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Multi-criteria analysis of porous asphalt mixtures with aramid fiber under adverse conditions

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ABSTRACT

This study the functional performance of super porous asphalt mixtures with two types of aramid fibers against adverse events during their service life. This research was organized in 4 phases: first, particle loss after extreme weather conditions was evaluated. Second, the permeability and clogging resistance was assessed. Third, its resistance to fuel spillage was studied. Fourth, a multi-criteria analysis was performed to determine the best performing mixture considering all the studied variables.

Regarding the results, mixture with aramid and polyolefin was the best performing blend according to the multi-criteria analysis. The fiber content allowed for acceptable performance in terms of particle loss despite having a higher void content than the reference mixtures. In addition, a higher permeability and clogging resistance was found, so the use of such fibers did not negatively affect the internal structure of the mixture. Finally, it had a higher resistance to fuel spillage due to the use of polymer-modified bitumen.

1. Introduction

Porous asphalt are structures used to solve water drainage problems. This type of asphalt has several advantages over dense asphalt. Its main advantages are: decreases noise emissions [1,2] and increases road safety because it improves stormwater runoff and minimizes hydroplaning [3-6]. However, porous asphalt has an important disadvantage with respect to dense asphalt: it has a lower mechanical strength [7].

Due to the above, different types of fibers have been added to porous asphalt mixtures to improve their mechanical performance [8]. In this regard, aramid fibers have shown significantly better performance than other fibers [9]: they do not hinder the production and manufacturing process [10], mitigate binder drainage [11], reduce particle loss and increase the indirect tensile strength [12-14], reduce cracking [15], improve stability at high temperatures [16] and increase toughness and resistance to groove formation [17,18].

So, the mechanical capacity of porous mixtures asphalts can be improved by adding aramid fibers. However, their performance against adverse events during the operation phase is still unknown, for example:

- The magnitude of particle loss after extreme weather conditions is unknown: [19-22] addressed the impact of freeze-thaw cycles on the performance of porous mixtures, but did not consider particle loss. Only [23] evaluated particle loss through the Cantabro test under freeze-thaw cycles, but did not consider the use of fibers.
- The damage to the permeability due to the possible obstruction of its voids by debris is unknown: [24,25] evaluated the permeability of the pavement, but did not consider the clogging potential of the mixtures. While [1,26-29] did consider the clogging but did not consider the use of fibers.
- The impact of fuel spillage on porous pavements has not been studied. This is important because the aggregates are more exposed in highly porous mixtures than in dense mixtures, due to their high void content, so external agents such as fuel spills can be even more damaging.

Consequently, considering the good performance of porous asphalt mixtures with aramid fibers [30,31], and the low level of knowledge of their performance in adverse conditions during the operation phase, the

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objective of this research was to evaluate the response to three adverse situations: particle loss after extreme weather cycles, permeability capacity with pore clogging and mass loss after fuel spills.

To meet the objective of this research, four porous asphalt mixtures already studied mechanically in a previous investigation were studied [31]: two reference mixtures without fibers and two experimental mixtures with two types of aramid fibers. The investigation was divided into 4 phases: The first phase evaluated particle loss after freezing and thawing cycles. The second phase evaluated the permeability and clogging resistance. In the third stage, the resistance to possible fuel spills was evaluated. Finally, in the fourth stage, the mixture with the best performance was determined by TOPSIS multi-criteria analysis. All results were statistically evaluated using Minitab software.

2. Materials, specimen preparation and methodology of study

2.1. Materials

Two different binders have been used typical bitumens used in Spain: the first 50/70 penetration grade and the second was polymer-modified bitumen (PMB 45/80–65). Their main properties are included in Table 1.

The aggregates used for the design of porous asphalt mixtures are: ophite as coarse aggregate, limestone as fine aggregate and hydrated lime as filler. Their main properties are included in Table 2.

As mentioned, two aramid fibers selected from previous research have been studied [31] (Fig. 1): the first is called Pulp and is purely aramid, and the other is called Mixed and is a mix of aramid and polyolefin. Their main properties are summarized in Table 3.

2.2. Specimen preparation

The configuration of the four asphalt mixtures studied in this investigation are shown in Table 4. All contents were considered with respect to the weight of the mixture.

The dosage of the 4 mixtures was selected according to previous research [31]. The mixtures were dosed by volume and were made according to Spanish standards. Fig. 2 presents the particle size distribution of the studied mixtures: the reference mixtures were adjusted to a traditional PA16 mixture, while the experimental mixtures were designed to be highly porous.

Table 5 shows the volumetric properties and mechanical behavior of the four mixtures developed in previous research [31]. The objective of the past research was to design highly porous mixtures with similar mechanical behavior.

Regarding the results presented in Table 5, although the two experimental mixtures have a higher percentage of voids than the two reference mixtures, all four mixtures have acceptable mechanical performance due to the use of aramid fibers in the two experimental blends. For this reason, it is interesting to develop the objective of this research by evaluating the performance of the four mixtures against adverse

Table 1

Properties of binder.

Binder type	Test	Value	Standard
50/70	Penetration (25°C, mm/10)	57	EN 1426
	Specific Gravity	1.04	EN 15326
	Softening point (°C)	51.6	EN 1427
	Ductility force (5°C, J/cm ²)	-	-
	Elastic recovery (25°C, %)	-	-
	Fraass brittle point (°C)	-13	EN 12593
PMB 45/80-65	Penetration (25°C, mm/10)	56.00	EN 1426
	Specific Gravity	1.03	EN 15326
	Softening point (°C)	74.10	EN 1427
	Ductility force (5°C, J/cm ²)	3.11	EN 13589
	Elastic recovery (25°C, %)	88.00	EN 13398
	Fraass brittle point (°C)	-16	EN 12593

Table	2	
Proper	ties of a	aggregates.

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

events during their lifetime: particle loss after extreme temperatures, permeability capacity with pore clogging and mass loss after fuel spills.

2.3. Methodology of research

The results of the four phases of the research were evaluated with the Minitab statistical program. The T-Student test was performed when the results complied with a normal distribution and there was homogeneity of variances. Otherwise, the Mann-Whitney U test was applied. The confidence interval was always 95%, which means that the results are significantly different when the p-value is less than 0.05.

2.3.1. Phase 1: Particle loss after extreme temperatures

To determine the performance of the samples against particle loss under adverse temperatures, the samples were frozen for 16 hours at a temperature of -20° C (Fig. 3a), and later immersed in a 60° C water bath for 8 hours (Fig. 3b). This process was repeated twice. Then, five samples of each mixture were conditioned according to EN 12697–17 and tested in the Cantabro test on the Angeles machine (Fig. 3c) at 300 revolutions at a frequency of 33 rpm. To determine the particle loss, the samples were weighed before and after the test.

2.3.2. Phase 2: Permeability and clogging resistance test

To evaluate permeability and resistance to clogging, the permeability test according to EN 12697–19 was used (Fig. 4. a). The falling head permeameter was used at room temperature in Marshall specimens. Five samples of each type of mixture were used for the test. The permeability of the samples was measured at different clogging levels:

- Level 0: Test with clean water (Fig. 4. b).
- Level 1: Test with 10 g of limestone added to the water (Fig. 4. c)
- Level 2: Test with 20 g of limestone added to the water (Fig. 4. d)

Limestone, with a maximum size of 2 mm, was added to the water to penetrate with it and clog the path the fluid would take through the holes, as reported in [32].

Then, permeability (k) was measured as the time it takes for a specific volume of water to pass through the sample Following Darcy's law, the permeability was determined as shown in the Eq. 1.

$$k = \frac{aL}{At} \ln\left(\frac{h_1}{h_2}\right) \tag{1}$$

Where *a* is the inner cross-sectional area of the inlet standpipe; *L* is the thickness of the specimen; *A* is the cross-sectional area of the specimen; *t* is time and h_1 and h_2 are the initial and final heights of the water level.

2.3.3. Phase 3: Fuel spills resistance test

To evaluate the resistance of the four mixtures to potential fuel spills on roads, the behavior of the porous pavement was analyzed by immersing the Marshall samples in a container filled with diesel fuel for a period of 2 hours (Fig. 5, left). After the two hours, the specimens were removed from the container and placed in a mesh basket at 25° C for





Fig. 1. Fibers Pulp (left) and fibers Mixed (right).

Table 3

Properties of fibers.

Detail.	Fibre 1 (Pulp)	Fibre 2 (Mixed)	
	Aramid	Aramid	Polyolefin
Form	Pulp	Monofilament	Serrated
Density (g/cm ³)	1.44	1.44	0.91
Length (mm)	1.0 - 1.5	19	19
Tensile Strength (MPa)	2700 - 3600	2758	483
Decomposition temperature (°C)	> 450	> 450	157

Table 4

Detail of mixtures studied.

Results	Ref. 50/ 70	Ref. PMB	Exp 1	Exp 2
Binder type	50/70	PMB 45/ 80–65	PMB 45/ 80–65	PMB 45/ 80–65
Binder content (%)	4.5	4.5	5.3	5.3
Fiber Type	-	-	Pulp	Mixed
Fiber content (%)	-	-	0.05	0.15



Fig. 2. Reference and experimental particle size distribution.

another 2 hours period. Finally, the mass loss (M_L) expressed as a

Table 5

Volumetric properties and mechanical behavior of experimental mixtures [31].

	Ref. PMB	Ref. 50/70	Exp. 1	Exp. 2
Density	$\textbf{2.011} \pm \textbf{0.0}$	2.032 ± 0.0	1.864 \pm	$1.869~\pm$
			0.0	0.0
Total voids (%)	22.6 ± 0.4	21.3 ± 0.8	$\textbf{27.4} \pm$	$\textbf{27.3} \pm$
			1.0	0.1
Interconnected voids	15.1 ± 0.5	14.6 ± 1.3	$21.0~\pm$	$\textbf{22.7}~\pm$
(%)			1.8	0.2
Binder drain down (%)	0.00	0.00	0.00	0.07
Particle loss- dry	10.6 ± 1.5	15.4 ± 1.6	14.3 \pm	14.1 \pm
conditions (%)			3.1	4.8
Particle loss- wet	10.8 ± 2.0	20.2 ± 4.8	17.9 \pm	$\textbf{24.7}~\pm$
conditions (%)			5.0	4.2
ITS- dry conditions (kPa)	1063.0 \pm	982.0 \pm	896.0 \pm	911.0 \pm
	90.3	104.1	87.6	46.4
ITS- wet conditions	$980.0 \ \pm$	771.0 \pm	796.0 \pm	758.3 \pm
(kPa)	80.7	40.8	20.7	72.0
ITS ratio (%)	92	79	89	83

percentage of the specimens was calculated using Eq. 2. Four replicates were tested and the mean value was used for the analysis.

$$M_L(\%) = -\frac{m_i - m_f}{m_i} \times 100$$
 (2)

Where m_i is the specimen weight before the diesel immersion, and m_f is the specimen weight 24 hours after the diesel immersion (Fig. 5, right).

2.3.4. Phase 4: Multicriteria analysis

In order to define which specimen is superior in terms of overall performance, the multi-criteria analysis "technique of preferential order by similarity to ideal solution" (TOPSIS) is used [33,34].

The objective of TOPSIS is to determine which of the four specimens performs best according to 4 criteria: particle loss, permeability, clogging resistance and fuel spills resistance.

To do this, a decision matrix is established consisting of criteria (columns) and alternatives (rows). Each criterion has the same weight because any of the adverse events studied is equally detrimental to the integrity of the mixture during its useful life. The general form is shown in Eq. 3.

$$M_{\rm d} = \begin{pmatrix} x_{11} & x_{12} & \cdots & x_{1z} \\ x_{21} & x_{22} & \cdots & x_{2z} \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nz} \end{pmatrix}$$
(3)

Where x_{nz} corresponds to the performance of alternative "n" with



Fig. 3. Angeles machine of the Cantabro test (a). Marshall sample at -20°C (b). Marshall sample at 60°C (c).



Fig. 4. (a) Permeability test (b) level 0 clogging (c) level 1 clogging (d) level 2 clogging.

respect to criterion " z ". The next step is to obtain the normalized matrix by means Eq. 4.

$$r_{nz} = \frac{x_{nz}}{\sqrt{\sum_{i=1}^{z} (x_{nz})^2}}, \text{ con } n = -1, 2, -3..., m; z = -1, 2, 3..., m$$
 (4)

Then, the weighted normalized matrix must be obtained, which is nothing more than the multiplication of each value by the weight assigned based on the importance of each criterion, according to Eq. 5.

$$v_{nz} = [w_z \bullet r_{nz}] \tag{5}$$

Where v_{nz} is the weighted normalized decision matrix and w_z is the importance of criterion " z ". Consider the condition of Eq. 6 to be satisfied.

$$\sum_{z=1}^{n} w_z = 1 \tag{6}$$

Then, to determine the positive ideal solution and the negative ideal solution, the case of each criterion is analysed. For example, with respect to particle loss, the beneficial criterion will be the lower of the values, as opposed to permeability, where the predominant value will be the higher value. This is summarized in Eqs. 7 and 8.

$$v^{+} = (v_{1}^{+}, v_{2}^{+}, ..., v_{z}^{+}) = \{(\max v_{nz} | z \in \alpha), \{(\min v_{nz} | z \in \beta)\}$$

$$\in \beta\}$$
(7)

$$v^{-} = (v_{1}^{-}, v_{2}^{-}, ..., v_{z}^{-}) = \{(\max v_{nz} | z \in \alpha), \{(\min v_{nz} | z \in \beta)\} \in \beta\}$$
(8)

With α and β associated with beneficial and detrimental according to each criterion.

Next, it will be necessary to determine the relative distance of the alternatives to the ideal solution and to the anti-ideal solution. This is determined according to Eq. 9 and 10.

Distance ideal solution =
$$d^+ = \sqrt{\sum_{z=1}^{n} (v_{nz} - v_j^+)^2}$$
, n = 1, 2, 3...z (9)

Distance anti ideal solution =
$$d^- = \sqrt{\sum_{z=1}^{n} (v_{nz} - v_j^-)^2}$$
, n
= 1,2,3...z (10)

Finally, the priority ranking is elaborated, giving higher hierarchy to the one that obtained the highest value when applying Eq. 11.

Relative distance to the ideal solution =
$$\frac{d^-}{d^+ + d^-}$$
 (11)

3. Results and discussion

3.1. Phase 1: Evaluation of particle loss in extreme climates

The results of the Cantabro test, after the samples were subjected to extreme conditions, are shown in Fig. 6. The Ref PMB displayed the highest ravelling resistance, which is logical because the samples have a lower content of voids and use a polymer-modified binder. Among



Fig. 5. Fuel spills resistance test (left) and sample after test (right).



experimental mixtures, The Exp 2 had a higher resistance than Exp 1. Furthermore, Exp 2 has an equivalent performance to ref 50/70 despite having a much higher void content. It seems that the polyolefin in Exp 2 had a positive effect. However, the results do not have significant differences (Table 6). At the same time, Exp 1 obtained the worst result with the highest particle loss: the high voids content and Exp 1 fibers do not seem to have a positive effect, this can be explained by the fibers being damaged and exposed by the water that has penetrated, frozen and thawed in the voids by the temperature cycles, result that coincides with that investigated by [35].

There is a high variability in the results, especially in the case of the Exp 1. The p-values are presented in Table 6: Exp. 1 does not have significant differences with any mixture due to its high variability. Exp 2 behavior is significantly different than the Ref PMB. However, Exp 2 does not present significant differences with ref 50/70.

3.2. Phase 2: Permeability and clogging resistance test

Fig. 7 presents the permeability results of the reference and experimental mixtures. At level 0, all the mixtures have permeability values above the recommended minimum of 1.2 mm/s [13,36,37]. Nevertheless, the increment in the percentage of interconnected air voids had a great impact in the permeability. Despite the high permeability of the

Table 6

p-values of Cantabro test.

Mixture	p- value		
	Particle loss	Status	
PMB-Exp 1	0.128	Not significant	
PMB-Exp 2	0.024	Significant	
50/70-Exp 1	0.932	Not significant	
50/70-Exp 2	0.734	Not significant	
Exp 1-Exp 2	0.875	Not significant	

reference mixtures, the experimental mixtures double it, showing a better performance. Table 7 shows the p-values of this tests. In this case, the results of experimental mixtures were statistically different from those obtained by the references mixtures, although there are not significant differences between both experimental mixtures.

The increase in the percentage of air voids also influenced the resistance against clogging of the experimental mixtures. When the first 10 g of fine limestone are added (level 1), the difference between the experimental and reference mixtures is even greater; while the reference mixtures are below the recommended minimum permeability of 1.2 mm/s, the experimental mixtures are still far from this value, and their permeability is about three times that of the reference mixtures.

At level 2, the reference mixtures are approximately impermeable, while the experimental mixtures still show a slight permeability capacity, although lower than the recommended minimum. This means that the experimental mixtures may require three times as much debris as the reference mixtures to clog.

3.3. Phase 3: Resistance to fuel spills test

The damage caused by fuel spills is shown in Fig. 8. In this case, the most important parameter was the type of binder used despite the very high percentage of voids of the experimental mixtures. There were not significant differences among the Exp 1, Exp 2 and Ref PMB mixtures, while the 50/70 reference mixture had a significantly lower resistance against fuel spills (Table 8). In this case, the higher percentage of voids was not a determinant parameter, probably because the fibers are not affected by the fuel, compensating the high percentage of voids.

3.4. Phase 4: Multicriteria analysis

The general decision matrix of the multicriteria analysis was based on the information presented in Fig. 9.

When considering the importance of each performance, the distances of each alternative to the ideal and anti-ideal solution are shown in figure Fig. 10.

The relative distance of each of the mixtures is summarized in Table 9.

Experimental mixture 2, with aramid and polyolefin fibers, turns out to be the closest to the ideal solution. This can be explained by its good performance in terms of particle loss. Also, it had excellent performance in permeability and clogging resistance due to the high number of voids and interconnected voids. Finally, it had a very low mass loss when immersed in fuel due to the polymer-modified binder.

On the other hand, the 50/70 reference blend was the worst performer according to the multi-criteria analysis. This makes sense since it had a regular particle loss in the Cantabro test, despite having a lower percentage of voids than the experimental mixes, probably due to



Fig. 7. Results of permeability and clogging resistance test.

Table 7

p-values permeability test and clogging resistance.

Mixture	xture Permeability test Clogging resistance					
	p- value		p- value		p- value	
	Permeability	Status	Permeability ¹	Status	Permeability ²	Status
PMB-Exp 1	0.029	Significant	0.010	Significant	0.077	Not significant
PMB-Exp 2	0.023	Significant	0.000	Significant	0.010	Significant
50/70-Exp 1	0.025	Significant	0.007	Significant	0.068	Not significant
50/70-Exp 2	0.020	Significant	0.002	Significant	0.012	Significant
Exp 1-Exp 2	0.881	Not significant	0.745	Not significant	0.691	Not significant



Table 8

p-values fuel spill resistance test.

Mixture	p- value		
	Mass loss	Status	
PMB-Exp 1	0.258	Not significant	
PMB-Exp 2	0.391	Not significant	
50/70-Exp 1	0.000	Significant	
50/70-Exp 2	0.002	Significant	
Exp 1-Exp 2	0.398	Not significant	

the type of binder used. At the same time, due to its lower void percentage, it had a very low clogging resistance and also lost mass when immersed in the fuel. The most likely reason for the poor performance is that the binder used was not modified with polymers.







Fig. 10. Euclidean distances to ideal and anti-ideal solutions.

Table 9

Performance ranking of porous asphalt mixtures.

Mixture	Relative proximity	Rank
Exp. 2	0.80	1
Exp. 1	0.66	2
Ref. PMB	0.50	3
Ref. 50/70	0.19	4

4. Conclusions

Functional properties of two experimental porous asphalt mixtures with two types of fibers were studied. Their behaviour was analysed under three adverse conditions to which they may possibly be subjected during their service life. In this respect, it is possible to conclude:

- In terms of particle loss after extreme temperatures, experimental mixtures are equivalent to Ref. 50/70 even though the former have a much higher percentage of voids. However, they have a lower performance than the Ref. PMB.
- The experimental mixtures are much more permeable than the reference mixtures. The experimental mixtures double their drainage capacity and are also more resistant to clogging. This makes the experimental mixtures particularly suitable for managing rainfall in areas suffering from flooding.
- Experimental mixtures showed the same resistance against fuel spills than reference mixture with a polymer modified bitumen. In this case, aramid fibers compensate the effect of the voids, and the type of binder was the most determinant factor.

Finally, it can be affirmed that the Exp 2 mixture was the best performing by the TOPSIS multi-criteria analysis. This can be explained by the fact that Exp. 2 presents acceptable performance against particle loss, a permeability that is statistically higher than the reference mixtures and a resistance to fuel spills equivalent to the reference asphalt mixtures. The behavior of the experimental mixtures makes them suitable for urban context, areas with flooding problem or permeable pavements. For this reason, in the future, its environmental and economic impact should be evaluated to consider the possibility of scaling up this type of pavement.

CRediT authorship contribution statement

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

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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C. Delafuente-Navarro et al.

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