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Selection of Additives and Fibers for Improving the Mechanical and Safety Properties of Porous Concrete Pavements through Multi-Criteria Decision-Making Analysis

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Abstract: Despite the number of environmental advantages that porous concrete (PC) pavements can provide, they are mainly used in light-traffic roads, parking lots and sidewalks due to their low mechanical strength. This research focuses on the common additives employed in PC pavements, according to a literature review, with the aim of increasing their mechanical strength while maintaining an acceptable infiltration capacity. The results demonstrated that the combination of superplasticizers and air-entraining additives can provide indirect tensile strength values over 2.50 MPa, with an infiltration capacity over 0.40 cm/s. In addition, polypropylene fibers were seen to provide very good safety properties, preserving some structural integrity in the case of failure. All mixtures studied obtained outstanding skid resistance results under both dry and wet conditions.

Keywords: porous concrete pavements; multi-criteria analysis; additives; mechanical properties; safety properties; permeability

1. Introduction

Porous concrete (PC) mixtures have been shown to be one of the best solutions to mitigating the problem of climate change. As some authors have pointed out, PC is a special material used in pavement technology with the purpose of infiltrating rainwater into the ground or catching it for future use. This entails refilling underground water levels, which decrease in urban areas because of human consumption, or catching water for use in dry seasons [1,2]. Other environmental benefits that PC pavements can provide include vehicle–pavement noise reduction; decrease of temperature due to sunlight reflection; higher skid-resistance on the pavement surface, providing greater safety for users; and through the use of specific products, the removal of air pollutants through a process of photocatalysis [3]. In addition, some authors have investigated whether the high air void content in porous pavements makes it susceptible to low-temperature transverse cracking, concluding that the use of these pavements is feasible in cold regions [4].

Despite the environmental advantages that PC mixtures can offer, their use has been limited mainly to light-traffic roads, parking lots and sidewalks [5,6]. This, because of the high porosity they have (around 15%–30%), decreases their load-bearing capacity, limiting their ability to resist traffic loads [7–10]. The higher the number of air voids (AVs) in the structure, the lower the adhesion bridges formed by the cement paste between the coarse aggregate particles, and hence the PC strength decreases. The porous structure in this kind of mixture is formed basically of coarse aggregates (CA) with sizes normally in the range of 4–12 mm, with low or no fine content, in order to ensure a pore structure with high infiltration capacity that allows rainwater infiltration. This open structure reduces the strength of PC mixtures that can reach mechanical strengths which are about 60% lower than common concrete pavements [2,11,12].

Furthermore, improving PC strength has become a relevant topic for researchers and practitioners who are also looking to improve the environmental benefits of this material. The simplest way to improve both, the mechanical and environmental properties of PC mixtures, is by using additives and fibers. According to the literature review, the combination of silica fume with superplasticizers is the most commonly used combination of additives in PC mixtures [6,11,13,14]. This is because they can increase the load resistance capacity, although the mixture tends to require more water [15]. Some studies have successfully demonstrated an improvement in the bearing capacity and permeability when combining these additives [2,16].

Finally, set retarders, which are used to delay the setting time of concrete, demonstrated an increase in the AV content of porous mixtures, augmenting infiltration but affecting the bearing capacity [17–19]. Other different additives have demonstrated better results in comparison with mixtures without additives, such as viscosity modifiers, air-entraining additives, and different kinds of fibers [8,10,20–25], improving the workability and increasing the mechanical properties of the material.

The present research evaluates the use of additives in porous concrete mixtures with the intention of increasing the mechanical strength of the PC layer in porous pavements. With this aim, a reference PC mixture has been designed. This mixture has been further modified by using a set of additives, and the resulting PC materials have been assessed to obtain their mechanical and hydraulic properties.

2. Materials and Methods

2.1. Sample Preparation

This investigation consists of two parts. Firstly, different dosages of additives are analyzed separately. For this analysis, the mixture in Table 1(A) was employed. The mixtures remained were kept under curing conditions for 7 days. Once the optimal amount of each additive was ascertained, in the second part of the research, different additive combinations were used in order to evaluate the improvement of properties, where the dosages in Table 1(B) were employed. In addition, mixtures remained under curing conditions for 28 days.

Table 1. Mixture dosages employed. AG: aggregate gradation; s/c: sand–cement ratio; w/c: water–cement ratio; VMA: void proportion in mineral aggregate; CA: coarse aggregate.

(A) Mixture Dosage Employed for the Analysis of Additives Separately.								
Characteristics	**AG (mm)**	**s/c**	**w/c**	**VMA (%)**	**Cement (kg/m^3)**	**CA (kg/m^3)**	**Sand (kg/m^3)**	**Water (kg/m^3)**
	8–12	0.50	0.35	44.30	292.05	1618.33	146.03	119.42
(B) Mixture Dosage Employed for the Analysis of Additives Combinations.								
Characteristics	**AG (mm)**	**s/c**	**w/c**	**VMA (%)**	**Cement (kg/m^3)**	**CA (kg/m^3)**	**Sand (kg/m^3)**	**Water (kg/m^3)**
	4–8	0.50	0.30	47.00	344.81	1540.71	172.40	120.06

Portland Cement I 52.5R UltraVal was employed as the cementitious material, with a specific weight of 3.14 kg/cm^3, according to EN-1907-6 standard. Porphyric aggregate was used in sizes of 4–8 mm and 8–12 mm for CA and 0–2 mm for sand. Two different AGs were employed because of the material availability. Cylindrical specimens with a diameter of 102 mm and a height of 65 mm were used to assess the mechanical and hydraulic characteristics of the PC mixtures. They were compacted in a mechanical press to control the compaction effort at an application speed of 250 N/s, up to a limit of 85,000 N.

2.2. Additives

An extensive literature review was done in order to identify the most common additives used in PC mixtures. The amounts employed by some authors, as well as the ones established in the technical data of the additives, were noted. The additives' names, dosages, as well as references are shown in Table 2.

Table 2. Additives employed and their dosage.

Additive	Use	Code	Mixture	Dosage *	Note	Reference
Carbon-steel fibers	Increases the compressive and tensile strength of the mixtures.	CSF	CSF-1 CSF-2 CSF-3	3.42 8.33 27.39		[14]
Polypropylene fibers	Increases the tensile strength of the mixtures.	PF	PF-1 PF-2 PF-3	0.68 1.15 2.46		[6,17,26]
Air-entraining	-Reduces the viscosity of the cement paste. -Increases the air voids in the mixture. -Increases strength of PC mixtures.	AE	AE-1 AE-2 AE-3	0.15 1.50 3.00		[6,13,26–28]
Microsilica	Normally use in combination with superplasticizers, resulting in improvements in the mechanical resistance.	MS	MS-1	5.00	Not removing cement.	[2,11,13,14,16]
			MS-2	5.00	Removing cement.	
			MS-3	10.00	Removing cement.	
			MS-4	15.00	Removing cement.	
Nanosilica	Improves the microstructure of the mixture and increases strength.	NS	NS-1 NS-2 NS-3 NS-4	0.50 5.00 10.00 15.00		[29–31]
Superplasticizer	-Decreases the water needed in the mixture. -Increases mechanical strength.	SP	SP-1	1.50	Removing 0% of water.	[2,6,11,13,14,16,18,27,28]
			SP-2	1.50	Removing 5% of water.	
			SP-3	1.50	Removing 10% of water.	
			SP-4	1.50	Removing 15% of water.	
			SP-5	0.50	Removing 5% of water.	
			SP-6	2.50	Removing 5% of water.	
Viscosity modifier	Makes the cement paste more workable.	VM	VM-1 VM-2 VM-3	0.50 0.65 0.80		[6,17,18,27]
Set retarder	Increases the workability time by delaying the concrete hardening.	SR	SR-1 SR-2 SR-3	0.20 1.40 2.50		[11,17,18]

Note: * % of cement weight.

2.2.1. Fibers

Two different types of fibers were used. Carbon-steel fibers are used when a high-resistance concrete is required. They are very thin and provide good ductility and structural reinforcement under bending, traction, and shear stress. Some researchers achieved increases of about 40% in compressive strength of PC, and around 16% in flexural strength, when adding 40 kg/m^3 of carbon-steel fibers. However, permeability decreased by 25%, due to the reduction of the air void proportion in the mixture by about 22% [14]. The length of the fibers is approximately 1 cm.

Polypropylene fibers are used to avoid fissures appearing in the concrete caused by humidity, so reducing cracks. Moreover, compressive and flexural strength can be increased. In addition, in the case of failure, structural integrity can be maintained by the fibers, preventing the pavement from collapsing. Some studies achieve an increase in compressive strength by more than 30%, and tensile strength by almost 35%, using 0.9 kg/m^3 of polypropylene fibers in the mixture [32]. Other experiments were able to increase the compressive strength by 6% using fibers in a dosage of 0.5% of total volume of the mixture. These researchers studied the use of 1% fibers by total volume of the mixture, but compressive strength decreased by around 17%, so they concluded that the amount of fibers was too high and the mixture was not able to blend in a homogeneous way [33]. The length of the fibers was around 5.4 cm.

2.2.2. Air-Entraining

Despite not being commonly used in PC mixtures, air-entraining additives are employed to create resistance to freeze-thaw cycles [34]. In addition, the concrete mixture tends to become more workable because the air trapped in the concrete increases. Some researchers studied the influence of cement flow on compressive strength, employing air-entraining additives in the mixture. Results revealed that at lower flow, air-entraining mixtures were 25% stronger than mixtures without the additive, but at higher flow, air-entraining mixtures decreased their strength to be around 20% less than mixtures without it [28].

2.2.3. Microsilica and Nanosilica

Microsilica is a powder used in concrete in small quantities (normally between 5%–10% of cement weight), because it increases the need for water in the mixture. For this reason, it is common to combine it with superplasticizers, to reduce the amount of water [15]. Although it does not significantly improve the mechanical performance of the mixtures, it is considered to decrease the environmental impact by reducing the cement fraction in the mixture. Some researchers observed that the mechanical results of mixtures were influenced not only by the microsilica, but also by the gradation adopted, where at lower gradation, an increment in the compressive strength of around 7% was obtained [11].

In addition, nanosilica, which is used as a liquid additive, tends to react with the Calcium Hydroxide ($Ca(OH)_2$), improving cement properties. Thus, higher compressive strength values can be achieved [35]. Some studies determine this additive improves cement paste quality, increasing its durability [29,31].

2.2.4. Superplasticizer, Viscosity Modifier, and Set Retarder

Superplasticizers enable water content to be reduced in mixtures without losing consistency and workability. According to some studies, this additive can reduce the amount of water by up to 30%, and can improve rheological properties of concrete. Other investigations have concluded that these additives can increase mechanical properties of PC mixtures [13,36]. These improvements occur because the water to cement ratio of mixtures is reduced [37].

Viscosity modifier additives help to make mixtures more workable, although they do not represent a significant improvement in mechanical terms. As PC mixtures are dryer and more difficult to handle because of the lack of fines and less water, in comparison with a conventional concrete, viscosity modifiers help to make the mixture more fluent, facilitating its placement and compaction [17].

Set retarding additives are used to control cement hydration. In addition, they can act as lubricants when pouring concrete from a mixer, improving its workability and performance characteristics [11]. Nevertheless, some studies obtained air voids (AVs) of up to 37%, decreasing the compressive strength by more than 60% in mixtures with superplasticizer [18].

2.3. Laboratory Tests

2.3.1. Permeability

A falling-head permeameter was employed in order to measure the infiltration capacity of the samples. It consisted of a PVC tube of 10 cm diameter, adjusted with metal clamps, to keep the sample steady. On top of the mold a metacrylate tube was placed, where water was introduced to perform the test. This metacrylate tube was calibrated to measure a fall of 20 cm. Finally, employing Darcy's law, the infiltration coefficient was calculated, according to Equation (1):

$$k = \left[\frac{\left(A_{sample}\right)\left(h_{sample}\right)}{\left(A_{tube}\right)(t)}\right]\left[ln\left(\frac{h_1}{h_2}\right)\right] \tag{1}$$

where k is the permeability capacity (cm/s), A_{sample} is the area of contact of the sample, h_{sample} is the height of the sample, A_{tube} is the area of the tube's gap, t is the time it takes the water to go from the higher point, h_1 to h_2. For the calculation of the porosity (P), Equation (2) was employed:

$$P = \frac{V_{Tot} - \left[W_{DRY} * \left(\frac{\%_{CA}}{\rho_{CA}} + \frac{\%_S}{\rho_S} + \frac{\%_C}{\rho_C}\right)\right] - W_{DRY} * \frac{\%_W}{\rho_W}}{V_{Tot}} * 100 \tag{2}$$

where W_{DRY} corresponds to the mixtures' weights under dry conditions. $\%_{CA}$, $\%_S$, $\%_C$ and $\%_W$ represent the percentages of the total mixture of CA, sand, cement and water respectively. ρ_{CA}, ρ_S, ρ_C and ρ_W represent the density of the mixture's components mentioned above.

2.3.2. Indirect Tensile Strength

The Indirect Tensile (IT) test was performed in order to analyze the mechanical strength of the PC specimens according to the EN 12390-6 standard. This test enables the behavior of the pavement to be understood when vehicles apply load on the cross section of the sample, causing a tensile stress in it that leads to failure. The IT test description, equipment and equations can be seen in the EN 13286-42, EN 12390-6, and EN-12390-1 standards.

2.3.3. Skid Resistance

The Skid Resistance of the samples was evaluated through the British Pendulum Test based on the ENV 12633:2003 standard. The device consists of a calibrated pendulum that swings across the sample, making contact with it. The end of the pendulum has a special rubber that represents a tire. A scale from 0 to 150 is used to measure a British Pendulum Number (BPN). This test is performed under dry and wet conditions, where the rubber from the pendulum and the sample's surface get wet. The area of contact of the samples was fixed in a 7 cm distance to enable comparison among them. This test was performed within the study of additive combinations.

2.4. Multi-Criteria Decision-Making

2.4.1. Criteria Weighting

(1) Fuzzy AHP Weighting

To establish the priorities among the variables (tests), the Analytical Hierarchy Process (AHP) method was selected. Starting with a comparison scale, proposed by Saaty [38], and used by several authors [39–41], a scale of 9 values of importance is proposed as shown in Table 3. However, some authors claim this technique cannot capture the ambiguity present in a subjective comparison [39]. To solve this issue, the AHP method is combined with Fuzzy sets to deal with this uncertainty, using triangular and trapezoidal membership functions mainly [42]. The Fuzzy scale of relative importance is shown in Table 3 as well. To organize the data, a matrix can be formed, where rows correspond to the different alternatives (n direction), and columns to the variables or tests performed (m direction).

Table 3. Saaty's scale of comparison and Fuzzy scale of comparison.

Linguistic Term	Numerical Value	Fuzzy Scale (l, m, u)
Equal	1	(1, 1, 1)
Moderate	3	(2, 3, 4)
Strong	5	(4, 5, 6)
Very strong	7	(6, 7, 8)
Extremely strong	9	(9, 9, 9)
Intermediate values	2	(1, 2, 3)
	4	(3, 4, 5)
	6	(5, 6, 7)
	8	(7, 8, 9)

The Fuzzy triangular membership function was employed, as demonstrated in Figure 1, where "l", "m", and "u" refer to the lower, medium, and upper fuzzy numbers of the triangular axis.

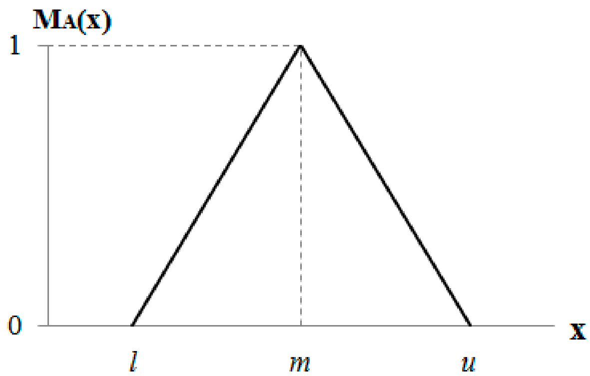

Figure 1. Fuzzy triangular membership function.

For the AHP method, variables are placed in an "n" factor matrix, and a value of importance is assigned when making the pairwise comparison among the variables. For example, if the IT test has a value of importance of 2 with respect to the permeability test, then permeability will have a value of importance of 1/2 with respect to IT. That is the reciprocal value, as seen in Equation (3):

$$A = \begin{bmatrix} a_{11} & \cdots & a_{1j} & \cdots & a_{1n} \\ \vdots & & \vdots & & \vdots \\ a_{i1} & \cdots & a_{ij} & \cdots & a_{in} \\ \vdots & & \vdots & & \vdots \\ a_{n1} & \cdots & a_{nj} & \cdots & a_{nn} \end{bmatrix}, \; a_{ii} = 1, \; a_{ij} = \frac{1}{a_{ji}}, \; a_{ji} \neq 0 \tag{3}$$

The same procedure is employed for the Fuzzy triangular membership function, with the variations of Equation (4):

$$\widetilde{A^{-1}} = (l,\ m,\ u)^{-1} = \left(\frac{1}{u},\ \frac{1}{m},\ \frac{1}{l}\right) \tag{4}$$

Following the same example, and according to Table 3, instead of a value of importance of 2, IT will have a value of importance of (1,2,3) with respect to permeability. Therefore, permeability will have a value of importance of (1/3,1/2,1/1) with respect to IT. As a second step, the Fuzzy geometric mean value, $\widetilde{r_i}$, is calculated with Equation (5):

$$\widetilde{r_i} = \widetilde{A_1} x \widetilde{A_2} = (l_1,\ m_1,\ u_1)(l_2,\ m_2,\ u_2) = (l_1 * l_2,\ m_1 * m_2,\ u_1 * u_2) \tag{5}$$

Being $\widetilde{A_1}$ and $\widetilde{A_2}$ the tested variables. Then, numbers obtained are summed in order to obtain 3 values only, representing *l, m, u*, applying Equation (6). Then, Equation (4) is used again.

$$\widetilde{A_1} + \widetilde{A_2} = (l_1,\ m_1,\ u_1) + (l_2,\ m_2,\ u_2) = (l_1 + l_2,\ m_1 + m_2,\ u_1 + u_2) \tag{6}$$

Thus, the Fuzzy weights, $\widetilde{w_i}$, can be calculated with Equation (7):

$$\widetilde{w_i} = \widetilde{r_i}\,(\widetilde{r_1} * \widetilde{r_2} * \ldots * \widetilde{r_n})^{-1} \tag{7}$$

Finally, with Equation (8), the final weights, w_i, are obtained:

$$w_i = \left(\frac{l + m + u}{3}\right) \tag{8}$$

The sum of the weights, w_i, must be equal to 1. If not, then the weights have to be normalized with Equation (9):

$$\overline{w}_i = \frac{w_i}{\sum w_i} \tag{9}$$

(2) Entropy weighting

This method is employed when decision-makers have conflicting views on the value of weights. In the AHP method, the decision-maker gives an opinion on different variables to make pairwise comparison. In the entropy method, this is not needed, as it is a parameter that describes how much different alternatives approach one another in respect to a certain variable. It is based on the amount of information available to determine the index's weight [43]. Therefore, the weights calculated are different for each separately evaluated additive. Steps are as follows:

First, it is important to determine whether the variable, x'_{ij}, is beneficial or not. That is, to state whether the desired result has to be the highest or the lowest of a series of values. For that, Equations (10) and (11) are used respectively. Where x_{ij} corresponds to any value of a series of essays on a determined test:

$$x'_{ij} = \frac{x_{ij}}{max_j x_{ij}},\ (i = 1, \ldots,\ m;\, j = 1, \ldots,\ n) \tag{10}$$

$$x'_{ij} = \frac{min_j x_{ij}}{x_{ij}},\ min_j x_{ij} \neq 0,\ (i = 1, \ldots,\ m;\, j = 1, \ldots,\ n) \tag{11}$$

This requires dividing each result of a test by the maximum value obtained, if we want the maximum value to be the most important, or dividing the minimum value by each result, if we desire the lowest result to be the most important. Then, the entropy, H_j, of the variables is calculated with Equation (12):

$$H_j = -h\sum_{i=1}^{m} f_{ij}\, lnf_{ij},\ (i = 1, \ldots,\ m; j = 1, \ldots,\ n) \tag{12}$$

where, f_{ij} is calculated with Equation (13), and h with Equation (14). m corresponds to the sum of $f_{ij}\, lnf_{ij}$, in a vertical way:

$$f_{ij} = -\frac{x'_{ij}}{\sum_{i=1}^{m} x_{ij}},\ (i = 1, \ldots,\ m; j = 1, \ldots,\ n) \tag{13}$$

$$h = \frac{1}{\ln(m)} \tag{14}$$

Finally, with equation (15), the entropy weight, w_j, of the variable is determined:

$$w_j = -\frac{1 - H_j}{n - \sum_{j=1}^{n} H_j},\ \sum_{j=1}^{n} w_j = 1,\ (i = 1, \ldots,\ m; j = 1, \ldots,\ n) \tag{15}$$

2.4.2. Technique for Order Performance by Similarity to Ideal Solution (TOPSIS)

The TOPSIS method, based on dimensions, tries to select solutions that are closer to an ideal solution, and further from a negative ideal solution [44,45].

The TOPSIS method consists of the following steps:

1. Normalize results by means of Equation (16), where n_{ij} refers to a normalized number from any x_{ij} value (results from tests). m determines the summation in a vertical way:

$$n_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}; j = 1, 2, \ldots, n; i = 1, 2, \ldots, m \tag{16}$$

2. Then, the normalized values, n_{ij}, are multiplied by the weights, w_j, determined in Section 2.4.1, with Equation (17):

$$V_{ij} = n_{ij}w'_{ij}; j = 1, 2, \ldots, n; i = 1, 2, \ldots, m \tag{17}$$

3. Equations (18) and (19) are used to determine the ideal solution and the negative ideal solution, respectively. Where K is the beneficial criteria set index (when maximum value is wanted), and K' is the non-beneficial criteria set index (when minimum value is wanted).

$$\left\{V_1^+, V_2^+, \ldots, V_n^+\right\} = \left\{\left(Max_i V_{ij} \middle| j \in K\right), \left(Min_i V_{ij} \middle| j \in K'\right) \middle| i = 1, 2, \ldots, m\right\} \tag{18}$$

$$\left\{V_1^-, V_2^-, \ldots, V_n^-\right\} = \left\{\left(Min_i V_{ij} \middle| j \in K\right), \left(Max_i V_{ij} \middle| j \in K'\right) \middle| i = 1, 2, \ldots, m\right\} \tag{19}$$

4. The distances between the ideal solution and the negative ideal solution are calculated with Equations (20) and (21), respectively, where S_i^+ and S_i^- are values obtained from the subtraction of V_{ij} from the maximum or minimum value, V_j, obtained from the V_{ij} values.

$$S_i^+ = \left\{\sum_{j=1}^{n} (V_{ij} - V_j^+)^2\right\}^{0.5}; j = 1, 2, \ldots, n; i = 1, 2, \ldots, m \tag{20}$$

$$S_i^- = \left\{\sum_{j=1}^{n} (V_{ij} - V_j^-)^2\right\}^{0.5}; j = 1, 2, \ldots, n; i = 1, 2, \ldots, m \tag{21}$$

5. Finally, the relative closeness, C_i, of the ideal solution is obtained with Equation (22). Where, higher values of C_i represent a better hierarchical position of the alternative.

$$C_i = \frac{S_i^-}{S_i^+ + S_i^-}; i = 1, 2, \ldots, m; 0 \leq C_i \leq 1 \quad (22)$$

2.4.3. Weighted Aggregate Sum Product Assessment (WASPAS)

The WASPAS method is based in aggregation operators, and makes a combination of two multi-criteria decision-making methods: the Weighted Sum Method (WSM), and the Weighted Product Method (WPM). These two components are balanced by a "λ" parameter, with values from 0 to 1. When λ = 1, the alternatives hierarchy is calculated with the WSM. On the contrary, when λ = 0, then the hierarchy is calculated with the WPM. Generally, λ = 0.5 is employed [46].

The WASPAS method consists of the following steps:

1. Normalize the data results. The beneficial (when the highest value is wanted) and non-beneficial (when the lowest value is wanted) equations are employed. Represented by Equations (23) and (24), respectively:

$$n_{ij} = \frac{x_{ij}}{max_i x_{ij}} \quad (23)$$

$$n_{ij} = \frac{min_i x_{ij}}{x_{ij}} \quad (24)$$

2. Then, WSM and WPM are calculated with Equations (25) and (26), respectively. Where the WSM is a sum of the multiplication between the weights obtained in Section 2.4.1 and the normalized values n_{ij}. WPM, is a multiplication, in a horizontal way, of the square normalized values of each variable in the matrix:

$$WSM = \sum_{j=1}^{n} n_{ij} w_j \quad (25)$$

$$WPM = \prod_{J=1}^{n} \left(n_{ij}\right)^2 \quad (26)$$

3. Finally, the relative importance, Q_i, of each alternative is calculated. Here, a combination of the WSM and WPM is performed, through the use of Equation (27):

$$Q_i = \lambda WSM + (1 - \lambda) WPM \quad (27)$$

3. Results and Discussion

3.1. Study of Additives Separately

The test results obtained in the first step of the research are summarized in Table 4. This table shows the general results obtained in each laboratory test for different dosages of every additive used separately in order to determine the optimum dosages for all the mixtures analyzed. The following sections discuss the results.

Table 4. Permeability (k) and indirect tensile (IT) strength results obtained from the additives study.

Additive	Mixture	Results							
		ρ (kg/m^3)	σ	AV (%)	σ	k (cm/s)	σ	IT (MPa)	σ
Viscosity modifier	Control *	2042.382	18.431	23.570	0.007	1.192	0.138	1.103	0.044
	VM-1	2043.649	27.250	23.615	0.010	1.394	0.379	1.374	0.145
	VM-2	2026.703	17.230	24.248	0.006	1.571	0.255	0.889	0.161
	VM-3	2040.081	10.357	23.831	0.004	1.277	0.116	1.090	0.341
Set Retarder	Control *	2042.382	18.431	23.570	0.007	1.192	0.138	1.103	0.044
	SR-1	2034.980	24.056	23.939	0.009	1.58	0.360	1.256	0.129
	SR-2	1930.538	48.487	27.842	0.018	2.603	0.245	0.590	0.087
	SR-3	2007.256	27.162	24.975	0.010	1.488	0.134	0.451	0.064
Carbon-steel fibers	Control *	2042.382	18.431	23.570	0.007	1.192	0.138	1.103	0.044
	CSF-1	2022.908	22.708	24.237	0.009	1.102	0.096	1.104	0.217
	CSF-2	2015.601	5.479	25.002	0.002	1.126	0.095	0.941	0.122
	CSF-3	1980.594	1.801	28.123	0.001	1.233	0.169	0.586	0.037
Polypropylene fibers	Control *	2042.382	18.431	23.570	0.007	1.192	0.138	1.103	0.044
	PF-1	2024.668	28.655	23.893	0.011	1.014	0.138	1.188	0.214
	PF-2	2024.569	19.859	23.944	0.007	1.143	0.136	1.248	0.036
	PF-3	1988.423	16.048	25.434	0.006	1.100	0.263	0.800	0.080
Nanosilica	Control *	2042.382	18.431	23.570	0.007	1.192	0.138	1.103	0.044
	NS-1	2015.406	15.121	24.627	0.006	1.251	0.034	1.252	0.057
	NS-2	2038.430	14.239	24.194	0.005	1.025	0.226	1.184	0.128
	NS-3	2014.117	6.241	25.564	0.002	1.098	0.135	1.121	0.113
	NS-4	2020.678	9.204	25.782	0.003	0.956	0.134	1.221	0.267
Superplasticizer	Control *	2042.382	18.431	23.570	0.007	1.192	0.138	1.103	0.044
	SP-1	1987.013	13.669	25.781	0.005	2.105	0.236	0.996	0.166
	SP-2	2015.494	11.884	25.043	0.004	2.133	0.160	1.283	0.263
	SP-3	1991.194	30.865	26.271	0.011	2.176	0.373	1.221	0.124
	SP-4	2008.427	21.193	25.959	0.008	1.987	0.245	1.035	0.207
	SP-5	2017.740	13.511	24.866	0.005	1.145	0.204	1.255	0.155
	SP-6	1948.366	16.721	27.632	0.006	2.479	0.281	0.966	0.298
Air-entraining	Control *	2042.382	18.431	23.570	0.007	1.192	0.138	1.103	0.044
	AE-1	2056.737	22.181	23.126	0.008	0.961	0.186	1.492	0.204
	AE-2	2060.941	22.832	22.968	0.009	0.826	0.120	1.273	0.118
	AE-3	2015.277	24.177	24.675	0.009	1.398	0.426	1.206	0.093
Microsilica	Control *	2042.382	18.431	23.570	0.007	1.192	0.138	1.103	0.044
	MS-1	2042.287	21.740	23.673	0.008	0.984	0.055	1.049	0.178
	MS-2	2010.806	14.756	24.773	0.006	1.336	0.238	1.076	0.132
	MS-3	2054.212	26.447	23.586	0.010	0.595	0.252	0.959	0.052
	MS-4	2054.013	22.282	24.033	0.008	0.489	0.096	1.201	0.118

Note: * Refers to the same mixture.

3.1.1. Results Discussion of Permeability and Indirect Tensile Strength

Permeability results were very good for all mixtures, where almost every additive tended to improve it, in comparison with the Control mixture. Only the air-entraining and the microsilica additives obtained poorer results, in most of the dosages used, than the Control mixture, as seen in Figure 2. A similar behavior was observed with microsilica, where the material increases the density (ρ) of the mixture as it replaces some cement.

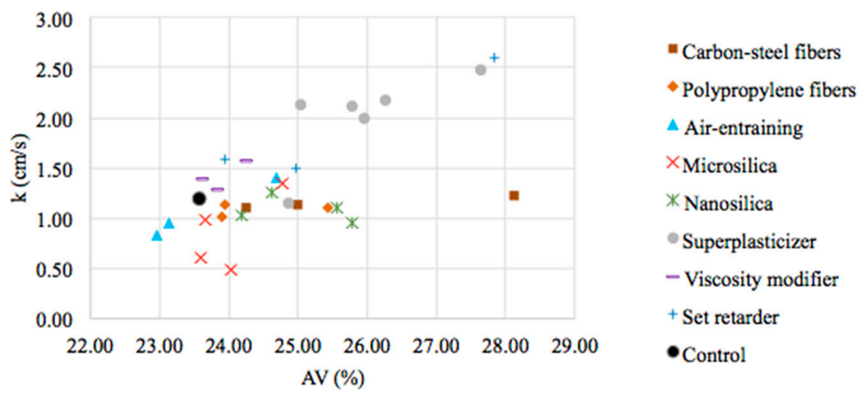

Figure 2. Correlation between air voids (AV) and permeability (k) capacity—Additives study.

In addition, superplasticizer and set retarder (mixture SR-2 only), led to the highest permeability of all the additives, because of the high AV obtained by these mixtures. This can be explained because both additives make the mortar more workable and tend to coat the aggregates better, increasing the aggregates volume, and hindering the compaction, leading to more AV and less ρ, as seen in Figure 3.

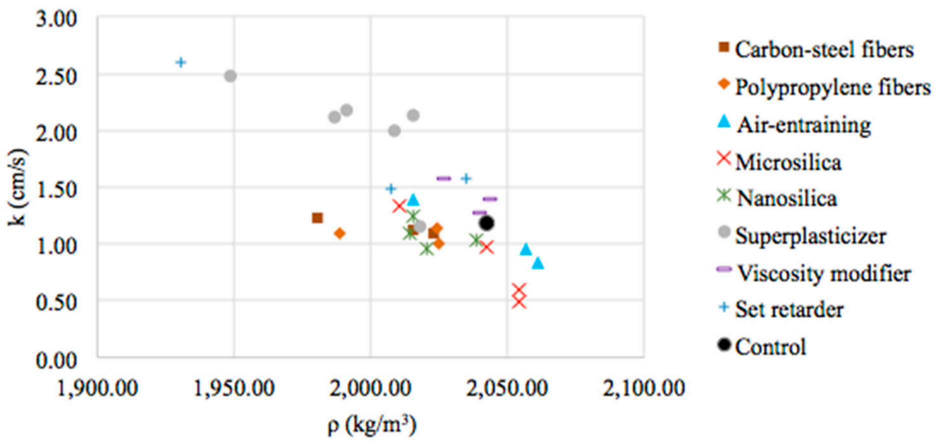

Figure 3. Correlation between density (ρ) and permeability (k) capacity—Additives study.

Air-entraining additives led to the highest IT values, as seen in Figure 4. Following the same explanation as in the previous section, the higher ρ provided by the additive increased the adhesion between aggregate particles, leading to a stronger sample, as seen in Figure 5.

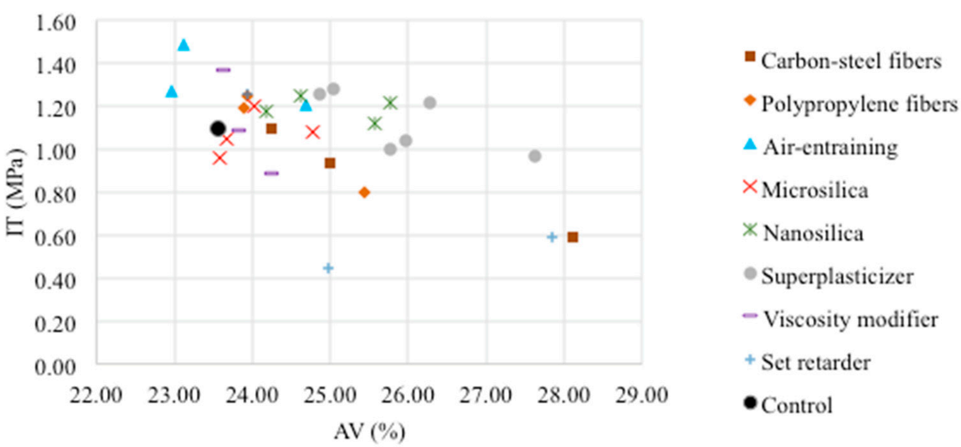

Figure 4. Correlation between air voids (AV) and indirect tensile (IT) strength.

Carbon-steel fibers led to lower IT results in all the mixtures in comparison with the Control mixture. This is because the fibers were 1 cm in length, and were not able to provide sufficient adhesion between particles and the mortar because of the AV. In addition, infiltrated water tended to corrode the fibers, affecting their functionality. Moreover, some fibers tended to remain on the sample surface, making it dangerous for users, especially for cyclists, who can suffer scrapes if they fall.

The set retarder additive also obtained a very low indirect tensile (IT) strength. This is because the coating of the whole aggregate surface, that increased AV (Figure 4), and decreased ρ (Figure 5), led to thinner and weaker mortar bridges that connected the aggregate particles, causing premature failure.

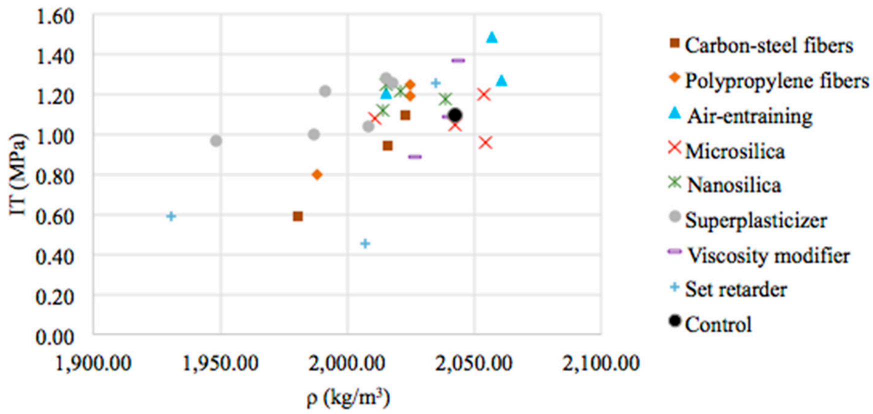

Figure 5. Correlation between density (ρ) and indirect tensile (IT) strength.

Mixture MS-4 (the one with more microsilica), showed 58.97% less permeability than the control mixture, because microsilica tended to be denser than cement, increasing the volume of the mixture and decreasing the permeability. Compared with mixture SR-2 (the best permeability result), mixture MS-4 showed 81.21% less permeability, while the control mixture had 54.21% less permeability than SR-2. Despite these results, it was noticed that all results comply with the American standards on the minimum permeability of porous surfaces of 100 m/day (0.012 cm/s) [47]. On the other hand, mechanical values were higher in mixture MS-4, which showed 50.87% more IT strength than mixture SR-2. Mixture AE-1 provided the best IT results, with 19.50% more capacity than mixture MS-4, and 26.07% more than the Control mixture. Despite these results, according to some authors [20], the evaluated mixtures can be adopted for pedestrian areas, squares, footpaths and parks. Only mixture AE-1 could be considered valid for use in bike paths. In light of the above, it can be stated that each additive provides different advantages and disadvantages, so additives should be selected according to the pavement traffic conditions (traffic type and volumes). In general, additives lead to improvements in PC mixture properties, but in the case of carbon-steel fibers, results did not provide an enhancement. The best permeability result was measured for CSF-3, which provided just 3.43% higher capacity than the control mixture, but 46.87% lower IT strength. The best mechanical result was obtained for CSF-1, which gave practically the same result as the control mixture. Therefore, it can be stated that these fibers provide little improvement for small dosages. Nevertheless, some additive combinations can considerably improve both permeability and IT strength.

3.1.2. Multi-Criteria Selection of Best Dosage for Each Additive

As the main objective of this study is to increase the mechanical capacity of PC mixtures, and the k results were outstanding in all the evaluated mixtures, it was decided to give more importance to the IT strength when implementing the Fuzzy AHP weighting. According to the Fuzzy scale in Table 3, a "Moderate" (values of 2,3,4) importance was given to the IT strength with respect to k capacity. This is because the best correlation between k and IT has to be used, considering the maximum possible strength. Table 5 represents the AHP and entropy weights obtained. The entropy weights were different for every additive because each analysis was performed separately.

Table 5. Fuzzy AHP and entropy weights employed for the multi-criteria analysis—Additives study.

Additive	Weights			
	Fuzzy AHP		Entropy	
	k	IT	k	IT
VM	0.371	0.629	0.548	0.452
SR	0.371	0.629	0.425	0.575
CSF	0.371	0.629	0.562	0.438
PF	0.371	0.629	0.546	0.454
NS	0.371	0.629	0.45	0.55
SP	0.371	0.629	0.368	0.632
AE	0.371	0.629	0.444	0.556
MS	0.371	0.629	0.328	0.672

Table 6 shows the multi-criteria results of both the TOPSIS and WASPAS methods, as well as the ranking of the additive dosages for each additive evaluated. In this way, the optimum dosage recommended for PC mixtures is established. For each additive, 3 different dosages were employed, except for the superplasticizer, where, in addition, different percentages of water were removed from the mixture. In the case of microsilica, the need to remove cement from the mixture was evaluated.

Table 6. Additives study multi-criteria analysis results and rankings.

Additive	Mixture	Fuzzy AHP Weights				Entropy Weights			
		Weights		Ranks		Weights		Ranks	
		TOPSIS	WASPAS	TOPSIS	WASPAS	TOPSIS	WASPAS	TOPSIS	WASPAS
Viscosity modifier	Control +	0.395	0.786	2	3	0.314	0.778	4	4
	VM-1 *	0.852	0.957	1	1	0.748	0.937	1	1
	VM-2	0.276	0.769	4	4	0.439	0.831	2	2
	VM-3	0.392	0.801	3	2	0.348	0.804	3	3
Set Retarder	Control +	0.592	0.706	2	2	0.542	0.683	2	3
	SR-1 *	0.726	0.843	1	1	0.680	0.797	1	1
	SR-2	0.401	0.644	3	3	0.452	0.703	3	2
	SR-3	0.092	0.432	4	4	0.109	0.456	4	4
Carbon-steel fibers	Control +*	0.963	0.987	1	1	0.924	0.981	1	1
	CSF-1	0.891	0.960	2	2	0.789	0.940	2	2
	CSF-2	0.675	0.875	3	3	0.642	0.887	3	3
	CSF-3	0.109	0.688	4	4	0.211	0.776	4	4
Polypropylene fibers	Control +	0.688	0.926	3	3	0.717	0.946	2	2
	PF-1	0.765	0.914	2	2	0.640	0.896	3	3
	PF-2 *	0.941	0.985	1	1	0.892	0.978	1	1
	PF-3	0.100	0.740	4	4	0.182	0.789	4	4
Nanosilica	Control +	0.489	0.907	4	4	0.564	0.913	2	2
	NS-1 *	1.000	1.000	1	1	1.000	1.000	1	1
	NS-2	0.368	0.898	3	3	0.325	0.888	4	4
	NS-3	0.359	0.889	5	5	0.401	0.888	3	3
	NS-4	0.387	0.894	2	2	0.314	0.877	5	5
Superplasticizer	Control +	0.389	0.771	3	3	0.392	0.773	6	6
	SP-1	0.516	0.803	7	7	0.514	0.803	4	5
	SP-2 *	0.795	0.947	1	1	0.796	0.947	1	1
	SP-3	0.783	0.924	2	2	0.783	0.924	2	2
	SP-4	0.500	0.805	6	6	0.498	0.805	5	4
	SP-5	0.383	0.764	4	4	0.386	0.765	7	7
	SP-6	0.594	0.840	5	5	0.591	0.840	3	3
Air-entraining	Control +	0.374	0.780	4	4	0.436	0.789	3	3
	AE-1 *	0.576	0.877	1	1	0.506	0.854	2	2
	AE-2	0.277	0.750	3	3	0.231	0.731	4	4
	AE-3	0.582	0.877	2	2	0.650	0.891	1	1
Microsilica	Control +	0.779	0.909	2	2	0.764	0.910	2	2
	MS-1	0.548	0.821	3	3	0.536	0.827	3	3
	MS-2 *	0.819	0.934	1	1	0.791	0.930	1	1
	MS-3	0.113	0.655	5	5	0.109	0.671	5	5
	MS-4	0.305	0.727	4	4	0.346	0.756	4	4

Note: + Refers to the same mixture. * Refers to the best mixture of each additive study.

It can be observed from Table 6 that despite the multi-criteria and weighting method adopted, the rankings were the same for all additive studies, with some minimum variations. However, the best mixture in each additive was the same, no matter which method was employed, except for the air-entraining, where the Fuzzy AHP method selected the mixture with the highest indirect tensile (IT) strength, while the entropy selected the one with the highest permeability (k) capacity.

Carbon-steel fibers were the only material for which the Control mixture obtained a better ranking. This is because of the reasons explained in Section 3.1.2. Therefore, these fibers were not used for the additive combinations study. In the case of microsilica, mixture MS-2 (5% of microsilica by weight of cement) obtained the highest ranking because of its high permeability and good correlation between the k and IT values. Nevertheless, for the additive combination study, mixture MS-4 was used. This is because, on the one hand, IT strength is higher than with MS-2, and, on the other hand, because MS-4 uses 15% of cement weight of microsilica, when removing this percentage of cement, it is considered to be more sustainable.

Polypropylene fibers decreased IT values when the fiber amount increased. This is because these fibers, as well as improving mechanical capacity, helped reinforce the pavement in the case of failure, thus increasing safety. Moreover, some studies demonstrated that polypropylene tends to oxidate at high temperatures, over 50 °C [48], where an oxygen uptake time for 50 mmol/kg is 60 hours when exposed to the environment [49], reducing its strength by around 40% in a time of 25 weeks [50]. For the rest of the additives studied, the multi-criteria analysis results determined the best dosage to be the one with the highest IT value. Table 7 demonstrates the additive dosages employed for the additive combinations study, as well as the improvement in k and IT they obtained, in comparison with the Control mixture results.

Table 7. Additives dosages employed for the additives combinations study, and their improvement in permeability (k) and indirect tensile (IT) strength in comparison with the Control mixture.

Sample	Δk (%)	ΔIT (%)
Control	-	-
VM-1	16.98	24.54
SR-1	32.58	13.83
CSF-1 *	−7.57	0.05
PF-2	−4.08	13.17
NS-1	4.97	9.31
SP-2	78.96	16.28
AE-1	−19.33	35.25
MS-4 **	−58.94	8.88

Note: * Not employed in the additive combination study. ** Not the best mixture according to the analysis, but considered being more sustainable.

3.2. *Study of Additives Combinations*

Once the optimal amounts of each additive were obtained, different additive combinations were assessed in order to evaluate improvements in the mixtures. In addition, in this part of the study, the skid resistance, under dry and wet conditions, was measured in order to provide better safety properties for the PC mixtures designed. Table 8 shows the different additive combinations proposed, and Table 9 shows the general results obtained from the laboratory tests.

Table 8. Additives combinations and dosages employed.

Combination	Additive Dosage (% of Cement Weight)							
	VM	SR	CSF	PF	NS	SP *	AE	MS **
Control	-	-	-	-	-	-	-	-
A	0.50	0.20	-	1.15	0.50	1.50	0.15	15.00
B	0.50	0.20	-	1.15	0.50	1.50	-	-
C	-	-	-	1.15	-	1.50	0.15	-
D	-	-	-	1.15	0.50	1.50	-	15.00
E	0.50	-	-	1.15	-	1.50	0.15	-
F	0.50	0.20	-	1.15	-	-	0.15	-

Note: * Removing 5% of water weight. ** Removing 15% of cement weight.

Table 9. Additives combinations general results.

Combination	Results											
	ρ (kg/m^3)	σ	AV (%)	σ	k (cm/s)	σ	IT (MPa)	σ	BPN Dry	σ	BPN Wet	σ
Control	2074.215	15.762	22.066	0.006	0.232	0.046	1.892	0.061	73.000	1.364	58.000	2.252
A	2078.734	22.355	24.308	0.008	0.133	0.082	1.871	0.211	67.000	17.362	56.000	13.723
B	2058.847	22.354	23.407	0.008	0.293	0.099	2.216	0.287	68.000	1.561	57.000	7.409
C	2085.151	24.916	22.360	0.009	0.436	0.112	2.750	0.307	68.000	14.907	56.000	13.251
D	2069.256	19.858	24.552	0.007	0.158	0.063	1.761	0.139	69.000	3.044	58.000	3.845
E	2074.715	19.085	22.810	0.007	0.392	0.124	2.553	0.390	69.000	11.744	59.000	10.200
F	2059.168	17.438	22.876	0.007	0.316	0.083	1.619	0.124	72.000	9.634	59.000	7.718

3.2.1. Results Discussion of Permeability, Indirect Tensile Strength and Skid Resistance

As seen in Figure 6, permeability (k) results were very good for every mixture. It can be seen that k decreases while air voids (AVs) increase. This is contrary to what normally occurs, but it may be attributed to the fact that air-entraining additives help to control the voids in the structure of the mixture while a good workability of the mortar is achieved. For this reason, mixtures C, E, and F (all with air-entraining), obtained the highest permeability rates. On the other hand, mixtures A and D had the lowest infiltration, so it can be stated that microsilica and nanosilica tend to block the interconnected voids, as these additives might make the paste more dense, even though there are more AVs in the samples. In addition, employing all the additives (mixture A) gave the lowest infiltration of all mixtures, as the volume of the paste increased.

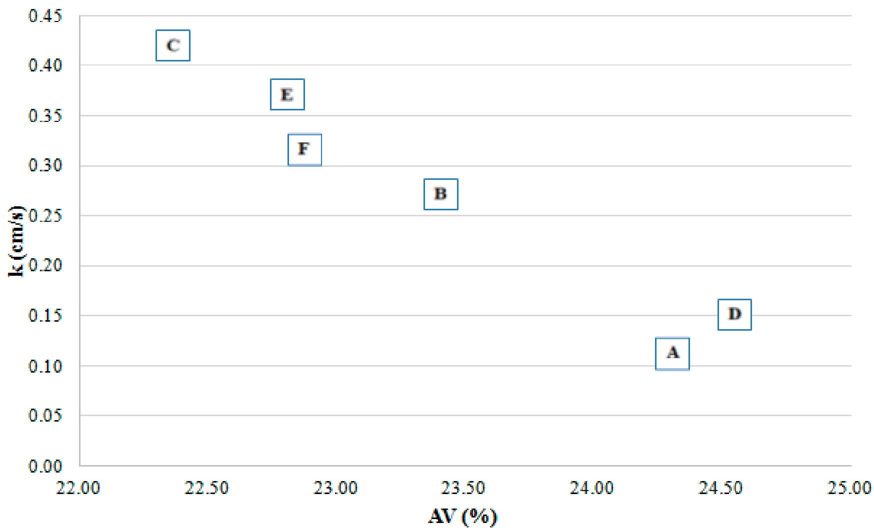

Figure 6. Correlation between air voids (AVs) and permeability (k) capacity—Additives combinations study.

The Control mixture obtained an infiltration of 0.232 cm/s, as seen in Table 9. This means that microsilica and nanosilica decreased the infiltration capacity by about 50% and 35% for mixtures A and D respectively. The rest of the mixtures improved their capacity, mixture C being the one that provided the highest increase, over 80%. Nevertheless, all mixtures complied with the minimum permeability capacity required by the American standards, which is 100 m/day (0.012 cm/s) [47], mixture A being closest to the minimum, with 14.91% higher values than the standard requirement.

Figure 7 shows the correlation between AV and IT. Here, mixtures A and D again obtained the lowest results, so it can be stated that microsilica makes the paste lose adhesiveness as the amount of cement is decreased. In addition, superplasticizers tend to make the mixtures more workable, flexible and adhesive, increasing mechanical resistance in the mixtures. Mixture F did not have this additive, so it was the most rigid mixture, obtaining the lowest IT strength result, as it had 22% less strength than the Control mixture.

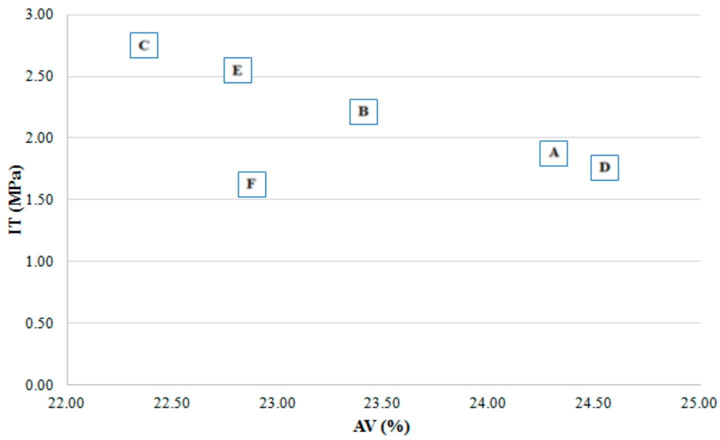

Figure 7. Correlation between air voids (AVs) and indirect tensile (IT) strength—Additives combinations study.

Mixture C provided the best results in the IT strength test, improving it by about 45% with respect to the control mixture. The combination of superplasticizer and air-entraining additives tended to provide the mixture with sufficient adhesion to improve the mechanical values. Polypropylene fibers, instead of mechanical improvement, can provide more safety for drivers, maintaining the pavement together in the case of failure and cracking. It can be observed that all combinations showed significantly improved mechanical properties, where, according to some authors' investigations [20], mixtures B, C, and E are suitable for mid-volume urban roads, while mixtures A and D are suitable for low-volume urban roads and parking lots. Finally, mixture F can perform well when used for bike paths.

Skid resistance results were, in general, very good for all mixtures, as seen in Figure 8. Although results were around 5% and 3% lower under dry and wet conditions, respectively, than the Control mixture. However, mixtures E and F provided around 1.50% higher friction under wet conditions. Mixture F provided the highest results in both scenarios, since the lack of superplasticizer additives can increase the roughness of the mixtures, especially under wet conditions. Nevertheless, despite the additive employed, under dry conditions, friction tends to decrease (around 1.30% lower for mixture F). In this case, mixture C obtained one of the lowest results in both scenarios, as the air-entraining can increase the void area on the surface, making the pendulum of the test preserve its energy, decreasing friction.

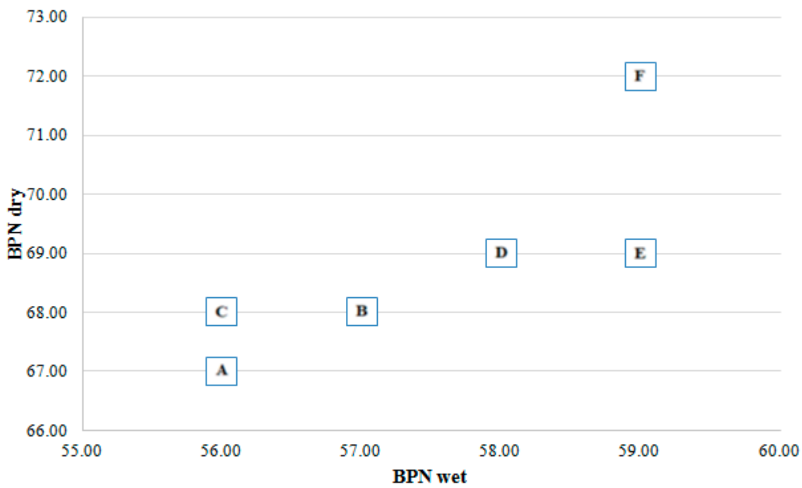

Figure 8. Correlation between the British pendulum number (BPN) under dry conditions and wet conditions—Additives combinations study.

3.2.2. Multi-Criteria Selection of Best Additive Combination

Table 10 shows the Fuzzy AHP and entropy weights obtained for the analysis. The same importance as Section 3.1.2 was given to the IT strength and the k capacity when implementing the Fuzzy AHP weighting. For skid resistance, it was considered that IT had a "Strong" (values of 4,5,6) importance compared to skid resistance under dry and wet conditions. This is because skid resistance was considered to have good values in all combinations for dry and wet conditions, so strength was considered a priority. When comparing k capacity with skid resistance, k was considered to have an intermediate value of importance of 2 (values of 1,2,3), in accordance with Table 3, as the main objective of a PC pavement is to infiltrate the water into the ground. Skid resistance under wet conditions was considered to have an intermediate value of importance of 2 with skid resistance under dry conditions because friction is considered very important and more risky when the pavement is wet than when dry.

Table 10. Fuzzy AHP and entropy weights employed for the multi-criteria analysis—Additives combinations.

Variable	Weights	
	Fuzzy AHP	Entropy
k	0.210	0.067
IT	0.555	0.137
BPN dry	0.100	0.379
BPN wet	0.135	0.417

In Table 11, the multi-criteria results and the ranking of the combinations studied with the TOPSIS and WASPAS methods are shown. As can be seen, the Fuzzy AHP weights designated combination C as the best option, in both TOPSIS and WASPAS methods. This is because it obtained the highest values in IT, and the best k capacity as well. When employing the entropy weights, combination E obtains the highest ranking, because skid resistance under wet conditions has a greater importance, and so a more even combination between the alternatives is used. Combination E obtained the highest value of skid resistance under wet conditions, and the second best IT and k results.

Table 11. Additives combinations multi-criteria analysis results and rankings.

Combination	Fuzzy AHP Weights				Entropy Weights			
	Weights		Ranks		Weights		Ranks	
	TOPSIS	WASPAS	TOPSIS	WASPAS	TOPSIS	WASPAS	TOPSIS	WASPAS
Control	0.273	0.718	5	4	0.387	0.912	5	4
A	0.173	0.641	6	7	0.144	0.844	7	7
B	0.528	0.809	3	3	0.487	0.909	3	5
C	0.973	0.986	1	1	0.741	0.953	2	2
D	0.113	0.642	7	6	0.186	0.867	6	6
E	0.835	0.933	2	2	0.763	0.962	1	1
F	0.295	0.704	4	5	0.408	0.913	4	3

It can be observed that the use of superplasticizers and air-entraining improves the properties of PC mixtures (combinations C and E). Combination A uses these additives as well, but the microsilica tended to clog the mixture, decreasing its k capacity considerably. Combination F obtained the lowest IT strength result, due to the lack of superplasticizer, which was seen to increase workability of the mixture considerably, increasing the ρ of the mixture and enhancing adhesion between aggregate particles. This combination obtained the highest skid resistance value (under both dry and wet conditions), where the viscosity modifier and the set retarder tended to enhance the AV proportion increasing friction on the surface of the mixture. Polypropylene fibers were not significant in improving IT results, but were considered very important for safety reasons as explained in Section 3.1.2.

Table 12 demonstrates the improvements of every combination in every test performed, in comparison with the Control sample. It can be stated that combination C was the best mix of additives to improve mechanical and safety properties of PC pavements. Despite obtaining 6.85% and 3.45% less skid resistance under dry and wet conditions, respectively, all PC mixtures satisfied all the minimum skid resistances British Pendulum Numbers (BPNs) suggested in [51] for dry conditions, and the conditions for common highways with traffic flow greater than 2000 vehicles/day under wet conditions.

Table 12. Additives combinations improvement in permeability (k), indirect tensile (IT) strength, and skid resistances British pendulum number (BPN) under dry and wet conditions in comparison with the Control mixture.

Combination	Δk (%)	ΔIT (%)	ΔBPN Dry (%)	ΔBPN Wet (%)
Control	-	-	-	-
A	−42.48	−1.14	−8.22	−3.45
B	26.49	17.1	−6.85	−1.72
C	87.88	45.35	−6.85	−3.45
D	−31.77	−6.96	−5.48	0
E	69.06	34.91	−5.48	1.72
F	36.17	−14.43	−1.37	1.72

4. Conclusions

This research evaluates the most common additives employed in PC pavements according to an extensive literature review. Through the use of TOPSIS and WASPAS multi-criteria decision-making methods, in addition to integrating and comparing the Fuzzy AHP and entropy weighting procedures, different dosages of additives were studied to achieve optimization. Moreover, different additive combinations were tested trying to determine the combination with the best mechanical and safety performance, while maintaining a good permeability. The following conclusions can be stated:

- Carbon-steel fibers did not improve IT strength and k capacity, in comparison with the Control mixture.
- The size of the fibers (1 cm in length) is not enough to maintain a proper adhesion between the aggregate particles due to the AV proportion present.
- The water infiltrated tended to oxidize the carbon-steel fibers. Therefore, they were not used in the additive combination analysis.
- All the additives produced an improvement in the mixtures' workability, the viscosity modifier being the one that gave the best IT strength values. The Set-retarding additive provided the highest k capacity.
- According to the TOPSIS and WASPAS multi-criteria decision-making methods, a combination between superplasticizer, air-entraining, and polypropylene fibers, gives the PC mixture the highest IT strength and k capacity.
- Set-retarding and viscosity-modifying additives tended to improve skid resistance.
- Additional research is needed in order to assess the full environmental benefits of the proposed pavement type. This includes studies on different aggregates and gradations, the installation of pavements under different climatic conditions, as well as the evaluation of alternative binding materials, such as geopolymers and alkali-activated cements, to reduce carbon footprint.

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