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Evaluation of the effect of different compaction methods on porous concrete pavements: Correlation with strength and permeability

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Abstract

The main purpose of the article was to evaluate the correlation between the indirect tensile strength and the permeability capacity of Porous Concrete (PC) pavements. The compaction method employed plays a critical role in this correlation. However, even though PC pavements have been studied in many places around the world, using different compaction methods, a profound analysis of these methods has not been carried out yet. This research introduces a study of five different compaction methods: axial compression, gyratory, impact, multilayer impact, and tamping rod, with diverse treatments in each one to obtain the best correlation between the indirect tensile strength and the permeability capacity. Results demonstrated that the impact compaction method, at 50 blows on only one side of the sample, gives the best strength-permeability correlation, with an Indirect Tensile (IT) strength value of 2.75 MPa, and a permeability (k) capacity of 0.56 cm/s.

Keywords

Porous concrete pavements; compaction methods; indirect tensile strength; permeability; multi-criteria decision-making.

1 Introduction

Cities have played a very important role in human development for centuries, as they concentrate the main economic activities, industry, resources (as well as their consumption), and waste and emissions generation (Sinha et al. 2002). As the world population grows, urban population density rises, and cities need to expand by constructing more infrastructure. Therefore, there is a huge environmental impact because conventional construction methods do not consider environmental care (Sinha et al. 2002). Of the many problems this presents, water management and pollution affects the population in a very direct way (International Water Association 2017). Water gets polluted because the natural water cycle is interrupted by the impermeable barrier formed by roads and buildings, where water cannot infiltrate through the natural soil, instead reaching city pavements, which causes runoff and adds pollutants (Rodriguez-Hernandez et al. 2013). At the same time, this causes safety problems for drivers and pedestrians (Chen, Wang, and Zhou 2013). As part of the solution, porous pavements have gained increasing attention, since they are able to infiltrate rainwater into the ground, recharging the aquifers, or enabling water to be saved for other uses such as agriculture or human consumption (International Water Association 2017; Rodriguez-Hernandez et al. 2013). These pavements consist mainly of asphalt or cement concrete. Different studies have been done around the world, and the implementation of these materials depends mainly on the characteristics of the place where they are being deployed (Alvarez, Martin, and Estakhri 2011; Tennis, Leming, and Akers 2004).

Porous Concrete (PC) pavements are a special type of pavement that consist of an open graded aggregate structure designed to maintain high porosity, usually around 20 % (Brake, Allahdadi, and Adam 2016; Giustozzi 2016; Khankhaje et al. 2017; Rangelov et al. 2016), to let rainwater infiltrate through the structure (Lian and Zhuge 2010; Tennis, Leming, and Akers 2004). This results in a lower mechanical capacity of the pavement. As a recent material, porous pavements still do not have a specific methodology of design that guarantees enough traffic resistance, and so they are mainly used in parking lots, sidewalks and minor roads.

Compaction work is a critical characteristic that determines the pavement's behavior during its lifetime (Bonicelli et al. 2015). It is known that laboratory results vary from in-situ tests and applications. Some studies have suggested that the compaction work done could be the cause of failures in some pavements (Giustozzi 2016; Lian and Zhuge 2010). In addition, as PC mixtures are a different kind of concrete, compared to conventional concrete, suitable compaction must be done in order to maintain a good permeability capacity, as well as appropriate resistance to traffic (Chandrappa and Biligiri 2017; Kevern, Schaefer, and Wang 2009).

There have not been many studies yet related to compaction work on PC pavements, mainly because this kind of work is usually compared with conventional concrete, which is usually compacted manually or vibrated. However, some researchers would suggest that conventional concrete tests might not apply to PC pavements (Rizvi et al. 2009). For example, the slump test tends to be a very ineffective evaluation method in PC pavements due to their high porosity and dry cement paste (Kevern, Schaefer, and Wang 2009). In addition, some studies have been done on PC mixtures, where gyratory compaction is employed, simulating field conditions (Kevern, Schaefer, and Wang 2009). Other researchers compacted PC mixtures with a standard Proctor hammer with 20 blows, simulating surface compaction (Rizvi et al. 2009). This study evaluates five different compaction methods, with different procedures applied to the mixtures, in order to estimate the effects they have in terms of indirect tensile strength and permeability.

2 Materials and methods

2.1 Materials

Ordinary Portland cement, with a specific weight of 3.14 gr/cm^3, was used as a cementitious material. Basalt gravel was used as coarse aggregate with a size of 5-10 mm (sieves No. 4 to 3/8" according to the ASTM E 11 standard (ASTM E11 2020)), and fine aggregate in a size ranging from filler (< 0.080 mm or sieve No. 200 according to the ASTM E 11 standard (ASTM E11 2020)) to 2.38 mm (sieve

No. 8 according to the ASTM E 11 standard (ASTM E11 2020)), as shown in Fig. 1. The basalt characteristics are summarized in Table 1, were the specific gravity, absorption, density, and voids in the aggregate, were evaluated according to ASTM C 127 (ASTM C127 2001), ASTM C 128 (ASTM C128 2015), and EN 1097-3 (EN 1097-3 1999), respectively.

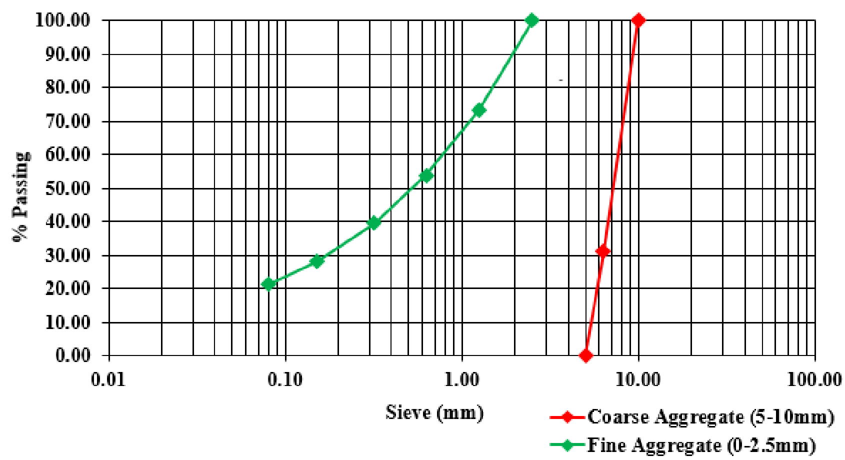

Fig. 1. Aggregates Gradation Curve

Table 1. Basalt Characteristics

Characteristic	Results	Note	Standard
Specific gravity	2.59		ASTM C 127
Absorption	1.96 %	5-10mm	ASTM C 127
	4.03 %	0-5mm	ASTM C 128
Density	1.37 gr/cm^3	uncompacted	EN 1097-3
	1.49 gr/cm^3	compacted	
Voids in aggregate	47.14 %	uncompacted	EN 1097-3
	42.43 %	compacted	

The same PC dosage was implemented for all the compaction methods analyzed. A sand-cement (s/c) ratio of 0.50 was employed, as well as a water-cement (w/c) ratio of 0.30. The mixtures were designed to maintain a porosity of 20 %. Five different compaction methods were evaluated to observe the differences in the indirect tensile strength and permeability of the specimens, with the same porosity: Compaction by axial compression, Gyratory compaction, Impact compaction (Marshall), Multi-layer impact compaction (Proctor standard), and Tamping rod compaction.

For each method, four different compaction forces were applied, according to EN 13286-53 (EN 13286-53 2004), EN 12697-31 (EN 12697-31 2019), EN 12697-30 (EN 12697-30 2018), EN 13286-2 (EN 13286-2 2010), and EN 12350-1 (EN 12350-1 2019) standards, and what other authors have applied in PC mixtures (Bonicelli et al. 2015; Ghashghaei and Hassani 2016; Kevern, Schaefer, and Wang 2009; Kim, Gaddafi, and Yoshitake 2016). In addition, three samples were manufactured per compaction force in order to obtain a more accurate result. In the case of the axial compression method, only one force was tested. This was because it was considered to be the Control mixture as this technique manages the force and height of the samples in a very efficient way. It is important to clarify that it is not possible to perform exactly what is stipulated in the standards, as porous concrete behaves differently from conventional concrete. Therefore, the best method and force is attempted.

Finally, samples were designed to have a diameter of 101.6 mm and a height of 65 mm, except for the gyratory compaction method, where samples had a diameter of 150 mm and a height of 97.5 mm. In Table 2 the dosage and standard used for each compaction method is shown. The following section explains each compaction method.

Table 2. Mixture dosage employed

Compaction method	Standard	Cement (kg/m^3)	Coarse Aggregate (kg/m^3)	Sand (kg/m^3)	Water (kg/m^3)	Porosity (%)	Simulates
Axial compression	EN 13286-53	344.85	1510.50	172.43	119.77	20.00	Roller witout vibration
Gyratory	EN 12697-31	344.85	1510.50	172.43	119.77	20.00	Roller compactor
Impact (Marshall)	EN 12697-30	344.85	1510.50	172.43	119.77	20.00	Drum roller compactor
Multilayer impact (Proctor)	EN 13286-2	344.85	1510.50	172.43	119.77	20.00	Vibratory drum roller
Tamping rod	EN 12350-1	344.85	1510.50	172.43	119.77	20.00	Concrete vibrator

2.2 Methods

2.2.1 Compaction methods

2.2.1.1 Axial compression

This compaction method can simulate the static part of a drum roller (the action of the weight, without the vibration). This method is known for being used in the production of concrete blocks. However, the reason for its implementation in the PC mixtures used in this investigation is to obtain and control the final thickness of the samples. This enables the definition of the theoretical porosity (20 %), and the evaluation of different dosages, varying only the PC components, without modifying the porosity. The compaction is not done through force control, but through displacement control, where a height of 6.5 cm was calculated for the mixtures. The piston of the machine moved at 10 mm/min, until it reached a maximum force of 8.50 ton, when it reached a mass flow around 0.05 ton/s. The device employed for this compaction is shown in Fig. 2A.

The test is based on the EN 13286-53 standard (EN 13286-53 2004), where just one compaction force was employed, assuming that at higher compaction force, the indirect tensile strength would increase, and the permeability would decrease. This mixture was considered to be the Control mix.

2.2.1.2 Gyratory compaction

According to some authors, the gyratory compactor can simulate the kneading produced by a roller compactor. Normally a pressure of 0.60 MPa is employed in the laboratory (Kevern, Schaefer, and Wang 2009). The device consists of a mold with cylindrical walls, with an inner diameter of 150 mm. In addition, it has a base plate at the bottom that rotates at a constant speed of 30 rpm, with the aim of confining the mixture during compaction. The mold tends to be positioned at an angle of 1.25° (Fattah, Hilal, and Flyeh 2019). The device employed for this compaction can be seen in Fig. 2B, where 100 gyrations is the normal standard number employed for the test, although the number can be changed in order to evaluate different possibilities. For this investigation, 25; 50; 75 and 100 gyrations at a pressure of 0.60 MPa were employed, according to EN 12697-31 standard (EN 12697-31 2019). Some authors state that more than 100 gyrations can decrease the porosity of PC samples considerably (Kevern, Schaefer, and Wang 2009).

2.2.1.3 Impact compaction

Impact compaction has been employed by many researchers as it can also reproduce in-situ PC characteristics with a low standard deviation (Bonicelli et al. 2015). The Marshall device is employed, consisting of a hammer with a flat, circular base with a diameter of 98.4 mm (3 7/8”). A piston of 4.54 kg (10 lb) is installed at a height of 456.2 mm (18”) above the base, as seen in Fig. 2C. The hammer is released, hitting the sample. The compaction depends on the number of blows applied to the mixture. Standard EN 12697-30 (EN 12697-30 2018) establishes 50 blows per side of the mold, but 35 blows can be acceptable when considering lightweight traffic, and 75 blows when considering heavyweight traffic. In addition, some researchers have claimed that more than 20 blows in PC mixtures tend to clog the sample almost completely, eliminating the permeability capacity, but increasing mechanical strength (Bonicelli et al. 2013). For this investigation, 10; 20; 35 and 50 blows were evaluated in order to obtain the best result in terms of the balance between permeability and indirect tensile strength of the samples.

2.2.1.4 Multilayer impact compaction

This compaction method is used mainly to determine the relationship between dry density and water content of compacted soils. There are two Proctor tests: standard and modified. The difference between the two is in the weight and height of the hammer employed where, for the former, a mass of 2.50 kg and a height of 305 mm are used, while for the latter, a mass of 4.50 kg and a height of 457 mm are used, according to the EN 13286-2 (EN 13286-2 2010) standard.

For this research, the Proctor standard method was utilized, because it was considered that the modified method could clog the samples considerably. The mold employed had a diameter of 100 mm, and a height of 120 mm, as seen in Fig. 2D. Samples were compacted in two separate layers using 10: 20; 25; and 35 blows per layer. The literature reviewed confirmed that compressive strength over 15 MPa with permeability rates around 0.50 cm/s can be obtained, employing 3 layers of 10 blows each (Torres, Hu, and Ramos 2015). Other studies found compressive strength values over 20 MPa, with similar permeability rates, of 0.58cm/s, with 2 layers and 20 blows each (Rizvi et al. 2009).

2.2.1.5 Tamping rod compaction

This method is done manually, with a rod of 16 mm diameter and 600 mm height. It consists in tamping the sample with a certain number of blows over its surface, in different layers, as shown in Fig. 2E. Standard EN 12350-1 (EN 12350-1 2019) establishes 3 layers of 25 blows each for specimens with a 100 mm diameter and a 200 mm height, or 150 mm diameter and 300 mm height.

However, as the samples made for this research were 65 mm high, it was decided to perform 2 layers of 10; 15; 20; and 25 blows each.

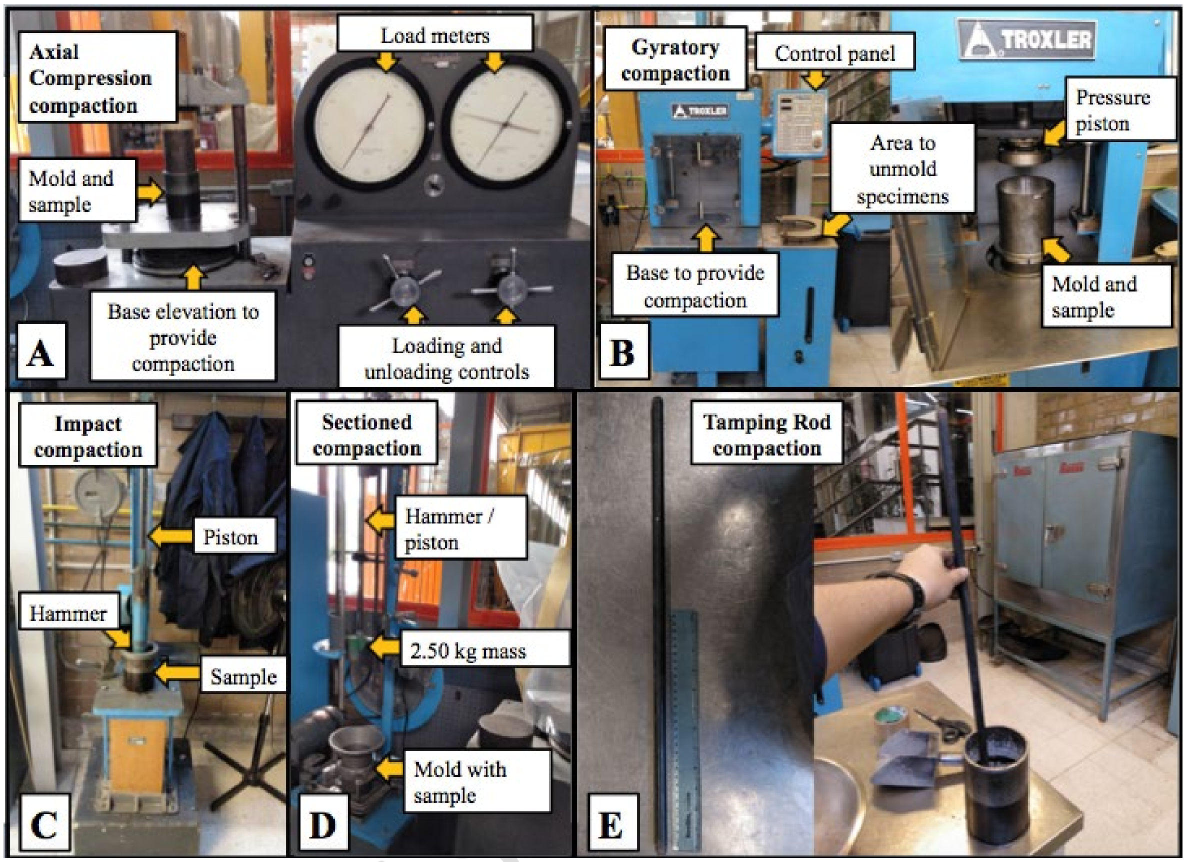

Fig. 2. Compaction devices employed

2.2.2 Tests

2.2.2.1 Porosity and permeability

Permeability (k) capacity was measured with a falling head permeameter. It consisted of a transparent PVC tube of 300 mm height and a diameter of 85 mm. The tube was calibrated in order to establish a fall of 200 mm. Time is counted from when the water level reaches the highest mark. When it reaches the lowest mark, the clock stops; then, employing Darcy's law, the permeability coefficient k is calculated, according to equation (1):

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

Where k is measured in cm/s. A_{sample} is the area of contact between the water and the sample's surface, expressed in cm^2, h_{sample} represents the height of the sample, in cm, A_{tube} is the area of the tubes gap, t is the time it takes water to go from the highest point h_1 to the lowest point h_2. By applying the ASTM C1688 (ASTM C1688/C1688M-13 2009) standard, the porosity (P) can be calculated by substracting the real density of the mixtures from the theoretical density, then dividing by the value by the theoretical density and multiplying by 100, as seen in equation (2):

$$\boldsymbol{P = \left(\frac{\rho_t - \rho}{\rho_t}\right) * 100} \qquad (2)$$

Where ρ_t corresponds to the theoretical density, calculated as the sum of the total mass of the material proportions employed to elaborate the mixture, divided by the volume of the mold, and ρ is the real density obtained from the net mass of the concrete divided by the volume of the container.

2.2.2.2 Indirect tensile strength

Mechanical strength was measured through the Indirect Tensile (IT) test, according to the EN 12390-6 standard (EN 12390-6 2010). The test, equations and machine description required for the implementation of this procedure can be found in the EN 13286-42 (EN 13286-42 2003), EN 12390-6 (EN 12390-6 2010), and EN 12390-1 (EN 12390-1 2014) standards respectively. With this test it is possible to analyze the resistance to traffic loads in PC pavement designs, where a controlled load is applied to the cross section of the sample, causing a perpendicular deformation that eventually produces failure.

As the gyratory samples are bigger in size than the rest of compaction methods evaluated, equation 3, from EN 12390-6, was implemented in order to calculate the IT of the sample according to its size, where F corresponds to the maximum load in newtons (N), L is the contact length of the sample in mm, and d is the diameter of the sample, in mm. Therefore, results with the gyratory samples can be compared with the other methods.

$$IT = \frac{2F}{\pi L d} \quad (3)$$

3 Results

As the force applied for each blow, or gyration, in every compaction method is different due to the type of equipment and standard specification, the forces were standardized in order to be able to view all of them in one single graph and understand the different behaviours of the mixtures. This is shown in Table 3, where the loading rate in MPa/sec is the parameter that was used to compare the mixtures' results. Table 3 also shows the average results obtained for the indirect tensile (IT) strength, permeability (k), as well as the density (ρ), and porosity of each mixture. The standard deviation (σ) of the tests is provided, as each mixture consisted of 3 samples. The first column of Table 3 shows the type of impact the mixture receives. For example, the Gyratory method applies gyrations to the mixture, while the other methods apply blows. The Axial Compression method compacts the mixture at a constant force; therefore, the second column represents the units per second of the test, or the rate at which each unit is applied. The Axial Compression method applies 500 Newtons per second, until it reaches a total force of 10.40 MPa (85,000 N). Mixtures generally fail before the maximum load is reached. The Gyratory method applies 0.51 gyrations per second, the Impact method 0.83 blows per second, the Multilayer Impact method 0.64 blows per second, and the Tamping Rod 1.06 blows per second. As the rod in the latter method has a certain weight (1 kg), and area of contact (2.01 cm^2), the procedure to calculate the compaction effort in the Tamping Rod method was the same as the rest of techniques, applying a height of fall between 10-15 cm.

The “Total effort” column indicates the maximum stress applied to the mixture when the test is finished. The Gyratory method acts with a stress of 0.60 MPa from the beginning of the test, and is kept the same until the test is over. The number of gyrations, and time of test cause the difference in the compaction. In the rest of the methods, the load is different depending on the number of blows employed. The “Time of test” column represents the total time required to perform the test, and the

“Compaction effort column” shows the load applied per second. The reason for using this last column in the following graphs instead of the total force is because the Axial Compression method does not use this amount of force, but reaches it after 170 seconds.

Mixtures are denominated by the initial of the compaction method employed: Axial Compression (A), Gyratory (G), Impact (I), Multilayer Impact (M), and Tamping Rod (T). In addition, the number of blows, gyrations or tons applied to the mixture, follow the letter of the name.

Table 3. Standardization of compaction efforts and mixtures: general results

Mixture	Unit	Unit/sec	Total effort (MPa)	Time of test (sec)	Compaction effort MPa/sec	ρ (gr/cm^3)	σ	Porosity (%)	σ	k (cm/s)	σ	IT (MPa)	σ
A-8	Newton	500.00	10.40	170.00	0.06	2.11	0.02	25.48	0.81	0.13	0.05	1.19	0.34
G-100	Gyration	0.51	0.60	195.67	0.60	2.34	0.01	16.29	0.31	0.11	0.03	1.76	0.07
G-75			0.60	146.75	0.60	2.24	0.01	19.86	0.49	0.14	0.03	1.28	0.40
G-50			0.60	97.83	0.60	2.18	0.01	22.06	0.24	0.28	0.06	1.15	0.09
G-25			0.60	48.92	0.60	2.09	0.03	25.09	0.99	0.61	0.17	0.96	0.19
I-50	Blow	0.83	0.12	60.00	0.10	2.22	0.01	21.37	0.25	0.56	0.16	2.75	0.39
I-35			0.09	42.00	0.07	2.12	0.03	24.83	1.09	0.70	0.24	2.55	0.41
I-20			0.05	24.00	0.04	2.04	0.01	27.68	0.40	1.15	0.12	2.04	0.24
I-10			0.03	12.00	0.02	1.86	0.02	33.89	0.80	2.04	0.34	0.55	0.05
M-35	Blow	0.64	0.13	55.00	0.09	2.04	0.03	27.64	1.17	0.31	0.04	1.22	0.17
M-25			0.10	39.29	0.06	1.96	0.03	30.58	0.92	0.84	0.57	1.14	0.24
M-20			0.08	31.43	0.05	1.93	0.03	31.67	1.11	1.41	0.14	0.84	0.44
M-10			0.04	15.71	0.02	1.76	0.00	37.43	0.00	4.38	0.45	0.43	0.02
T-25	Blow	1.06	0.14	23.69	0.15	1.81	0.03	35.83	1.03	1.43	0.47	0.85	0.14
T-20			0.11	18.95	0.12	1.76	0.02	37.90	0.34	1.82	0.25	0.88	0.11
T-15			0.09	14.21	0.09	1.70	0.01	39.08	0.38	2.29	0.10	0.77	0.13
T-10			0.06	9.48	0.06	1.64	0.03	41.76	0.90	4.93	1.09	0.72	0.07

3.1 Porosity and permeability

As can be seen in Table 3, mixture T-10 (Tamping rod, 10 blows) produced the highest porosity and permeability (k). Although its total load is higher than some other mixtures, the fact that the rod employed for the test has a very small area of contact (diameter of 16 mm) leads to low compaction. Moreover, it could be suggested that this method settles the mixture in the mold rather than employing full compaction. In addition, mixtures that were designed for a sample height of 65 mm remained over 10 mm taller, leading to very high porosity. Therefore, permeability capacity in this mixture was very high. The Multilayer Impact method obtained high permeability rates as well, especially at lower compaction loads, such as in the case of mixture M-10. In this scenario, the total force was so low, in addition to the hammer and tamping rod having a small area of contact, that an uneven sample surface was obtained. This can be seen in Fig. 3, where a 10-blow, multilayer impact-compacted sample is shown. In addition, the division between the two layers compacted is clearly noted, concluding that there is no good adhesion between the two layers.

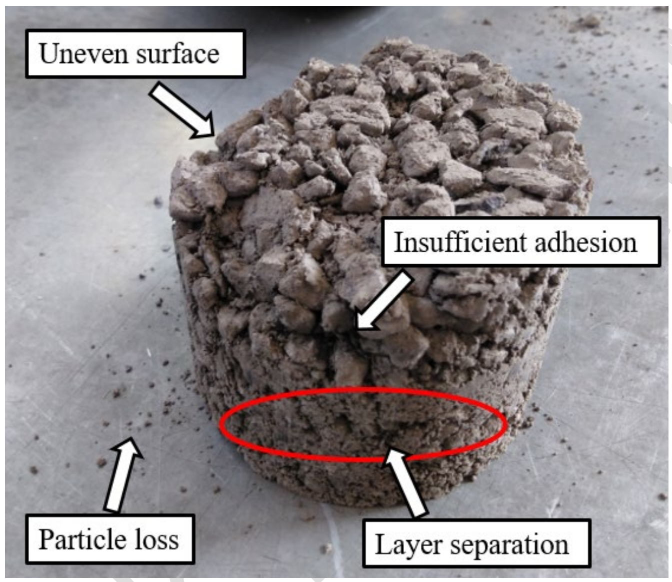

Fig. 3. Multilayer impact compaction sample with uneven surface and particle loss

Fig. 4a and b show the correlation of the permeability (k) and porosity, respectively, with the compaction effort. It can be seen that both parameters tend to decrease when the compaction load increases. As can be seen, the Gyratory method employed the highest load, resulting in the lowest permeability and porosity rates, even lower than Control mixture A-8. The Multilayer and Tamping Rod methods obtained higher values of permeability, especially at fewer blows, surpassing Control mixture A-8 by 37 times. The Gyratory samples align over the same loading rate, as the force was constant, only the number of gyrations of the test varying. The greater the amount of gyrations, the lower the permeability and porosity, and viceversa.

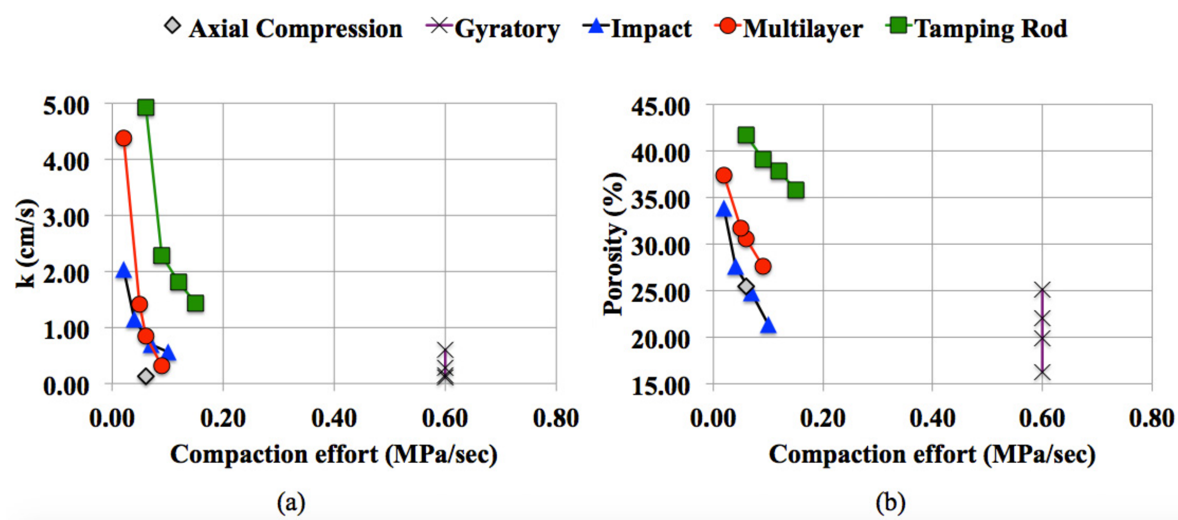

Fig. 4. Correlation between the Compaction effort and (a) permeability (k), (b) porosity

Mixture A-8 produced one of the lowest permeability results, outperforming only mixture G-100. The effort employed in the Axial Compression method may have been too high, settling the aggregate particles better in the mold, and so decreasing the porosity. Only mixtures G-100, G-75, and G-50 obtained lower porosity values, as the Gyratory method uses both vertical pressure and gyratory action, exerting more stress. However, all mixtures complied with the minimum permeability capacity required by American standards of 100 m/day (or 0.012 cm/s) (Andres-Valeri et al. 2018).

3.2 Indirect tensile strength

In contrast to the permeability and porosity, the density (ρ) and the indirect tensile (IT) strength increased when the compaction increased, as seen in Fig. 5a and b. The Gyratory method obtained the highest densities, but mixtures I-20, I-35 and I-50 exceeded its strength, using the Impact method. Mixture I-50 achieved the highest strength, 57 % higher than Control mixture A-8. The Gyratory, Impact and Axial Compression methods achieved strengths over 1 MPa, while the Multilayer Impact and Tamping Rod methods did not.

According to the results shown in (Bonicelli, Arguelles, and Pumarejo 2016), the Impact method can provide mixtures for mid-volume urban roads, as mixtures I-20, I-35 and I-50 achieved indirect tensile strengths over 1.90 MPa. The Gyratory method can achieve mixtures for low-volume urban roads and parking lots, obtaining indirect tensile strengths between 1.70-1.90 MPa, as is the case of mixture G-100. Mixture G-75 may be acceptable for pedestrian areas, as its indirect tensile strength was between 1.20-1.50 MPa, similar to mixture M-35 compacted with the Multilayer Impact method. The rest of the mixtures must be reinforced with additives to improve their strength in order to be suitable for use. An additive study in PC mixtures can be seen in (Elizondo-Martínez et al. 2020).

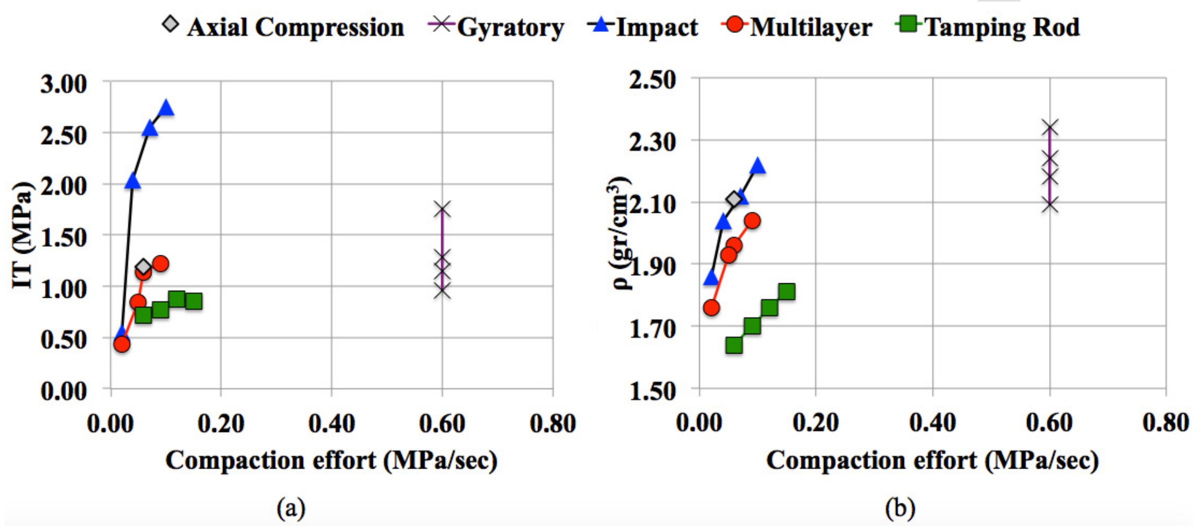

Fig. 5. Correlation between the Compaction effort and (a) Indirect Tensile Strength (IT), (b) density (ρ)

4 Discussion

4.1 Importance of the compaction methods and tests performed

To get insight into the importance of the compaction methods and tests performed, an ANOVA analysis was carried out. The normality of each compaction method values was previously verified using the Shapiro-Wilk test, where the p-values obtained are listed in Table 4. All values are normally distributed, according to a significance level of 0.05 (Fisher 1992). The p-value corresponds to a one-tail analysis, where the hypothesis is the probability of obtaining a value, μ, higher than 1.20, for the indirect tensile strength, and higher than 0.012 for the permeability. This according to the analysis in the Results section, to evaluate the proper use of the pavement, where all the outcomes stated that there is around 50 % of probability to achieve values over 1.20 MPa and 0.012 cm/s, with 95 % of confidence, as seen in Table 4. Finally, the importance of each compaction method can be determined with the ANOVA, where the Multilayer method represents the best correlation between the permeability and indirect tensile, with 33 % of importance. The high values of permeability provided by this method, along with the average indirect tensile strength results, lead to greater importance. The Impact method accomplished the highest indirect tensile strength, and good permeability values, although not as high as the Multilayer method. Therefore, it is the second most important, with 24.94 %.

Table 4. Normality and ANOVA comparison among results of each compaction method and indirect tensile (IT) strength and permeability (k) results

Compaction Method	Normality (Shapiro-Wilk test)		DF*	SSD*	p-value		Importance (%)
	IT	k			IT	k	
Gyratory	0.847	0.351	3.000	0.671	0.500	0.501	21.765
Impact	0.364	0.548	3.000	0.769	0.501	0.501	24.944
Multilayer	0.717	0.285	3.000	1.017	0.519	0.501	33.002
Tamping Rod	0.824	0.213	3.000	0.625	0.508	0.501	20.290

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

Performing the analysis simultaneously with all the compaction methods, it is possible to calculate the influence of the compaction methods on the permeability and the indirect tensile strength. As seen in Table 5, permeability has an importance of 66.76 %. This means that the permeability is the parameter which is most affected, in a positive or negative way, by the compaction method and load applied, in comparison with the indirect tensile strength.

Table 5. Influence of the compaction methods on the permeability and indirect tensile strength

Test	DF*	SSD*	p-value	Importance (%)
Permeability	15.000	1.871	0.502	66.761
Indirect Tensile strength	15.000	0.931	0.760	33.239

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

4.2 Selection of the best compaction method and load

The Analytical Hierarchy Process (AHP) multi-criteria decision-making method was employed in order to determine the best compaction method, as well as the optimal load, in terms of indirect tensile strength and permeability. The AHP method is one of the most widely used decision-making procedures, mainly because of its simplicity (Jato-Espino et al. 2014). The procedure can be seen in (Skibniewski and Chao 1992). It consists in performing pairwise comparison, based on the criterion of the person making the decision, as it gives values of priority to the variables under study (compaction methods and force in this case). The AHP method was introduced by Saaty (Saaty 1980), proposing a Table with values from 1 to 9, where the lowest value means an equal level of importance between two variables, and the highest value an absolute importance of one variable over another (Al-harbi 2001), as seen in Table 3.

The AHP multi-criteria decision-making analysis can help to make a more exact decision, as it aids in determining not only the best compaction method, but also the optimal effort in order to obtain the best permeability-indirect tensile strength relationship. Table 6 shows the results of the AHP analysis, where the weights obtained for every test, as well as the total weight is shown. It can be seen that mixture I-50 obtained the highest total weight, making it the optimal compaction methodology to implement in PC mixtures. It obtained the highest indirect tensile strength, with 2.75 MPa. In terms of permeability, a performance of 0.56 cm/s is acceptable. Following mixture I-50, mixture I-35 obtained the second highest weight. This mixture would be suitable for lightweight traffic. Overall, the Impact compaction method turned out to be the best procedure to implement in PC pavements. Although this compaction method simulates drum roller compaction, field verification should be performed, as laboratory tests may not reflect field behavior.

Table 6. AHP Multicriteria decision-making analysis results

Mixture	Weight		Total weight	Hierarchy
	k	IT		
P-8	0.04381	0.01619	0.0160	15

G-100	0.08639	0.01436	0.0278	6
G-75	0.05054	0.01785	0.0183	11
G-50	0.03985	0.02082	0.0159	16
G-25	0.03018	0.02677	0.0144	17
I-50	0.22072	0.02472	0.0686	1
I-35	0.17856	0.02963	0.0576	2
I-20	0.1229	0.03706	0.0432	5
I-10	0.01443	0.07397	0.0199	9
S-35	0.04708	0.02274	0.0184	10
S-25	0.03709	0.03335	0.0177	13
S-20	0.02319	0.04747	0.0168	14
S-10	0.01282	0.19683	0.0456	4
T-25	0.02527	0.05104	0.0181	12
T-20	0.02742	0.06555	0.0218	8
T-15	0.02082	0.08277	0.0236	7
T-10	0.01896	0.2389	0.0563	3

Mixture T-10 achieved the third place in the AHP analysis, mainly because of the high permeability it obtained, with 4.92 cm/s. This is considered to be a very high permeability for PC mixtures, providing very high porosity (41.76% for this mixture), but very low indirect tensile strength (0.72 MPa). Mixture M-10 obtained the lowest indirect tensile strength, with 0.43 MPa, justifying the conclusion that compaction with blows in two layers is not that effective due to the lack of adhesion between the layers.

5 Conclusions

This paper evaluates different compaction methods and efforts in order to determine the ideal procedure to obtain the best indirect tensile strength-permeability trade-off for PC mixtures. A correlation among different PC mixture compaction methods was made with the intention of comparing different results more accurately. It is important to state that the experimental results of this study may not reflect field performance. Field verification should be done and this is suggested as a future line of investigation. The following conclusions can be drawn:

- The Impact compaction method (or drum roller compaction) demonstrated the highest indirect tensile strength, with an acceptable permeability. This method allowed the mixture to be compacted in the mold very efficiently. The number of blows employed, as stated by the EN 12697-30 standard, enables control of compaction according to different scenarios: heavyweight traffic, lightweight traffic, and normal traffic. This enables the control of the loads according to the needs of the pavement.

- The Gyratory compaction method (mimicking the kneading produced by a roller compactor) showed very good compaction in the samples. However, the indirect tensile strength was not as high as with impact compaction, and the permeability performance was very low. This method produced greater clogging of the samples because of the gyrations employed by the equipment.

- The Multilayer Impact compaction method (mimicking vibratory drum roller compaction) demonstrated a very uneven surface. In fact, these mixtures tend to lose aggregate particles because the adhesion is not sufficiently strong. In addition, as the compaction was done to two layers, the separation between them was very noticeable and failure occurred mainly through this, providing a low indirect tensile strength. This led to high permeability, especially at lower numbers of blows, because of the high porosity achieved, which increased due to particle loss during manufacture.

- Tamping Rod compaction (mimicking the concrete vibrator) obtained the highest permeability, as this method tends to settle the mixture components rather than employing compaction force. This leads to taller samples, and higher porosity, with low indirect tensile strength, as the cement paste bridges that link the aggregate particles were thinner and weaker.

- The Axial Compression compaction method (mimicking the static effect of the roller) was used to make a reference mixture as it was considered a procedure that enables the porosity proposed to be obtained. However, results demonstrated that it had one of the lowest permeability values and indirect tensile strength higher only than the Tamping Rod mixtures, and mixtures M-10 and M-20. This behavior can be explained because the compaction employs displacement control rather than strength control, so when the proposed height was achieved, the compaction force was decreased.

- Overall, the Impact compaction method provided the best results for the purposes of this investigation, where higher indirect tensile strength can be achieved and the PC pavements resistance to traffic is better, increasing its lifetime. However, when PC is employed in places with low loading expectation like sidewalks, other compaction methods, such as gyratory or multilayer impact, could provide a good solution, achieving higher permeability values and so better runoff during rain events.

Future research should be carried out in this line of investigation in order to confirm the advantages of the selected compaction method. The research may include the study of the inner structure of porous concrete samples, employing different types of aggregates and gradations, as well as methods of evaluation like Magnetic Resonance Imaging (MRI) and Nuclear Magnetic Resonance (NMR) techniques.

Data availability statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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