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EXPLORATORY STUDY OF POROUS ASPHALT MIXTURES WITH ADDITIONS OF RECLAIMED TETRA PAK MATERIAL

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ABSTRACT

The use of cellulose fibers (CF) has become a common technique for reducing draindown problems in porous asphalt (PA) mixtures, helping to increase the bitumen content and providing thicker binder films. In this research, a laboratory study was conducted to assess the suitability of using recycled Tetra Brick Aseptic (TBA) containers as an environmentally friendly substitute for virgin cellulose fibers used in PA pavements. The results obtained showed that recycled TBA

material was a suitable addition for PA mixtures, providing similar, or sometimes greater, improvements than commercial CF.

KEYWORDS: Porous Asphalt; Porous Friction Course; Open-graded friction course; Permeable Pavement; Stabilizing additives; Cellulose Fibers; Tetra Brick.

1. INTRODUCTION

Porous asphalt (PA) mixtures are special asphalt mixtures, characterized by a large air void (AV) content, generally higher than 18-20%, which allow water infiltration through their porous structure [1]. PA mixtures have been widely used all over the world as a surface layer in roads and pavements due to their safety and environmental benefits in relation to other types of asphalt mixtures. The main advantages provided by PA surfaces are the decrease in pavement noise and splash, the increase in safety by reducing the skidding risk and the hydroplaning effect in wet conditions, and the enhancement of visibility in wet weather conditions [2].

Although porous asphalt mixtures were developed more than 30 years ago, their first applications as a surface layer were unsatisfactory due to the premature aging of the mixtures and their raveling damage, limiting their application over time [1]. The continuous development of polymer modifications of bituminous mixtures and other additions led to the development of a new generation of PA mixtures with improved characteristics [3]. The addition of Styrene Butadiene Styrene (SBS) or Styrene Butadiene Rubber (SBR) polymers, crumb rubber, low density polyethylene and the addition of different kinds of fibers to PA mixtures have significantly increased their strength and durability [3, 4], increasing their service life and allowing their continuous use for more than ten years [5].

The asphalt binder content is an important factor in the mechanical performance of PA mixtures. High binder contents increase the coating of the coarse aggregates, providing thicker binder films over the aggregates, increasing the strength and the durability of PA mixtures [3]. However, a binder excess may produce draindown and reduce the infiltration capacity of PA mixtures [1].

With the aim of reducing these problems, additives are normally incorporated to stabilize mixtures with high binder contents, preventing draindown problems [6] and increasing the resistance to raveling of PA mixtures. In the last decade some researchers have studied the influence of the addition of different types of natural and synthetic fibers as stabilizing additives in PA mixtures to obtain mixtures with high bitumen content without causing draindown problems [3, 7, 8]. The results of this research showed that Cellulose Fibers (CF) were more effective than polyester fibers for reducing draindown in PA mixtures [7], but can be more susceptible to the water effect than other types of fibers [9]. The addition of little amounts of CF, between 0.2 and 0.5% by weight of mixture, was recommended for reducing draindown problems [3], augmenting the long-term resistance to raveling and the Indirect Tensile Strength (ITS) of PA mixtures, but sacrificing part of their infiltration capacity [4, 7, 10, 11, 12].

Progressive social awareness about sustainability matters has increased the interest in reusing recycled materials for different purposes, including asphalt mixtures. Tetra Brick® Aseptic (TBA) packaging has been widely used worldwide to commercialize liquid foods such as milk or fruit juices, resulting in an annual production of nearly 30 billion containers, being one of the most common residues in recycling centers. This kind of containers is mainly composed of cellulose (63%), low-density polyethylene (30%) and aluminum (7%) [13], making it difficult to recycle due to the need to separate these different compounds.

The composition of TBA packages raises the possibility of reusing them as a stabilizing additive for asphalt mixtures. With the aim of studying the suitability of reclaimed TBA material for this purpose, a laboratory study was performed. The main aim of the research was to analyze the influence of the additions of reclaimed TBA packages on PA mixtures and compare their performance with commercial CF, normally used in PA pavements.

2. MATERIALS AND METHODS

2.1 Aggregates

A coarse basaltic aggregate was used for producing PA mixtures, with a particle density of 2921 kg/m³, a flakiness index of 12 and a Los Angeles coefficient of 16. Limestone filler was added in a constant range of 4.5% by weight of mixture. The aggregates gradation can be seen in Figure 1.

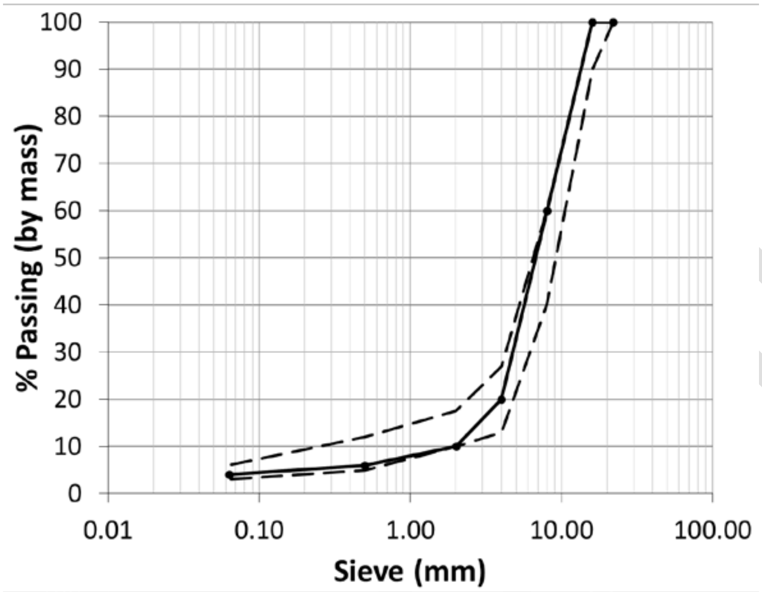

Figure 1. Gradations of PA mixtures used

The gradation was selected according to the Spanish requirements for PA-16 mixtures [14], and designed for maximizing the air void content in mixture by using a specific methodology: the Bailey method [15]. This methodology is a systematic approach to blending aggregates that provides aggregate interlock as the backbone of the structure. The method provides a set of tools that provides a better understanding of the relationship between aggregate gradation and mixture voids [15]. After applying this method to the range of gradations that can be used for PA-16 mixtures according to the Spanish requirements [14], the best gradation in terms of air void content was selected. In this gradation the finer part of the aggregates was reduced and the dosages of the coarse aggregates were optimized according to the Bailey method, resulting in Voids in Mineral Aggregates (VMA) between 26 and 28% after compaction, measured according to the standard EN 1097-3 [16].

2.2 Bitumen

One conventional 50/70 penetration grade bitumen (50/70) was used for producing the tested PA mixtures. The main characteristics of the used bitumen are summarized in Table 1.

Table 1. Characteristics of 50/70 conventional bituminous binder

CHARACTERISTIC	STANDARD	VALUE
Penetration at 25ºC, 100g, 5s (0.1mm)	EN 1426	65
Softening Point (ºC)	EN 1427	47.2
Penetration index	EN 12591	-1.3
Fraas Fragility point (ºC)	EN 12593	-9

2.3 Fibers

Two different types of fibers were used as stabilizing additives for PA mixtures: commercial CF and recycled TBA material. Commercial CF, produced to be used in asphalt pavements, was selected for comparing the effects of recycled TBA material. These fibers were supplied by a local company in pellet form, with virgin cellulose fibers coated by a bituminous binder. The characteristics of the cellulose pellets used are shown in Table 2. Commercial CF were added to PA mixtures according to the manufacturer's recommendations. The process consists of shredding the cellulose pellets to separate the cellulose fibers and adding the material obtained to the aggregates before being heated in the oven to prepare the PA samples.

Table 2. Commercial Cellulose Fiber Characteristics

PELLET CHARACTERISTICS	
Cellulose fiber Content	87-93 %
Pellet Length	2-8 mm
Pellet thickness	4±1 mm
Bulk Density	440-540 g/l
CELLULOSE FIBER CHARACTERISTICS	
Cellulose content	80±5%
Average fiber length	1100 µm
Average fiber thickness	45 µm
BITUMEN CHARACTERISTICS	
Penetration at 25 ºC	50/70 mm
Softening Point	46-54 ºC

TBA material was obtained from recycling TBA packages. For recycling TBA containers, the packages were initially washed and air dried, and finally shredded. After that, the material obtained was sieved and divided into two different size fractions: 0.5-1mm and 1-2mm. The characteristics of the TBA fibers used for producing the tested PA mixtures is showed in Table 3. The cellulose content was obtained through manufacturer information, while bulk density and average fiber length were obtained by sieving and/or weighting 3 samples of the used TBA material.

Table 3: Characteristics of TBA fibers

TBA CHARACTERISTICS	
Cellulose content	63%
Bulk density	520-560 g/L
Average fiber length	830 μm (in 0.5-1mm fraction) 1460 μm (in 1-2mm fraction)

Preliminary tests were conducted in order to select the most suitable reclaimed TBA material size and method for addition to PA mixtures. The criteria used for this purpose was the maximization of the resistance to raveling measured by the Cantabro test in unaged specimens according to EN 12697-17 [17], and the air void content in mixtures measured by the geometrical method according to EN 12697-8 [18].

2.4 PA Mixtures

A set of PA mixtures with different fiber concentrations and bitumen dosages was produced. Control mixtures with the normally used specifications for Spanish PA-16 mixtures and reference mixtures without fiber addition were included for comparison purposes. The tested PA mixtures are summarized in Table 4.

Cylindrical specimens with a diameter of 101.6±0.1 mm were used for the experimental program. Test samples were compacted by 50 blows per side from a Marshall hammer according to the European standard EN 12697-30 [19], resulting in specimens' heights of 61.5±2.5 mm.

2.5 Laboratory tests

The tests performed and the reference standards are shown in Table 5. The volumetric properties of the PA mixtures tested were assessed by measuring the bulk density, total air voids (AV) and interconnected air voids (IAV) of the tested mixtures. In addition, closed air voids were calculated as the difference between AV and IAV.

Table 4. PA mixtures tested

MIXTURE	**BITUMEN**		**FIBERS**	
	Type	**Dosage (% b/w of mix)**	**Type**	**Dosage (% b/w of mix)**
R1	50/70	5%	-	-
R2		5.5%	-	-
CF1-1				0.25%
CF1-2	50/70	5%	CF	0.5%
CF1-3				0.75%
CF2-1				0.25%
CF2-2	50/70	5.5%	CF	0.5%
CF2-3				0.75%
TBA1-1				0.25%
TBA1-2	50/70	5%	TBA	0.5%
TBA1-3				0.75%
TBA2-1				0.25%
TBA2-2	50/70	5.5%	TBA	0.5%
TBA2-3				0.75%

Type of fibers: CF: Cellulose Fibers; TBA: Reclaimed Tetra Brick Aseptic fibers

Table 5. Laboratory test performed

PARAMETER	**METHOD/STANDARD**	**COMMENTS**
Bulk Density	EN 12697-6 [20]	-
Total Air Voids (AV)	EN 12697-8 [18]	-
Interconnected Air Voids (IAV)	ASTM D7063 – 05 [21]	-
Vertical Permeability	Falling head permeameter.	Water head between 30 and 10 cm.
Draindown	EN 12697-18 [22]	-
Particle Loss (Cantabro test)	EN 12697-17 [17]	Aged specimens according to Spanish standard NLT 362/92 [23]
Indirect Tensile Strength (ITS)	EN 12697-23 [24]	-

Water Sensitivity	EN 12697-12 [25]	-

Vertical permeability (K) was measured with a falling head permeameter according to Equation (1) based on the Darcy's Law.

$$K = A \cdot \frac{L}{t} \cdot ln\left(\frac{h_1}{h_2}\right) \qquad (1)$$

Where A is the cross section of the specimen in mm², L is the height of the specimen in mm, t is the time in seconds, in which the water head decreases from the initial height, h_1, to the final height, h_2, also measured in mm.

The stability of the tested PA mixtures was assessed by performing draindown tests. The mechanical performance of the tested PA mixtures was evaluated by measuring the Indirect Tensile Strength (ITS) and the raveling resistance of PA mixtures. The raveling resistance was assessed by measuring the particle loss through the Cantabro test, performed at 25ºC. This test measures the Particle Loss (PL) of asphalt specimens after being placed in the Los Angeles Drum for 10 minutes at 30 rpm by using Equation (2).

$$PL(\%) = 100 \times \frac{(W_1 - W_2)}{W_1} \qquad (2)$$

Where W_1 and W_2 are the initial and the final weights of the specimens in grams. The test was performed on conditioned specimens according to Spanish standard NLT 362/92 [23]. The conditioning method consisted in submerging the specimens in water at 60ºC for 24h and conditioning them for another 24 hours at air (25ºc); it being recommended that the PL should not exceed 35% in these conditions.

The ITS was measured in dry (ITS_{dry}) and wet (ITS_{wet}) conditions, for assessing the water sensitivity through calculating the Indirect Tensile Strength Ratio (ITSR). The ITSR is defined as the ratio of the dry ITS, and the ITS retained by a mixture after being immersed during 72h in a water bath at 40˚C, and it was calculated according to Equation (3); a minimum ITSR value of 85% being recommended.

$$ITSR(\%) = 100 \times \frac{ITS_{Wet}}{ITS_{Dry}} \qquad (3)$$

2.6 Statistical analysis

The data obtained was statistically analyzed in order to support the discussion of the results and the conclusions section. For normal and homoscedastic data distributions, parametric statistical tests were used, while for non-normal and/or non-homoscedastic data distributions, non-parametric statistical tests were applied. The statistical tests used for comparing the data obtained for the different mixtures tested are shown in Figure 2. All the statistical tests were performed with a confidence level of 95%, and hence the tested hypothesis was considered to be true when the statistical significance (Sig) of the test result was lower than 0.05.

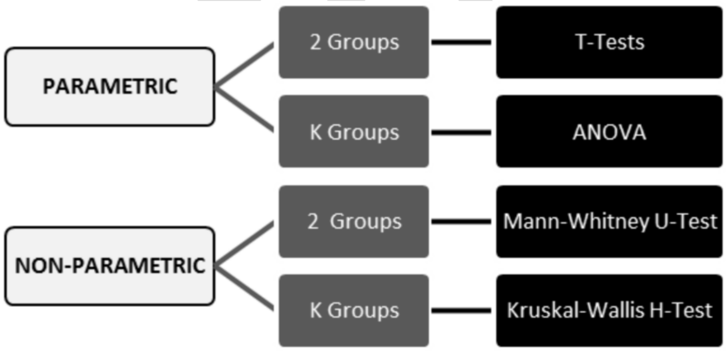

Figure 2. Statistical Tests used for the statistical analysis

3. RESULTS AND DISCUSSION

3.1 Preliminary results for TBA material

Before producing the PA mixtures summarized in Table 4, preliminary tests were conducted to determine the optimal size and addition method for TBA material based on Air void content and

Cantabro test results of the produced PA mixtures. Two different size fractions were initially assessed: 0.5-1 mm and 1-2mm. The material was added to the aggregates, in a similar way to the method used for commercial CF. Bitumen content was fixed at 4.5% by weight of mixture because it is the most common bitumen dosage in Spanish PA mixtures, and in order to assess the influence of fiber length and addition method without considering draindown effects in mixtures. The PA mixtures produced were tested to obtain the AV and PL according to the Cantabro test performed at 25ºC in unaged specimens. The results obtained are shown in Table 6.

Table 6. Results of the preliminary tests for selecting optimal size of TBA material

Bitumen Type	Bitumen Content (% b/w of mix)	TBA content (% b/w of mix)	Fiber length (mm)	Air Voids (%)	Particle Loss (%)
50/70	4.5	0	-	20.7	7.7
50/70	4.5	0.2	0.5-1	19.7	7.1
50/70	4.5	0.4	0.5-1	19.1	7.1
50/70	4.5	0.6	0.5-1	19.8	7.4
50/70	4.5	0.2	1-2	19.4	5.4
50/70	4.5	0.4	1-2	19.7	4.5
50/70	4.5	0.6	1-2	18.8	5.7

It can be observed that the best performance is provided by 1-2mm sieved TBA material, this fraction being selected to produce PA mixtures with reclaimed TBA additions. The TBA material size was fixed at 1-2 mm, and two different addition methods were assessed: adding the sieved material with the aggregates, similarly to the method used for commercial CF, and their addition with the hot bitumen. The results obtained in these preliminary tests (Table 7) showed that the addition of the reclaimed TBA material with the aggregates was the most suitable method, leading to stronger mixtures with high void contents, and hence was selected for producing PA mixtures.

Table 7. Results of the preliminary tests for selecting the addition method of TBA material

Bitumen Type	Bitumen Content (% b/w of mix)	TBA content (% b/w of mix)	Adding method	Air Voids (%)	Particle Loss (%)
50/70	4.5	0	-	20.5	8.1
50/70	4.5	0.5	A	20.5	4.4
50/70	4.5	0.5	B	20.1	4.8

Adding Methods: A-Addition with aggregates, and B-Addition with the Bitumen

3.2 Draindown and volumetric analysis

The results obtained for the volumetric analysis of the PA mixtures summarized in Table 4 as well as their draindown and permeability values are shown in Table 8. It can be observed that draindown was only detected in reference mixtures, indicating the difficulty of obtaining PA mixtures with bitumen contents higher than 4.5% without using stabilizing additives. The results showed that the addition of CF and TBA fibers enables the bitumen dosage to be increased, avoiding possible draindown problems for all the tested dosages of fibers. As the effective bitumen content was higher in mixtures with fibers, a slight increase in the bulk density was observed in relation to reference mixtures for both binder dosages.

The results obtained showed differences among the tested mixtures, significant differences being observed in total air voids (AV), interconnected air voids (IAV) and permeability values (Sig<0.003). The addition of commercial CF or recycled TBA produced reductions in the average AV and IAV in the range of 1-3% in relation to reference mixtures, leading to 20-50% lower permeability coefficients (Sig<0.003). In the spite of the important reduction of permeability due to fibers inclusion in mixtures, minimum permeability values observed in fiber-modified PA mixtures are higher than 100 m/day (1.2 mm/s), minimum recommended permeability value according to ASTM D7064-04, indicating the suitability of the produced mixtures in terms of infiltration capacity. Fiber type and dosages do not seem to significantly affect the AV, IAV and permeability results in the range of dosages tested (Sig>0.077). However, increasing dosages of fibers seems to progressively reduce average AV and IAV as can be seen in Figure 3.

Table 8. Bulk density, air voids, vertical permeability and draindown of the tested PA mixtures

MIX	**Bulk Density (g/cm³)**		**Air Voids (%)**						**Permeability (mm/s)**		**Draindown (% b/w of mix)**
			Total		**Interconnected**		**Closed**				
	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	
R1	2.08	0.03	22.4	1.00	15.2	1.24	7.2	0.30	2.8	0.8	1.5
R2	2.09	0.03	21.2	1.10	13.5	1.59	7.7	0.53	2.5	0.7	1.8
CF1-1	2.11	0.02	21.1	0.91	13.4	0.81	7.7	0.29	2.0	0.6	0
CF1-2	2.13	0.01	20.5	0.19	13.1	0.13	7.5	0.29	1.8	0.1	0
CF1-3	2.13	0.02	20.2	0.63	12.5	0.63	7.8	0.37	1.5	0.1	0
CF2-1	2.09	0.03	19.8	1.01	12.4	0.89	7.4	0.44	1.4	0.7	0
CF2-2	2.13	0.03	19.8	1.01	12.2	1.00	7.6	0.37	1.9	0.7	0
CF2-3	2.15	0.03	19.1	1.00	11.5	0.52	7.6	0.59	1.3	0.2	0

TBA1-1	2.11	0.02	21.0	0.77	13.7	0.85	7.4	0.27	2.3	0.4	0
TBA1-2	2.13	0.04	20.4	1.35	12.7	1.32	7.7	0.36	1.8	0.5	0
TBA1-3	2.13	0.01	20.4	0.56	13.0	1.00	7.4	0.58	1.5	0.4	0
TBA2-1	2.13	0.02	19.7	0.61	12.3	1.12	7.4	0.74	1.6	0.6	0
TBA2-2	2.13	0.03	19.9	1.04	12.6	0.95	7.3	0.11	2.0	0.4	0
TBA2-3	2.14	0.02	19.5	0.84	12.2	0.89	7.2	0.45	1.5	0.3	0

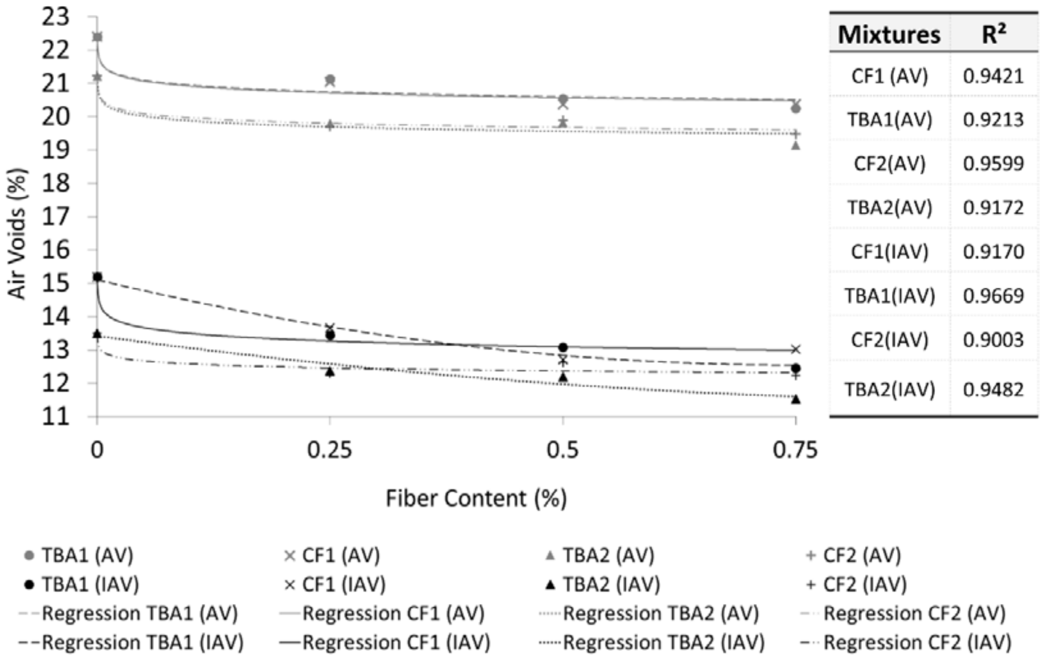

Figure 3. Average total air voids (AV) and interconnected air voids (IAV) depending on the bitumen dosage and fiber content.

As can be observed, the bitumen dosage proved to be the most important factor influencing the void content of the PA mixtures tested, causing reductions in AV and IAV of between 1 and 2% on average when increasing the bitumen content from 5 to 5.5% (Sig<0.003). Increasing dosages of commercial CF or TBA material progressively reduces the total and interconnected air void content in PA mixtures. Although both fibers produced similar effects in the AV, IAV and permeability (Sig>0.514), IAV results seem to be affected by the fiber type. The use of TBA material resulted in more compact mixtures than CF in terms of interconnected air voids, so that for a fiber dosage of 0.75%, TBA1 mixtures showed similar IAV to CF2 in spite of the lower bitumen content. This fact could be due to the contribution of the polyethylene and aluminum contained in TBA packages, which could affect the pore structure, resulting in fewer connected pores.

These results suggest that the addition of CF or TBA material eliminated draindown, allowing the effective binder content in PA mixtures to be increased. As the binder content increases, the air void content decreases for both fiber types, resulting in PA mixtures with similar volumetric properties independently of the fiber type and the dosage used. As the unconnected air voids were very similar for all mixtures, the reduction in the air void content in mixtures with fibers was mainly the result of the reduction in the interconnected air voids, also resulting in a reduction of the infiltration capacity. These results indicate that the addition of CF and TBA material mainly reduces the pore diameter, producing a reduction in the IAV, but not significantly affecting the unconnected air voids.

3.3 Particle loss (Cantabro test)

As can be observed in Table 9, all the tested mixtures with fiber additions underwent PL lower than 35%, fulfilling the requirements for their use as a surface layer in roads according to Spanish standard NLT 362/92. The R2 mixture showed PL lower than 35% while R1 is beyond this limit. According to these results, by using commercial CF or recycled TBA material, mixtures with 5% of 50/70 bitumen can be produced, which provides much lower PL than reference mixtures without fibers. Obtained PL showed to be importantly lower than those obtained in previous research [26, 27, 28] for PA mixtures with similar binder dosages, but with higher air void contents, where SBS-modified bituminous binders was used, in combination with basaltic aggregates, alone or partially replaced by RAP aggregates. The PL results showed also to be very similar than those observed in mixtures that includes also cellulose and glass fibers, and with air void contents very similar to those observed in this research.

The results of the Cantabro test showed differences in the PL for the different mixtures tested, which were statistically significant (Sig=0.000).By increasing the bitumen content from 5 to 5.5%, the PL were significantly reduced in reference mixtures (Sig=0.029), being lowered 29%

on average.. The PL obtained for PA mixtures with fibers, were very similar for the dosages tested (Sig>0.259). The only exception to this was the CF1 group (sig=0.035), in which the CF1-3 mixture showed significantly higher PL than CF1-1 and CF1-2 (Sig<0.047). This fact can be explained by an excess of cellulose fibers in the mixture in relation to the bitumen content, which could reduce the cohesion provided by the bituminous mastic, leading to a higher susceptibility to lose aggregate particles. As commercial CFs were mainly composed of cellulose, their cellulose content is higher than for reclaimed TBA material, leading to the observed result.

Table 9. Mechanical test results for the PA mixtures

MIX	Particle Loss (%)		Indirect Tensile Strength (kg/cm^2)				Indirect Tensile Strength Ratio (%)
			Dry		Wet		
	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	
C-PMB	21.56	2.13	10.86	0.90	9.72	0.54	89.50
C-CB	48.05	7.75	9.77	0.54	9.24	0.68	94.58
R1	42.08	9.16	9.36	0.98	9.35	0.72	99.93
R2	30.68	6.03	9.69	0.29	9.41	0.59	97.11
CF1-1	21.53	3.66	11.03	0.64	10.13	0.85	91.81
CF1-2	20.03	2.73	11.36	0.40	10.64	0.49	93.63
CF1-3	30.43	4.18	10.56	0.90	9.00	0.77	85.19
CF2-1	15.10	0.18	10.52	0.71	10.46	0.63	99.57
CF2-2	18.35	5.47	11.28	0.56	10.12	0.68	89.72
CF2-3	19.15	4.35	10.50	0.34	9.12	0.30	86.70
TBA1-1	21.38	2.71	10.31	0.09	9.77	0.56	94.71
TBA1-2	20.35	8.44	11.15	0.92	9.76	0.34	87.57
TBA1-3	19.98	7.10	9.67	0.40	8.75	0.60	90.46
TBA2-1	18.25	8.10	11.39	0.95	10.37	0.44	91.04
TBA2-2	12.95	3.56	11.34	0.75	10.04	0.41	88.53
TBA2-3	14.30	3.49	11.16	0.21	9.91	0.42	88.76

PA mixtures made with TBA material showed 13-14% lower average PL than mixtures with CF; however, the data dispersion is high and these differences are not statistically significant (sig>0.117). It can be observed that recycled TBA material could give PA mixtures similar advantages to those provided by commercial CF, or even higher. In fact, the best mixture in terms of resistance to raveling was TBA2-2, providing average PL in aged conditions of 13%, enabling the reduction of the average PL by 52% in relation to reference mixtures with the same bitumen content (Sig<0.030). This mixture also showed improvements in relation to PA mixtures with commercial CF, reducing the average PL by 30% in relation to mixtures with the same content of commercial CF and by 15% in relation to CF2-1, the best mixture with commercial CF in terms of resistance to raveling. However, these differences proved not to be statistically significant (Sig>0.149). Similarly to what occurs for reference mixtures, by increasing the bitumen content from 5% to 5.5%, the PL were lowered by 27% on average for both types of fibers. Higher bitumen contents increase the amount of bituminous mastic that coats the aggregate particles, resulting in thicker asphalt binder films on the aggregates. The thicker the bonding layer, the higher the resistance to water action and raveling, and hence the lower the particle loss of the mixture.

3.4 Indirect Tensile Strength Ratio (ITSR)

It can be observed in Table 9 that mixtures with fiber additions showed generally higher Indirect Tensile Strength (ITS) than reference mixtures. Analyzing the influence of the fiber dosage in mixtures with fiber additions, it can be observed that, as the fiber content increases, the ITS results tend to decrease, especially in wet conditions where the differences between mixtures of the same group ranged 10%. Mixtures with commercial CF in a dosage of 0.75% showed the worst ITS values for both bitumen contents (Sig<0.043) even lower than those provided by reference mixtures. Something similar occurs with TBA material, the TBA1-3 mixture providing the worst ITS results of the TBA 1 group, (Sig<0.047). In the TBA 2 group, the TBA 2-3 mixture also proved to be slightly weaker than the others, but in this case there were no significant differences among mixtures (Sig>0.276). These results confirm that an excess of cellulose in PA mixtures could lead to the reduction in the mixture's strength, especially in combination with water effects, as was also observed in the Cantabro tests performed on aged specimens.

Grouping the results obtained by fiber type and bitumen content, it can be observed that for both bitumen contents both fibers perform very similarly (Sig>0.128). However, by increasing the bitumen content from 5 to 5.5%, mixtures with commercial CF showed similar ITS results for all CF dosages, while mixtures with TBA material showed 10% higher average ITS_{dry}. The CF1-2 mixture showed the best ITS results, with 22% higher ITS_{dry} than reference mixtures with the same bitumen content (Sig<0.043), and very similar results to the C-PMB mixtures (Sig>0.114), or even slightly higher.

With the exception of the TBA 2-3 mixture, the TBA 2 group performs well, the TBA2-1 mixture having 18% higher ITS_{dry} than the reference mixture with the same bitumen content (Sig<0.029), also with a very similar performance to the CF1-2 mixtures, or even slightly better (Sig=0.329).

It can be observed in Table 7 that all the mixtures tested provided an ITSR higher than 85%. Reference mixtures showed the highest ITSR values, nearing 100% for both reference mixtures, and higher than those obtained for control mixtures, probably due to the high bitumen content. On the other hand, in mixtures with fibers, as the fiber content increases, the ITSR tends to decrease. In fact, by increasing the fiber content from 0.25% to 0.75% the ITSR values were decreased by 2-4% for mixtures with TBA material, and by 6-13% in mixtures with commercial CF, indicating a higher susceptibility of commercial CF to the water effect than recycled TBA material has.

4. CONCLUSIONS

An exploratory laboratory study was performed to assess the suitability of using recycled TBA material as a stabilizing additive for PA mixtures. With this aim, different TBA fiber lengths and dosages were assessed by various tests. Once the most suitable characteristics of TBA material for use in asphalt mixtures were obtained, a set of PA mixtures were produced, assessed and compared to mixtures with commercial CF additions.

The addition of TBA material produced similar effects on the AV and permeability of PA mixtures to commercial CF. Although the statistical analysis showed that the volumetric properties of PA mixtures were very similar for both additions, the regression analysis showed a slightly higher reduction in IAV for mixtures with TBA material.

Recycled TBA material provided similar improvements in the resistance to raveling in PA mixtures to commercial CF, or even higher, reducing the PL by 40-50% compared to reference mixtures with the same bitumen content. The TBA 2-2 mixture (5.5% of 50/70 bitumen and 0.5% of TBA) showed the best resistance to raveling of all the tested mixtures, providing average PL in aged conditions of 13%.

The influence of the commercial CF and TBA material on the ITS proved to be limited, the maximum increments in ITS observed were in the range of 22% in mixtures with fiber additions compared to reference mixtures. Both fibers seem to provide similar improvements in PA mixtures over the ranges of dosages tested. However, increasing bitumen contents positively interacted with TBA material, resulting in stronger mixtures than those obtained with CF.

As the fiber content increases, the ITSR tends to decrease for both fibers, especially in mixtures with CF, indicating the susceptibility of cellulose to the water effect, and a slightly better resistance to water of mixtures with recycled TBA material compared to those with CF.

Based on the results of this study, it can be concluded that TBA material is suitable for use as a stabilizing additive in PA mixtures, its inclusion being recommended at a dosage of 0.25-0.5% by weight of mixture to provide the best mechanical results without excessively reducing the permeability and air voids of PA mixtures.

Further research is needed in order to assess the performance of TBA modified PA mixtures by using performance-based tests in order to validate the results obtained in this research, including the performance evaluation in aggressive environmental conditions that can affect Aluminium present in TBA material. In addition, the comparison of TBA fibers with other stabilizing additives such as mineral fibers, and the interaction with other types of bituminous binders could be of interest for researchers and practitioners.

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