdot S_i} \quad (2)$$

Where W is the compaction energy in kJ; m is the mass in kg; N is the total number of cycles applied; α is the angle of inclination of the cylindrical specimen in *rad*; A is the transverse area of the specimen in m^2; h_i is the sample height of i^{th} cycle in m; S_i is the shear stress of i^{th} cycle in kN/m^2.

2.4.5. Stiffness and fatigue resistance

The stiffness modulus and fatigue resistance of AC mixtures was evaluated by means of the four-point bending test according to the European Standards EN 12697 – 26 (Annex B) [37] and EN 12697 – 24 (Annex D) [38], respectively. Prismatic specimens whose dimensions are 410 mm × 60 mm × 60 mm were obtained by cutting asphalt concrete slabs of 80 mm height. For both tests, a total of eight specimens per mixture design were performed. The stiffness test was conducted at 20 °C under strain-controlled mode with a strain amplitude of 50μ m/m. The modulus and the phase angle of different frequencies, starting from 0.1 Hz to 30 Hz were recorded directly from the testing apparatus. Fatigue test was conducted at 20 °C, applying a frequency of 30 Hz under strain-controlled mode. The strain amplitude varied in a range from 100 to 350μ m/m. From this test, the main test parameters attained were the strain at one million cycles and the fatigue law with the following equation:

$$lnN = C_1 - C_2 ln\varepsilon \quad (3)$$

Where N is the number of loading cycles for a given level of strain ε (μm/

m); *C1* and *C2* are the fatigue constants.

2.5. Statistical analysis

The Minitab software was applied to assess the significance level obtained from the addition of fibers and the recyclability potential of FRAC mixtures. Therefore, the normality of data and the homogeneity of variance among the experimental mixtures were initially checked through the Anderson-Darling and the Levene statistical test, respectively. Parametric tests were performed in those cases where data was normally distributed and has presented homogeneity of variance. Otherwise, non-parametric tests were applied. A confidence level of 95% and a significance level of 5% were considered for the statistical analysis. Table 6 summarizes the statistical tests employed.

3. Results and discussion

3.1. Bulk density and air voids

The results concerning the bulk density and the air voids are presented in Table 7. In the same way, the Marshall test was applied to the specimens once the volumetric properties were calculated. Accordingly, the Marhsall Stability, flow, and Stability/flow coefficient values were recorded as shown in Table 7. All the mixtures have air voids contents between 4.0% and 6.0%, which is suitable for AC mixtures to be used as surface layer. However, the FRAC1 mixture design presented an air void content of 6.17%. This could be due to fibers make the compaction more difficult. To check statistical differences among the mixtures, 2 sample-t tests were performed as all mixes were normally distributed and presented homogeneity of variance (see Table 8). Based on the results, there is a statistical difference between the control mixture and FRAC1 mixture, suggesting that the addition of fibers could increase the voids inside the mix. Similarly, mixtures prepared with PANRAP showed lower values of air voids being statistically significant. However, despite of these changes in terms of voids, not statistical differences were found in Marshall Stability as well as the flow for all mixtures.

3.2. Indirect tensile strength and moisture sensitivity results

The ITS results of both dry and wet conditions, as well as ITSR, are depicted in Fig. 4. All mixtures showed ITSR values of approximately 90%, complying with the requirements established in the Spanish regulations which suggest an ITSR higher than 85%. Accordingly, the damage by the action of water was not deemed a big concern for any type of mixture. It is worth mentioning that it is convenient to analyze the ITS results separately, since the ITSR only measures the ratio of the wet to dry strength. Despite not having observed significant differences (see Table 9), FRAC1 mixture did not show notable changes in the ITS values in comparison to control mixture meanwhile the FRAC2 mixture presented slight increments of 8.90% and 8.43% in the ITS_{dry} and ITS_{wet} respectively, even when FRAC1 has a significantly higher percentage of voids. On the other hand, Control-PANRAP and FRAC-PANRAP mixtures reached improvements of 34.73% and 54.41% over the ITS_{dry} values and notable variations of 29.64% and 47.41% in the ITS_{wet} response being statistically significant as shown in Table 9.

The results of fracture properties are displayed in graph form in Fig. 5. The trend was similar to the observed in ITS values; not significant changes were noted in fracture properties obtained from specimens conditioned in both dry and wet conditions between control and FRAC1 mixtures, which is a good result if we take into consideration the higher percentage of voids of this experimental sample. With respect to the FRAC2 mixture, higher values in all fracture properties were registered. However, only PE energy and toughness in dry conditions were the statistically significant responses, as shown in Table 9. Regarding mixtures that incorporate PANRAP, the increment in fracture properties was relatively higher in comparison to the Control mixture. The toughness measured in both dry and wet specimens increased by 47.93% and 17.64%, respectively, in the CONTROL-PANRAP mix when compared to the control mixture. In the same way, the FRAC-PANRAP mixture performs well, giving the highest values of fracture properties among all the experimental designs.

Table 6
Parametric and non-parametric tests.

Data	Parametric tests	Non-parametric tests
2 groups	2 samples *t*-test	Mann-Whitney test
k groups	One way Anova/ Tukey	Kruskall Whallis test

The higher values of ITS in the mixtures prepared with PANRAP could be attributed to the increment in the stiffness of the mixes due to PANRAP, despite the soften penetration grade binder used. This result ties well with previous studies wherein asphalt mixtures manufactured with RAP contents had a superior tensile strength than conventional mixtures without RAP [39]. Regarding fracture properties, the common belief is that the more RAP content, more brittle the mixture becomes. Nevertheless, it could be expected that the fiber reinforcement and the addition of a softer binder have a positive influence on the fracture behavior of the mixture.

Previous investigations suggest that fibers bring ductility to the mix, acting as a barrier and preventing the formation and propagation of cracks [6]. Due to the aging process, part of the mixture turned more brittle. However, the results showed greater growth in the fracture properties suggesting that fibers could have meaningful participation in the interlocking effect of the aggregate-binder matrix even in the aged conditions. The manufacturing of AC mixture incorporating high PANRAP content seems not to be a problem when evaluating the fracture properties of the specimens. In the same way, a new modified fiber-reinforced AC mixture can be manufactured, incorporating 50% PANRAP obtaining positive results in indirect traction and fracture performance.

3.3. Rutting

The rutting test is quite useful for evaluating the performance of the AC mixture when exposed to high temperatures. Fig. 6 displays the results obtained from the wheel tracking test. From the test, the linear slope or rate of deformation (mm/1000 cycles) after 5000 cycles was calculated per each mixture as well as the rut depth (mm) once 10.000 load cycles were applied. According to Anderson-Darling normality test, all results were normally distributed, and therefore two samples *t*-test were done to check statistical differences with respect to the control mixture (see Table 10). FRAC1 and FRAC2 mixtures depicted remarkable improvements in both the slope and rutting depth in comparison to the control mixture being statistically significant (Table 10). Lower values of the slope and rut depth indicate better stability of the mix and more resistance to the flow force [14]. Accordingly, FRAC1 and FRAC2 showed improvements of 75% in the slope and a reduction of 39.65% and 30.90% in the rut depth in relation to the control mix. Despite the slight increase in the binder content of FRAC2 mixture over the FRAC1 mixture, there were not significant differences in both slope and rut depth. As suggested by other researches [12,14,40], fibers contribute to stabilize the mixture at high temperatures avoiding the fluidity of the bitumen, which could be also linked with the higher compaction energy required by the experimental mixtures.

Regarding mixtures manufactured with PANRAP, they also performed well, giving good results in the resistance to permanent deformation as compared to the control mixture. Control-PANRAP mixture displayed reductions of 58.33% and 32.94% in the slope and rut depth, respectively. However, only the slope was statistically significant. Meanwhile, FRAC-PANRAP mixture presented notable improvements of 75.00% and 47.52% in both the slope and permanent deformation, respectively. Since the PANRAP component of the mixture is aged, part

Table 7
Bulk density and air voids results.

Bulk density and voids EN 12697–8	Units	Control		FRAC1		FRAC2		Control-PANRAP		FRAC-PANRAP	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Density	g/cm3	2.45	0.01	2.42	0.00	2.43	0.00	2.45	0.01	2.45	0.01
Voids in mixture	(%)	5.10	0.36	6.17	0.10	5.58	0.16	4.41	0.27	4.47	0.20
Voids in aggregates	(%)	15.29	0.32	16.29	0.09	16.42	0.14	13.49	0.25	13.55	0.19
Marshall Stability	kN	15.75	0.85	16.23	0.70	15.91	0.53	15.56	0.64	14.73	0.67
Flow	mm	3.80	0.28	4.23	0.61	4.74	0.61	3.32	0.52	3.39	0.17
Stability/flow coefficient	kN/mm	4.10	0.50	3.90	0.55	3.39	0.36	4.78	0.75	4.35	0.29

Table 8
p-Values and statistical significance from density, voids, and Marshall test.

	Density (g/cm^3)				
	Control	FRAC1	FRAC2	Control-PANRAP	FRAC-PANRAP
P - value	–	0.01	0.01	0.424	0.28
Significance	–	YES	YES	NO	NO
	Voids in the mixture (%)				
	Control	FRAC1	FRAC2	Control-PANRAP	FRAC-PANRAP
P - value	–	0.01	0.07	0.028	0.039
Significance	–	YES	NO	YES	YES
	Voids in aggregates (%)				
	Control	FRAC1	FRAC2	Control-PANRAP	FRAC-PANRAP
P - value	–	0.01	0.00	0.00	0.00
Significance	–	YES	YES	YES	YES
	Marshall Stability (kN)				
	Control	FRAC1	FRAC2	Control-PANRAP	FRAC-PANRAP
P - value	–	0.42	0.67	0.742	0.118
Significance	–	NO	NO	NO	NO
	Flow (mm)				
	Control	FRAC1	FRAC2	Control-PANRAP	FRAC-PANRAP
P - value	–	0.27	0.05	0.179	0.068
Significance	–	NO	NO	NO	NO
	Stability/flow coefficient (kN/mm)				
	Control	FRAC1	FRAC2	Control-PANRAP	FRAC-PANRAP
P - value	–	0.50	0.05	0.238	0.562
Significance	–	NO	NO	NO	NO

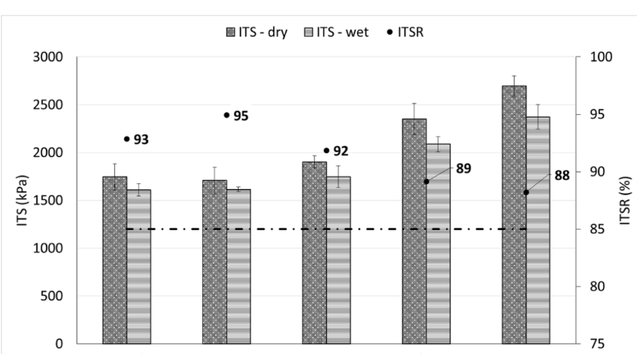

Fig. 4. Indirect tensile strength and moisture sensitivity results.

of the bitumen became stiffer increasing the rutting resistance. These results provide good evidence of the recyclability potential of mixtures prepared with fibers incorporated in virgin mixture in terms of permanent deformation. Similarly, virgin mixture with fibers and high PANRAP content showed high performance in the rutting resistance.

Table 9
P-values and statistical significance from ITS and moisture sensitivity results.

	ITS_{dry} (kPa)				
	Control	FRAC1	FRAC2	Control-PANRAP	FRAC-PANRAP
P - value	–	0.71	0.11	0.00	0.00
Significance	–	NO	NO	YES	YES
	ITS_{wet} (kPa)				
	Control	FRAC1	FRAC2	Control-PANRAP	FRAC-PANRAP
P - value	–	0.89	0.11	0.03	0
Significance	–	NO	NO	YES	YES
	ITSR (%)				
	Control	FRAC1	FRAC2	Control-PANRAP	FRAC-PANRAP
P - value	–	0.76	0.88	0.61	0.51
Significance	–	NO	NO	NO	NO
	FE_{dry} (kPa)				
	Control	FRAC1	FRAC2	Control-PANRAP	FRAC-PANRAP
P - value	–	0.92	0.10	0.01	0.00
Significance	–	NO	NO	YES	YES
	PE_{dry} (kPa)				
	Control	FRAC1	FRAC2	Control-PANRAP	FRAC-PANRAP
P - value	–	0.56	0.03	0.00	0.00
Significance	–	NO	YES	YES	YES
	$Toughness_{dry}$ (kPa)				
	Control	FRAC1	FRAC2	Control-PANRAP	FRAC-PANRAP
P - value	–	0.65	0.05	0.00	0.00
Significance	–	NO	YES	YES	YES
	FE_{wet} (kPa)				
	Control	FRAC1	FRAC2	Control-PANRAP	FRAC-PANRAP
P - value	–	0.09	0.19	0.09	0.03
Significance	–	NO	NO	NO	YES
	PE_{wet} (kPa)				
	Control	FRAC1	FRAC2	Control-PANRAP	FRAC-PANRAP
P - value	–	0.49	0.89	0.108	0.01
Significance	–	NO	NO	NO	YES
	$Toughness_{wet}$ (kPa)				
	Control	FRAC1	FRAC2	Control-PANRAP	FRAC-PANRAP
P - value	–		0.19	0.09	0.01
Significance	–	NO	NO	NO	YES

3.4. Energy of compaction

The compactability results of the mixtures can be observed in Fig. 7. For a given density level, it is seen that the required accumulated energy is greater in the case of fiber-reinforced asphalt concrete mixtures. However, to be more precise and to seek the statistical differences, parametric tests were carried out since the data obtained from the test followed a normal distribution, although no significant differences were noted among all mixtures in terms of voids. The addition of fibers slightly increased the energy required to compact the specimens. Besides, not significant differences were observed between FRAC1 and FRAC2 mixtures, even though the FRAC2 mixture has a higher bitumen

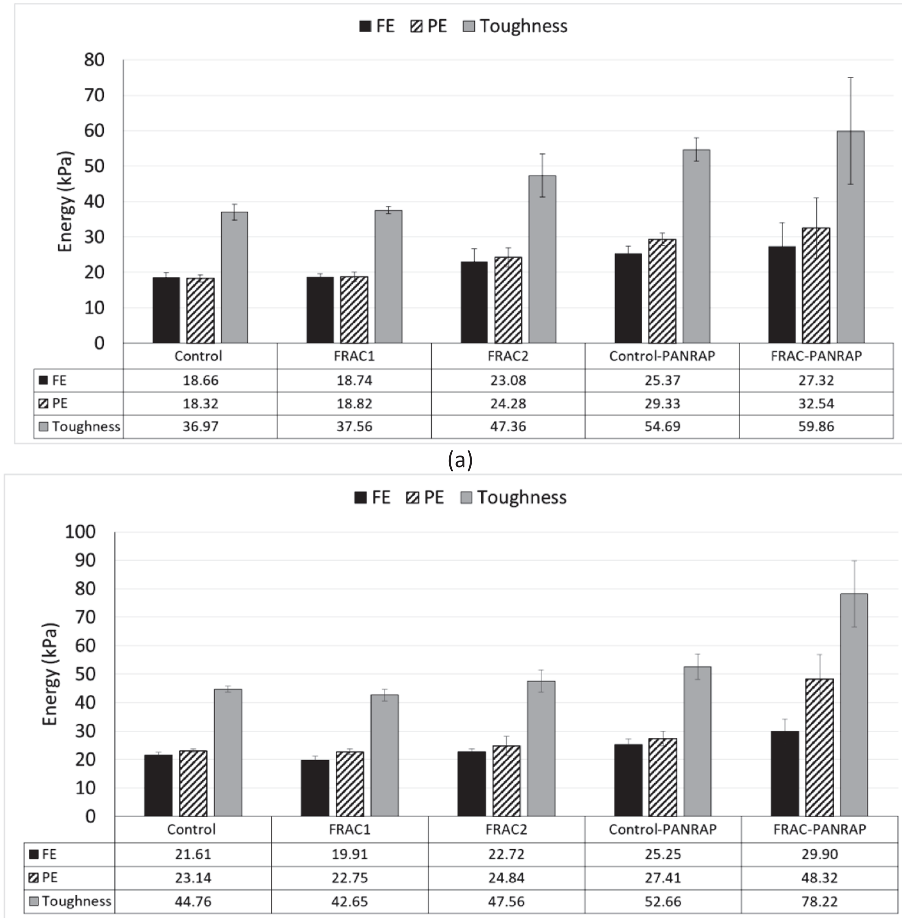

Fig. 5. Fracture properties. Dry conditions (a); Wet conditions (b).

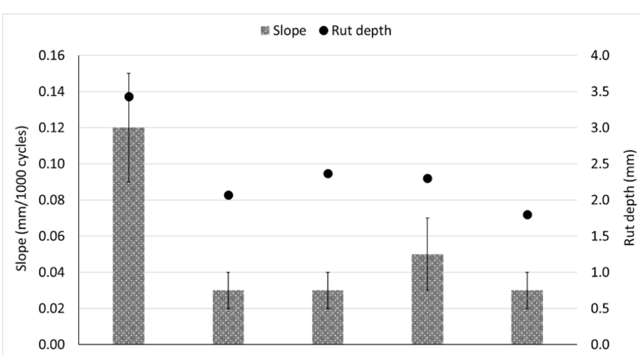

Fig. 6. Slope and Rut depth of wheel tracking test.

Table 10
P-values and statistical significance from rutting test results.

	Slope mm/1000 cycles				
	Control	FRAC1	FRAC2	Control-PANRAP	FRAC-PANRAP
P - value	–	0.034	0.034	0.044	0.034
Significance	–	YES	YES	YES	YES
	Rutting depth (mm)				
	Control	FRAC1	FRAC2	Control-PANRAP	FRAC-PANRAP
P - value	–	0.025	0.035	0.129	0.009
Significance	–	YES	YES	NO	YES

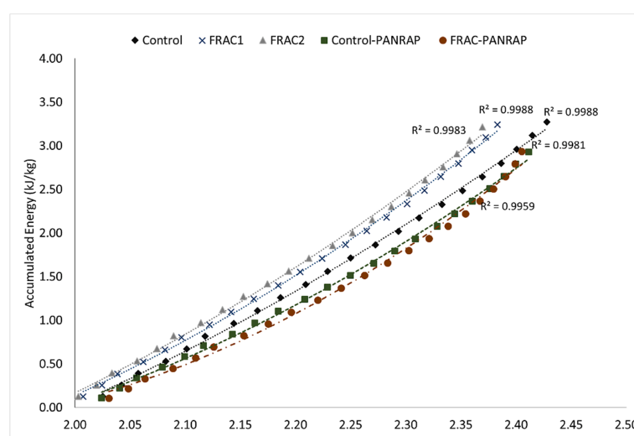

Fig. 7. Compactability results.

content.

Regarding experimental designs manufactured with PANRAP, not statistical differences were noticed between them. In the same way, although both mixes are slightly below the control mix not statistical changes were presented.

3.5. Stiffness and fatigue life

From the stiffness test, the dynamic modulus, as well as the phase

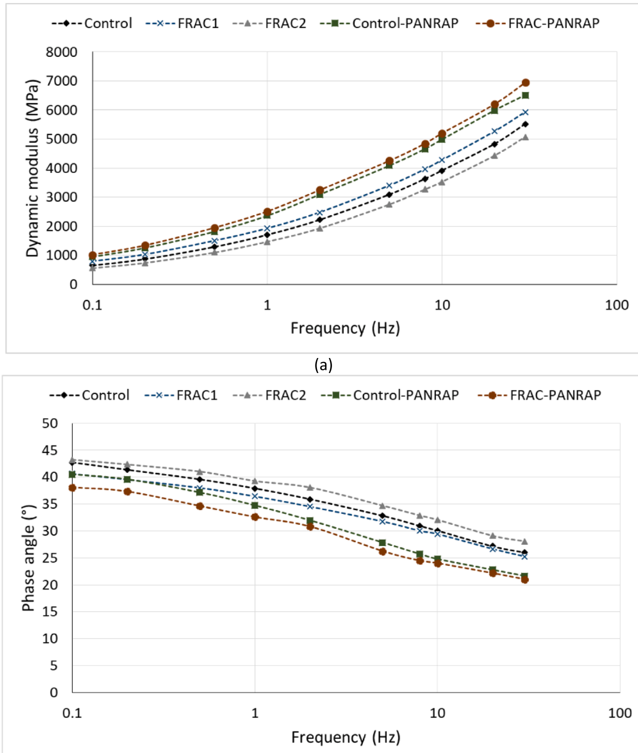

Fig. 8. Stiffness test results; (a) Dynamic Modulus; (b) Phase angle.

angle, were recorded at different levels of frequencies, as shown in Fig. 8. Based on the results, the FRAC1 mixture presented higher values of dynamic modulus and lower values of phase angle for all the frequencies when compared to the control mixture. The increase in modulus and the decrease in the phase angle imply a much more elastic and stiffer mixture than the control mixture. In agreement with other studies, fibers reinforce the mixture through a three-dimensional network and by the absorption of the asphalt, leading to an improvement in the stiffness and viscoelastic behavior [41]. On the other hand, the FRAC2 mixture presented lower values of modulus and greater response in the phase angle. The above could be because this mixture has a higher bitumen content, making it less rigid and more viscous. However, not statistical differences were observed between the mixtures. Regarding recycled mixtures with and without fibers, the dynamic modulus was higher and the phase angle lower compared to the reference mixture. For both designs, statistical differences were found in comparison to the reference mixture. Besides, it was expected that the addition of fibers stiffens the mixture. The trend suggests that the recycled mix with the addition of fibers behaved more rigid than the recycled mixture without fibers. However, there were no significant differences between the Control-PANRAP and FRAC-PANRAP mixtures.

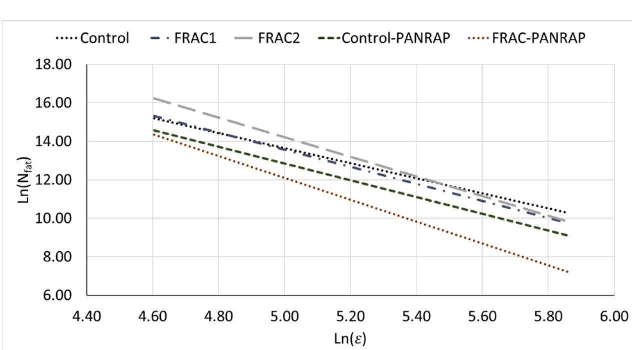

Fig. 9. Fatigue testing results.

Fig. 9 displays the experimental results obtained from the fatigue test. In the same way, the initial stiffness at 30 Hz (S_0) after 100 cycles, the characteristic strain after one million cycles, the number of cycles to failure at 100 micro strain, the constants of the fatigue law, and the R^2 values can be seen in Table 11. It is worth mentioning that the failure criterion was defined when the dynamic module has degraded to half of its initial value ($S_0/2$). Overall, the R^2 values were >0.85 indicating a good correlation in all mixes. According to results, similar fatigue life was found between the control and the FRAC1 mixture regarding the strain at the 10^6 of cycles. However, the FRAC1 mixture displayed a higher stiffness giving evidence that fiber addition could turn the mixture stiffer but keeping the same fatigue resistance than the control mixture. An increment in the dynamic modulus indicates a greater bearing capacity against the traffic loads transferring lower stresses to the layers below [42].

In the same way, the FRAC2 mixture displayed a higher fatigue resistance at the millions of cycles while keeping the same initial modulus than the control mixture. It seems that the inclusion of fibers stabilized the amount of extra bitumen added improving the adherence in the mixture as suggested in previous studies [11]. Regarding mixes manufactured with PANRAP, although they presented lower fatigue performance with respect to the control mixture, the stiffness was higher, and the content of new virgin bitumen added was lower. For the entire range of strain levels, the number of cycles was greater in the Control-PANRAP as compared to the FRAC-PANRAP. However, when the strains started to decrease, the gap in the fatigue life became closer. In any case, both mixes had approximately the same fatigue life at the millions of cycles. However, the FRAC-PANRAP mixture presented a higher stiffness. Accordingly, the reinforcement effect of fibers can also be observed in mixtures prepared with recycled material.

4. Conclusions

In the current research, the reinforcing effect of adding PAN fibers in an AC mixture was evaluated experimentally. Besides, the recyclability potential of the aged mixture with PAN fibers was investigated by manufacturing new mixes with PANRAP contents of 50%. Marshall Stability, air voids, ITS, moisture sensitivity, rutting resistance, the energy of compaction, stiffness, and fatigue were the main properties analyzed. The main findings obtained from this research are summarized as follows:

- The increase in the percentage of voids does not affect negatively the behavior of the experimental mixtures. Similar ITS, moisture sensitivity, and fracture property results were found in the FRAC1 mixture in relation to the control mixture, and slight improvements were reported by the FRAC2 design. On the other hand, both mixtures manufactured with 50% PANRAP showed notable improvements in these responses.

Table 11
Main parameters obtained from the fatigue test.

Parameter	Unit	Control	FRAC1	FRAC2	Control-PANRAP	FRAC-PANRAP
S_0 at 100 cycles AND 30 Hz	MPa	4138	4525	4016	6362	7236
Strain at 10^6 cycles	μm/m	142	140	161	119	110
N_{fat} at 100 μm/m	cycles	4.00E + 06	4.49E + 06	1.13E + 07	2.14E + 06	1.71E + 06
C1	–	33.30	35.74	39.71	34.69	40.54
C2	–	3.93	4.43	5.10	4.37	5.69
R^2	–	0.96	0.91	0.99	0.92	0.85

- All mixtures yielded remarkable results regarding rutting resistance in relation to the control mixture. No statistical differences were observed between FRAC1 and FRAC2 mixture despite the second had higher binder content. Although both mixtures were prepared with 50% PANRAP content, the recycled mixture with fibers performed better. The above suggests the addition of fibers in recycled mixtures could even positively improve the permanent deformation of the mixture.
- The addition of PAN fibers with the same binder content increased the dynamic modulus and decreased the phase angle making the mixture more elastic and keeping the same fatigue resistance than a conventional mixture. In relation to mixtures prepared with PAN-RAP, the reinforcement effect of fibers is also notable since it increases the stiffness while keeping the same fatigue resistance.
- Suitable mechanical performance of bituminous mixtures prepared with 50% of recycled mixture with fibers have been evidenced experimentally. Nevertheless, additional experimental support is necessary evaluating other fiber types and contents. Finally, the assessment of mechanical performance of new bituminous mixtures incorporating real RAP with fibers is highly recommended.

CRediT authorship contribution statement

Carlos J. Slebi-Acevedo: Conceptualization, Methodology, Investigation, Validation, Writing – original draft. **Pedro Lastra-González:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing. **Daniel Castro-Fresno:** Validation, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Ángel Vega-Zamanillo:** Methodology, Formal analysis, Writing – review & editing, Supervision.

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.

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