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A multi-criteria decision-making analysis for the selection of fibers aimed at reinforcing asphalt concrete mixtures.

Abstract

In the last few years, fibers have been proposed as one of the most important additives for the development of reinforced asphalt mixtures. The optimal fiber selection is a very complex task, as an extensive range of criteria and alternatives have to be taken into account. Decision support systems have been applied in the construction sector, but not for selecting fibers for bituminous mixtures. To fill this gap, two Multi-Criteria Decision-Making Analysis methodologies for the selection of the best fiber to be used in Asphalt Concretes are presented in this paper. The Weighted Aggregate Sum Product Assessment (WASPAS) methodology and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) integrated with Fuzzy Analytic Hierarchy Process (FAHP) are used to evaluate the effect of various types of fibers on the mechanical performance of bituminous mixtures. Given the uncertainty involved, a stochastic simulation is proposed using the Monte Carlo method. A statistical analysis is carried out to verify the results obtained. Both methods of multi-criteria analysis were effective, with TOPSIS being slightly more conservative in the assignment of performance scores. Synthetic fibers proved to be a suitable option as did fibers with high tensile strength and elastic modulus.

Keywords: Asphalt Concrete ; Fibers; FAHP; WASPAS; TOPSIS; Monte Carlo.

Highlights:

Several fiber alternatives were evaluated to select the most appropriate for AC mixtures.

MCDMA is considered a good tool for ranking the fibers based on their mechanical properties.

Two MCDMA techniques were implemented for fiber-reinforced asphalt concrete analysis.

Fuzzy AHP was implemented to establish the criteria set.

The uncertainty in the decision-making process was addressed by using Monte Carlo Simulation.

1. Introduction

1.1 Fibers in asphalt mixtures

Asphalt Concrete (AC) mixtures have been broadly considered the appropriate choice for flexible pavements due to the numerous advantages that they offer such as strong adhesion between bitumen and aggregates and good stability (Abtahi *et al.* 2010). Additionally, AC is preferred to other types of mixtures (e.g. Porous Asphalt, PA) for maintenance, overlays, composites and multi-course asphalt applications (Echols 1989). This type of mixtures comprises the upper part of the pavement and can be used as base, binder or wearing courses of the road structure. The main goals of the asphalt layers are to support traffic loads, transmit strain to the subgrade and ensure a good bearing capacity throughout the pavement's lifetime (Jain *et al.* 2013). Other goals include providing comfort and safety, good adherence in wet conditions, skid resistance and roughness (Xiong *et al.* 2015). However, traffic loads cause severe damage to the pavement structure, such as cracking and permanent deformation, which can be severely intensified by water and temperature (Hejazi *et al.* 2008, Abtahi *et al.* 2010, Slebi-acevedo *et al.* 2019). In order to reduce road failures and to increase their durability, engineers and scientists are constantly searching for new mechanisms or additives to improve the mechanical performance of asphalt mixtures (Fitzgerald 2000, Sibal *et al.* 2000, Xiang Ma, Qiang Li 2018). In this regard, fibers have proved to provide additional tensile strength and strain energy to the mixture when it is subjected to fracture and fatigue processes by traffic loads (MAHREZ *et al.* 2005, Ge *et al.* 2014, Yoo and Al-Qadi 2014). Similarly, several studies have reported the benefits of adding fibers to AC mixes as well as the relevant improvements in terms of tensile strength, moisture susceptibility, ductility, rutting resistance and fatigue properties (Cleven 2000, Fu *et al.* 2000, Moghaddam *et al.* 2014, Yin and Wu 2018).

The mechanical performance of different types of fibers such as lignin, asbestos, polyester, polyacrylonitrile, nylon, polypropylene or (Zhu *et al.* 2007, Jahromi and Khodaii 2008, Chen *et al.* 2009, Tapkın *et al.* 2009, Xu *et al.* 2010, Kim *et al.* 2018b, Yin and Wu 2018, Apostolidis *et al.* 2019, Slebi-acevedo *et al.* 2019) have been investigated. Wu *et al.* (2008) reported an increase of the number of cycles to fatigue failure when adding 0.3% polyester fibers to the mixture. Chen *et al.* (2009) suggested a polyester fiber content of 0.35% by weight of mixture for AC mixtures. Regarding the mineral fibers, Xiong *et al.* (2015) studied the effects of adding basalt and brucite fibers to asphalt concrete. Significant high-temperature stability, low-temperature cracking resistance and moisture susceptibility was obtained. As for the polypropylene fibers, a 58% increase in the marshall stability index of AC was achieved by Tapkın (2008) when adding 1.0% fibers. Moreover, the author indicated that 1% of polypropylene extends the fatigue life by 27% (Tapkın 2008). Finally, Lee *et al.* (2005b) concluded that adding 1% by volume of 12-mm-long nylon fibers increased the fracture energy of the asphalt concrete. However, fiber-reinforced asphalt concrete (FRAC) with nylon fibers presented a 18% decrease of its indirect tensile strength.

Therefore, fibers are certainly good for the reinforcement of asphalt mixes. However, depending on their physical characteristics, they enhance certain mechanical properties in the mix more than others, which makes it difficult to determine which fiber is best and which one contributes most to the overall performance of asphalt mixtures. For instance, steel fibers increase Marshall stability, rutting resistance and indirect tensile strength (Wang *et al.* 2016), but do not have a relative influence on particle loss resistance (García *et al.* 2013); likewise, organic fibers prevent the drain-down of binder in the mixture (Abiola *et al.* 2014), but reduce the adherence with the aggregate (Narayan 2010); moreover, synthetic fibers like polyester improve high-temperature stability and increase the flexural strain at low temperature (Jenq, Y. S., Liaw, C. J., & Lieu 1993, Zhu *et al.* 2007), but make the optimum binder content in the mixture increase (McDaniel 2015).

Thus, even though several fiber types have been shown to improve the mechanical behavior of asphalt concrete, there is a lack of appropriate methodology and evaluation techniques to support decision making (Bagočius *et al.* 2013). Actually, the increasing use of fibers for the development of new pavement structures has made the decision-making process much more difficult. Finally, the information from experts in academia and industry about the criteria and priorities that should be considered is still scarce.

1.2 MCDMA techniques for the selection of fibers

Multi-Criteria Decision Making Analysis (MCDMA) is a suitable alternative for organizing and solving problems that involve multiple criteria (Majumder 2015). Different multi-criteria approaches have been considered over the years in the construction sector (Al-Harbi 2001, Wang and Elhag 2006, Zavadskas, Vilutienė, *et al.* 2014). Odeck (1996) proposed a Data

Envelopment Analysis (DEA) to evaluate the efficiency improvement of rock blasting in Norway. Mosallam and Mikawi (1996) applied a systematic approach based on the Analytic Hierarchy Process (AHP) to evaluate the use of advanced composite materials in the repair of deteriorated bridge columns. Pan (2008a) used a fuzzy AHP instead of a conventional AHP methodology for the selection of an appropriate bridge construction method. According to other authors (Jato-Espino, Castillo-Lopez, *et al.* 2014, Kubler *et al.* 2016), the inclusion of fuzzy sets enables engineers to handle the uncertainty and vagueness involved in decision-making problems. In a different study, Rahman *et al.* (2012) proposed a decision support system for roofing material selection based on the Technique of Ranking Preferences by Similarity to Ideal Solution (TOPSIS). Similarly, Şimşek *et al.* (2013) applied the same technique along with Taguchi optimization to determine the optimal mix proportions of high-strength self-compacting concrete. Hybrid multi-criteria decision-making approaches have been used as well. Jato-Espino *et al.* (2014) employed a hybrid model considering the Spanish Integrated Value Model for Sustaintability Assessment (MIVES) and AHP methodologies for the selection of urban pervious pavements. Similarly, Lombera and Garrucho (Lombera and Garrucho 2010) applied the same approach to the development of an environmental analysis of industrial buildings.

Identifying the most effective decision-making technique for the selection of the best reinforcement fibers in AC mixtures is a challenge. The AHP methodology, widely used for construction-related problems due to its flexibility (Jato-Espino, Castillo-Lopez, *et al.* 2014), is a Multi-attribute decision-making technique that makes use of human judgement. However, the participation of human thinking comes with fuzziness and vagueness and hence, imprecise judgement can be generated in the decision-making process. Some researchers (Chaharsooghi *et al.* 2012) suggest that the Fuzzy AHP (FAHP) deals better with the imbalance of the decision makers' judgement scale, as it also considers the uncertainty associated with the evaluation process. Both AHP and FAHP methods have been used for criteria weighting in decision-making proceses as they enable the comparison of dissimilar alternatives while reducing personal bias (Kubler *et al.* 2016). TOPSIS is the most widely used decision-making technique in the construction field after AHP (Jato-Espino, Castillo-Lopez, *et al.* 2014). Its calculation process, based on the closest distances to the positive and negative ideal solutions, uses a straightforward structured algorithm that imposes no limits on decision makers about criteria and alternatives (Rashidi and Cullinane 2019). Additionally, it enables alternatives to be ranked according to the quantitative data provided in the literature. However, it does not provide either weight elicitation nor consistency-checking for judgments (Roszkowska n.d.), which is the reason methods such as FAHP are used along with the TOPSIS.

On the other hand, in the last few years, some authors (Zavadskas, Turskis, and Antucheviciene 2012) have argued that the Weighted Aggregated Sum Product Assessment (WASPAS) methodology performs more accurately than others. In fact, Zakarevicius et al. (Zavadskas, Turskis, Antucheviciene, *et al.* 2012) suggested that WASPAS is more robust than the WSM and WPM approaches. Few construction-related study cases have been evaluated using this approach. Zavadskas *et al.* (2015) used the WASPAS technique to select the most suitable contractor. Yazdani (2016) used Factor Relationship (FARE) together with WASPAS in order to determine the weighting criteria for the further selection of hard magnetic materials. Zavadkas (Zavadskas, Skibniewski, *et al.* 2014) ranked the civil engineering journals progress by employing the same methodology. This approach enables integrated multi-criteria decision-making modelling. Bagocious (Bagočius *et al.* 2013) hybridized WASPAS and Entropy for deep water port selection. The latter was used to estimate the criteria weightage whereas WASPAS was used to rank the alternatives.

This research aims to select the fiber that provides the best mechanical performance of Asphalt Concrete mixes. For this, qualitative and quantitative data are used and several alternatives and selection criteria are considered. The criteria weighting is addressed by using the AHP method under a fuzzy environment (FAHP) in order to take into account the uncertainty of the evaluation process. Then, the alternatives are ranked and the best solution is identified by using WASPAS and TOPSIS methodologies. As previously said, the literature suggests that both methods clearly stand out when assessing construction-related topics. Moreover, there has been no comparative analysis of the two techniques for those specific topics.

The problem associated with imprecise input parameters is handled by employing stochastic simulations. The Monte – Carlo (MC) method is used in this case to deal with uncertainty and risk, but unlike in others (Vinodh *et al.* 2014, Alam *et al.* 2018, Rashidi and Cullinane 2019), in which uncertainty is only taken into account for the criteria estimation and quantitative data are managed through crisp numbers, the MC method is used in this research to consider quantitative variables not as single numbers but as probability distributions. A statistical analysis is carried out to support the discussion of the results.

2. Methodology

2.1 Weighting methodologies

Defining appropriate criteria to measure the mechanical performance of fibers in hot mix asphalt implies applying rule-based decision support to evaluate the influential factors. Weighting methodologies comprise two weighting approaches: the objective one, where mathematical models are employed without consideration of the decision matrix; and the subjective one, where the weights are selected depending on the preference information provided by the decision matrix (Vinodh *et al.* 2014, Santos *et al.* 2019). In this paper, the Analytical Hierarchy Process (AHP), a subjective approach, was considered since it enables the information based on the knowledge and experience of experts in the topic to be compiled. In order to prioritize the weighting criteria and deal with vagueness of human thought (Naghadehi *et al.* 2009), fuzzy sets were added. To include different points of view, experts from industry, academia and representatives of public institutions were selected to answer a comprehensive questionnaire for determining the weights of the main criteria.

2.1.1 Analytic Hierarchy Process (AHP)

AHP is a computational method for decision making introduced by Saaty in 1980 (Saaty 1980). This technique consists of making a distribution of decisions based on a hierarchy or priority that helps to visualize the criteria that create the most impact on the desired objective, while adjusting to the current needs. To apply this type of analysis, it is necessary to follow a series of steps. Firstly, a hierarchical structure has to be developed with an objective on the top level, the criteria on the second level and the alternatives arranged on the third level, as shown in **Fig. 1**. The second step is to create a pairwise comparison matrix and determine the relative importance of different attributes or criteria with respect to the goal. To quantify this, Saaty (1980) proposed a comparison scale of relative importance in which one means equal importance and nine represents extreme importance (**Table 1**). The third step is to build a pairwise comparison matrix. This matrix is equivalent to the number of criteria used in the decision-making process. After decision makers evaluate the criteria, the linguistic equivalent

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term can be used to transform qualitative information into numerical scales. Once the matrix is obtained, the eigenvector technique is used to obtain the relative importance weighting of each of the attributes (Triantaphyllou and Mann 1995). Decision makers' preferences have high influence on AHP results and the assessment of qualitative criteria may be imprecise. For this reason, the consistency ratio (C.R.) is measured to check the consistency of the data. Pairwise comparison matrices can be considered consistent when the ratio between the consistency Index (C.I.) and the Random Index (R.I) is less than 0.1. A detailed discussion of the procedure can be found in (Saaty 1980).

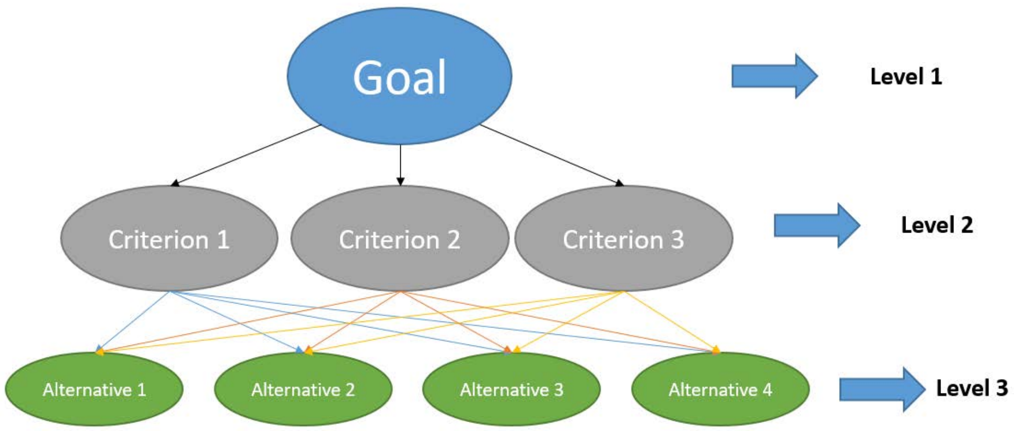

Fig. 1. The general decision structure in AHP

Table 1. Saaty's Scale of relative importance

Numerical Value	Linguistic equivalent term
1	Equal importance
3	Moderate Importance
5	Strong Importance
7	Very strong importance
9	Extreme importance
2,4,6,8	Intermediate values

2.1.2 Fuzzy Analytical Hierarchy Process (FAHP)

Some researchers reported that Fuzzy AHP produced accurate results in the decision-making process (Gnanavelbabu and Arunagiri 2018). Fuzzy sets were introduced by Zadeh in 1965 as a mathematical way of representing the uncertainty and vagueness of ordinary language (Yajure 2015). The method solves hierarchical problems applying fuzzification or converting linguistic terms into a membership function. There are a variety of membership functions among which gamma, lambda, triangular and trapezoidal are suggested by other authors (Yajure 2015). However, to reflect the vagueness of parameters in decision-making processes, triangular and trapezoidal membership functions have been the most commonly used (Gul *et al.* 2018). In this research, the triangular membership function $\mu_A(x)$ (see **Eq. (1)**) was adopted as shown in **Fig. 2.,** where a, m and b are the lower, middle and upper fuzzy numbers of the triangular axis.

$$\mu_A(x) = \begin{cases} \dfrac{x-a}{m-a} & a \le x < m \\ \dfrac{b-x}{b-m} & m \le x < b \\ 0 & Otherwise \end{cases} \tag{1}$$

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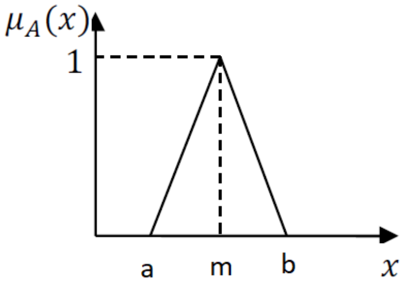

Fig. 2. Triangular membership function

On the scale of relative importance (see **Table 1**), crisp numbers are replaced with fuzzy numbers. It can be seen that assigning a unique number to any term is not justified or is very imprecise. To solve this issue, the Fuzzy scale of relative importance is presented as shown in **Table 2.** Once the conversion from crisp to fuzzy sets is established, several algorithms can be applied (Yajure 2015, Gnanavelbabu and Arunagiri 2018, Gul *et al.* 2018). Laarhoven *et al.* (1983) introduced the first studies that applied fuzzy logic to AHP in 1983; Chang (1996) proposed, in 1996, a new approach for handling AHP using triangular fuzzy numbers for a pairwise comparison scale of AHP. In this research, Buckley's FAHP method was used. A brief description of the procedure is given as follows. Details can be found in (Gul and Guneri 2016, Gul *et al.* 2018).

Step 1. Construct the pairwise comparison matrix among all criteria and/or attributes, taking into account the dimensions of the hierarchy system. The scale contains nine linguistic terms which correspond to triangular membership functions, as can be observed in **Fig.3.** Furthermore, linguistic terms are assigned according to expert opinions, indicating the importance of each parameter compared to the others.

$$\tilde{A} = \begin{bmatrix} 1 & \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{21} & 1 & \cdots & \tilde{x}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{x}_{n1} & \tilde{x}_{n2} & \cdots & 1 \end{bmatrix} = \begin{bmatrix} 1 & \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ \left(\frac{1}{\tilde{x}_{21}}\right) & 1 & \cdots & \tilde{x}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \left(\frac{1}{\tilde{x}_{n1}}\right) & \tilde{x}_{n2} & \cdots & 1 \end{bmatrix} \tag{2}$$

$$\tilde{x}_{ij} = \begin{cases} \tilde{1}, \tilde{3}, \tilde{5}, \tilde{7}, \tilde{9}\ criterion\ i\ is\ the\ importance\ relative\ to\ criterion\ j \\ 1 \qquad i = j \\ \tilde{1}^{-1}, \tilde{3}^{-1}, \tilde{5}^{-1}, \tilde{7}^{-1}, 9^{-1} criterion\ j\ is\ the\ importance\ relative\ to\ criterion\ i \end{cases} \tag{3}$$

Step 2. Define the fuzzy geometric mean matrix applying Normalization of the Geometric Mean (NGM) to compute local weights.

$$\tilde{r}_i = (\tilde{x}_{i1} \otimes \tilde{x}_{i2} \otimes \ldots \otimes \tilde{x}_{in})^{\frac{1}{n}} \tag{4}$$

Step 3. Apply fuzzy addition and fuzzy multiplication to **d**etermine the fuzzy weights of each criterion.

$$\tilde{w}_i = \tilde{r}_i \otimes (\tilde{r}_1 \oplus \tilde{r}_2 \oplus \ldots \oplus \tilde{r}_n)^{-1} \tag{5}$$

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Where $\widetilde{w}_i$ represents the fuzzy weight of each criterion i and its components $\widetilde{w}_i = (a_{wi}, m_{wi}, b_{wi})$ justify the lower, middle and upper value of the fuzzy weight of criterion i.

Step 4. Determine the Center of Area (CoA) to find the best non-fuzzy performance as follows (Gul *et al.* 2018); other techniques like the max–min operator technique can be applied due to their simplicity and efficiency (Pan 2008b).

$$w_i = \frac{[(bw_i - aw_i) + (mw_i - lw_i)]}{3} + aw_i \tag{6}$$

Table 2. Fuzzy Scale of relative importance

Linguistic term	Crisp	Fuzzy
Equal importance	1	(1,1,1)
Moderate importance	3	(2,3,4)
Strong importance	5	(4,5,6)
Very strong importance	7	(6,7,8)
Extreme importance	9	(9,9,9)
Intermediate Values	2	(1,2,3)
	4	(3,4,5)
	6	(5,6,7)
	8	(7,8,9)

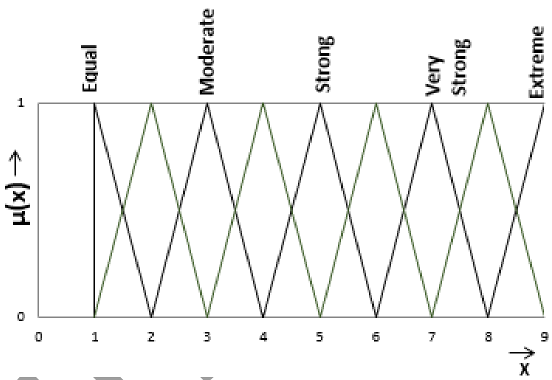

Fig.3 Fuzzy triangular membership functions for linguistic terms

2.2 Weighted Aggregated Sum Product ASsessment (WASPAS)

This method developed by Chakraborty and Zavadskas in 2004 (Zavadskas, Turskis, and Antucheviciene 2012) is one of the most robust new MCDMA utility-determining approaches (Mardani *et al.* 2017). This approach is a combination of the Weighted Sum Model (WSM) and Weighted Product Model (WPM). Based on these initial criteria values, an Optimization of WASPAS is developed to reach higher measurement accuracy (Zavadskas, Turskis, and Antucheviciene 2012). Numerous studies have been carried out with this method, such as an ecological and economic assessment of a multi-dwelling house modernization (Staniūnas *et al.*

2013), selection of a deep water port (Bagočius *et al.* 2013), decision making regarding business issues (Hashemkhani Zolfani *et al.* 2013), evaluation of solar projects based on regional priorities (Vafaeipour *et al.* 2014), among others.

The process of application of this method to a generic problem can be summarized as follows (Mardani *et al.* 2017).

Step 1. Define the decision-making problem, establish the limits in which the project is framed, select the appropriate parameters to evaluate, and choose the possible alternatives that will be taken into account.

Step 2. Establish the decision criteria. Denote the weightage or relative significance of each criterion. Develop a decision/evaluation matrix $X = [x_{ij}]_{m*n}$, where m represents the number of alternatives and n the number of criteria.

Step 3. Normalize the weighted decision matrix for beneficial and non-beneficial criteria, as can be seen in **Eqs. (7) and (8),** respectively.

$$Non\ Beneficial = \frac{min\ (X_{ij})}{(X_{ij})} \quad (7)$$

$$Beneficial = \frac{X_{ij}}{max\ (X_{ij})} \quad (8)$$

Step 4. Calculate the total relative importance using the Weighted Sum Model (WSM) of each alternative.

$$A_i^{WSM} = \sum_{j=1}^{n} W_{j*X_{ij}} = Q_i^1 \quad (9)$$

Where w_j represents the weight of the j^{th} criterion

Step 5. Assess the total relative importance of each alternative by the Weighted Product Model (WPM) using the following equation.

$$A_i^{WPM} = \prod_{j=1}^{n} X_{ij}^{W_i} = Q_i^2 \quad (10)$$

Step 6. A joint generalized criterion of weighted aggregation of the additive and multiplicative methods is as follows. Note that there is an equal contribution of A_i^{WSM} and A_i^{WPM} for total assessment.

$$Q_i = 0{,}5 * Q_i^1 + 0{,}5 * Q_i^2 \quad (11)$$

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Step 7. A more generalized equation for determining the total relative importance of each alternative is as follows.

$$Q_i = \lambda Q_i^1 + (1 - \lambda) Q_i^2 \tag{12}$$

$$\lambda = 0, 0.1, 0.2, \dots, 1$$

Step 8. Following the extreme function, find the optimal values of λ.

$$\lambda = \frac{\sigma^2(Q_i^{(2)})}{\sigma^2(Q_i^{(1)}) + \sigma^2(Q_i^{(2)})} \tag{13}$$

Step 9. Determine the variances $\sigma^2(Q_i^{(1)})$ and $\sigma^2(Q_i^{(2)})$ as follows.

$$\sigma^2\left(Q_i^{(1)}\right) = \sum_{j=1}^{n} w_j^2 \sigma^2(x_{ij}) \tag{14}$$

$$\sigma^2\left(Q_i^{(2)}\right) = \sum_{j=1}^{n} \left(\frac{\prod_{j=1}^{n} X_{ij}^{w_j} * w_j}{(x_{ij})^{w_j} (x_{ij})^{(1-w_j)}} \right)^2 \sigma^2(x_{ij}) \tag{15}$$

Step 10. Determine the estimates of variances of normalized initial criteria values according to the equation below.

$$\sigma^2(x_{ij}) = (0.05\, x_{ij})^2 \tag{16}$$

2.3 Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)

Proposed by Hwang and Yoon (Hwang and Yoon 1981), it is considered one of the most common multi-objective methods (Zhang *et al.* 2018). It is a solution that increases the benefit criteria/attributes and decreases the cost criteria/attributes (Wang and Elhag 2006). The opposite can occur, increasing the cost criteria/attributes and decreasing the benefit criteria/attributes. This method has been widely used in the literature, such as for programming problems (Abo-Sinna and Amer 2005), robotics (Agrawal *et al.* 1991), civil engineering (Gáspár *et al.* 2016, Abdel-malak *et al.* 2017), health (Zyoud and Fuchs-Hanusch 2017) or sustainability assessment (Mulliner *et al.* 2016), among others. This method bases its theory on the Euclidean distances of the alternatives from benefits and ideal costs (Marković 2010). The best alternative will be the one which has the shortest distance from the ideal beneficial solution and the farthest distance from the ideal cost solution (Roghanian *et al.* 2010). This concept of alternative Euclidean distance measurement makes this method an important branch of decision making (Shih and H.-J. Shyur 2007).The TOPSIS method is structured as follows.

Step 1. Establish the decision matrix, which is composed of "n" alternatives and "m" decision criteria/attributes. All the aspects are assigned to the alternatives with respect to each criterion that forms the decision matrix $X = [x_{ij}]_{m*n}$

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Step 2. Normalize the decision matrix using the following equation.

$$r_{ij} = \frac{X_{ij}}{\sqrt{\sum_{j=1}^{n} X_{ij}^2}}, i = 1, \dots, n; j = 1, \dots, m \tag{17}$$

Where r_{ij} is the normalized criteria rating.

Step 3. Construct the weighted normalized decision matrix $V = \left(v_{ij}\right)_{m*n}$.

$$v_{ij} = w_j r_{ij}\,,, i = 1, \dots, n; j = 1, \dots, m \tag{18}$$

Where w_j is the weightage of each criteria. $\sum_{j=1}^{m} w_j = 1$ must be fulfilled.

Step 4. Determine the best and worst value indicators.

$$V_j^+ = \{v_1^+, \dots, v_2^+\} = \{\max_j v_{ij} | \text{j} \in \Omega_\text{b}), \{\min_j v_{ij} | \text{j} \in \Omega_\text{c}), \tag{19}$$

$$V_j^- = \{v_1^-, \dots, v_2^-\} = \{\max_j v_{ij} | \text{j} \in \Omega_\text{b}), \{\min_j v_{ij} | \text{j} \in \Omega_\text{c}), \tag{20}$$

Where Ω_b and Ω_c are the benefit and cost criteria set, respectively.

Step 5. Calculate the Euclidean distances of each alternative from the positive ideal solution and the negative ideal solution, as follows.

$$S_i^+ = \left(\sum_{j=1}^{m} \left(V_{ij} - V_j^+\right)^2 \right)^{0.5} \tag{21}$$

$$S_i^- = \left(\sum_{j=1}^{m} \left(V_{ij} - V_j^-\right)^2 \right)^{0.5} \tag{22}$$

Step 6. Calculate the relative closeness of each alternative to the ideal solution.

$$P_i = \frac{S_i^-}{S_i^+ + S_i^-} \tag{23}$$

2.4 Stochastic Simulations

In a multi criteria decision-making analysis, a large number of variables are taken into account. These variables are not entirely deterministic, but are accompanied by uncertainty associated with the degree of representativeness of the data. Therefore, stochastic simulations enable the assignment of probabilistic formulations to the variables under consideration and so the risk is associated with the correct determination of the decisions (Prada *et al.* 2011). Simulation

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methods have been applied as a tool to evaluate the reliability of complex state limit functions (Silva. 2005). The Monte Carlo simulation is presented as a simple, practical tool for estimating the randomness of the variables involved.

2.4.1 Monte Carlo simulations

This method is based on random sampling to artificially simulate the behavior of a system. It has been applied in various fields of engineering in the last decades (Schueller 1997). Regarding pavement engineering, this technique has been used in several situations such as a regional sensitivity analysis of pavement design (Wu *et al.* 2017); the selection of urban pervious pavement (Jato-Espino, Rodriguez-Hernandez, *et al.* 2014); the simulation of cohesive fracture in quasi-brittle materials (XT *et al.* 2010); the assessment of fatigue life of rubberized asphalt concrete with reclaimed asphalt pavement (Luo *et al.* 2013); or the analysis of energy consumption and CO2 emission of asphalt pavement maintenance (Yu *et al.* 2018), among others.

The procedure, adapted from (Silva. 2005), includes the definition of the analysis function Y, which describes the problem in terms of all random variables, i.e. $Y = f(X_1, X_2, \dots, X_n)$. In this research, the WASPAS and TOPSIS methodologies were used to establish the stochastic decision-making analysis. Then, the probability distribution and the parameters of each random variable were determined. Triangular, beta, normal and lognormal distributions have been reported to be suitable to generate random numbers in the literature (Malcolm *et al.* 1959, Clark 1962, Vose 1996). A number of N = 1000 simulations has been suggested for evaluating random samples, obtaining an adequate convergence of the results with a low computational cost (Jato-Espino, Rodriguez-Hernandez, *et al.* 2014). Random values $\hat{x}_i$ were generated for each one of the variables X_i according to the selected probability distribution function. Given the large number of random variables and the statistical parameters supplied by (Kim *et al.* 2018a), normal distribution was considered in the input variables. The analysis function Y was assessed using stochastic simulations for each random variable, i.e. $\hat{y}_i = f(\hat{x}_1, \hat{x}_2, \hat{x}_3, \dots, \hat{x}_n)$, in order to extract statistical information from the results.

2.4.2 Statistical Analysis

The efficiency and precision of the simulation can be confirmed by statistical analysis. Parametric statistical tests are used when random independent samples are normally distribuited and present homogeneity of variance. In this stochastic analysis, *one-sample t - tests and one-way analysis of variance (ANOVA) tests* were carried out to determine whether there were any statistically significant differences between the values of one or more independent groups as appropriate. Otherwise, if the data followed a non-normal distribution, non parametric tests such as the U of Mann-Whitney test was used. Additionally, the Anderson Darling Normality test was used to determine the normality and homoscedasticity of data. All the statistical tests were performed with a confidence level of 95%.

3.0 Selection of the most suitable fiber

The structure of the proposed framework followed in this research is shown in **Fig.4.** First, documentation and findings about FRAC were recorded. Then, the proposed framework introducing AHP and fuzzy sets were used to obtain criteria weighting considering the opinion of experts in the assessment process and a logical computational process to synthethisize data. Finally, in order to evaluate and select the fiber that most improves the mechanical performance of the asphalt concrete, two multi-criteria decision-making analyses were carried out with two

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different groups of fibers, applying stochastic simulations and statistical analysis. The first group evaluates the performance of fibers of different origins (mineral, organic and synthetic), whereas in the second group, several alternatives are proposed involving different percentages in asphalt concrete of four synthetic fibers: polypropylene (PP), polyester (Pe), nylon (Ny) and carbon (C). Following the application of the WASPAS and TOPSIS methodologies listed above, the selection of the fiber according to mechanical performance is detailed.

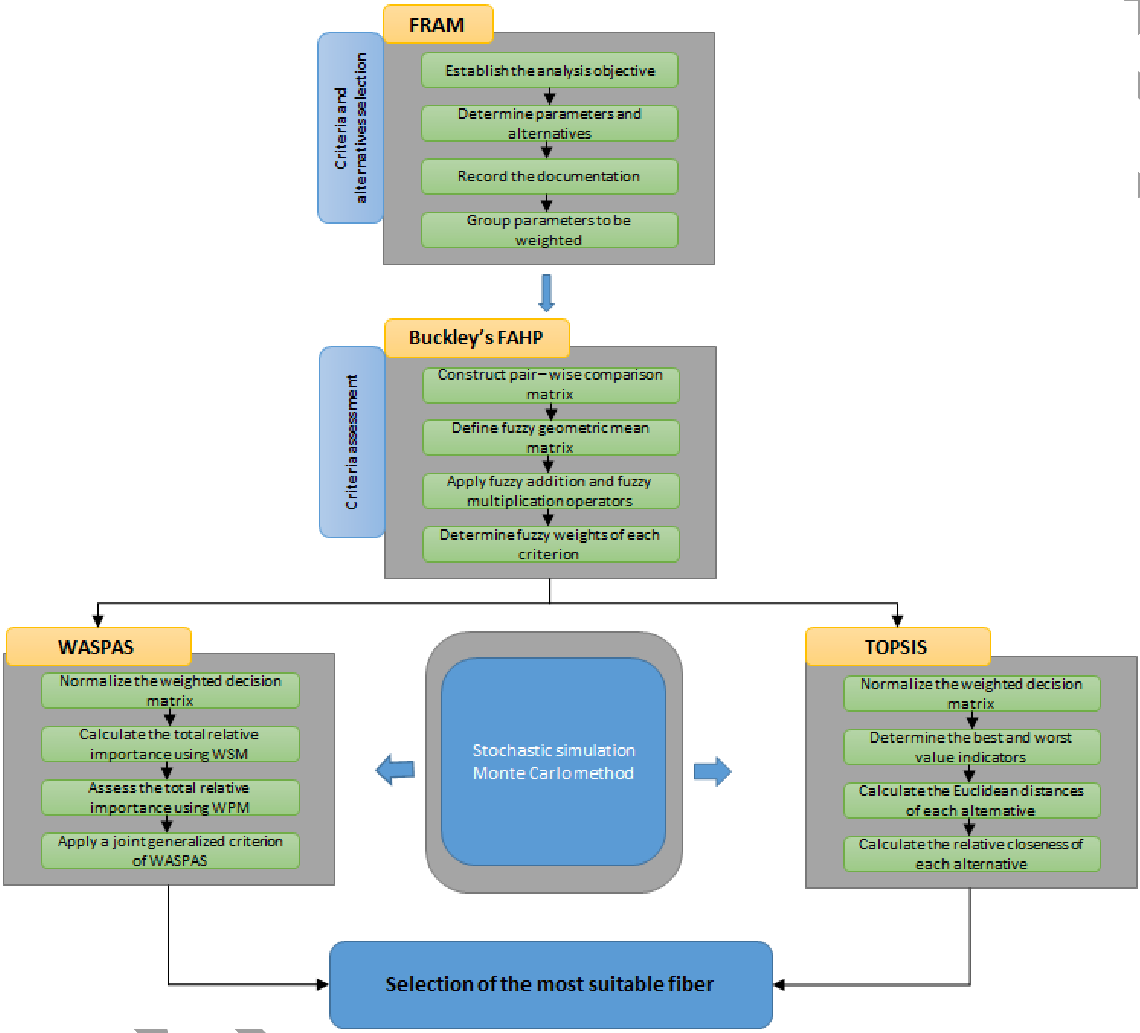

Fig.4. Structure of the proposed framework.

3.1 Definition of the decision-making problem

As a first step, the alternatives and attributes to be evaluated must be established based on the data collected from the technical literature. To enable comparative analysis, the investigations carried out by Xu *et al.* (2010), Chen *et al.* (2010) and Kim *et al.* (2018) were considered as the main references for assessing the influence, in terms of mechanical performance, of using different types of fibers in AC. Additionally, the research done by Slebi-Acevedo *et al.* (2019) and Abtahi *et al.* (2010) served as secondary references to perform the decision-making analysis.

3.1.1 Definition of reference mixtures and fibers

Reference mixtures are crucial for the evaluation of the alternatives in the decision-making problem, as their mechanical performance is necessary for comparison with the asphalt mixtures reinforced with fibers.

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For the first group, an AC mixture with 13 mm maximum aggregate size, 5.29% optimum asphalt content and 3.97% air voids was chosen. A 0.3% content of four different types of fibers was considered for the mixture: two synthetic (polyester and polyacrylonitrile), one organic (lignin) and one mineral fiber (asbestos). Regarding the second group, an AC mixture was selected with 13 mm maximum aggregate size, 5.34% optimum asphalt content and 3.70% air voids. Fiber contents of 0.5% and 1.0% by volume of mixture were chosen for this group. Thus, although keeping in mind the relevance of the fiber content for the mixture performance, contents remain constant in group one (only one fiber content) and two (two contents per type of fiber) as this research is more focused on the selection of the most suitable fiber. In **Table 3**, the main characteristics of the reference asphalt mixtures are shown. **Table 4** shows the different fibers considered as well as their most relevant properties. The much more attention gained nowadays by the synthetic fibers due to the extensive development of the manufacturing market as well as the relevant mechanical properties of many of them and, on the other hand, the health hazard attributed to some mineral fibers such as the asbestos, are among the reasons to focus on these types of fibers in the second group. The reason the two groups cannot be collated into one is that the tests performed and the parameters obtained were different.

Table 3 Characteristics of reference asphalt mixtures for group 1 and group 2

Characteristics	Reference mixture - Group 1	Reference mixture - Group 2
Type of mixture	Asphalt concrete	Asphalt concrete
OAC*	5.29	5.34
Air void volume	3.97	3.70
Types of fibers	Polyester	Polypropylene
	Polyacrylonitrile	Polyester
	Lignin	Nylon
	Asbestos	Carbon
Dosage	0.30%	0.50 - 1.00%**

*Optimum asphalt content. ** Dosage by volume of mixture.

Table 4 Fiber properties

Features	Fiber Type							
	Group one				Group two			
	Polyester	Polyacrylonitrile	Lignin	Asbestos	Polypropylene (PP)	Polyester (Pe)	Nylon (Ny)	Carbon (C)
Diameter (mm)	0.020	0.013	0.045	N/A	0.040	0.041	0.023	0.007
Length (mm)	6.0	5.0	1.1	5.0	6.0	6.0	12.0	12.0
Tensile Strength (Mpa)	531	910	N/A	30 - 40	500	1147	800	4900
Elastic modulus (Mpa)	N/A	N/A	N/A	N/A	3500	11600	3500 - 7000	230000
Melting point (°C)	N/A	N/A	N/A	N/A	160	256	220	over 1000
Length diameter ratio	300	385	24	N/A	150	146	522	1714

N/A, Not Available

3.1.2 Establishing indicators and alternatives

In **Table 5 and Table 6** the alternatives and indicators of groups 1 and 2 are shown, respectively. The notation of fiber alternatives in group 2 includes type of fiber and volume fraction (e.g., PP0.5 denotes an asphalt concrete with a 0.5% polypropylene fiber content by volume of mixture). While alternatives are established based on the amount of different types of fibers used in both groups, indicators are linked to the tests done to the asphalt mixtures.

As mentioned before, data have been collected after a very meticulous review of the related scientific literature as a result of which, several papers with the highest scientific standards were selected as the most appropriate sources of information to define the indicators and evaluate the different alternatives. Results of experimental tests such as flexural strength, toughness or rutting resistance on fiber-reinforced asphalt mixtures with analogous formulation but different types of fibers were analysed for their use in **Table 5** and **Table 6**. The differences (expressed as percentages) between the results of the fiber-reinforced mixes and those of the control mixtures were determined and used as scores of the alternatives for all the indicators. In group 1, for example, it can be seen that the use of polyester fibers results in a 19.57% improvement of the rutting resistance at 2500 cycles when compared to the performance of the reference mixture. Unlike in group 2, in group 1, the reference sample was not considered as an alternative because all the remaining alternatives resulted in an improvement with respect to it.

Table 5 Indicators and alternatives for group 1.

	Alternative - Fiber type			
Indicators	Polyester	Polyacrylonitrile	Lignin	Asbestos
Increase in binder content	7.75 %	5.86%	15.31%	9.64%
Increase in air voids in mixture	6.05%	5.04%	8.82%	7.81%
Rutting resistance at 2500 cycles	19.57%	32.56%	8.43%	11.40%
Flexural strength at -10°C	8.16%	6.49%	11.77%	12.67%
Flexural strength at 0°C	5.26%	3.28%	12.43%	6.08%
Flexural strain at -10°C	4.00%	2.00%	6.00%	3.00%
Flexural strain at 0°C	3.81%	5.24%	4.76%	2.62%
Fatigue life stress ratio 0.5 at material failure	57.66%	66.78%	40.88%	22.52%
Indirect tensile strength (ITS)	6.88%	8.30%	1.11%	3.74%
Pre-crack toughness	46.15%	26.92%	0.10%	34.61%
Post-crack toughness	41.54%	71.01%	15.47%	26.67%
Total toughness	43.52%	61.11%	12.03%	28.71%
ITS after Water freeze-thaw results	4.89%	3.87%	0.10%	0.10%

Table 6 Indicators and alternatives for group 2.

	Alternative - Fiber Type								
Indicators	Control	PP0.5*	PP1.0	Pe0.5	Pe1.0	Ny0.5	Ny1.0	C0.5	C1.0
Marshall stability (kN)	0%	12.60%	0.00%	15.30%	18.90%	8.10%	21.60%	-2.70%	2.70%
Flow resistance (mm)	0%	-2.30%	-10.00%	9.40%	-12.90%	8.70%	-1.00%	11.00%	3.90%
Air voids in mixture (%)	0%	6.80%	0.00%	-0.80%	14.90%	-5.70%	-1.90%	4.90%	2.20%
Indirect Tensile Strength (MPa)	0%	2.40%	-1.20%	1.20%	4.70%	-1.20%	7.10%	-4.70%	0.00%
Indirect Tensile Strength ratio	0%	3.70%	0.00%	2.50%	6.30%	0.00%	6.30%	-2.50%	3.70%
Dynamic Stability (cycles/mm)	0%	-4.10%	-27.50%	103.90%	62.70%	110.20%	51.00%	2.00%	7.30%
Rate of deformation [mm/min]	0%	5.30%	63.20%	-52.60%	-36.80%	-52.60%	-36.80%	-5.30%	-10.50%
Flexural Strength (MPa)	0%	-17.30%	1.00%	3.10%	1.00%	-4.10%	3.10%	-8.20%	12.20%
Strain capacity (%)	0%	7.70%	30.80%	0.00%	-7.70%	46.20%	7.70%	23.10%	23.10%

3.1.3 Definition of criteria/attributes

Defining the criteria/attributes based on the indicators considered is a crucial task. Once again, a good selection requires an accurate review of the technical literature to find the references (Chen and Xu 2010, Xu *et al.* 2010, García *et al.* 2013, 2015) that enabled the indicators to be grouped in the appropriate way. As a result, the decision-making criteria shown in **Table 7** for both groups emerged.

The criteria proposed must be both representative and influential. The mechanical parameters obtained and the criteria evaluated represent the mechanisms by which the pavement is affected by traffic loads. The main degradation mechanisms assessed in empirical and mechanical design methodologies are rutting and fatigue life. Aditionally, hot mix asphalts are viscoelastic materials whose mechanical properties depend on temperature. Asphalt concrete becomes fragile at low temperatures while it behaves in a more viscous way at intermediate and high temperatures. Furthermore, moisture is a significant factor in the deterioration of the asphalt pavement. Loss of cohesion and stiffness in the binder film, failure of the adhesive bond between aggregates and bitumen (stripping) and degradation of aggregate, particularly when the asphalt concrete is subjected to freezing, are considered the three main mechanisms of moisture damage in asphalt pavements (Cheng *et al.* 2003). Based on all this, the decision-making criteria (**Table 7)** included a total of six criteria/attributes for both groups, each of which is considered sufficiently descriptive and inclusive to reflect the mechanical performance of AC mixes.

Table 7. Criteria/attributes for group 1 and group 2

Group	Criteria/Attributes	Indicators
1	Volumetric Properties	Binder content
		Air voids in mixture
	Rutting Resistance	Rutting Resistance at 2500 cycles
	Flexural strength	Flexural strength at - 10°C
		Flexural strength at 0°C
		Flexural strain at -10°C
		Flexural strain at 0°C
	Fatigue Life	Fatigue life stress ratio 0.5 at material failure
	Fracture Energy	Indirect tensile strength
		Pre-crack toughness
		Post-crack toughness
		Total toughness
	*ITS after freeze-thaw cycle	ITS after freeze-thaw cycle
2	Marshall Stability	Marshall Stability
		Flow Resistance
	Volumetric Properties	Air voids in mixture
	ITS	Indirect Tensile Strength
	Moisture Sensitivity	Indirect Tensile Strength Ratio (ITSR)
	Rutting Resistance	Dynamic stability
		Rate of deformation
	Flexural Strength at Low Temperatures	Flexural Strength
		Strain capacity

3. 2 Weighting Criteria

Once the decision–making criteria was defined for the two groups, the expert judgment was requested to provide assessment on the relative importance of the selected criteria. A series of questionnaires were elaborated and sent to experts in academia, private companies and public sector institutions. A total of 25 of them were finally completed, which helped to prioritize the criteria from different perspectives. Thus, 60% of the experts consulted currently work in

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universities or research centers, whereas the remaining 40% work in construction companies or national administrations such as national road authorities or similar. Therefore, although many of the experts do their work as senior researchers, some of them work as professional project engineers, project managers and/or team leaders. As for their area of expertise, more than 50% of the people surveyed are part of the construction or road engineering departments of their organization, while 25% of them work in areas more directly related to the development of road materials and the rest in other road-related areas such as geotechnical or transport engineering. Finally, in terms of geographical dispersion, 12 different nationalities were involved in this process, with most of the experts working in European countries such as Norway, Spain, Italy, Germany or The Netherlands, and only 20% of them working for American institutions.

Questionnaires were elaborated for both groups based on the attributes defined above. These surveys were represented on a numerical scale from 1 to 9 where each odd number indicated linguistic terms and the even numbers indicated the intermediate values between two adjacent judgments. The experts had to indicate the importance of each parameter compared to the others and select the most appropriate according to their professional experience. A sample question given in the questionnaire is shown in **Fig.5**. The survey's data were processed applying the fuzzy AHP methodology mentioned above in order to determine the appropriate weights of decision criteria according to the decision makers. Although the FAHP method is more accurate because it reduces the bias in the decision-making process, FAHP results were compared with conventional AHP results. For Group 1, both methodologies indicate that fatigue life has a higher priority than the other parameters, as shown in **Fig.6.a**. This makes sense as it has proven to be one of the main causes of damage to pavement structure (Lee *et al.* 2005a, Liu *et al.* 2012). Regarding Group 2 (see **Fig.6.b**), rutting resistance, flexural strength and moisture sensitivity top the list of the main criteria affecting FRAC. According to Tarefder et al. (Tarefder and Ahmad 2015), water causes loss of adhesion between the asphalt binder and the aggregate, generating the stripping phenomena. On the other hand, traffic loads induce fissures at the bottom of the asphalt layers due to the loss of flexural strength undergone by asphalt mixtures and plastic deformation that is accumulated at the top of the pavement due to the continuous passage of vehicles.

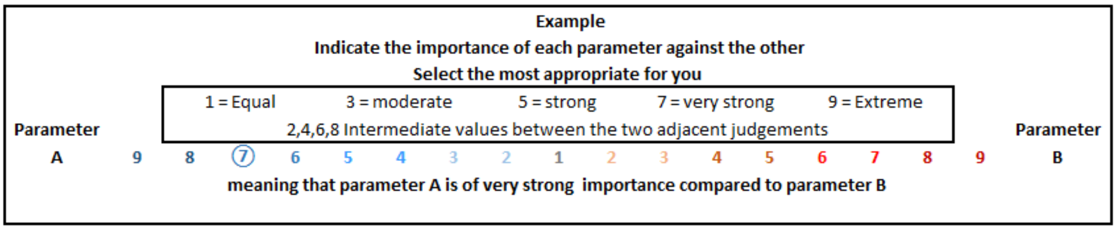

Fig.5. Sample question given in the questionnaire

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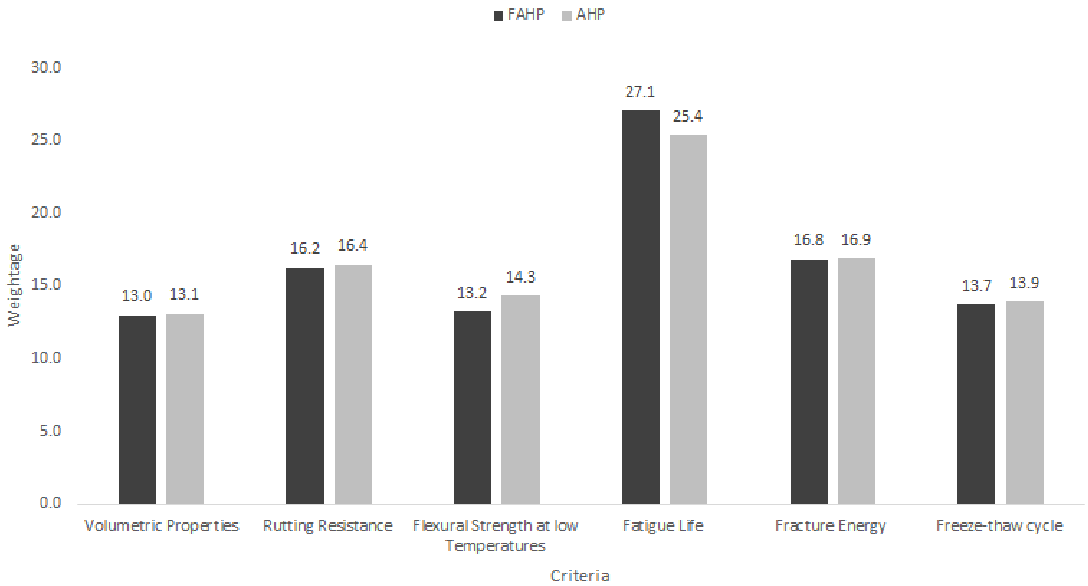
a. Group 1



b. Group 2

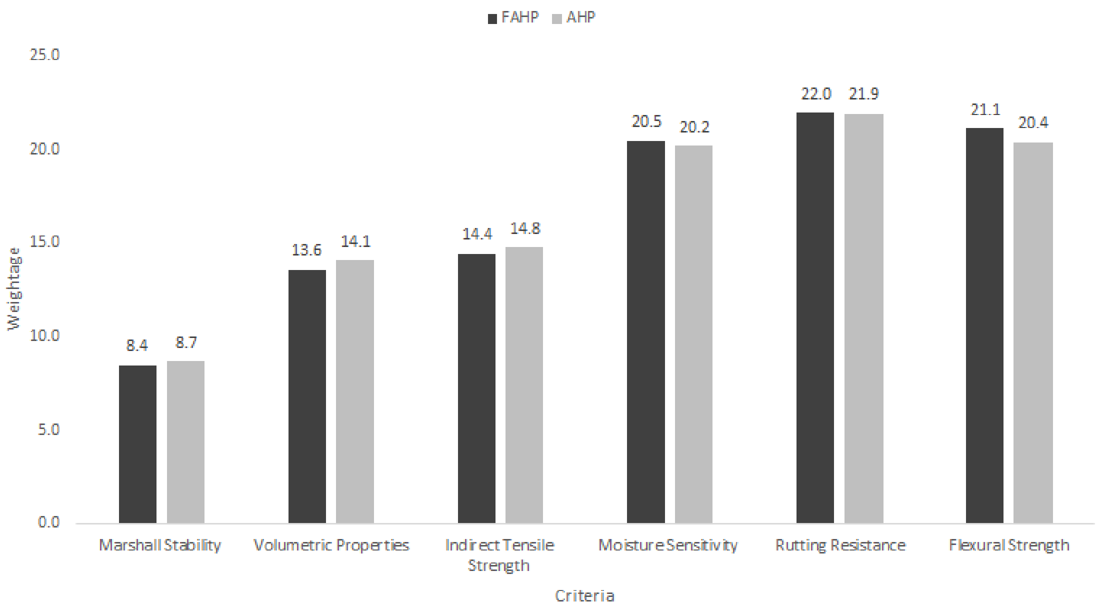


Fig.6. FAHP and AHP values from a. Group 1, b. Group 2.

The results were analysed with Minitab software to find statistical differences between the AHP and FAHP methodologies. Firstly, the *Anderson Darling normality test* was carried out to determine whether the survey's data for each parameter have a normal distribution. Consequently, with the results obtained, parametric and non-parametric tests were used with a confidence interval of 95% to visualise the statistical significance of the two methods; in this case a statistical significance greater than 0.05 implies that data are distribuited normally and a parametric test can be applied. It is interesting to note that the most prioritized criteria in both groups follows a normal distribution and p values in the two methods are fairly similar, as shown in **Table 8.** In addition**,** *One-way ANOVA and U Mann – Whitney tests* were performed on the parametric and non parametric tests, with respect to each criteria, to find statistical differences between the two methods. Although the FAHP technique can be considered as an advanced analytical method in comparison to traditional AHP, statistical significance differences were not reported for the two groups, as shown in **Table 9.** Many researchers who have studied the FAHP technique (Chang, D. Y. 95AD, Buckley 1985a, 1985b, Chaharsooghi *et al.* 2012) have proven that this methodology provides full description in decision-making processes in comparison to the conventional AHP technique. Although the conventional AHP method cannot deal with the fuzziness and vagueness existing in decision-making judgements (Chaharsooghi *et al.* 2012), both methodologies prioritize the criteria in the same way. Chaharsooghi et al. (Chaharsooghi *et al.* 2012) suggested that a classical method should be employed when it is clear that the information/evaluation is certain. Therefore, the experts' opinions play a fundamental role in the criteria weightage. If the assessments made by both methods do not match, the fuzzy method would be the most appropriate given that FAHP deals with membership functions, decreasing the imbalance in the scale of judgement. It is worth mentioning that as the information and decision makers' judgements can deviate, the FAHP method is developed as a natural necessity in the decision-making analysis.

Table 8. Anderson - Darling Normality test from Group 1 and 2

Group 1

Criteria	Volumetric Properties	Rutting Resistance	Flexural strength at Low	Fatigue Life	Fracture Energy	Freeze-thaw Cycle
FAHP p - Value	< 0.005	0.093	0.019	0.351	< 0.005	0.047
AHP p - value	< 0.005	0.095	0.472	0.379	< 0.005	0.021
Test	Non-parametric	Parametric	Non-parametric	Parametric	Non-parametric	Parametric

Group 2

Criteria	Marshall stability	Volumetric Properties	Indirect Tensile Strength	Moisture Sensitivity	Rutting Resistance	Flexural Strength
FAHP p - Value	0.01	< 0.005	< 0.005	< 0.005	0.702	0.498
AHP p - value	< 0.005	< 0.005	< 0.005	< 0.005	0.724	0.428
Test	Non-parametric	Non-parametric	Non-parametric	Non-parametric	Parametric	Parametric

Table 9. Summary of statistical significance between the FAHP and AHP methods.

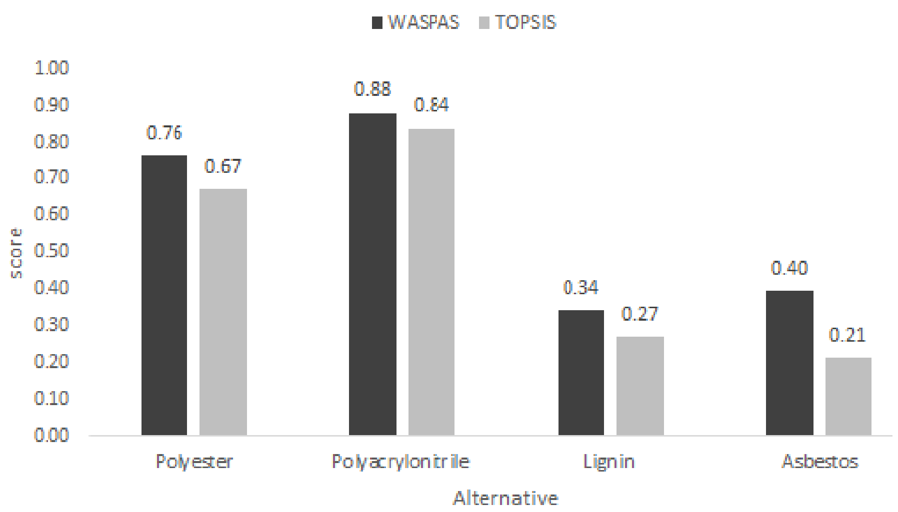
Group 1			Group 2		
Criteria	Statistical Significance	P - value	Criteria	Statistical Significance	P - value
Volumetric properties	Not Significant	0.6727	Marshall Stability	Not Significant	0.7963
Rutting resistance	Not Significant	0.888	Volumetric Properties	Not Significant	0.7248
Flexural strength at Low Temperatures	Not Significant	0.4386	Indirect Tensile Strength	Not Significant	0.7603
Fatigue Life	Not Significant	0.695	Moisture Sensitive	Not Significant	0.6899
Fracture Energy	Not Significant	0.5573	Rutting Resistance	Not Significant	1
Freeze-Thaw Cycle	Not Significant	0.6899	Flexural Strength	Not Significant	0.888

3.3 Assessment of alternatives.

Fig.7.a presents the comparison of the alternatives corresponding to Group 1. Using both methodologies it can be seen that the fibers providing the mixtures with the greatest mechanical performance are synthetic fibers. The difference between synthetic fibers and the others is quite large, and although all of them improve the mechanical properties of HMA, synthetic fibers are suggested as an initial option, Polyacrylonitrile fiber predominating. In this group, the results obtained for both methodologies are quite close. Thus, although its formulation is based on different concepts, it can be noted that the TOPSIS method provided lower values than WASPAS

in the performance score, probably because this method considers the Euclidean distance from positive and negative ideal solutions (Wu *et al.* 2018). Regarding the synthetic fibers, **Fig.7.b** shows the results of the multi-criteria analysis carried out based on the results obtained by Kim and Yoo (Kim *et al.* 2018a). According to the criteria assessment the alternatives rank as follows: Ny0.5 > Pe0.5 > Ny1.0 > Pe1.0 > C1.0 > control > C0.5 > PP0.5 > PP1.0 for the WASPAS methodology and Ny0.5 > Pe0.5 > Ny1.0 > Pe1.0 > C1.0 > C0.5 > control > PP0.5 > PP1.0 using the TOPSIS method. In both cases, the first five positions are the same, with nylon and polyester being the best fibers for use in asphalt concrete. As in Group 1, TOPSIS values were lower than when applying the WASPAS methodology in Group 2. Differences in the results may be associated with the algorithms used by these techniques. The TOPSIS methodology calculates its rankings based on the distance of the alternatives to the ideal solution while WASPAS applies aggregation operators on the normalized values. Moreover, both methods are considered quite flexible, as they do not differ in the ranking decision and the implementation in distinct decision-making problems is easy and practical.

a. Group 1



b. Group 2

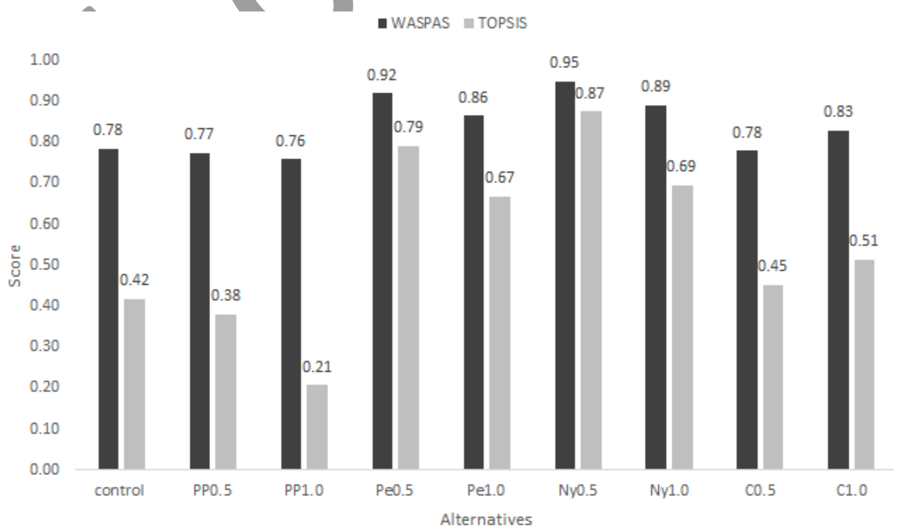
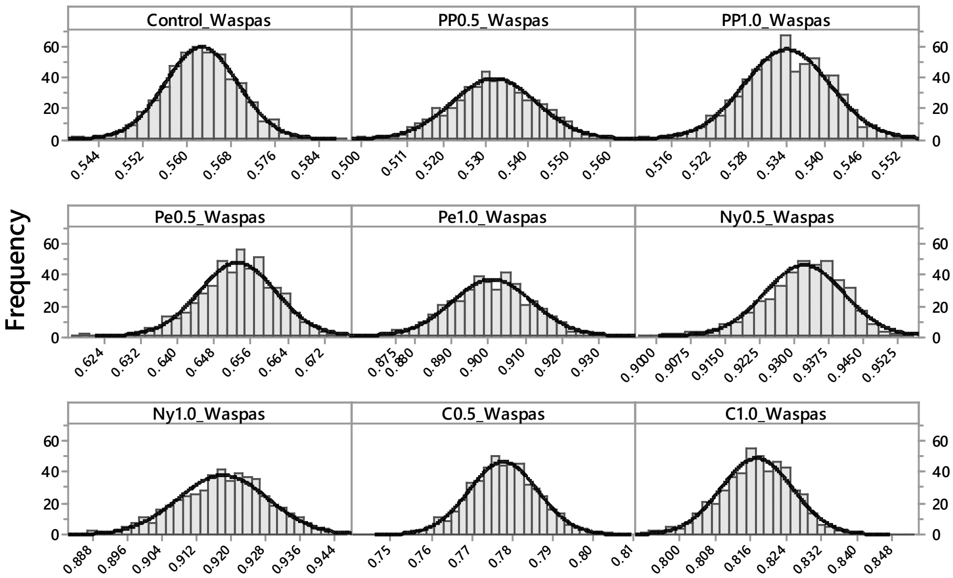


Fig.7. Performance comparison of alternatives a. Group 1 b.Group 2

3.4 Results of the Monte Carlo Simulation

Given the availability of the data, a reliability analysis was applied to Group 2, where a normal distribution was chosen to carry out the simulations. The decision matrix was composed of 9 alternatives, where 81 random samples were considered for performing 1000 simulations, as stated in section 2.4. Eighteen histograms and Probability Density Functions (PDF) were obtained, which are shown in **Fig.8** according to the WASPAS and TOPSIS methodologies. By carrying out a reliability analysis and evaluating the risk associated with the uncertainty of each one of the variables, it is possible to obtain the mean values of each alternative and their standard deviation, as shown in **Fig.9.**

a. Waspas Methodology



b. Topsis Methodology

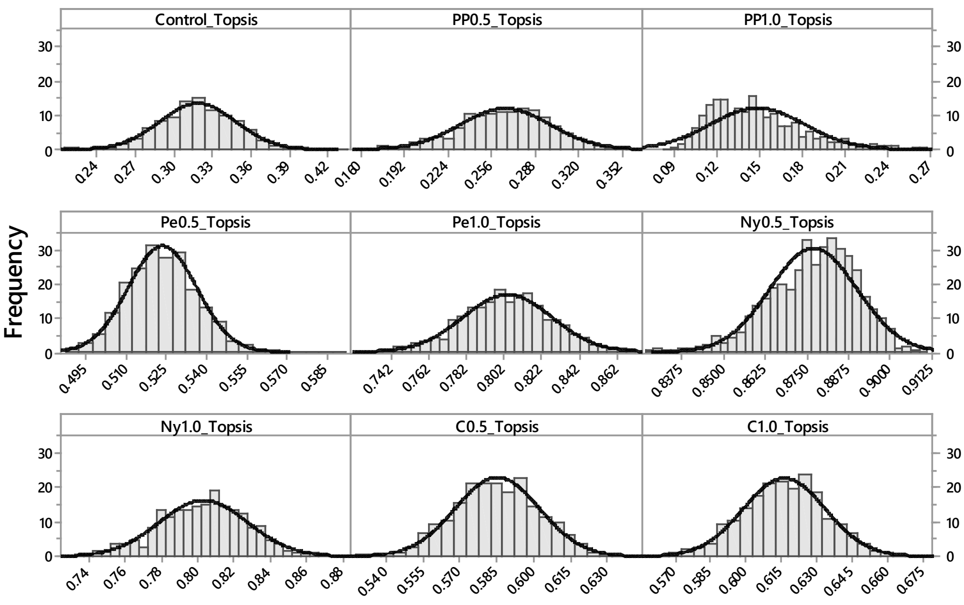
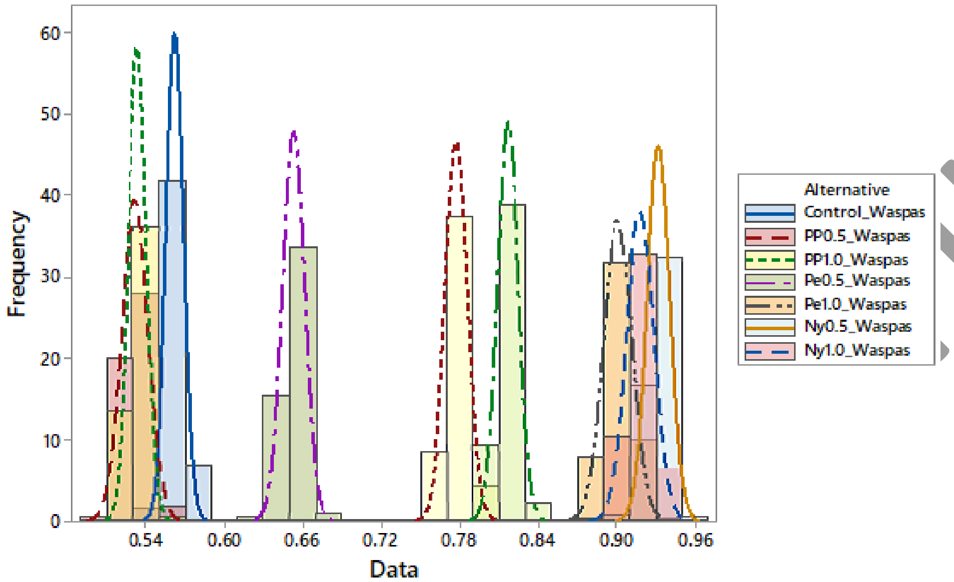


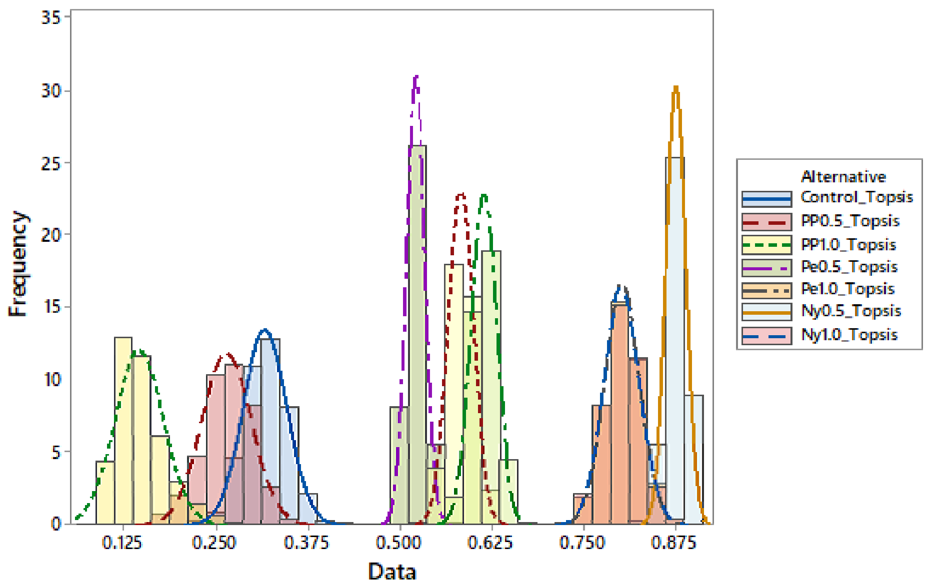
Fig.8 Histograms and Pdfs of control mixes obtained from MCDMA with stochastic Simulation.

	Waspas Methodology								
Alternative	Control	PP0.5	PP1.0	Pe0.5	Pe1.0	Ny0.5	Ny1.0	C0.5	C1.0
Mean	0.56	0.53	0.53	0.65	0.90	0.93	0.92	0.78	0.82
SD	0.007	0.010	0.007	0.008	0.011	0.009	0.011	0.009	0.008



(a)

	Topsis Methodology								
Alternative	Control	PP0.5	PP1.0	Pe0.5	Pe1.0	Ny0.5	Ny1.0	C0.5	C1.0
Mean	0.32	0.27	0.15	0.52	0.81	0.88	0.80	0.59	0.62
SD	0.031	0.033	0.032	0.013	0.023	0.013	0.024	0.017	0.018



(b)

Fig.9 Mean values and standard deviations of Group 2 alternatives by using Monte Carlo Simulations. (a) WASPAS method (b) TOPSIS method

WASPAS with Monte Carlo simulations (WASPAS MC) rank the scores from highest to lowest as follows: Ny0.5 > Ny1.0 > Pe1.0 > C1.0 > C0.5 > Pe0.5 > Control > PP0.5 > PP1.0. These scores coincide with those obtained when using TOPSIS with Monte Carlo simulations (TOPSIS MC). Additionally, when the stochastic simulations were taken into account, the TOPSIS methodology showed greater dispersion in the scores compared to the WASPAS methodology. Considering the uncertainty of the input parameters in the model, the scores changed for the different alternatives. For example, the score changed from 0.77 to 0.53 for the alternative PP0.5, while the alternative Ny0.5 only recorded changes of 0.02. Moreover, Control, PP0.5, PP1.0 and Pe0.5 displayed differences in the scores of more than 0.2, whereas the other alternatives showed variations of less than 0.05 when applying the WASPAS MC technique. Regarding the TOPSIS MC method, the score differences were greater for the alternatives Pe0.5, Pe1.0 and C0.5 so it might be concluded that the abrupt changes are due to high deviations originating in the experimental results. Although Alternative C0.5 did not obtain the highest score, it did not register changes after the Monte Carlo simulations so it can be considered a reliable alternative in comparison to other alternatives such as PP1.0.

3.5 Discussion of alternatives

Synthetic fibers have proven to be the best alternative. Polyacrylonitrile fiber tops the ranking in Group 1 probably because it significantly improves the fatigue life. This was considered the most important criteria according to expert opinions, which is logical as it constitutes the most important load-related problem in flexible pavements. This fiber type has shown great affinity with bitumen and high networking effect in the mixture (Chen *et al.* 2009). Polyester fibers have already been applied to roads, e.g. 6.35-mm-long polyester fibers were used in a flexible pavement in the city of Tacoma and no problems were registered for four years (Toney 1987). Moreover, Shaopeng et al. (Wu *et al.* 2008) reported increases in the mechanical performance of AC mixes with the same percentage of polyester fibers mentioned above. Lignin and asbestos fibers were the least preferred alternatives. Although lignin fibers can improve the mechanical performance of the mixture, a greater amount of bitumen is required that ultimately results in additional costs. On the other hand, the exposure to asbestos has been widely reported to be a health hazard (Park 2018, World Health Organisation 2010). Regarding Group 2, which only considers synthetic fibers, Nylon seems to be the most promising alternative. Several researchers have used recycled waste nylon fibers from toothbrushes and hairbrushes in stone matrix asphalt mixtures. Good results were obtained when using 1.0% fiber content with respect to high-temperature stability, low-temperature cracking and moisture susceptibility, while providing a bridging effect in the mixture and reducing crack propagation (Yin and Wu 2018). In China every year, 80,000 tons of nylon thread is produced, which, if not recycled, can generate problems of waste and pollution.

According to the results, it could be said that the reinforcement improvement in the asphalt mix is linked to the fiber's physical properties, as reported by other researchers (Lee *et al.* 2005b, Tapkın *et al.* 2009, Park *et al.* 2015, Slebi-acevedo *et al.* 2019). Thus, a higher tensile strength and a greater elastic modulus provides the mixture with better mechanical performance. In this sense, in Group 1, it can be seen that polyacrylonitrile and polyester, the fibers with the highest values of these parameters, obtained the best scores. Regarding Group 2, the same effect does not occur, as even though carbon fibers possess excellent mechanical properties, the results in the asphalt mix were not as expected. This may be due to a bad mixing process, as mentioned by Kim et al. (Kim *et al.* 2018a). According to these authors, clusters might have been formed after adding the fibers to the mixture, impeding their good distribution and deteriorating the mixture's mechanical properties.

It should also be analyzed whether a greater length of the fibers will generate a better interlocking effect and the formation of a three-dimensional network. In Group 1, fibers with similar length were used, except those of lignin, which were shorter in comparison to the others. In group 2, Nylon and carbon fibers were twice the length of polyester and polypropylene fibers (Table 4). However, the multi-criteria decision-making analysis showed a similar performance value of the asphalt mixes with polyester and nylon fibers. In this regard, it is interesting to observe that although carbon fibers have higher length/diameter ratio and better mechanical properties, the score obtained by the mixes reinforced with this type of fiber was significantly lower, which might be due to an insufficient dispersion in the mix. As referred to by other authors, fibers with high length/diameter ratio may lump together and form clusters, leading to a poor blending process and poorer mixture performance (Abtahi *et al.* 2010, Kim *et al.* 2018a).

Additionally, it should be noted that the fiber content influences the mechanical properties of the AC mixtures. The multi-criteria analysis by both methodologies provided higher scores when 0.5% fiber content was used instead of 1.0%. It seems that, as different authors have experimentally determined (Moghadas Nejad *et al.* 2014), an excess of fibers might hinder proper dispersion, which ultimately could compromise the generation of the required interlocking effect with the aggregate. In other words, fibers inside the mixture would not be able to form the three-dimensional network that helps to prevent the formation and propagation of cracks (Park *et al.* 2015). On the contrary, an appropriate amount of fibers would help to provide a suitable dispersion, which would improve the tensile properties of the mixture and provide more ductility to the mixture (Abtahi *et al.* 2010).

Finally, fibers can improve certain properties of the mixture but negatively affect others. With the multi-criteria analysis, it could be observed that, in general, the control mixture was a better alternative than those in which unsuitable fibers in inadequate proportions were used.

The inclusion of stochastic simulations enabled the consideration of the uncertainty of the different alternatives and the criteria associated with each one of them. From the results obtained, a decrease in the performance score of each alternative was observed. Introducing stochastic simulations enables risk to be taken into consideration in the input parameters and therefore, providing more precision in the decision-making process.

4.0 Conclusion

Selecting an appropriate fiber based on the mechanical performance of the FRAC mixture is a crucial and complex task that requires delimiting complex decision variables with an integrated decision-making process. This paper demonstrates that multi-criteria design analysis can be used to select the optimal type of fiber for use in asphalt mixtures. In this sense, Polyacrylonitrile and Nylon fibers provided the best results according to the multicriteria analysis carried out with alternatives in Groups 1 and 2, respectively. Synthetic fibers proved to be a good option as well as fibers with high tensile strength and elastic modulus. The WASPAS and TOPSIS methodologies integrated with FAHP were applied to two case-studies and showed very similar results in terms of the alternatives selected, however, the TOPSIS provided lower performance score values than the WASPAS in both groups.

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The criteria set was determined at the beginning of the MCDMA by using the fuzzy version of the Analyticial Hierarchy Process (FAHP). In this research, AHP and FAHP were modelled and compared using two case-studies. Fatigue life for Group 1 and rutting resistance for Group 2, top the list of the criteria with greatest importance according to decision makers. In addition, it is important to mention that either of the two methodologies can be applied, however, FAHP is preferable as it includes fuzziness concepts in the inconsistency of decision makers.

Monte Carlo simulations and statistical analysis were implemented to evaluate the performance score of the various alternatives taking into acount the uncertainty of the input parameters. The results obtained were lower than those of the deterministic evaluation, with the statistical analysis showing a significant difference between the two approaches.

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