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MULTI-CRITERIA OPTIMUM MIXTURE DESIGN OF POROUS CONCRETE PAVEMENT SURFACE LAYERS

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Abstract

Research has been done to obtain a Porous Concrete (PC) mixture capable of bearing heavy traffic loads while maintaining sufficient air voids (AV) to percolate water into the ground. This research aims to establish several design parameters in PC mixture dosage in order to generate a multi-criteria methodology that helps to obtain a final product, which is beneficial for both citizens and environment. Compression strength, indirect tensile strength, permeability, skid resistance, and stiffness modulus were evaluated, employing different aggregate gradations (AG), water to cement (w/c) and sand to cement (s/c) ratios, designing with the Porous Concrete Design (PCD) methodology. Results demonstrated that the right addition of sand and AG can improve mechanical capacity by around 10% and permeability rates by around 25%. This investigation provides a starting point for the use of additives in PC mixtures that helps to bring multifunctional properties such as heat island mitigation, air purification (photo-catalysis) and noise reduction, among others.

Keywords

Porous concrete; mechanical properties; permeability; multi-criteria; safety properties.

1 Introduction

Porous pavements have been proposed as one of the main solutions to decrease the impact of climate change, related to the rapid urbanization of cities (Sansalone, Kuang, and Ranieri 2008; United Nations 2017). This urbanization entails increasing use of vehicles, vast consumption of natural resources, as well as escalating amounts of garbage and waste generated by the population, which are the main causes of climate change (International Water Association 2017). In addition, current construction methods tend to cover the cities with impermeable infrastructure, affecting the water cycle and decreasing the underground water levels (Rodriguez-Hernandez et al. 2013).

Porous Concrete (PC) is a special type of concrete mainly used in pavements with the characteristic of having the capacity of infiltrating rainwater (Lian and Zhuge 2010; Tennis, Leming, and Akers 2004). This is aimed at either letting it percolate into the ground or harvesting it for future uses. PC is designed to have a certain amount of air voids (AV), normally in the range of 15-30% (Brake, Allahdadi, and Adam 2016; Giustozzi 2016; Khankhaje et al. 2017; Rangelov et al. 2016), achieved with the aggregate gradation (AG) used. AG is a key issue conditioning PC's mechanical and hydraulic properties. This is caused by the void size and connection, as well as the continuity of the cement paste bridges formed (Agar Ozbek et al. 2013; Bonicelli et al. 2015; Chen et al. 2013). Cement paste constitutes another PC component, made up of a combination of cement, water and, sometimes, additives (Brake, Allahdadi, and Adam 2016; Giustozzi 2016; Khankhaje et al. 2017; Kim, Gaddafi, and Yoshitake 2016; Rangelov et al. 2016). Fine aggregate (sand) is avoided in most cases, with the goal of maintaining a reasonable permeability, although it can help to improve the mechanical properties considerably (Agar-Ozbek et al. 2013; Bonicelli et al. 2015; Crouch, Pitt, and Hewitt 2007; Lian and Zhuge 2010; Yang and Jiang 2003).

Over time, other advantages of PC have been highlighted, establishing it as a multifunctional material that can provide environmental, social and economic well-being. It also brings benefits such as sound absorption since, thanks to the high porosity, the noise generated between the tire and the road surface can be minimized (American Concrete Institute ACI Committee 522 2010). At the same time, it provides greater friction, increasing driver safety (Eriskin et al. 2017). Finally, with the addition of certain additives, PC pavements can provide a powerful tool to minimize pollutants in the air, thanks to photo-catalysis (Ballari et al. 2010; Hasan et al. 2017), and they can actively help prevent the increase of temperature in cities by reflecting solar radiation, minimizing the heat island effect (Li, Harvey, and Ge 2014).

Many investigations have been carried out aiming to create a PC mixture that fulfills the necessary mechanical, hydraulic and environmental characteristics for use in roads. Nevertheless, its application has been limited to parking lots, minor roads and sidewalks (Bonicelli, Giustozzi, and Crispino 2015; Golroo and Tighe 2011). Despite the fact that PC has been studied for many years, so far, no optimal dosage has been established. This decision-making problem can be solved with multi-criteria decision-making methods (MCD), to help researchers perform a complete analysis of the information needed to calculate the best dosage in each situation. Combining PC mixture results and using of precise mathematical procedures, the optimum characteristics can be obtained (Jato-Espino et al. 2014). In this research, the Analytic Hierarchy Process (AHP) is employed with the objective of combining the results obtained through different tests, with a pairwise comparison between the mixtures, in order to establish the mixture with the best behavior (Bobylev 2011; Jato-Espino et al. 2014).

This study evaluates different test results (variables according to the AHP method), such as mechanical strength, permeability, skid resistance (under dry and wet conditions), and elastic deformation of PC mixtures with the intention of understanding the different behavior these pavements with different dosages can present, obtaining an optimum mixture design. Different kinds of aggregate gradations, sand-cement (s/c) and water-cement (w/c) ratios are used and evaluated.

2 Materials and Methods

2.1 Materials

Portland Cement CEM I 52.5R UltraVal was used as a cementitious material, as it provides high strength in a short period. According to EN 1907-6 procedure, its measured specific weight was 3.14 g/cm^3. Three different w/c ratios were employed: 0.30, 0.35 and 0.40, in order to evaluate the influence of the water content on the PC mixture properties. Finally, three s/c ratios were used as well: 0.00, 0.50 and 1.00, with the aim of evaluating the influence of sand on the mixtures.

Ophite material was used as coarse aggregate (CA) and sand, employing different gradations using the U.S. FHWA 0.45 power chart gradation curve theory. Sizes from 2mm to 12.5mm were used for CA, divided in four different sizes: 2-4mm; 4-8mm; 4-12mm and 8-12mm, as can be seen in the aggregate gradation curve in Figure 1. This sizes were selected because bigger sizes give larger voids, making it difficult for the cement paste to adhere the aggregate particles, decreasing its strength. For sand, size ranged from filler (< 0.063mm), up to 2mm. Ophite characteristics are summarized in Table 1.

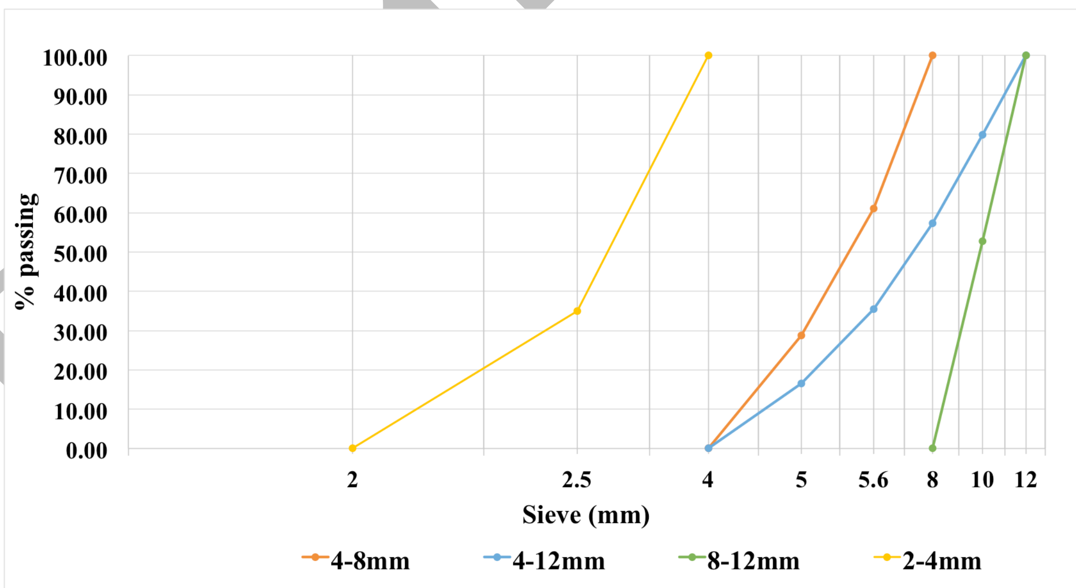

Figure 1. Aggregate Gradation Curve

Table 1. Ophite Characteristics

Characteristic	Results	Standard

Specific gravity	2.91		EN 1097-6
Absorption	1.03%	2-12.5mm	EN 1097-6
	0.70%	0-2mm	
Density	1.52 g/cm^3	uncompacted	EN 1097-3:1999
	1.85 cm/cm^3	compacted	
Voids in mineral aggregate (VMA)	48.16%	uncompacted	EN 1097-3:1999
	34.64%	compacted	

2.2 Mixtures Dosages

For this investigation, four types of AG, three different w/c and three s/c ratios were combined. An AV design was of 20% was proposed for all mixtures to be into the range of 15-30%. In order to determine the optimal amount of the mixtures to make, considering all the variables established, the statistical software Minitab 17 was employed for the design of experiments (DOE). A response surface design was created, where the variables' results are introduced, and the number of mixtures to elaborate is indicated. It is important to clarify that this design was only used as a tool to help in taking the decision about the total amount of the mixtures to produce in order to accomplish a complete evaluation. Figure 2 shows the comparison scheme planned, where a set of 31 different mixtures was considered for elaboration and analysis, from 72 possible mixtures (Table 2).

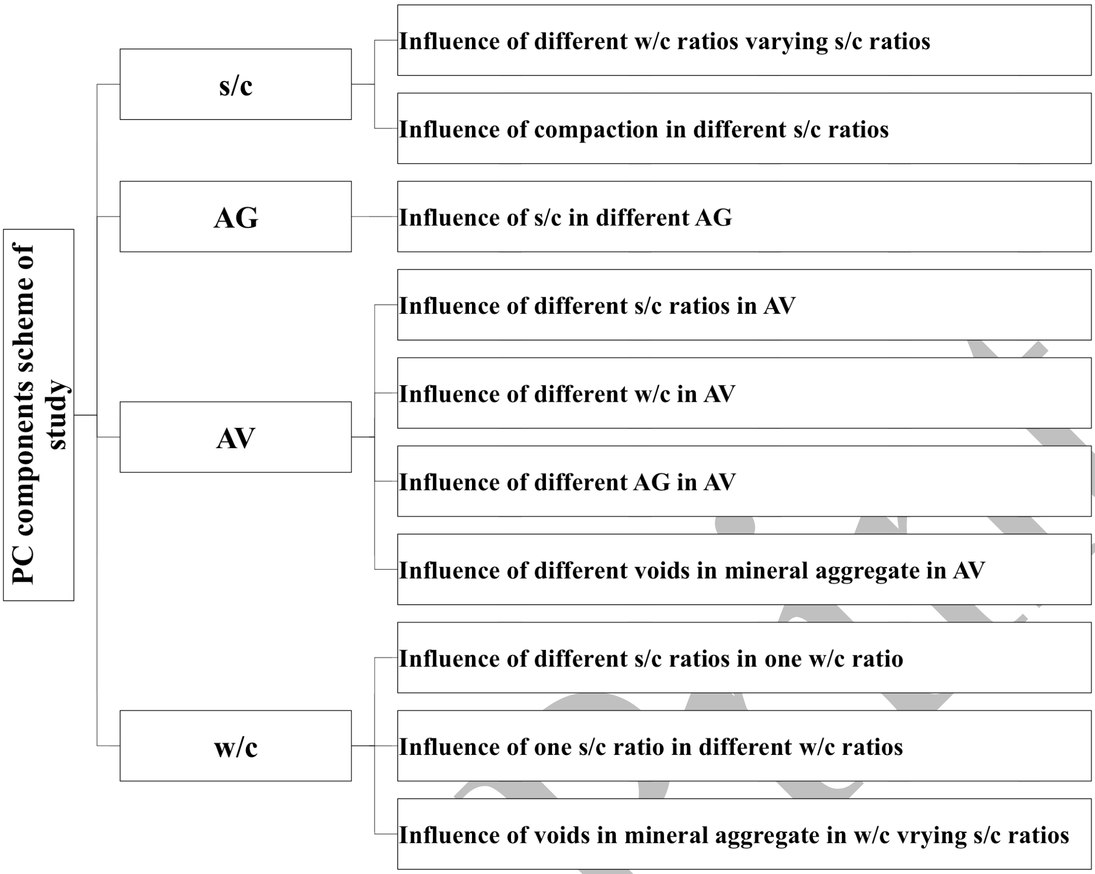

Figure 2. Scheme of PC mixture comparison

A new methodology, named PCD (Porous Concrete Design), based upon the normative ACI 522R-10 and ACI 211.3R-02, was employed, consisting in breaking the relation between CA and sand design, introducing sand in the cement paste design, making a mortar. Therefore, the amount of sand modifies cement and water quantities. CA depends on the particle density and its porosity. This methodology enables to keep the s/c and w/c ratios defined. The steps for the PCD methodology can be seen in (Elizondo-martinez et al. 2019).

Standard EN 1097-3:1998 was used to determine the voids in mineral aggregate (VMA). The test was performed twice (compacted and uncompacted) in order to establish a parameter for the VMA content. As seen in Table 1, the parameters ranged from 34.64% to 48.16%. Designs were chosen with VMA contents of 44.3% and 47%, with the purpose of evaluating the behavior with two different compaction degrees. Table 2 shows the different mixture dosages made. Specimens were cylindrical in shape, with a diameter of 10.2cm and a height of 6.5cm, compacted in Marshall Molds with a mechanical press and kept under curing for 28 days under water at ambient temperature to prevent the dehydration of the mixtures, as concrete tend to lose water once started to get harder.

Table 2. Mixture Proportions

Mixture code (a-b-c-d) *	AG (mm)	s/c	w/c	Cement (kg/m3)	VMA (%)
30-0-A-I	2-4	0.00	0.30	397.23	44.30
40-0-A-I	2-4	0.00	0.40	341.48	44.30
30-1-A-I	2-4	1.00	0.30	255.15	44.30
40-1-A-I	2-4	1.00	0.40	230.92	44.30
30-0-B-I	4-8	0.00	0.30	397.23	44.30
35-0-B-I	4-8	0.00	0.35	367.23	44.30
40-0-B-I	4-8	0.00	0.40	341.48	44.30
30-5-B-I	4-8	0.50	0.30	310.71	44.30
35-5-B-I	4-8	0.50	0.35	292.05	44.30
40-5-B-I	4-8	0.50	0.40	275.52	44.30
30-1-B-I	4-8	1.00	0.30	255.15	44.30
35-1-B-I	4-8	1.00	0.35	242.42	44.30
40-1-B-I	4-8	1.00	0.40	230.92	44.30
30-0-B-II	4-8	0.00	0.30	440.81	47.00
35-0-B-II	4-8	0.00	0.35	407.54	47.00
40-0-B-II	4-8	0.00	0.40	378.94	47.00
40-1-B-II	4-8	1.00	0.40	256.27	47.00
30-1-B-II	4-8	1.00	0.30	283.15	47.00
35-5-B-II	4-8	0.50	0.35	324.12	47.00
30-5-B-II	4-8	0.50	0.30	344.81	47.00
40-5-B-II	4-8	0.50	0.40	305.76	47.00
30-0-C-I	4-12	0.00	0.30	397.23	44.30
40-0-C-I	4-12	0.00	0.40	341.48	44.30
30-1-C-I	4-12	1.00	0.30	255.15	44.30
40-1-C-I	4-12	1.00	0.40	230.92	44.30
30-0-C-II	4-12	0.00	0.30	440.81	47.00
40-1-C-II	4-12	1.00	0.40	256.28	47.00
30-0-D-I	8-12	0.00	0.30	397.23	44.30
40-0-D-I	8-12	0.00	0.40	341.48	44.30
30-1-D-I	8-12	1.00	0.30	255.15	44.30
40-1-D-I	8-12	1.00	0.40	230.92	44.30

*[a] *Corresponds to the w/c ratios employed (0.30, 0.35, and 0.40)*

[b] *Corresponds to the s/c ratios employed (0.00, 0.50, and 1.00)*

[c] *Corresponds to the AG employed (A: 2-4mm; B: 4-8mm; C: 4-12mm; D: 8-12mm)*

[d] *Corresponds to the VMA employed (I: 44.30%; II: 47.00%)*

2.3 Methods

2.3.1 Permeability and Air Voids

Permeability was measured in the laboratory with a falling head permeameter, adapted from the "Laboratorio Caminos de Santander (LCS)" permeameter (Andres-Valeri et al. 2018). This device can measure the permeability of cylindrical specimens using a PVC tube with a 4" diameter with rubber inside as a mold. This mold is adjusted with metal clamps and a methacrylate tube is placed on top, calibrated to introduce water and measure permeability with a fall of 20cm. Employing Darcy's law, the permeability coefficient was calculated, according to Equation 1:

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

Where k is the permeability coefficient (cm/s), A_{sample} is the area of contact of the sample (cm^2), h_{sample} is the height of the sample (cm), A_{tube} is the area of the tube's gap (cm^2), t (in seconds) is the time it takes the water to go from the higher (h_1) to the lower line (h_2). For the calculation of the real porosity (P), once the mixture is elaborated, Equation 2 is employed:

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

Where W_{DRY} corresponds to the mixtures' weight under dry conditions. $\%_{CA}$, $\%_S$, $\%_C$ and $\%_W$ represent the percentage of the total mixture of CA, sand, cement and water respectively. P_{CA}, P_S, P_C, and P_W, represent the density of the mixtures' components mentioned above.

2.3.2 Indirect Tensile, Compression, and Stiffness

The Indirect Tensile (IT) test was performed according to EN 12390-6 standard. It was measured in order to analyze the resistance to traffic loads in PC pavement designs. The test consists in applying a controlled load over the cross section of the sample, causing a perpendicular deformation that leads to failure. The equipment and equations required for the test can be found in EN 13286-42 (AENOR 2003), EN 12390-6 (AENOR 2010) (Test and equation description) and EN 12390-1(AENOR 2014) standards (Machine description). In addition, Marshall Samples were cut into cubical forms in order to obtain a 1:1 ratio, of 6.5x6.5x6.5cm dimensions, to fulfill the requirements of EN 12390-3 standard (AENOR 2009) and perform the axial compression strength test (CS). Despite not fulfilling the minimum dimension specifications of 10x10x10cm, this helped in the comparison among the samples.

The stiffness modulus test evaluates the elastic deformation of the samples, trying to imitate rapid and constant loads generated by traffic on the pavement. Although concrete pavements are very rigid and their deformation is quite small, compared to asphalt pavements (this test was designed for this type of pavements), it was considered important to evaluate and compare porous concrete samples' deformation to observe possible cracking occurring, especially in urban roads. This test is described in EN 12697-26 standard (AENOR 2012). Loads of 4.50 kN and 6.00 kN were used. In addition, the test applies 16 punches to the sample, where punches 11 to 15 are the ones measured. This is because the load starts to increase from -0.10 kN and it reaches the desired load at punch 11.

2.3.3 Skid Resistance

The skid resistance of the samples was evaluated through the British Pendulum Test (BPT) (ASTM 2000a 2000). The device employed has a calibrated pendulum, with special rubber at the end that represents a patterned tire. When the pendulum falls and swings across the sample, it makes and loses energy. The British Pendulum Number (BPN) is obtained with a needle that points to a specific scale (from 0.00 to 100.00) when the pendulum and the sample interact. The test was performed under dry and wet conditions, wetting with water the rubber on the pendulum, as well as the sample surface. The area of contact was fixed to be of 7cm, enabling a comparison between the samples.

2.4 Statistical Analysis

2.4.1 Multi-criteria

In order to analyze the results, the AHP multi-criteria decision methodology (MCD) was used. Starting from the scale of comparison proposed by Saaty, on which many authors have based their research (Al-harbi 2001; Jato-espino et al. 2014; Skibniewski and Chao 1992), a scale of 9 values of importance was created to compare the different mixtures as alternatives (Table 3). The value depends on the result of the subtraction of the test values of each alternative in the pairwise comparison. With this, the variables studied separately are combined, calculating normalized weights, obtaining the mixture with the best behavior.

Table 3. AHP values of importance employed for every test performed

Parameter	k	IT	CS	Stiffness modulus	BPN (dry)	BPN (wet)	Value
				Criteria			
Equal to	0	0	0	0	0	0	**1**
Between	0 and 0.43	0 and 0.24	0 and 3.42	0 and 2492.13	0 and 7.25	0 and 7.50	**2**
Equal to	0.43	0.24	3.42	2492.13	7.25	7.50	**3**

Between	0.43 and 0.86	0.24 and 0.49	3.42 and 6.83	2492.13 and 4984.25	7.25 and 14.50	7.50 and 15	**4**
Equal to	0.86	0.49	6.83	4984.25	14.50	15	**5**
Between	0.86 and 1.28	0.49 and 0.73	6.83 and 10.25	4984.25 and 7476.38	14.50 and 21.75	15 and 22.50	**6**
Equal to	1.28	0.73	10.25	7476.38	21.75	22.50	**7**
Between	1.28 and 1.71	0.73 and 0.97	10.25 and 13.66	7476.38 and 9968.50	21.75 and 29	22.50 and 30	**8**
Equal to or greater than	1.71	0.97	13.66	9968.50	29	30	**9**

The steps for the AHP method can be stated in detail in (Saaty 1980), and are summarized as followed:

1. Alternatives are placed in an "n" factor matrix and a value of importance is assigned when making the pairwise comparison among the alternatives results. For example, if an alternative "A" has a value of importance of 5 with respect to an alternative "B", then, "B" will have a value of importance of 1/5 with respect to "A". That is the reciprocal value. This can be seen in equation 3:

$$A = \begin{bmatrix} a_{11} & \cdots & a_{1j} & \cdots & a_{1n} \\ \vdots & & \vdots & & \vdots \\ a_{i1} & \cdots & a_{ij} & \cdots & a_{in} \\ \vdots & & \vdots & & \vdots \\ a_{n1} & \cdots & a_{nj} & \cdots & a_{nn} \end{bmatrix}, a_{ii} = 1, a_{ij} = {}^{1}/_{a_{ji}}, a_{ji} \neq 0 \qquad (3)$$

2. The matrix is then normalized by dividing each value by the total sum of its column, as demonstrated in equation 4, where n_{ij} corresponds to the normalized value, and a_{ij} to the normal value in the matrix:

$$n_{ij} = \frac{a_{ij}}{\sum_{k=1}^{n} a_{kj}}; j = 1,2,\ldots,n; i = 1,2,\ldots,m \qquad (4)$$

3. The average value in each row in the normalized matrix is then calculated, obtaining a vector for each alternative. The higher the vectors' value, the better the hierarchy of the alternative among the others.

4. With the use of Table 5, weights are assigned to each variable. A value is designated according to the importance among the variables, and values are placed in a new matrix as equation 3. Then, step 2 and 3 are repeated, obtaining the variable's weights.

5. This process is made for each variable (test). Later, each alternative's value is multiplied by each variable with a weight, w_j, with the use of equation 5.

$$\tilde{A} = \sum_{j=1}^{n} w_j a_{ij} \tag{5}$$

6. An average value for each alternative in each variable is calculated, obtaining a vector. The vector with the highest value is considered to be the best alternative.

2.4.2 ANOVA

The analysis of variance (ANOVA) was performed in order to evaluate the results obtained for each test and determine the influence of the mixture components. It was implemented for each mixture component (AG, s/c, w/c, compaction level, and cement amount) and test (permeability, compression, indirect tensile, skid resistance under dry and wet conditions, and stiffness modulus). The results were calculated with the F of Fisher distribution when comparing the ANOVA. If F is less than the critical F (Obtained from the F Values Table of the Fisher distribution), then there is no significant difference between the data. On the contrary, when F is greater than the critical F, then a significant difference between the values is considered. The Microsoft Excel complement tool, Real Statistics, was employed for this test.

3 Results and Discussion

Table 4 depicts the mean values obtained in every test, as well as the standard deviation (σ) for each mixture.

Table 4. Mixtures Results

Mixture	AV (%)	σ	IT (MPa)	σ	k (cm/s)	σ	CS (MPa)	σ	BPN dry	σ	BPN wet	σ	Stiffness Modulus (MPa)	σ
30-0-A-I	21.86	0.69	1.47	0.09	0.19	0.02	16.70	1.63	75.00	0.00	65.00	1.07	18256.50	374.00
40-0-A-I	21.82	0.49	1.43	0.10	0.40	0.03	16.70	1.13	70.00	0.93	61.00	4.64	17627.50	3027.00
30-1-A-I	23.60	1.40	1.20	0.16	0.22	0.06	9.17	1.42	69.00	1.00	61.00	5.74	15318.50	144.00
40-1-A-I	23.27	0.75	1.44	0.15	0.23	0.03	14.00	0.90	63.00	1.67	55.00	5.48	17435.50	292.00
30-0-B-I	22.58	0.63	1.37	0.12	0.54	0.07	12.45	2.73	73.00	2.07	63.00	3.74	17038.50	647.00
35-0-B-I	23.17	0.55	1.43	0.14	0.58	0.09	15.15	2.38	67.00	15.03	50.00	4.17	19199.00	278.00
40-0-B-I	20.35	0.86	1.39	0.19	0.43	0.07	15.60	2.56	73.00	1.12	66.00	0.79	19077.00	416.00
30-5-B-I	22.89	0.23	1.51	0.15	0.48	0.07	14.55	1.72	66.00	1.19	59.00	1.00	21360.50	726.00

35-5-B-I	22.68	0.42	1.74	0.06	0.70	0.17	15.85	1.73	72.00	1.63	62.00	5.00	21087.00	29.00
40-5-B-I	23.76	0.46	1.49	0.10	0.71	0.12	14.45	2.83	68.00	4.16	59.00	2.50	19183.00	1204.00
30-1-B-I	23.16	0.55	1.69	0.23	0.54	0.06	18.15	1.88	68.00	2.93	58.00	7.11	18762.00	799.00
35-1-B-I	23.73	0.60	1.28	0.22	0.57	0.04	13.40	1.27	70.00	2.83	64.00	0.92	17985.00	211.00
40-1-B-I	19.76	0.97	1.41	0.10	0.42	0.03	14.90	0.70	85.00	0.53	80.00	4.75	18662.00	1543.00
30-0-B-II	23.14	0.72	1.57	0.15	0.37	0.11	16.10	3.03	64.00	4.33	54.00	3.21	17846.00	899.00
35-0-B-II	23.09	1.05	1.54	0.11	0.50	0.12	16.50	3.93	68.00	4.12	55.00	11.50	19401.00	1315.00
40-0-B-II	25.00	0.97	1.63	0.26	0.48	0.14	15.75	1.96	57.00	1.66	53.00	1.89	21921.00	4531.00
40-1-B-II	22.15	0.63	1.44	0.09	0.56	0.03	14.00	2.91	70.00	0.98	62.00	3.26	19260.50	2404.00
30-1-B-II	24.53	1.42	1.13	0.10	0.51	0.25	8.01	0.52	61.00	6.15	57.00	4.03	16683.00	1097.00
35-5-B-II	20.92	0.33	1.65	0.11	0.20	0.11	18.27	4.91	75.00	4.47	65.00	5.51	19195.00	2727.00
30-5-B-II	22.07	0.59	1.89	0.06	0.23	0.05	18.80	3.66	73.00	1.36	58.00	2.25	17899.00	1523.00
40-5-B-II	24.33	0.61	1.83	0.10	0.42	0.03	15.10	0.90	65.00	5.45	59.00	6.96	18431.50	142.00
30-0-C-I	21.14	0.64	1.37	0.05	0.60	0.06	12.60	3.33	80.00	0.00	61.00	0.52	17198.00	726.00
40-0-C-I	22.42	0.68	1.19	0.16	0.88	0.16	8.80	0.65	71.00	0.52	57.00	4.30	14146.00	1506.00
30-1-C-I	23.14	1.18	1.30	0.11	0.67	0.19	10.90	1.20	68.00	5.00	58.00	2.48	15195.50	558.00
40-1-C-I	23.48	1.30	1.44	0.26	0.87	0.13	12.80	2.42	65.00	0.00	55.00	3.96	14712.50	1924.00
30-0-C-II	22.15	0.67	1.69	0.20	0.41	0.15	14.60	2.97	69.00	0.96	61.00	2.80	16564.50	299.00
40-1-C-II	21.15	0.58	1.49	0.11	0.52	0.18	14.70	3.07	86.00	0.55	80.00	6.57	18855.00	2697.00
30-0-D-I	24.34	0.45	1.38	0.28	1.00	0.27	11.85	1.76	60.00	5.92	55.00	5.85	16547.50	313.00
40-0-D-I	24.57	0.82	1.10	0.05	1.40	0.05	7.88	0.73	64.00	9.09	52.00	2.76	11154.50	661.00
30-1-D-I	24.31	1.82	1.10	0.12	0.67	0.01	8.35	0.86	65.00	2.73	55.00	3.62	20838.00	7531.00
40-1-D-I	25.10	1.53	0.92	0.08	1.90	0.02	5.14	0.59	65.00	5.25	59.00	0.76	13478.00	1227.00

3.1 Permeability and Air Voids

Mixture 40-1-D-I had the greatest permeability, as seen in Table 4, infiltrating 1.9 cm/s. This happens because of the AG employed (8-12mm), which provides more AV in the mixture (25.1%, the highest) and, therefore, a higher permeability. However, comparing mixture 40-1-D-I with 40-0-D-I, the former obtained around 30% higher permeability, despite having an s/c of 1, while mixture 40-0-D-I did not have sand at all.

In addition, despite designing for an AV percentage of 20%, the real AV varied, where the AV percentage was always greater. This increment is a consequence of the compaction method, where the aggregate particles were not able to accommodate properly into the mold, leading to more voids in the mixture. Nevertheless, the behavior of the comparison of the mixtures' AV and the permeability was as expected, as higher AV percentages are associated with greater permeability, as seen in Figure 3, although this might not always happens if the concrete mixture is not properly consolidated. It is remarkable that mixtures with an AG of 2-4mm decreased in permeability while AV increased. This behavior could be explained because of the interconnected AVs in the mixture. As the gradation was small, the particles accommodated in a better way in the molds leading to fewer interconnected AVs (effective porosity), no matter whether sand was present in the mixture or not. A CT scan should give a fully understanding of this event.

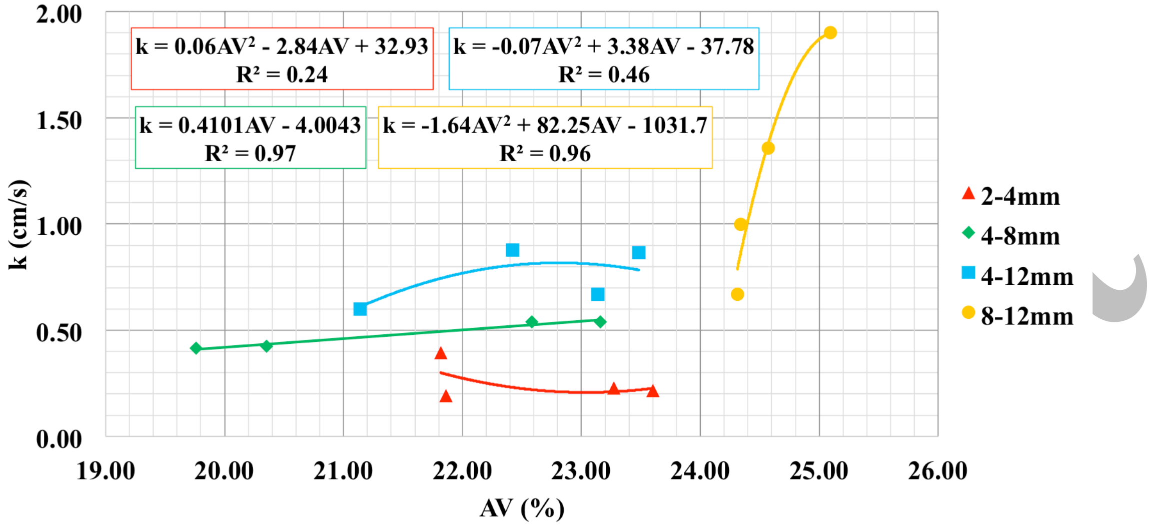

Figure 3. Correlation between Porosity and Permeability for every AG employed

Different AGs and dosages give rise to different void structures for the same AV volume established, varying the permeability capacity. Figure 4 demonstrates the permeability that can be obtained according to the AG employed: the higher the AG, the higher the AV percentage, so permeability is faster.

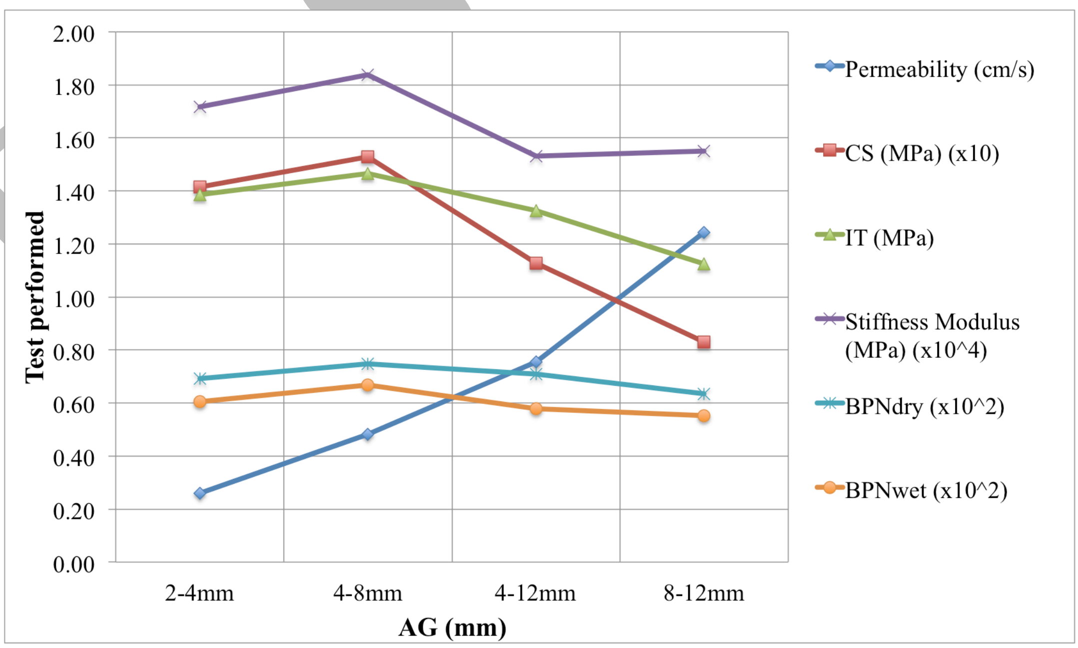

Figure 4. Correlation between AG and PC mixtures Results

3.2 Indirect Tensile, Compression, and Stiffness

The different mechanical results calculated for every mixture can be seen in Table 4. Mixture 40-1-D-I (greatest permeability) had the lowest results, with 5.14 and 0.92 MPa for CS and IT respectively. This is due to the large AV percentage of these mixtures caused by the large AG. Bridges formed by the mortar were not strong enough to maintain the necessary adhesion between particles, leading to a faster failure. On the contrary, the smallest AG, 2-4mm, was not as strong as expected and an AG of 4-8mm obtained the best results. This is mainly because the aggregate packing density was better, allowing mortar to produce better adhesion between particles. In addition, mortar contact area was greater in mixtures with AG of 2-4mm, finding failure in those spots, rather than in the aggregate itself. Mixture 30-5-B-II obtained the highest mechanical results in both CS and IT, with 18.80 and 1.89 MPa, respectively. In this case, despite the advantage of the 4-8mm AG, using an s/c ratio of 0.5 for sand helped to increase the mixture's resistance. In addition, w/c ratio of 0.30 helped to make a more workable and adhesive mixture. Finally, a VMA of 47% increased the amount of mortar in the mixture. At the same time, the aggregate amount is decreased 5%, in comparison with a VMA of 44.30%, leading to an increase in the mechanical strength.

Figure 5 demonstrates the correlation between CS and IT, obtaining an R^2 of 0.85. As seen in Figure 4, the behavior of the mechanical results has a decreasing tendency as the AG increases in both CS and IT. However, an AG of 4-8mm caused the best adhesion between particles, with respecting an acceptable hydraulic capacity.

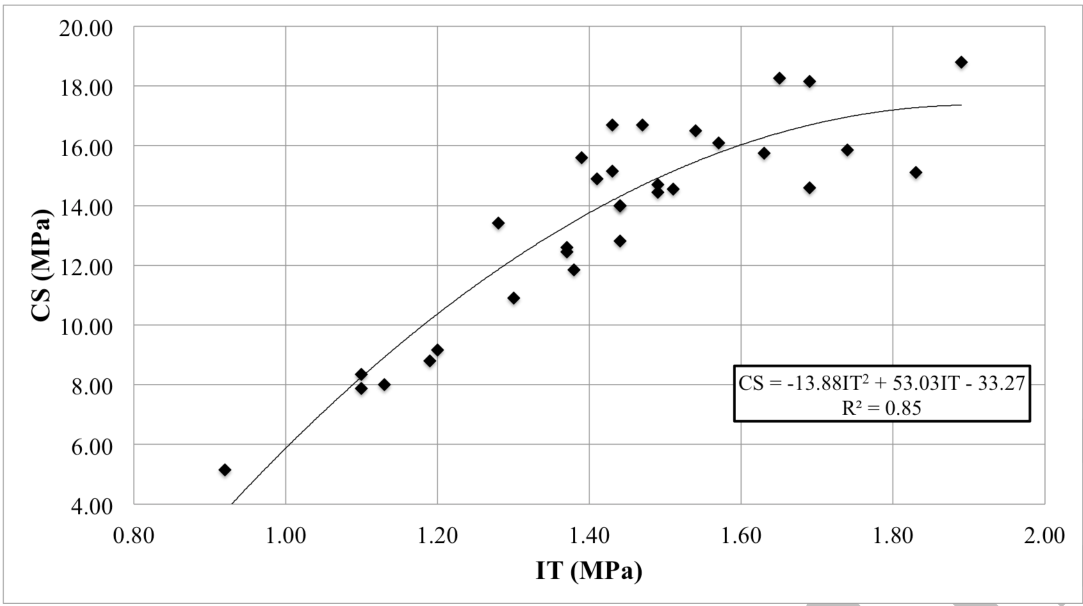

Figure 5. Correlation between CS and IT

As demonstrated in Table 4, the stiffness modulus in PC mixtures is quite high. Nearly every mixture surpassed 15,000 MPa. However, cracking can occur in PC mixtures, especially in urban areas, following the pattern of the voids and the mortar, leading to failure of the pavement. An AG of 4-8mm was the best size, as seen in Figure 4, in addition to using a greater compaction (VMA of 47%), because particles settle better in the mixture and the mortar covers them more efficiently. Mortar bridges between particles are smaller and failure can be delayed. Additionally, sand, in a ratio of s/c = 0.50, increases mortar resistance and workability improving cracking resistance.

Figure 6 shows the correlation between the stiffness modulus and the AV. Despite obtaining a very low R^2, of 0.05, it can be noticed that at higher AV, the tendency of the elastic deformation resistance decreases. The AG determines this behavior, where, as seen in Figure 4, a size of 4-8mm represented the most rigid PC mixtures of the lot.

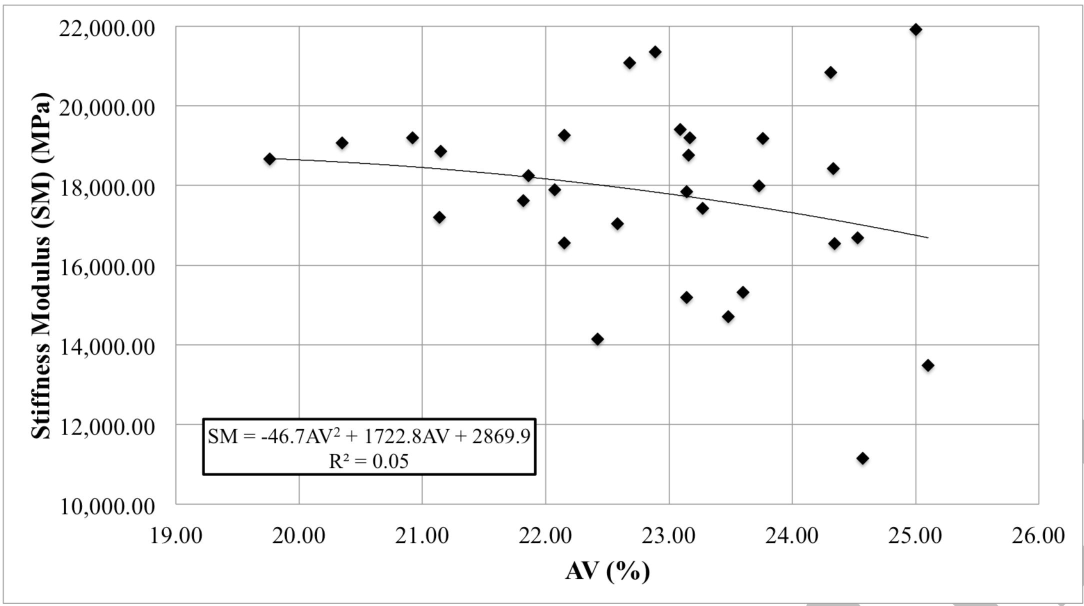

Figure 6. Correlation between Stiffness Modulus and AV

3.3 Skid Resistance

Table 4 shows the results obtained from the BPT. As can be seen, all mixtures obtained very good results, where mixture 40-1-B-I and 40-1-C-II got the highest BPN. A w/c ratio of 0.40 and an s/c ratio of 1 turned out to be the best for skid resistance. This is because sand tends to give the mixture a rougher surface. Another factor that influences the skid resistance of the pavement is the AG used. Mixtures with AG of 2-4mm provided better results when removing sand from the mixture, mainly because the mortar without sand, having a lower density, tends to stay at the surface, increasing the area of contact. This can be verified with the mechanical and hydraulic results. It was observed that skid resistance decreases around 14% when the pavement is wet. The highest loss of skid resistance was for mixture 35-0-B-I, with 25.65%. This mixture did not have sand (s/c of 0 and w/c of 0.35). The lowest loss, of 5.88%, was for mixture 40-1-B-I, with an s/c of 1 and w/c of 0.40.

The correlation between the results of the BPN dry and BPN wet is acceptable, as seen in Figure 7, obtaining an R^2 of 0.78. According to the results, when the pavement is wet, skid resistance decreases around 15%. In addition, as seen in Figure 4, it is noticed that at higher AV (due the AG employed), BPN tends to decrease. This is because AV reduces the vehicle tire contact area with the pavement, making it difficult to brake.

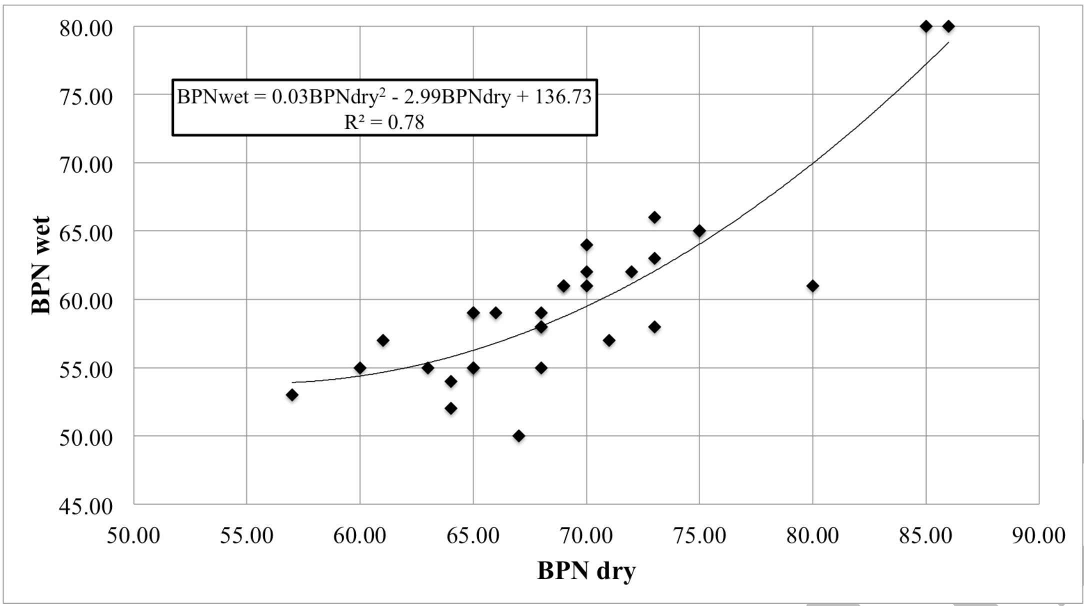

Figure 7. Correlation between BPN (dry) and BPN (wet)

3.4 Optimum Mixture Design

3.4.1 Multi-criteria

Table 5 shows the values of importance considered for the AHP analysis among the variables, where both IT and CS were considered the most important values. This is because all mixtures presented good results in permeability, skid resistance and elastic deformation, and strength becomes a critical value so that the mixture can be used as pavement surface. Therefore, for example, permeability was given a value of importance of 0.40 in comparison to IT, with a level of importance of 0.60 in comparison with permeability.

Table 5. Values of importance among variables

Mixture	IT	k	BPN dry	BPN wet	CS	Stiffness modulus
IT		0.60-0.40	0.90-0.10	0.90-0.10	0.50-0.50	0.95-0.05
k	0.40-0.60		0.40-0.60	0.40-0.60	0.40-0.60	0.70-0.30
BPN dry	0.10-0.90	0.60-0.40		0.40-0.60	0.10-0.90	0.70-0.30
BPN wet	0.10-0.90	0.60-0.40	0.60-0.40		0.20-0.80	0.70-0.30
CS	0.50-0.50	0.60-0.40	0.90-0.10	0.80-0.20		0.95-0.05
Stiffness modulus	0.05-0.95	0.30-0.70	0.30-0.70	0.30-0.70	0.05-0.95	

In Table 6, the best five mixtures from the analysis are shown. The best mixture according to this analysis is 30-5-B-II, which obtained the highest strength of all mixtures. In terms of permeability, its rates where one of the lowest, but still enough to manage storm events. AG of 4-8mm was the best option when designing PC mixtures. In addition, mortar plays a very important role as cement proportion helps to increase adhesion between particles, sand helps to increase mechanical performance and skid resistance, and water proportion helps to make the mixture more workable. An excess amount of water can lead to clogging at the bottom of the sample, and lack of water can lead to clogging at the top. Both scenarios can considerably decrease resistance.

Table 6. Top five mixtures variable's weight results

Mixture	IT	k	BPN dry	BPN wet	CS	Stiffness modulus	Total weight
30-5-B-II	0.03595	0.00165	0.00265	0.00158	0.02956	0.00156	0.01216
30-1-B-I	0.02308	0.00334	0.00133	0.00158	0.02426	0.00187	0.00924
35-5-B-II	0.01841	0.00145	0.00313	0.00379	0.02563	0.00299	0.00923
35-5-B-I	0.02682	0.00538	0.00221	0.00273	0.01498	0.00284	0.00916
40-5-B-II	0.03150	0.00228	0.00089	0.00187	0.01164	0.00122	0.00823

3.4.2 ANOVA

According to Table 7, AG and the cement proportion are the two components that have greatest influence on the mixture properties. In terms of permeability, AG influences the AV of the mixture and consequently the permeability rates. In terms of mechanical capacity, the importance of the cement proportion increases significantly, being a little higher in the IT. This means that cement provides more adhesion to the mortar, maintaining good attachment between the aggregate particles. Additionally, as the AG decreases, the accommodation in the mold improves, lowering the AV and increasing the mechanical strength. This behavior can also be explained by the stiffness modulus results. In terms of skid resistance, AG and cement amount are almost equally important as both the AV in the surface layer of the mixture and the mortar coverage affect this capacity.

The s/c and w/c ratios obtained the same importance in every test as both sand and water influence the behavior of the mortar, increasing or decreasing the cement's adhesive capacity. Finally, the compaction degree was the variable with the lowest importance of all.

Table 7. ANOVA Results

Variable	Permeability				Compression Strength			
	DF*	SSD*	Variance	Importance (%)	DF*	SSD*	Variance	Importance (%)
Gradation	2.00	304.13	9.71	85.90	1.00	204.42	4.41	57.56
s/c	2.00	8.64	1.37	2.44	1.00	20.58	0.19	5.79
w/c	2.00	8.64	1.06	2.44	1.00	20.58	0.19	5.79
VMA	1.00	3.06	1.12	0.86	1.00	10.51	2.79	2.96
Cement	1.00	29.60	1.73	8.36	8.00	99.04	3.68	27.89
Variable	**Indirect Tensile Strength**				**Stiffness Modulus**			
	DF*	**SSD***	**Variance**	**Importance (%)**	**DF***	**SSD***	**Variance**	**Importance (%)**

Gradation	1.00	0.51	3.37	33.03	1.00	$72.20x10^6$	4.08	49.91
s/c	1.00	0.18	0.90	11.67	1.00	$17.32x10^6$	1.77	11.97
w/c	1.00	0.18	0.23	11.67	2.00	$17.32x10^6$	0.44	11.97
VMA	1.00	0.06	22.74	3.66	5.00	$7.28x10^6$	3.26	5.03
Cement	6.00	0.62	0.55	39.97	4.00	$30.55x10^6$	1.09	21.12
Variable	**Skid Resistance (Dry)**				**Skid Resistance (wet)**			
	DF*	**SSD***	**Variance**	**Importance (%)**	**DF***	**SSD***	**Variance**	**Importance (%)**
Gradation	1.00	635.75	2.38	32.58	1.00	654.94	2.78	25.04
s/c	2.00	264.00	0.68	13.53	2.00	522.00	0.92	19.96
w/c	1.00	264.00	1.02	13.53	1.00	522.00	1.35	19.96
VMA	1.00	182.00	2.63	9.33	1.00	194.83	1.08	7.45
Cement	1.00	605.44	1.45	31.03	2.00	721.44	1.70	27.59

**DF: Degrees of Freedom, SSD: Sum Squares of Deviation*

4 Conclusions

This paper evaluates the behavior of PC mixtures by employing different dosages using the PCD methodology. The main variables were studied (s/c ratio, w/c ratio, AG, compaction level and cement amount) and the main functions were characterized (hydraulic, mechanical and safety properties). According to the characteristics evaluated and the results obtained, it can be concluded that an optimum mixture dosage (mixture 30-5-B-II) was determined using MCD. This mixture can be a starting point for future studies in terms of adding environmental properties and improving hydraulic, mechanical and safety properties by using additives in the mixtures with the purpose of implementing them in pavement surface layers in cities. In addition, the following particular conclusions can be drawn:

- AG and cement proportion are the main factors that influence the results of PC mixtures, according to the ANOVA analysis, where an AG of 4-8mm obtained the best results. This is because AG influences the inner structure of the mixture, determining the relation between the AV and the mechanical performance. Cement influences other factors such as the necessary amount of water and sand to ensure adhesiveness of the mortar and the connection of the aggregate particles, fundamental for strength.
- In terms of safety, friction increases at lower AV contents, raising the area of contact between the tires and the pavements surface. However, a 100% impermeable surface will not provide enough friction during rain events, as water ponding will be presented.

- Sand increases friction by about 10-13% and 7-15% for dry and wet conditions, respectively, where an s/c ratio of 0.50 represented the best results. Higher amounts of sand will clog the pavements surface, leading to water pondings, decreasing friction.
- A w/c ratio of 0.35 was the best parameter. Despite obtaining the lowest mechanical capacity on average, the relation between mechanical capacity and permeability tended to be the best, and a few mixtures obtained high strength, due to other factors such as s/c, cement amount, and AG.
- Higher VMA's enables larger percentages of mortar in the mixtures, improving adhesion and friction between aggregate particles, increasing mechanical properties.

Future research should be done to improve the mechanical properties of PC mixtures,. In addition, performing CT scans to evaluate the hydraulic behavior the mixtures present due to the voids structure. Finally, the durability performance in northern climates should be studied to understand PC behavior in freeze-thaw environments.

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