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A combination of DOE – multi-criteria decision making analysis applied to additive assessment in porous asphalt mixture

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ABSTRACT
Porous asphalt (PA) mixture is setting off an attractive alternative to be used as surface layer in pavements due to the many profits this mixture provides in terms of noise, safety and environmental aspects. Nonetheless, its use is quite limited due to its low durability in comparison to dense graded asphalt mixtures, reason for which the incorporation of different additives is recommended. In this study, the impact of different types of binders and additives in porous asphalt mixtures are experimentally assessed. A total of 54 experimental designs were defined through the Taguchi design of experiments method. Total air voids, interconnected air voids, particle loss in dry and wet conditions and binder drain down were the responses obtained from the experimental tests. Since more than one response was obtained, three Multi-Criteria Decision-Making (MCDM) methods were performed to turn the multiple response optimisation problem into single-objective optimisation problem. Based on the experimental results and statistical analysis, polymer modified binders improve the ravelling resistance without affecting the functional performance of the mixture and without presenting the risk of binder drain down.

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KEYWORDS
DOE; MCDM; PA mixture; fibres; polymer modified bitumen; hydrated lime

Highlights

- PA mixtures modified with different additives were experimentally tested.
- A consistent design of experiments was proposed for additive selection in PA mixture.
- A robust MCDM analysis was proposed to deal with the responses obtained.
- PMB 45/80–65 significantly improves the overall performance of PA mixture.

1. Introduction

The use of PA mixtures as surface layer has been considered an attractive choice in the development of the new generation of sustainable and eco-friendly highways infrastructures. This mixture is characterised by the existence of stone-on-stone contact in the coarse granular skeleton and by the high air voids content that helps the water flow through their interconnected air pores, thus increasing the skid resistance and improving the water storm management (Mallick *et al.* 2000, Alvarez *et al.* 2010). Besides, it is well documented that this mixture mitigates the noise pollution generated by the tire-road contact. In the Netherlands, for example, more than 90% of its main highways employ PA mixture as surface layer with the intention of mitigating the noise generated by the passage of the vehicles (Zhang and Leng 2017). The installation of PA mixtures as wearing course provides noise levels reductions of approximately 3–4 dB (Liu *et al.* 2016). Other benefits reported in the literature are the reduction in the urban heat island effect and the enhancement in the driving visibility, especially in rainy days, by inhibiting the formation of mist (Xu *et al.* 2016).

Despite the multiple advantages of the PA mixtures from the safety and environmental point of view, their structural durability is quite weak as compared to the dense graded asphalt mixtures. Due to their large porosity the service life expectancy of the PA mixture is about 10 years approximately (Zwan *et al.* 1972). Ravelling, that can be defined as the loss of particles due to the passage of the vehicles, is considered the main type of failure observed in this type of mixtures (Alvarez *et al.* 2011). This type of failure, that happens in the stone-to-stone contact region (Mo *et al.* 2011), is product of a poor asphalt binder film thickness (Mallick *et al.* 2000) and a deficient adhesion in the asphalt binder-aggregate matrix due to environmental conditions (i.e. oxidation and moisture damage) (Poulikakos and Partl 2004). According to Massahi *et al.* (2018), several factors influence the ravelling phenomena including the void percentage in the mixture and the binder-aggregates cohesive and adhesive capacity. For that reason, porous friction courses are being developed with high quality materials among which are the modified binders with polymers. The research carried out by Kandhal and Mallick (1999) showed that the use of polymer modified binders and fibres in PA mixtures decrease the abrasion loss and hence improve the durability of the mixture. Similarly, according to Spanish regulations (PG-3 2015), only the use of polymer modified binders for roads with high traffic levels is allowed. China has popularised the use of PA mixtures in many regions and currently employs modified bitumen as binder (Xu *et al.* 2016). Furthermore, based on the

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international experience, Nielsen (2006) reported that countries that design PA mixtures with modified binders do it because they improve aging resistance and increase the binder film thickness. In another research, Punith *et al.* (2004) observed that an increase in the thickness of the binder film can be easily achieved by employing a polymeric asphalt. Likewise, the authors reported improvements in the cohesion, cracking resistance and durability of PA mixtures. In other countries like France and Netherlands, the use of polymer modified binder is not common and hence it is only used for special purposes (Nielsen 2006). Moleenar *et al.* (2004) reported that there is still no information on how PMB actually improves the ravelling resistance of PA and hence whether employing this modified bitumen is cost-effective.

Other additives have gained attention as a reinforcement in PA mixtures such as the use of fibres (Ma *et al.* 2018, Gupta *et al.* 2019). Natural fibres such as cellulose are quite common as stabiliser agent to prevent the binder leakage and for allowing the increase of the binder film thickness. However, the use of synthetic fibres seems to be another option since they act as a reinforcement while minimise the drainage problems. In hot mix asphalt, it is documented that fibres contribute to support the tensile loads of the mixture generated by the passage of the vehicles. Besides, it is mentioned that fibres generate a three-dimensional networking effect favouring the interlocking effect with the aggregates inside the mix (Abtahi *et al.* 2010). Similarly to polymers, fibres contribute to increase the viscosity and stiffness of asphalt binders (Chen *et al.* 2009). Some experience found in the literature suggests that fibres act as a barrier preventing the formation and propagation of cracks (Park *et al.* 2015). Some mechanical properties such as fatigue life, moisture sensitivity, thermal cracking and ravelling resistance are improved in asphalt mixtures with fibres inclusion (Xu *et al.* 2010, Kim *et al.* 2018). In addition, previous authors have reported that synthetic fibres help to minimise the binder drain down significantly (Tanzadeh and Shahrezagamasaei 2017).

The large porosity and the poor contact regions contained in the porous asphalt make this mixture also quite vulnerable to moisture damage and prone to stripping phenomenon, which can be described as the loss of adherence between the surface of coarse particles and asphalt binder by the action of water (Little *et al.* 2006). To deal with the aforementioned, some additives commonly denominated anti-stripping agents have been developed in order to alter the physicochemical properties of the binder, making it more hydrophobic (Ravi Shankar *et al.* 2018). More clearly, these additives help to improve the bonding forces existing between the bituminous binder and the aggregates. Previous studies also argue that anti-stripping additives improve also the aging characteristics of asphalt binder (Hunter and Ksaibati 2002). On the other hand, hydrated lime (HL) is considered a potential filler that acts as anti-stripping additive, turning the hydrophilic particles into hydrophobic (Khodaii *et al.* 2012). Several improvements in terms of toughness, rutting and fatigue resistance have been reported with the use of HL (Hunter and Ksaibati 2002, Haghshenas *et al.* 2015). Further investigations reported that the binder interacts with HL increasing the stiffness of the mastic and decreasing the empathy with water (Hunter and Ksaibati 2002, Arabani *et al.* 2012). Similarly, HL improves the adhesion between the surface of the aggregate and the binder, especially in those aggregates more susceptible to water damage like siliceous aggregates.

The application of different additives always has bilateral effects in PA mixtures. While they improve some mechanical properties, the performance in other aspects such as functionality or binder drain down issues might worsen. In the scientific literature, PA mixtures have commonly been analysed by traditional single-factor experimentation (i.e. testing one additive at a time); however, this procedure can be time-consuming and does not consider interactions between other additives or components (i.e. asphalt binder content) (Segurola *et al.* 1999, Varanda *et al.* 2017). In addition, it is still unclear what kind of admixture would be the most promising in terms of durability and functionality since few research efforts have been made considering various additives. As an alternative way, Taguchi design of experiments (DOE) is a statistical technique that can be employed to identify the individual and interactive effects of many factors and proportions that influence the response of the output parameters.

The objective of this research was to perform a laboratory assessment of different additives of the PA mixture and evaluate their effects in many responses from the functional and mechanical points of view. Accordingly, the Taguchi DOE method was applied to define the orthogonal array of experiments and a Multi-Criteria Decision-Making (MCDM) analysis was proposed to turn the multiple response problem into a single response problem. The application of the MCDM analysis comprised two main steps. The first one corresponded to identify the relative weights of the measured responses and the second one served to establish a unified index of all criteria and to perform a preference ranking among the set of alternatives. CRiteria Importance Through Inter-criteria Correlation (CRITIC) method was chosen for criteria elicitation since it is considered a multi objective decision-making approach where the participation of decision makers is not necessary and which facilitates the automated decision-making process. On the other hand, the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) was selected as the multi response optimisation technique to transform all the individual responses into a unified index. This technique is easily applied and does not require high computational cost when two or more responses are involved in the calculation process (Şimşek and Uygunoğlu 2016). TOPSIS approach relies on the concept of the positive and negative ideal solutions as the two reference points (Hwang and Yoon 1981). Accordingly, the preferred alternative would be the closest to the positive ideal solution and the farthest to the negative ideal solution. Likewise, the Weighted Aggregated Sum Product ASsessment (WASPAS), which considers the combination of two techniques denominated Weighted Sum Model (WSM) and Weighted Product Model (WPM), was chosen as an alternative MCDM analysis to check the robustness of the unified index and preference ranking due to the changes in the methodology applied. In previous investigations, Slebi-Acevedo *et al.* (2019, 2020a) evaluated the effects of fibres and polymer modified binders in PA mixture through MCDM techniques and conducted a study for assessing the impact of PA mixtures modified with HL and fibres combining

Table 1. Main properties of the different binders.

Binder	Binder type	Test	Standard Method	Value
A	50/70 conventional penetration grade.	Penetration at 25°C (mm/10)	EN 1426	57.00
		Specific Gravity	EN 15326	1.04
		Softening point (°C)	EN 1427	51.60
		Fraass brittle point (°C)	EN 12593	−13.00
		Viscosity at 100°C (Pa . s)	EN 13302	4840
B	PMB 45/80-65 Polymer modified binder	Penetration at 25°C (mm/10)	EN 1426	49.50
		Specific Gravity	EN 15326	1.03
		Softening point (°C)	EN 1427	72.30
		Fraass fragility point (°C)	EN 12593	−13.00
		Ductility force at 5°C (J/cm^2)	EN 13589	3.11
		Elastic recovery at 25°C (%)	EN 13398	90.00
		Viscosity at 100°C (Pa . s)	EN 13302	23100
C	PMB 45/80 - 75 Polymer modified binder	Penetration at 25°C (mm/10)	EN 1426	55.00
		Specific Gravity	EN 15326	1.03
		Softening point (°C)	EN 1427	74.10
		Fraass fragility point (°C)	EN 12593	−15.00
		Ductility force at 5°C (J/cm^2)	EN 13589	7.80
		Elastic recovery at 25°C (%)	EN 13398	92.00
		Viscosity at 100°C (Pa . s)	EN 13302	25150

design of experiments and MCDM analysis. The contribution of this study is the compilation of the additives previously studied along with the incorporation of new binders modified with polymers and anti-stripping agents. While the previous research contemplated an experimental design of 18 mixtures, this research brings together 54 different experimental mixtures, based on which a total of 324 compacted mixtures were performed.

2. Materials and experimental set-up

2.1. Materials

2.1.1. Binders

In this study, three types of binders were used: a conventional 50/70 penetration grade binder (binder A), and two polymer modified binders, PMB 45/80–65 (Binder B) and PMB 45/80–75 (Binder C). Their main properties according the supplier are presented in Table 1.

2.1.2. Aggregates

Ophite, which is a type of igneous rock, was used as the coarse fraction while the fine fraction was completed with limestone. Characterisation tests were performed according to European standards as shown in Table 2.

2.1.3. Fibres

In this study, a set of polyolefin-aramid fibres 19 mm long was selected as potential additive to be implemented in PA mixtures. Previous investigations have reported an outstanding performance in bituminous mixtures incorporating this set of fibres (Slebi-Acevedo *et al.* 2020a). Aramid fibres are characterised by having high tensile strength properties (>2700 MPa) and high thermal resistance (>450°C) as compared to other type of synthetic fibres (polyester, polypropylene, polyacrylonitrile). These fibres have been used since they do not melt during the mixing process, which provides a reinforcing mechanism within the mixture. On the other hand, polyolefin fibres have low melting point in comparison with aramid fibres and hence they act as a bitumen modifier (Fazaeli *et al.* 2016). In addition, these fibres act as a dispersing agent, avoiding that aramid fibres tangle together and facilitating their homogeneous mixing. The density of the set obtained according to the standard method EN 1097 – 6 was 0.947 g/cm^3. An illustration of the fibres is displayed in Figure 1.

Table 2. Physical properties of the aggregates used.

Characteristic	Value	Standard	Specification
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 Value	60	EN 1097 - 8	≥56
Fine Aggregate			
Specific Weight (g/cm^3)	2.724	EN 1097 - 6	–
Sand Equivalent	78	EN 933 – 8	> 55

2.1.4. Hydrated lime

Hydrated lime is commonly used as part of the filler in bituminous mixtures to improve the resistance to stripping and to plastic deformations as well as to decrease the stiffness rate due to the oxidation of bitumen (Rasouli *et al.* 2018). According to the provider, the main characteristics of the HL are given in Table 3. HL was initially mixed with aggregates before the addition of binder.

2.1.5. Liquid anti-stripping (LAS)

Due to the high exposition of PA mixtures to the action of water, a liquid anti-stripping (LAS) was also considered a potential admixture to decrease the moisture damage. Normally, LAS is used to enhance the adhesion in the binder-aggregate interface. More specifically, the amines, main component of the LAS, contribute to decrease the surface tension of the particles, thus improving the coverage area (Ravi Shankar *et al.* 2018). Along with the amines, the LAS used in the research is composed by phosphoric acid with fat alcohol reactions. Table 4 details the main physical properties of the anti-stripping additive used.

Figure 1. An illustration of polyolefin-aramid fibres.

2.2. Experimental set-up

2.2.1. Specimen preparation

Compacted PA mixtures were prepared according to the Spanish specification 'General Technical Requirements for Works of Roads and Bridges' (PG-3 2015), document approved by the Ministry of Public Works of the Government of Spain. The particle size distribution of the mixture corresponded to an open gradation curve which falls within the upper and lower limits established in the Spanish standard (PG-3 2015), as shown in Figure 2. For Binder A, the mixing temperature was 150°C while in the case of polymer modified binders B and C mixing temperatures of 170°C and 180°C were employed, respectively, as recommended by the provider. In all cases, the aggregates temperatures were 15°C higher than the mixing temperature according to the type of bitumen. Two binder contents of 4.50% and 5.00% were set to produce the PA mixtures in this study. In the case of the mixtures modified with fibres, the fibre addition was carried out by dry method, meaning that fibres were initially mixed and homogeneously distributed with aggregates prior to the addition of bitumen to the mixture. In the case of the mixtures treated with HL, the amount of HL added to the mixture was 3.0% by weight of aggregate, and it was added as a replacement of part of the filler within the mix. Finally, concerning the mixtures incorporating LAS, a 0.4% of additive by weight of bitumen was added to the bitumen and mixed continuously at 15,000 rpm for 3 min using a homogeniser, after which the binder/anti-stripping solution was placed into the hot aggregates previously mixed. The compaction of samples was done by applying 50 blows per side with the Marshall Hammer following the European Standard EN 12697 – 30.

Table 3. Main characteristics of HL.

Properties	value
Density (g/cm^3)	1.959
CaO content (%)	≥90
MgO content (%)	≤5
CO2 content (%)	≤4
Remained on sieve 0.2 mm (%)	≤2
Remained on sieve 0.09 mm (%)	≤7

Table 4. Physical properties of the LAS.

Properties	Value
Aspect	Viscous liquid
Color	Amber
Density at 20°C (g/cm^3)	0.90 ± 0.10
Viscosity at 20°C (cP)	250 ± 100
Flashpoint (°C)	> 150
pH	Acid

2.2.2. Functional tests

The air voids play a decisive role in the functional performance of the PA mixture as they help the water to drain through its internal structure, reducing this way the hydroplaning of the vehicles and the splash and spray effect during the rainy seasons, as well as mitigating the noise generated by the passage of vehicles. In this study, the total air voids (T_{AV}) were measured based on the volumetric determination test according to European Standard EN 12697 – 8. Similarly, the interconnected air voids (I_{AV}) were also calculated as another control response of the functionality of the mixture. Based on the volumetric properties of the sample, T_{AV} and I_{AV} responses were calculated by using Equations (1) and (2).

$$T_{AV}\ (\%) = \left(1 - \frac{m_{dry}}{V \cdot G_{mm}}\right) \times 100 \tag{1}$$

$$I_{AV}\ (\%) = \left(\frac{V - \dfrac{m_{dry} - m_{satw}}{\rho_{water}}}{V}\right) \times 100 \tag{2}$$

Where m_{dry} corresponds to the mass of the sample weighted in dry conditions, V corresponds to the volume of the sample geometrically calculated, G_{mm} is the maximum theoretical specific gravity of the mixture and m_{satw} is the mass of the saturated sample recorded in water.

2.2.3. Durability tests

Ravelling is considered the most common distress observed in PA mixtures (Alvarez *et al.* 2011, Putman and Kline 2012, Wu *et al.* 2020). This phenomenon can be described as the loss of aggregate due to the abrasive load generated by the passage of vehicles. Cantabro particle loss test developed in Spain (Calzada-Perez and Perez-Jimenez 1984) is one of the most popular tests to measure the ravelling resistance and so it was adopted in this study. The particle loss was actually calculated in dry and wet conditions according to European EN 12697 – 17 and Spanish NLT 362/92 standards, respectively. The test consists of measuring the loss of particles when a compacted PA mixture is subjected to abrasion in the Los Angeles machine without steel spheres. The test is performed at 25°C and a rotation speed of 30–33 rpm, and the mass loss after 300 revolutions is recorded. The particle loss in dry conditions

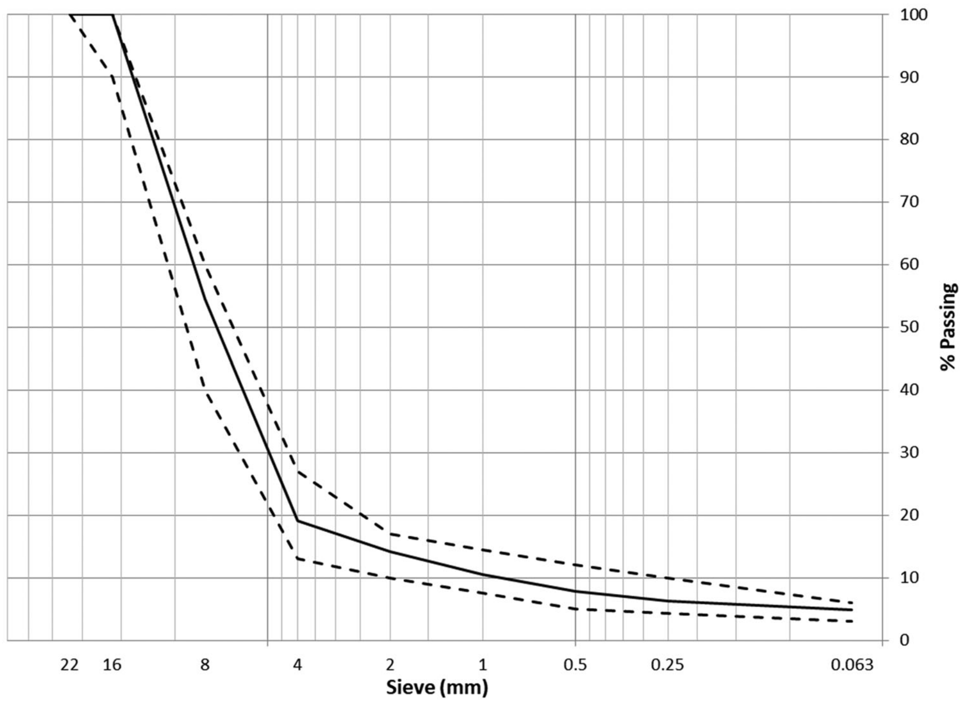


Figure 2. Open Gradation curve of the PA mixture.

($PL_{.dry}$) is then calculated by using Equation (3).

$$PL\ (\%) = \left(\frac{m_1 - m_2}{m_1}\right) \times 100 \quad (3)$$

Where m_1 and m_2 are the initial and final masses of the specimens. To measure the particle loss in wet conditions (PL_{wet}), the compacted samples are initially submerged in water at 60°C for 24 h and then placed in air conditions at 25°C for 24 h prior to carrying out the test.

2.2.4. Binder drain down test

Due to the low amount of fines in the mix, porous asphalt mixtures are prone to present binder drain down. In this study, the stability of the mixture was evaluated through the mesh basket drain down test according to European Standard EN 12697 – 18. The test calculates the portion of binder (*BD*) of an uncompacted PA mixture which separates itself from the total mixture and it is deposited outside of the mesh basket. In the case of samples manufactured with conventional 50/70 penetration grade binder, the test was carried out 25°C above the mixing temperature. As for the mixes prepared with polymer modified binders, the test was performed at a temperature 15°C higher than the manufacturing temperature. This test was replicated twice.

3. Methodology

Once the materials and the experimental set-up were defined, this section was focused on clarifying the methodology carried out in the research, which comprises two stages. Firstly, the Taguchi design of experiments method was conducted to perform the orthogonal array of experiments and to help to find out the more relevant control factors as well as the main parametric levels per control factor in the experimental evaluation of the PA mixture. In the second stage, a MCDM analysis was proposed to turn the multiple responses into a single response.

3.1. Design of experiments

As mentioned before, Taguchi technique was employed to plan and model the design of experiments. Full and fractional orthogonal arrays can be developed to analyse the different interactions between the parametric levels. Although fractional factorial design gives information concerning the interaction among the different parameters with reduced experimentation, in this study the full factorial orthogonal array was applied since most of the input parameters are categorical and the most complete reliable information with respect to the interaction between parameters is necessary. Therefore, a robust and consistent L_{54} orthogonal array was planned for experimentation. Binder Type (BT), Binder Content (BC), Fibre Content (FC) and Anti-stripping Admixture (ASA) were the main control factors considered, while total air voids, interconnected air voids, particle loss in dry and wet conditions and binder drain down test were the principal responses to be analysed individually. All control factors contain three parametric levels with the exception of BC, for which only two parametric levels were considered. Factors such as coarse aggregates and fine aggregates were kept as constant. The combination of the different parametric levels for the experimental design according to Taguchi method is shown in Table 5. A set of 54 experimental designs with six cylindrical specimens each were analysed as L_{54} orthogonal array and hence a total of 324 compacted PA mixtures were manufactured. Table 6 details the parametric levels presented in each PA mixture design.

Table 5. Control factors with their corresponding parametric levels.

Control factors	Notation	Level 1	Level 2	Level 3
Binder type	BT	A	B	C
Binder content (%)	BC	4.50	5.00	–
Fibre content (%)	FC	0	0.05	0.15
Anti-stripping admixture	ASA	none	HL	LAS

3.2. Multi-criteria decision-making analysis

With the Taguchi technique, individual responses can be analysed independently. However, when multiple criteria are involved in a decision-making process, an additional tool is required. Multi-criteria decision-making analysis is a powerful approach widely used in expert systems, maintenance optimisation and research operations, which can deal with the selection of the preferred alternative from a set of alternatives taking into account numerous criteria (Salih *et al.* 2019). In this study, three different MCDM analysis denoted as CRITIC, TOPSIS and WASPAS were utilised to select the additives that most positively affect the overall performance of the mixture. With this approach, the multi-response problem is turned into a single-response problem, which makes it easier the identification of the combinations of parametric levels of the different control factors yielding with the ideal performance.

3.2.1. CRITIC method

As proposed by Diakoulaki *et al.* (1995), CRITIC is the acronym for CRiteria Importance Through Inter-criteria Correlation. This method is aimed at determining the relative weights of the different responses in an objective manner, in such a way that the participation of decision makers is not necessary. CRITIC considers both the contrast intensity of each criterion and conflict assessment between the criteria of the decision-making process. As multiple data set were obtained due to the large number of experiments performed, this approach is considered appropriate for the allocation of weights. Further details about the steps and equations used for criteria elicitation according to the CRITIC method can be consulted in the following references: (Diakoulaki *et al.* 1995, Slebi-acevedo *et al.* 2020b).

3.2.2. TOPSIS method

TOPSIS is one of the most preferred methods to be applied to problems related with preference ranking of various alternatives and to convert multi-response optimisation problems into single-response optimisation problems (Şimşek and Uygunoğlu 2016, Kumar *et al.* 2019). According to the TOPSIS technique, positive and negative ideal solutions are calculated to identify the most preferred alternatives. Accordingly, the best option is the one that has the shortest Euclidean distance from the positive ideal solution and the largest Euclidean distance from the negative ideal solution. The closeness coefficient (*CC*) values are determined for each alternative to carry out the preference ranking. In consequence, larger values of CC implies better performance of the alternative. Further information concerning the mathematical algorithm is available in (Gul and Guneri 2016, Slebi-Acevedo *et al.* 2019).

Table 6. Full factorial design with Taguchi L_{54} orthogonal array.

Design	Code (Design-BT-BC-FC-ASA)	BT	BC (%)	FC (%)	ASA
1	1-A-4.50-0.00-None	A	4.50	0.00	None
2	2-A-4.50-0.00-HL	A	4.50	0.00	Hydrated lime
3	3-A-4.50-0.00-LAS	A	4.50	0.00	Liquid anti-stripping
4	4-A-5.00-0.00-None	A	5.00	0.00	None
5	5-A-5.00-0.00-HL	A	5.00	0.00	Hydrated lime
6	6-A-5.00-0.00-LAS	A	5.00	0.00	Liquid anti-stripping
7	7-B-4.50-0.00-None	B	4.50	0.00	None
8	8-B-4.50-0.00-HL	B	4.50	0.00	Hydrated lime
9	9-B-4.50-0.00-LAS	B	4.50	0.00	Liquid anti-stripping
10	10-B-5.00-0.00-None	B	5.00	0.00	None
11	11-B-5.00-0.00-HL	B	5.00	0.00	Hydrated lime
12	12-B-5.00-0.00-LAS	B	5.00	0.00	Liquid anti-stripping
13	13-C-4.50-0.00-None	C	4.50	0.00	None
14	14-C-4.50-0.00-HL	C	4.50	0.00	Hydrated lime
15	15-C-4.50-0.00-LAS	C	4.50	0.00	Liquid anti-stripping
16	16-C-5.00-0.00-None	C	5.00	0.00	None
17	17-C-5.00-0.00-HL	C	5.00	0.00	Hydrated lime
18	18-C-5.00-0.00-LAS	C	5.00	0.00	Liquid anti-stripping
19	19-A-4.50-0.05-None	A	4.50	0.05	None
20	20-A-4.50-0.05-HL	A	4.50	0.05	Hydrated lime
21	21-A-4.50-0.05-LAS	A	4.50	0.05	Liquid anti-stripping
22	22-A-5.00-0.05-None	A	5.00	0.05	None
23	23-A-5.00-0.05-HL	A	5.00	0.05	Hydrated lime
24	24-A-5.00-0.05-LAS	A	5.00	0.05	Liquid anti-stripping
25	25-B-4.50-0.05-None	B	4.50	0.05	None
26	26-B-4.50-0.05-HL	B	4.50	0.05	Hydrated lime
27	27-B-4.50-0.05-LAS	B	4.50	0.05	Liquid anti-stripping
28	28-B-5.00-0.05-None	B	5.00	0.05	None
29	29-B-5.00-0.05-HL	B	5.00	0.05	Hydrated lime
30	30-B-5.00-0.05-LAS	B	5.00	0.05	Liquid anti-stripping
31	31-C-4.50-0.05-None	C	4.50	0.05	None
32	32-C-4.50-0.05-HL	C	4.50	0.05	Hydrated lime
33	33-C-4.50-0.05-LAS	C	4.50	0.05	Liquid anti-stripping
34	34-C-5.00-0.05-None	C	5.00	0.05	None
35	35-C-5.00-0.05-HL	C	5.00	0.05	Hydrated lime
36	36-C-5.00-0.05-LAS	C	5.00	0.05	Liquid anti-stripping
37	37-A-4.50-0.15-None	A	4.50	0.15	None
38	38-A-4.50-0.15-HL	A	4.50	0.15	Hydrated lime
39	39-A-4.50-0.15-LAS	A	4.50	0.15	Liquid anti-stripping
40	40-A-5.00-0.15-None	A	5.00	0.15	None
41	41-A-5.00-0.15-HL	A	5.00	0.15	Hydrated lime
42	42-A-5.00-0.15-LAS	A	5.00	0.15	Liquid anti-stripping
43	43-B-4.50-0.15-None	B	4.50	0.15	None
44	44-B-4.50-0.15-HL	B	4.50	0.15	Hydrated lime
45	45-B-4.50-0.15-LAS	B	4.50	0.15	Liquid anti-stripping
46	46-B-5.00-0.15-None	B	5.00	0.15	None
47	47-B-5.00-0.15-HL	B	5.00	0.15	Hydrated lime
48	48-B-5.00-0.15-LAS	B	5.00	0.15	Liquid anti-stripping
49	49-C-4.50-0.15-None	C	4.50	0.15	None
50	50-C-4.50-0.15-HL	C	4.50	0.15	Hydrated lime
51	51-C-4.50-0.15-LAS	C	4.50	0.15	Liquid anti-stripping
52	52-C-5.00-0.15-None	C	5.00	0.15	None
53	53-C-5.00-0.15-HL	C	5.00	0.15	Hydrated lime
54	54-C-5.00-0.15-LAS	C	5.00	0.15	Liquid anti-stripping

Table 7. Experimental results of the individual responses.

	T_{AV} (%)		I_{AV} (%)		PL_{dry} (%)		PL_{wet} (%)		BD (%)
Design	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean
1	21.42	0.89	14.59	1.32	14.02	0.77	20.47	5.88	0.01
2	21.33	0.33	15.10	0.37	14.92	1.16	14.29	1.65	0.00
3	23.01	0.77	16.86	0.80	13.80	2.45	17.42	1.29	0.63
4	19.84	2.01	13.02	2.78	6.76	2.65	15.32	3.20	0.40
5	19.57	0.59	12.68	0.92	11.75	2.41	11.75	2.41	0.11
6	20.43	1.99	13.73	3.09	12.54	2.24	6.67	1.96	2.03
7	20.59	1.89	14.36	2.22	10.57	4.80	10.81	3.54	0.00
8	22.08	0.70	16.31	0.52	8.15	2.59	9.57	1.39	0.00
9	21.87	0.43	15.36	0.49	7.25	2.00	8.85	0.71	0.30
10	21.12	0.40	15.16	0.80	5.16	2.77	7.19	1.68	0.28
11	21.04	0.63	15.05	0.83	4.15	0.27	6.11	1.08	0.05
12	21.00	0.71	14.19	1.22	5.80	1.32	9.30	4.29	0.10
13	22.13	0.99	15.21	1.40	10.29	0.24	10.47	2.30	0.33
14	21.38	0.25	15.53	0.63	10.33	1.48	10.19	2.36	0.00
15	22.07	0.14	15.49	0.08	11.71	2.09	12.91	0.95	0.32
16	21.46	0.97	14.89	1.40	6.25	0.14	6.39	0.31	1.43
17	20.05	0.13	14.21	0.19	5.89	0.69	6.38	0.89	0.03
18	20.12	0.23	13.30	0.24	10.39	3.28	10.70	1.12	1.74
19	21.36	0.35	15.59	1.01	12.52	1.99	39.85	10.23	0.01
20	20.74	0.55	14.18	0.74	14.00	1.59	16.64	2.56	0.00
21	21.51	1.35	14.90	1.49	9.33	1.28	15.32	2.69	0.59
22	19.67	0.40	13.57	0.61	7.90	4.27	15.71	1.89	0.03
23	20.04	0.37	13.75	0.45	10.32	1.68	11.33	0.75	0.01
24	20.71	0.54	14.26	0.85	7.68	2.45	12.09	1.27	1.17
25	20.81	2.14	14.47	2.66	5.94	2.20	7.80	3.52	0.00
26	21.50	0.50	15.29	0.73	6.99	1.46	8.83	1.16	0.01
27	21.12	0.40	14.29	0.53	5.44	0.81	6.09	1.20	0.06
28	18.69	1.88	12.39	2.80	8.12	5.19	5.62	0.26	0.04
29	20.04	0.15	13.62	0.52	4.18	0.58	5.06	1.11	0.01
30	21.29	0.61	15.00	0.77	5.32	2.26	6.42	0.95	0.07
31	20.95	0.11	14.17	0.15	6.95	2.66	14.40	2.85	0.19
32	20.24	0.64	14.12	1.06	8.93	3.14	9.78	0.65	0.00
33	22.03	0.15	15.26	0.10	14.70	1.88	13.12	1.71	0.21
34	20.09	0.09	13.88	0.02	5.70	1.48	7.78	0.36	0.57
35	19.64	0.55	14.00	0.40	5.09	1.07	6.00	1.39	0.00
36	21.08	0.79	14.53	1.05	7.23	1.80	12.66	2.58	0.09
37	23.22	0.22	17.26	0.38	19.71	2.01	35.95	5.05	0.02
38	21.05	0.43	14.45	0.39	13.17	1.12	18.05	2.34	0.00
39	20.07	1.35	13.35	1.14	7.50	1.31	9.97	0.70	0.10
40	20.38	0.88	14.14	1.06	15.66	1.86	22.74	3.15	0.01
41	20.22	0.32	13.83	0.54	10.87	2.26	11.06	3.14	0.00
42	21.02	2.22	15.11	3.04	8.28	2.99	7.54	2.48	0.26
43	19.50	1.14	13.12	0.91	8.47	3.70	7.73	0.45	0.04
44	21.75	0.68	15.31	0.88	8.35	2.13	10.89	1.34	0.00
45	21.27	0.42	14.90	0.41	7.07	0.08	9.25	1.28	0.00
46	20.22	0.17	14.15	0.11	4.77	1.02	5.26	0.76	0.05
47	20.23	0.32	13.78	0.41	4.66	0.18	5.61	0.19	0.02
48	20.77	0.42	14.12	0.16	4.54	0.91	4.74	1.11	0.05
49	21.44	0.26	14.49	0.61	7.68	0.63	10.19	1.41	0.05
50	21.04	0.59	15.11	0.77	8.59	2.34	14.21	1.11	0.00
51	21.37	0.98	15.02	1.03	10.82	2.37	14.09	3.06	0.00
52	19.97	0.69	13.04	0.78	5.10	1.13	7.15	1.25	0.37
53	20.46	0.15	14.60	0.20	5.62	1.66	7.82	1.11	0.00
54	19.30	0.18	12.96	0.38	7.85	2.63	8.94	1.54	0.01

3.2.3. WASPAS method

The Weighted Aggregated Sum Product Assessment (WASPAS) was considered as an alternative MCDM analysis to transform the multiple-responses into single-response problem. This method, recently proposed by Chakraborty and Zavadskas (2014, Chakraborty *et al.* 2015), combines two approaches previously developed, the Weighted sum model (WSM) and the Weighted product model (WPM), providing a more robust and accurate methodology (Mardani *et al.* 2017). In WASPAS, the Joint Performance Score (JPS) values were also calculated for each of the alternatives. Similar than TOPSIS technique, higher values of JPS indicate a better performance as a unified index. The steps involved in solving multi-objective decision-making problem through WASPAS approach are explained in more detail in (Chakraborty *et al.* 2015, Keshavarz Ghorabaee *et al.* 2015, Slebi-acevedo *et al.* 2020b).

4. Results and discussion

4.1. Analysis of individual responses

The experimental results are shown in Table 7. First, all the responses were analysed individually in terms of main effect plots for means. Then, the MCDM analysis was performed to calculate the relative weights of the criteria in order to

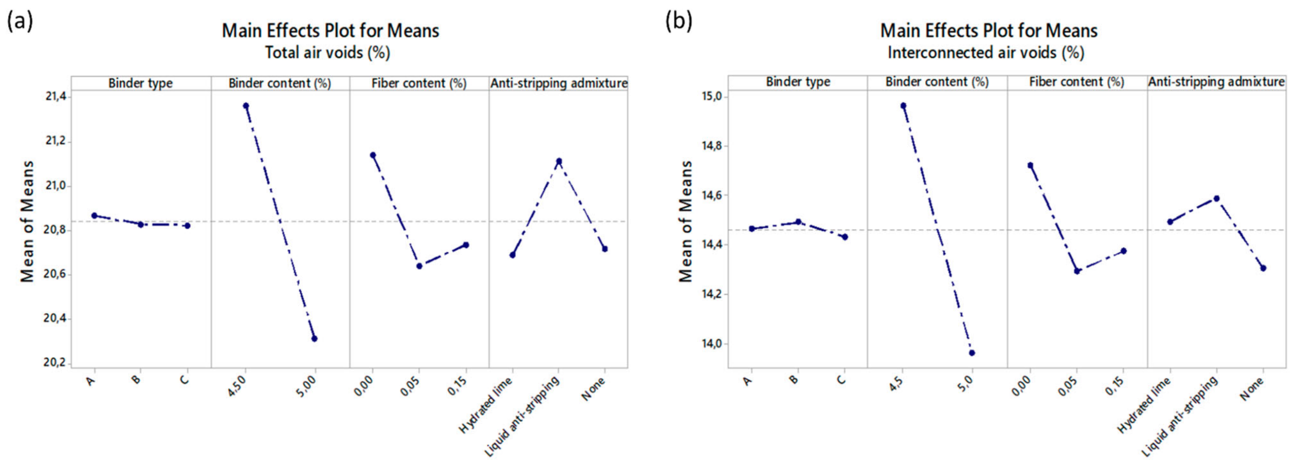


Figure 3. Main effects plot for means; (a) Total air voids; (b) Interconnected air voids.

turn the multiples response problem into a single response problem and to establish a unified index that allows the development of a preference ranking among the alternatives.

4.1.1. Functional responses

Figure 3 illustrates the main effects plot for mean values of T_{AV} and I_{AV}. According to these results, the Binder Content was the most relevant factor, affecting to both T_{AV} and I_{AV} functional responses, followed by fibre content, anti-stripping admixture and binder type. In the same way, the addition of fibres resulted in a decrease in the total and interconnected air voids whereas the use of liquid anti-stripping slightly increased the voids inside the mix. Concerning the use of hydrated lime as part of the filler, not significant changes were observed in total air voids and a slight increment occurred in the interconnected air voids. The fact that the type of bitumen does not significantly affect the functional response of the mixture is also to be hightlighted. In other words, regardless of the type of bitumen used, there are not significant changes with respect to the total and interconnected voids of the mixture. The close similarity found between total and interconnected air voids responses could be explained due to the narrow direct positive relation that exists between both responses, with a Pearson correlation coefficient of 86.92%, as shown in Figure 4. Despite the modification of all the PA mixtures designs, the range of values for functional responses varied from 18.69% to 23.22% for T_{AV} and from 12.39% to 14.46% for I_{AV}. Although in the majority of countries in Europe the minimum recommended porosity is 20%, in other countries such as the USA the recommended porosity is no less than 18% (Wu *et al.* 2020). Therefore, it could be said that all mixture designs could perform well despite the reductions in voids.

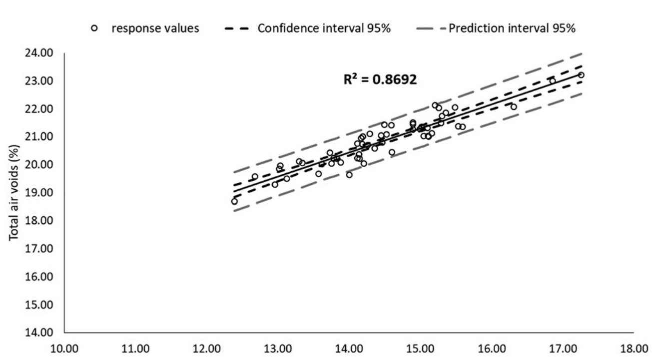
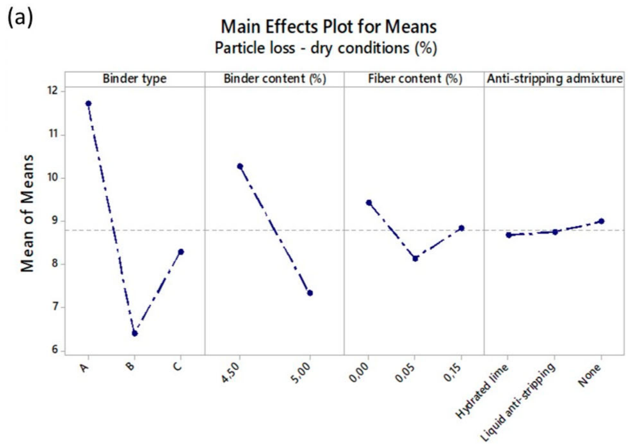


Figure 4. Relationship found between interconnected and total air void response.

4.1.2. Durability responses

The durability of the mixture was analysed in terms of particle loss in dry and wet conditions since it is the typical failure observed in PA mixtures, as said before. The main effects plot for mean values of PL_{dry} and PL_{wet} are illustrated in Figure 5. For the PL_{dry} response, BT was the most relevant factor followed by BC, FC and ASA factors. In addition, the optimal parametric levels for each control factor were found to be binder B for BT; 5.00% for BC; 0.05% for FC and HL for ASA. Regarding the PL_{wet} response, BT was also the most influential factor followed by BC, ASA and FC. The optimal levels for each control factor were very similar when compared to particle loss in dry conditions with the exception of the FC factor, being the use of fibres almost negligible. It is worth mentioning that in both cases, the use of polymer modified binder improves significantly the durability of the PA mixture. Previous investigations refer that binders modified with polymers have higher flexibility than conventional binders and hence, they enhance the bonding performance between the asphalt and the aggregates (Moreno-Navarro *et al.* 2015). Similarly, other authors argue that PMBs with high viscosities increase the adhesion between the binder and the particles, in agreement with the results found by Jiao *et al.* (2019). Additionally, greater amounts of binder help to coat aggregates effectively, avoiding the loss of particles. Concerning the addition of fibres, only improvements were appreciated in dry conditions while in wet conditions there is not a significant impact. Despite the latter, fibres prevent the binder drain down in the mix (see Section 4.1.3),



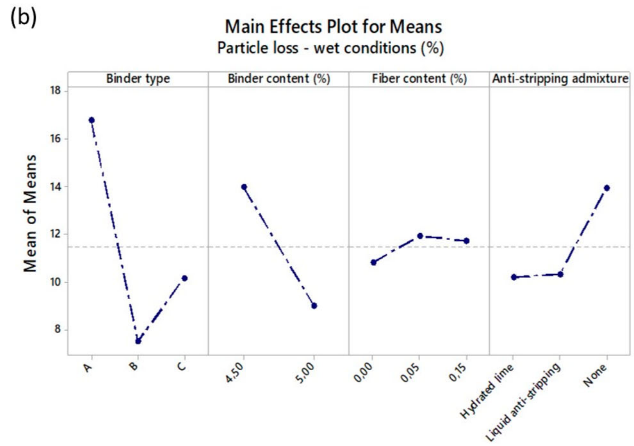


Figure 5. Main effects plot for means; (a) particle loss – dry conditions; (b) particle loss – wet conditions.

making it possible to increase the amount of bitumen and achieving higher binder quantities and greater durability of the mixture. The presence of hydrated lime and liquid anti-stripping reduced the particle loss when the samples were tested in wet conditions. However, in dry conditions, the inclusion of these additives did not depict a significant improvement in the ravelling resistance. Previous studies are consistent with this and have revealed that the use of these additives is suitable to increase the resistance against the moisture damage (Movilla-Quesada *et al.* 2012, Mohd Shukry *et al.* 2016, 2018).

4.1.3. Binder drain down response

The binder drain down was also tested in order to evaluate the stabiliser potential of the different additives used in the study. Based on the scientific literature, a maximum value of 0.3% is recommended for binder drain down in PA mixtures (Lyons and Putman 2013). Figure 6 shows the main effects plot for mean values of the binder drain down response. It can be observed that the ASA control factor was the most influential factor in affecting this response. This is because the liquid anti-stripping is the input that affects the binder drain down the most. It is believed that liquid anti-stripping softens the bitumen, making it more susceptible to draining. On the other hand, hydrated lime contributes positively to reduce the leakage of binder. Fibre content is the second factor that affects this response the most. According to Figure 6, the higher amount of fibres the lower the binder leakage. Therefore, polyolefin-aramid fibres could be considered as a suitable alternative to prevent binder drain down. Binder content and binder type were the last major factors affecting the binder drain down response. Generally, when the binder content increases, the susceptibility for the binder to drain becomes higher. However, polymer modified binders have higher viscosity and hence are less prone to drain. For the BT factor, Binder B was the most preferred parametric level to prevent the binder drain down followed by the binder C.

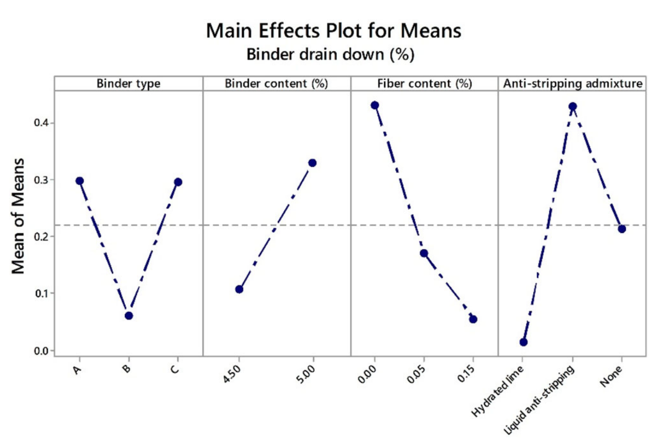


Figure 6. Main effects plot for binder drain down response.

4.2. Multi-criteria decision-making analysis

In the previous section, individual responses were analysed and it was observed that some modifiers improved some responses while in others the impact was less noticeable. Therefore, in this stage, a MCDM analysis was applied in order to turn all the multiple responses in one unique response and to find a clearer solution about the overall performance of the modified PA mixtures.

4.2.1. Responses weights determination according to CRITIC method

CRITIC was proposed as a weight assignment methodology to deal with the relative weights of each of the responses. Table 8 presents the final weights obtained for each criterion according. As said before, this method do not require the participation of decision makers as the criteria weights are assigned based on the information provided by the multiple data-sets. In that sense, the criteria are prioritised based on the quantity

Table 8. Quantity of information and weightage allocation for all the responses.

Responses	C_j	W_j
T_{AV} (%)	0.77	0.19
I_{AV} (%)	0.75	0.18
PL_{dry} (%)	0.88	0.22
PL_{wet} (%)	0.79	0.20
BD (%)	0.85	0.21

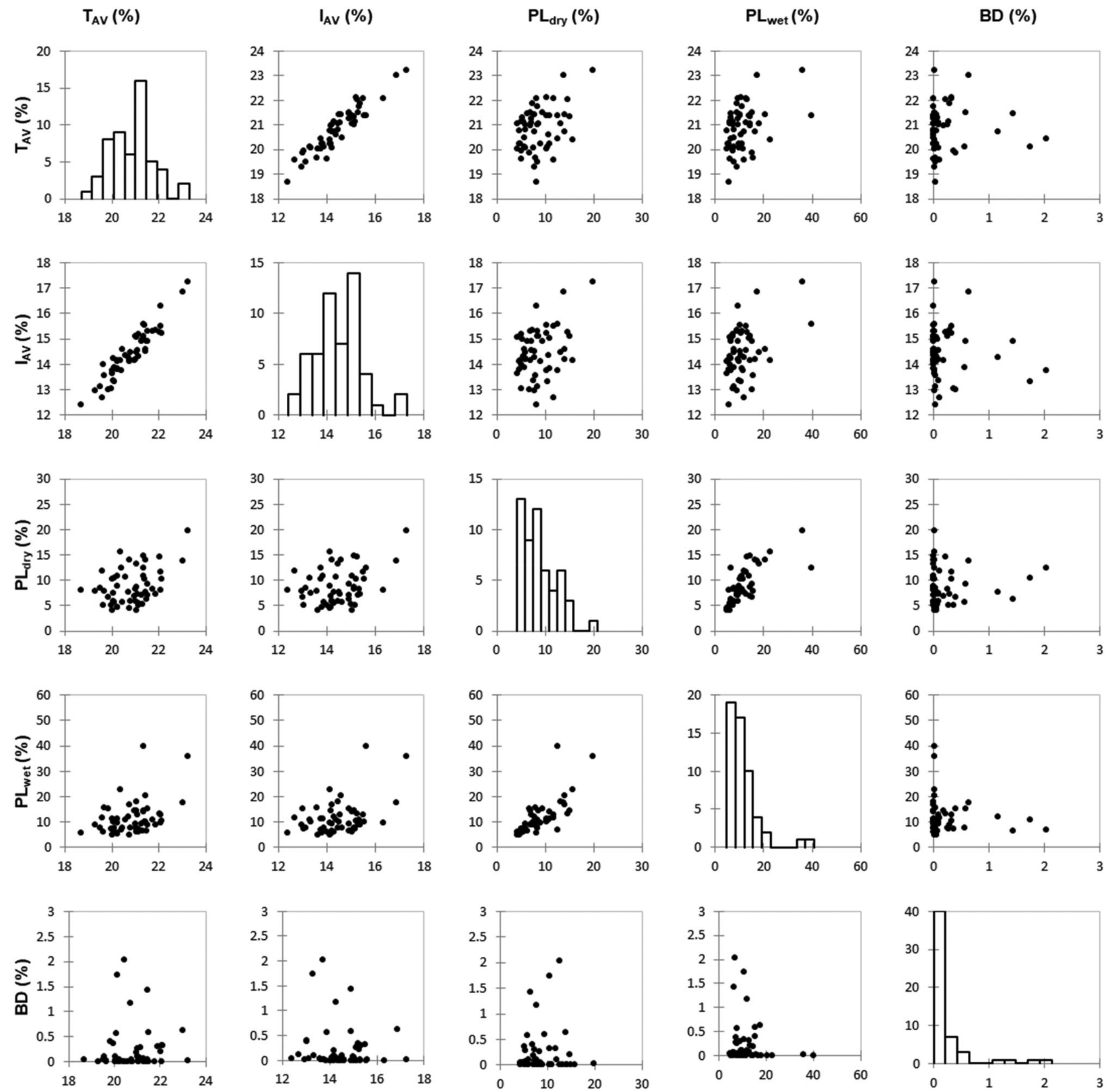


Figure 7. Histogram and scatter plots for the different criteria.

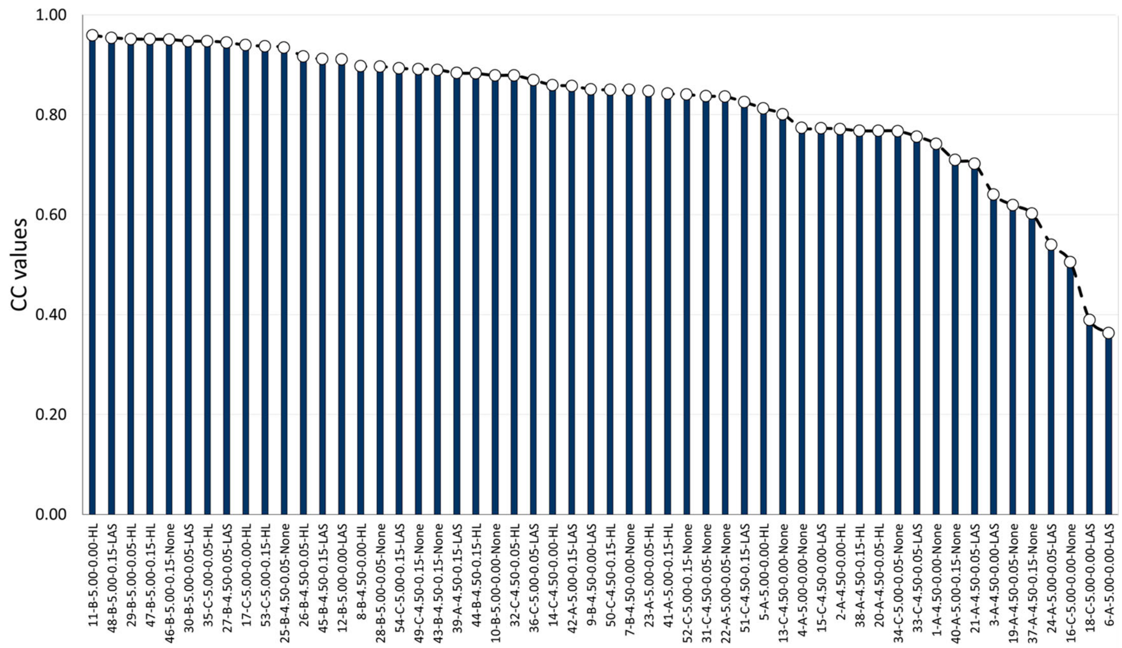
of information (Cj) contained in each criterion, which is determined according to the contrast intensity of the criterion and the conflict assessment among the criteria. In other words, the variability emitted by the data in each of the responses and the correlations among them quantify the information content of the criteria. As a consequence, responses with greater variability and lower correlation with respect to other criteria provide more information.

Table 9. Pearson coefficient values.

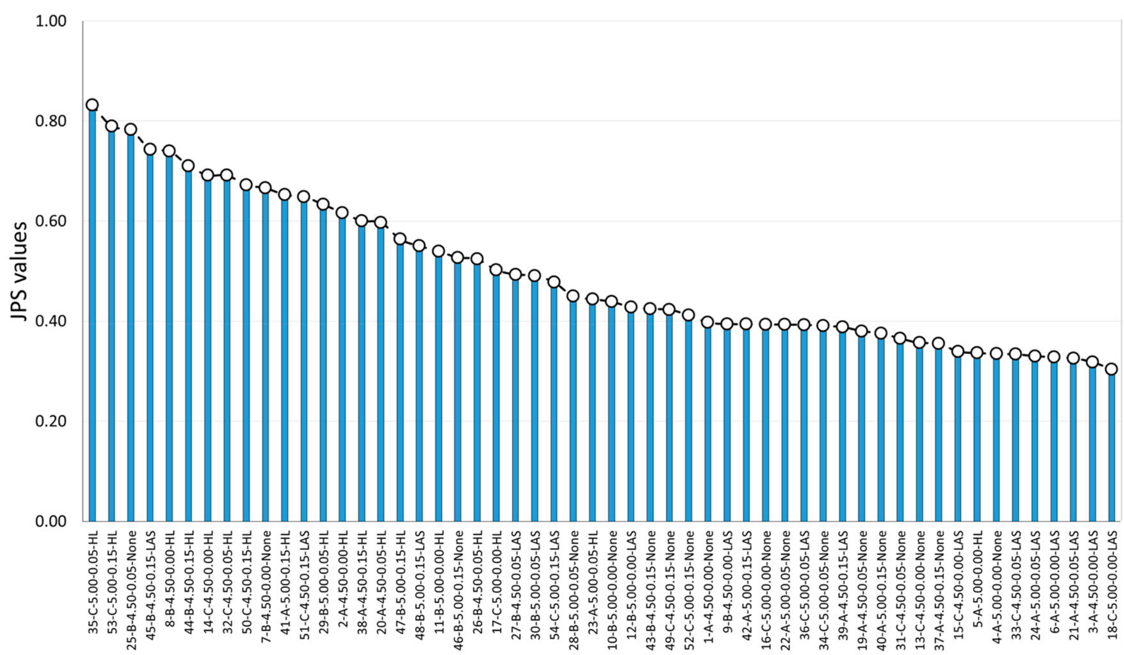
	T_{AV} (%)	I_{AV} (%)	PL_{dry} (%)	PL_{wet} (%)	BD (%)
***T_{AV}* (%)**	**1.00**	**0.93**	**0.39**	**0.40**	0.02
***I_{AV}* (%)**	**0.93**	**1.00**	**0.35**	**0.41**	−0.09
***PL_{dry}* (%)**	**0.39**	**0.35**	**1.00**	**0.73**	0.05
***PL_{wet}* (%)**	**0.40**	**0.41**	**0.73**	**1.00**	−0.12
BD (%)	0.02	−0.09	0.05	−0.12	**1.00**

Figure 7 depicts the matrix plot for the different criteria, which was essential for determining the relative weights in CRITIC. The diagonal plots present the histogram of the five criteria and the scatter plots display the trends observed between the responses. As it can be observed, the functional and durability responses have at least a close correlation, but not narrow relationship was found regarding BD. This was verified by calculating the Pearson coefficients shown in Table 9, with values in bold being statistically significant with a 95% confidence level (p-value < 0.05).

As it can be observed in Table 8, durability and binder drain down responses had higher response values than the functional responses. Despite that, all the responses were assigned with a relative weight of approximately 20%.



(a)



(b)

Figure 8. Preference ranking calculated by CC and JPS values according to TOPSIS (a) and WASPAS (b) methods.

4.2.2. Preference ranking according to TOPSIS and WASPAS methodologies

TOPSIS and WASPAS approaches were employed as MCDM tools to perform the preference ranking among the set of alternatives and to turn the multiple responses into single unified index. Consequently, CC and JPS values calculated from TOPSIS and WASPAS methodologies, respectively, are illustrated in Figure 8. The most promising alternatives are those with higher values. The experiments were presented in descendent order to facilitate the visualisation of the data. Accordingly, experimental designs number 11 and 35 were the most preferred options based on TOPSIS and WASPAS, respectively. Both mixtures performed very well in terms of their ravelling resistance, not compromising the functionality of the mix and the risk of binder drain down. From the methods applied, the results also suggest that TOPSIS tends to yield higher score values in comparison to WASPAS. Likewise, TOPSIS scores showed low variations in the first

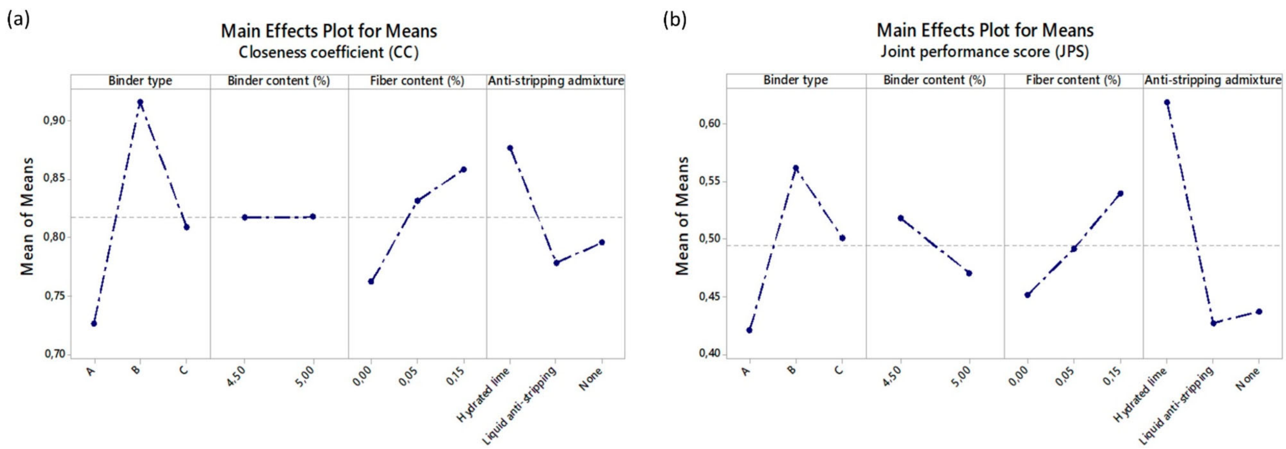


Figure 9. Main effects plot for means. (a) TOPSIS method. (b) WASPAS method.

positions of the preference ranking while in the last ones the gap between TOPSIS values was higher. In contrast, WASPAS scores presented large variations in the first positions whereas in the last ones variations were barely observed. Overall, the preference ranking is strictly associated with the type of algorithm employed. TOPSIS relies in the calculus of the Euclidean geometric distances to positive and negative ideal solutions and WASPAS on the other hand is a combination of additive and multiplicative utility functions. To investigate whether there is a correlation between the results obtained by both methods, the Pearson coefficient was calculated, yielding a value of 0.53 and being statistically significant (95% confidence level), which suggest that there exists a certain positive relationship between TOPSIS and WASPAS methods. However, as both methods apply different mathematical algorithms, the results in the preference ranking could differ, especially when a large number of alternatives are involved in the decision-making process. In spite of the differences found in the preference ranking, the main effects plot for data means according to TOPSIS and WASPAS methods were calculated (see Figure 9) to identify the most relevant parametric levels per factor. Based on these results, in both methodologies the optimal levels for BT, FC and ASA factors were the same. Thus, Binder B for the BT factor, 0.15% for the FC factor and HL for the ASA factor were the levels giving the best overall performance according to *CC* and *JPS* values. Regarding BC factor, in TOPSIS method (see Figure 9(a)) it is difficult to identify which parametric level is optimal since both look very similar. However, according to WASPAS the optimal level is achieved with level 1, which corresponds to a 4.50% binder content. The reason is probably that low quantities of binder help to increase the functional responses of the mixture as well as to avoid the risk of binder drain down.

5. Conclusions

In this study, the impact of different types of binders and additives in porous asphalt mixtures were experimentally assessed. A total of 54 experimental designs were planned through the Taguchi design of experiments method. Total air voids, interconnected air voids, particle loss in dry and wet conditions, and binder drain down were the responses obtained from the experimental tests. Since more than one response was obtained, three MCDM methods were performed to turn the multiple response optimisation problem into single-one optimisation problem. CRITIC method was utilised to find the relative weights among all criteria whereas TOPSIS and WASPAS methodologies were employed to do a preference ranking among the alternatives and to identify the optimal additives for the overall response of the mixture. Based on the experimental results and the statistical analysis the following conclusions can be drawn:

- PMB 45/80 – 65 improves significantly the overall performance of the PA mixture. This binder increased the ravelling resistance in both dry and wet conditions without affecting the functional performance of the mixture and without presenting the risk of binder drain down.
- Increasing the binder content contributes to minimise the ravelling potential. However, the functionality of the mixture as well as the binder drain down can be affected.
- Polyolefin-aramid fibres act very well as stabiliser agent and reinforcement since they reduce the particle loss in dry conditions. With the fibre addition, total and interconnected air voids are slightly reduced and not significant improvements in the ravelling resistance in wet conditions are observed.
- The use of HL as part of the filler did not reduce the voids in the mixture. Besides, the ravelling resistance in wet conditions was observed to be increased, reason for which avoiding the moisture damage is highly recommended. No improvement concerning the particle loss in dry conditions was observed with this additive. In the same way, HL contributed to reduce the binder drain down of the mixture.
- The liquid anti-stripping proved to be a good option to increase the ravelling resistance in wet conditions. However, it should be used in combination with fibres because as the binder softens, it becomes more prone to drain.
- The CRITIC method was presented as a powerful tool to determine the relative weights of the responses in an automated way by considering the results of the experiments. In general, all the responses were prioritised with approximately the same weight.

- This research introduced TOPSIS and WASPAS as innovative tools to be applied in cases when multiple responses are involved. Both methods were efficient to determine the optimal levels for the control factors. Although slight differences were found in the preference ranking, both techniques derived the same parametric levels for each control factor as the best overall performance value. Accordingly, binder B, 0.15% of polyolefin-aramid fibres and HL were selected as the best parametric levels. Regarding binder content control factor, it is recommended to evaluate new parametric levels between 4.50% and 5.00%.
- As a recommendation, future investigations should incorporate the combination of DOE and MCDM analysis to evaluate different additives in other different composites such as soils, dense-graded asphalt mixtures, concretes or geopolymers. In addition, other durability tests such as the freeze–thaw test could be incorporated to the DOE-MCDM analysis to further evaluate the impact of additives in the performance of the PA mixture.

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