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ORIGINAL ARTICLE

Influence of compaction energy on pervious concrete properties and vertical porosity distribution

Influência da energia de compactação nas propriedades do concreto permeável e na distribuição vertical da porosidade

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Abstract: Compaction is a fundamental step in pervious concrete production and affects its mechanical and hydraulic properties. In this study, two pervious concrete mixtures were compacted with three different energies, distributed in two and three layers. The effects on porosity, mechanical strength and hydraulic conductivity were evaluated. The increase in compaction energy resulted in a proportional reduction in porosity. Increases in compressive strength from 17 to 36% were observed. However, permeability reduced proportionally, with decreases of 0.2 to 0.4 cm/s. The three-layer compaction resulted in a more homogeneous vertical distribution of porosity when compared to the two-layer compaction. Although the aggregate/cement ratio was the most influential parameter, the compaction energy should also be considered in the pervious concrete mixture design. While increasing the compaction energy enhances the mechanical strength of pervious concrete, excessive compaction may cause the fracture of the coarse aggregate, reducing its mechanical and hydraulic performance. Thus, for each mixture an optimum compaction energy can be defined to maximize the performance of pervious concrete.

Keywords: compaction energy, vertical distribution, porosity, hydraulic conductivity.

Resumo: A compactação é uma etapa fundamental na produção do concreto permeável e afeta suas propriedades mecânicas e hidráulicas. Neste estudo, duas misturas de concreto permeável foram compactadas com três níveis de energia, distribuídas em duas e três camadas. O efeito na porosidade, resistência mecânica e condutividade hidráulica foi analisado. O aumento da energia de compactação resultou em uma redução proporcional da porosidade. Consequentemente, um aumento da resistência à compressão de 17 a 36% foi observado. No entanto, a permeabilidade reduziu proporcionalmente, com perdas de 0,2 a 0,4 cm/s. A compactação do concreto em três camadas resultou em um perfil de distribuição vertical da porosidade mais homogêneo quando comparado à compactação em duas camadas. Embora a relação agregado/cimento tenha sido o parâmetro mais influente, a energia de compactação também deve ser levada em consideração na dosagem do concreto permeável. Embora o aumento da energia de compactação melhore a resistência mecânica do concreto permeável, a compactação excessiva pode causar a fratura do agregado graúdo, reduzindo o seu desempenho mecânico e hidráulico. Dessa forma, para cada mistura uma energia de compactação ótima pode ser definida para maximizar o desempenho do material.

Palavras-chave: energia de compactação, distribuição vertical, porosidade, condutividade hidráulica.

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1 INTRODUCTION

Pervious concrete is a special concrete containing little to no fine aggregates in its composition [1]. Therefore, coarse aggregates are involved by a thin layer of cement paste, forming a structure of connected pores, allowing water to flow through it [2]. Pervious concrete is usually designed with porosities between 15 and 35%, resulting in hydraulic conductivity between 0.2 and 5.4 cm/s [1], [3]–[6]. Due to its specific characteristics, pervious concrete may be used in pervious pavements, aiming at capturing rainwater and allowing its infiltration in the soil. In addition, contributing to the reduction of stormwater runoff, pervious concrete also helps to reduce the effect of heat islands and the removal of water pollutants [7]–[11].

One of the difficulties of the pervious concrete mixture proportion is to develop mixtures with sufficient mechanical strength to be used in high volume roads, still keeping its water infiltration capability [12]. NBR 16416 [13] regulates the use of pervious concrete in sidewalks and low-volume roads in Brazil. For cast-in-place concrete, flexural strength must be greater than 1.0 MPa for sidewalks and greater than 2.0 MPa for low-volume roads. The standard establishes minimum compressive strength of 20 MPa regardless of traffic volume. According to Delatte [14] the flexural strength of pervious concrete should be between 2.1 and 3.5 MPa for collector and arterial roads. According to Akkaya and Çağatay [12], flexural strengths greater than 4.5 MPa would be required for high-volume roads.

Porosity is the property commonly used to control the pervious concrete properties and may be adjusted directly by the cement paste volume in the mixture [1]. In addition to reducing porosity, an increase in the cement paste amount results in a better bond between aggregates, improving the mechanical strength [2], [15]. However, excess cement paste might impact the pervious concrete pore structure, reducing its hydraulic conductivity. Thus, there is a limit to the amount of cement in the mixture, mainly to ensure a minimum permeability for the pervious concrete [16].

Even if porosity is the most used parameter to relate mechanical strength and hydraulic conductivity of pervious concrete, it is not always enough to describe the behavior of such properties. Other characteristics also influence the material performance, such as aggregate size [17]–[19], water/cement ratio [20], [21], cement paste consistency [22], [23] and pore size and distribution [17], [24], [25].

Compaction is another control parameter in the production of pervious concrete, resulting in a holistic approach to the design process [26]. A minimum of compaction is required to strengthen the bond between the aggregate particles, thus preventing pavement raveling [27]–[29].

The compaction energy may also be adjusted to control the pervious concrete porosity, affecting its physical and mechanical properties [30]–[33]. In addition to reducing porosity, an increase in the compaction level contributes directly to the pervious concrete compressive strength [2]. However, excessive compaction might reduce pore connectivity and, consequently, concrete hydraulic conductivity [34], [35].

The properties of pervious concrete are also influenced by the compaction method employed [6], [36]. Field and laboratory compaction are known to produce a vertical distribution of porosity, which increases linearly with the depth of the pervious concrete [37], [38]. Rao et al. [39] also observed a significant variation in pore number and size. Consequently, the mechanical and hydraulic properties of the concrete will also vary vertically. Martin et al. [40] and Pieralisi et al. [41] confirmed that the porosity vertical distribution directly affects hydraulic conductivity, being mainly impacted by the least porous layer. However, it is not very clear how mechanical strength is affected by the vertical porosity distribution. According to Chandrappa and Biligiri [42], a way of reducing the effect of the vertical porosity distribution is an increase in the number of layers in the compaction process. However, there are no reports in the literature on how the vertical porosity distribution is affected by the compaction method.

1.1 Research significance

Different variables might alter the final properties of pervious concrete. Compaction energy is highlighted as a variable that affects most pervious concrete properties. Although compaction has been the subject of many laboratory investigations, there is still little information about the influence of compaction method on vertical porosity distribution. To illustrate this, Table 1 summarizes the most relevant studies published in the last 15 years about the pervious concrete compaction. Therefore, this paper aims at evaluating how the compaction energy and the form of application affect the vertical porosity distribution. In this study, two pervious concrete mixtures were evaluated. Each mixture was compacted with three compaction energies (i.e., 95.2.,142.9 and 190.6 kJ/m^3) to evaluate the effect on mechanical and hydraulic performance. The pervious concrete specimens were produced with a different number of compaction layers (two and three layers) to evaluate the vertical distribution of porosity.

Table 1. Summary of studies about the effect of compaction energy on pervious concrete properties

		References								
		[2]	[30]	[31]	[37]	[39]	[40]	[31]	[43]	This study
Variables	Nº Compaction Layers									●
	Compaction Energy	●	●	●			●	●	●	●
	Aggregate to cement	●		●			●	●		●
Analysis	Mechanical/Physical	●	●	●	●		●	●	●	●
	Hydraulic conductivity	●	●	●			●	●	●	●
	Vert. Porosity Distribution				●	●	●			●

2 MATERIALS AND EXPERIMENTAL PROGRAM

To evaluate the effect of compaction energy on the properties of pervious concrete an experimental campaign was conducted as shown in Figure 1. In the first phase, pervious concrete mixtures were developed using compaction energy as the control variable. Three compaction energies were used in the compaction of pervious concrete mixtures. In this phase the aggregate/cement ratio (g/c) and the number of compaction layers were also evaluated as variables. In the second experimental phase the objective was to evaluate the vertical porosity distribution of the pervious concrete mixtures. The influence of the number of compaction layers on the vertical distribution of porosity was evaluated. The results obtained in this experimental campaign were used in the construction of regression models to establish the relationship between the properties of pervious concrete and the evaluated control parameters.

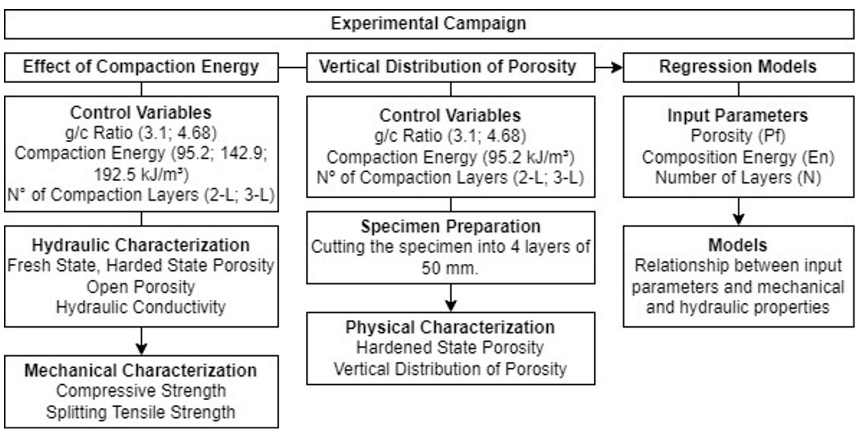

Figure 1. Experimental campaign, control variables and properties tested in pervious concrete mixtures

2.1 Mixture proportion and compaction procedure

Brazilian Portland cement CP II F-32 (equivalent to the cement ASTM Type IL Portland-limestone) was used in the pervious concrete mixtures. A basaltic coarse aggregate classified as Nº 89 according to the ASTM C33 [44] was used, as shown in Figure 2. The physical properties of coarse aggregate are shown in Table 2. To eliminate impurities and dust the aggregates were washed beforehand.

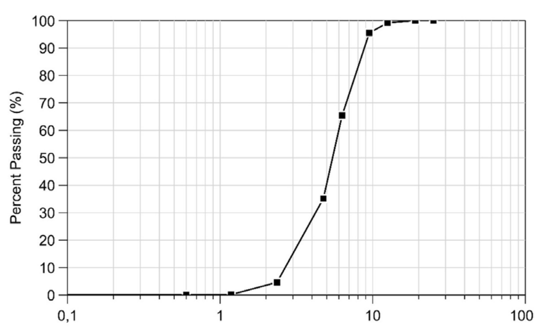

Figure 2. Aggregate grading curve

Table 2. Physical properties of coarse aggregate

Property	Testing Method	Value
Specific gravity	ABNT NBR 16917:2021 [45]	3.05 g/cm^3
Water absorption	ABNT NBR 16917:2021 [45]	0.87%
Dry rodded bulk density	ABNT NBR 16972:2021 [46]	1.67 g/cm^3
Maximum size	ABNT NBR 17054:2022 [47]	12.5 mm
Fineness modulus	ABNT NBR 17054:2022 [47]	5.7

Two pervious concrete mixtures (Mix A and Mix B) were developed to achieve fresh state porosities of 20 and 30% using 2-layer compaction and 10 Standard Proctor hammer blows per layer (equivalent to energy of 95.2 kJ/m^3). To achieve the target porosities, Mix A and B were developed with an aggregate/cement ratio (g/c) of 3.10 and 4.68, respectively. The w/c ratio was determined by the binder drainage test developed by Nguyen et al. [48]. Since sand was not used and the coarse aggregate was washed, a w/c ratio of 0.28 was sufficient for the pervious concrete mixture. This value is within the ACI 522R [1] recommended range of 0.26 to 0.40 and consistent with previous studies [49]–[51].

To evaluate the effect of compaction energy, the g/c ratio was kept constant in each mixture and the number of blows with a Standard Proctor hammer was adjusted. The specimens were prepared using cylindrical steel molds (100 mm x 200 mm) according to the procedure described in ASTM C192M [52]. The number of blows (Table 3) was adjusted to produce three different compaction energies (95.2, 142.9 and 190.6 kJ/m^3). The compaction energies used in this study were selected according to the range usually employed to produce pervious concrete in laboratory, from 50 to 200 kJ/m^3 [2], [18], [53]–[55]. To evaluate the effect of the vertical porosity distribution, the specimens were also produced with two and three compaction layers. In two-layer compaction (2-L), the mold was partially filled with concrete and compacted with half of the blows to produce the first layer. The second layer was immediately filled and compacted with the number of blows remaining. For the three-layer compaction (3-L) the same procedure was replicated, equally distributing the number of blows in the three layers. Since the g/c ratio was kept constant, the material content per cubic meter of concrete varied with the compaction energy. Table 3 shows the mixture proportion of pervious concrete and the actual material consumption.

Table 3. Pervious concrete mixture proportions

Mix	g/c	Nº Layers	Blows/ Layer	Compaction Energy (kJ/m^3)	Mixture proportion (kg/m^3) Aggregate	Cement	Water
A	3.1	2	10	95.2	1504	485	136
			15	142.9	1560	503	141
			20	190.6	1582	510	143
		3	6	95.2	1548	500	140
			10	142.9	1591	513	144
			14	190.6	1620	523	147
B	4.68	2	10	95.2	1536	328	92
			15	142.9	1582	338	95
			20	190.6	1610	344	96
		3	6	95.2	1574	336	94
			10	142.9	1625	347	97
			14	190.6	1652	353	99

2.2 Methodology

Twelve specimens were prepared for each mixture and compaction level. Fresh state density was determined for all specimens produced and the fresh state porosity was calculated by adapting the procedure described in ASTM C1688M [56]. Four specimens were used in the characterization of the hardened state porosity [57] and open porosity [58], which were later on used to determine the hydraulic conductivity. Compressive and tensile strength were also determined according to the ASTM C39 [59] and ASTM C496 [60] procedures, respectively, using four specimens each. To analyze the vertical distribution of the pervious concrete properties, the cylindrical specimens produced with 95.2 kJ/m^3 energy were crosscut into four slices of 50 mm height. Density and porosity were determined for each slice. The hydraulic conductivity was obtained using a falling head permeameter, according to the model suggested by ACI

522R [1]. The test was performed using an initial head of 50 cm and a final head of 10 cm. The test was carried out following ACI 522R [1] recommendations. Three measurements were performed for each sample.

3 RESULTS AND DISCUSSIONS

3.1 Porosity

The effect of the compaction energy and the number of compaction layers on the concrete porosity was evaluated for the mixtures A and B, as presented in Figure 3 and Figure 4. The compaction level influenced the pervious concrete porosity. Figure 3 shows that the reduction of the porosity was proportional to the increase of compaction energy. This effect was most significant between the compaction energies of 95.2 and 142.9 kJ/m^3. The porosity variation was lower between the energies 142.9 and 190.5 kJ/m^3. This was expected since the mixture compaction causes the approximation of coarse aggregate particles. However, compaction is hampered when the aggregate compactness gets closer to its maximum limit. Similar behavior was reported by Bonicelli et al. [43] and Crouch et al. [54].

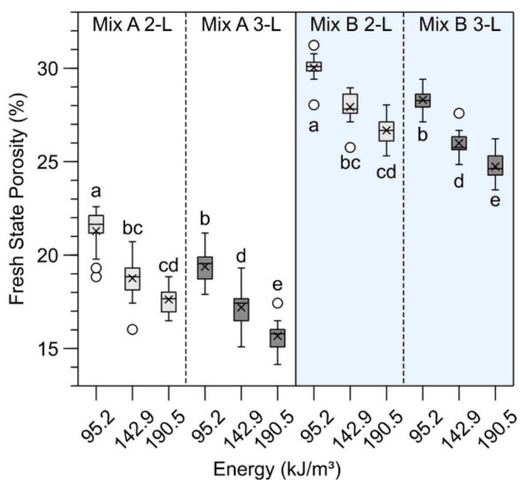

Figure 3. Boxplot distribution of fresh state porosity data of mixtures A and B

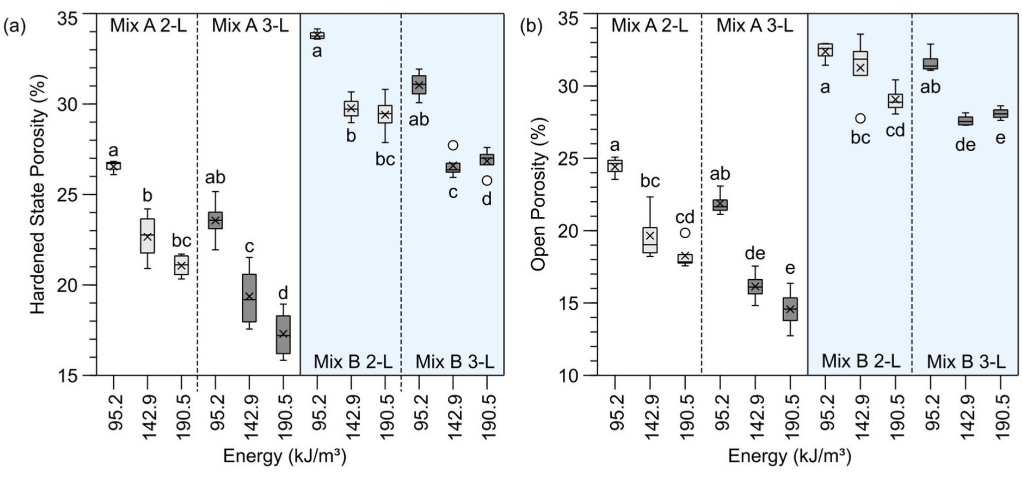

Figure 4. Boxplot distribution of mixtures A and B data: (a) hardened state porosity and (b) open porosity

For constant compaction energy, the number of layers was statistically significant in the pervious concrete porosity. The three-layer compacted mixtures resulted in fresh state porosity 2.0% below that of the two-layer compacted samples. The same effect was observed in the hardened state porosity and open porosity. The effect of the number of compaction layers is directly related to the vertical distribution of the pervious concrete porosity. As already reported by Haselbach and Freeman [37] and Martin et al. [40], the porosity increases in the deeper layers. In this study, the number of compaction layers was seen to alter the vertical porosity distribution (see Figure 5).

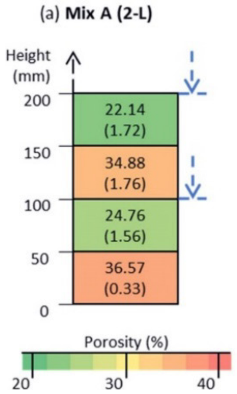

Figure 5. Vertical porosity distribution in mixtures A and B compacted with 95.2 kJ/m^3 energy, distributed in 2 (2-L) and 3 layers (3-L)

Figure 5a and 5c, show that in the 2-L samples there was a porosity gradient in each compaction layer. Porosity was lower in the top slice (150-200 mm) and increased significantly in the 100-150 mm slice. The same pattern was repeated in the bottom compaction layer (0-100 mm). Figure 5b and 5d show a more homogeneous porosity distribution in the 50-200 mm range of the 3-L samples. The bottom slice (0-50 mm) still resulted in the highest porosity. Thus, a reduction in the mean porosity of the three-layer compacted samples may be ascribed to the more uniform vertical porosity distribution.

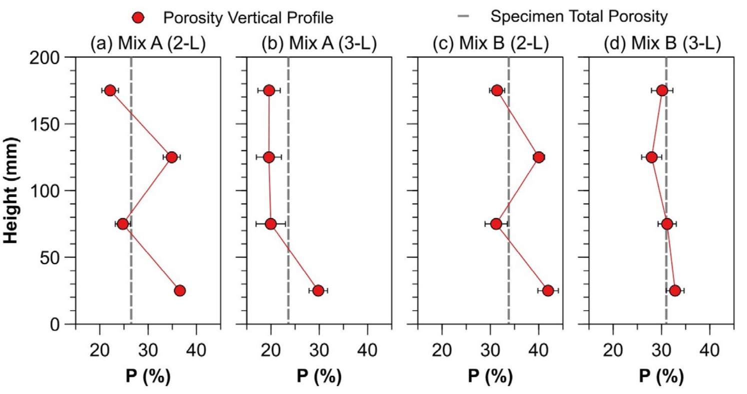

Figure 6. Vertical porosity profile and specimen total porosity of mixtures A and B compacted with 95.2 kJ/m^3 energy, distributed in 2 (2-L) and 3 layers (3-L)

Figure 6 shows the vertical porosity profile of mixtures A and B compared to the total porosity. Specimens compacted with 2 layers (Figure 6a and 6c) showed porosity profiles with greater deviation from total porosity. The maximum porosity in the profiles were approximately 9% higher than total porosity. Figure 6b and 6d show that 3-layer compaction generated a porosity profile with less deviation from total porosity. In Mix A the porosity was constant in the range 50-200 mm. The bottom slice (0-50 mm) still showed a significant deviation of 6% from the total porosity. For Mixture B the vertical profile was more homogeneous, showing no significant deviations from the total porosity.

Both the g/c ratio and the compaction energy are parameters of interest in the pervious concrete mixture design since they directly affect the concrete porosity. The g/c ratio, the compaction energy (E_n), the number of layers (N) and the fresh state porosity (P_f) can be described using the multiple linear regression model (R^2 = 0.96) represented in Equation 1.

$$P_f = 14.81 + 5.67 \cdot g/c - 99.5 \times 10^{-3} \cdot E_n + 217 \times 10^{-6} \cdot E_n^2 - 1.84 \cdot N \quad (1)$$

Figure 7 shows the regression model of fresh state porosity as a function of compaction energy and g/c ratio. Porosity reduced significantly with the reduction in the g/c ratio. This may be explained by the increase in the cement paste volume, which filled up the voids between the aggregate particles. The g/c variation from 4.68 to 3.10 resulted in a reduction of around 9% in fresh state porosity. The increase in compaction energy also resulted in the concrete porosity reduction, caused by the approximation of the aggregate particles. However, the compaction efficiency also reduced with the energy increase since this process was limited by the aggregate compactness. This evidence the existence of saturation energy, from that point onwards, no significant porosity variation occurs.

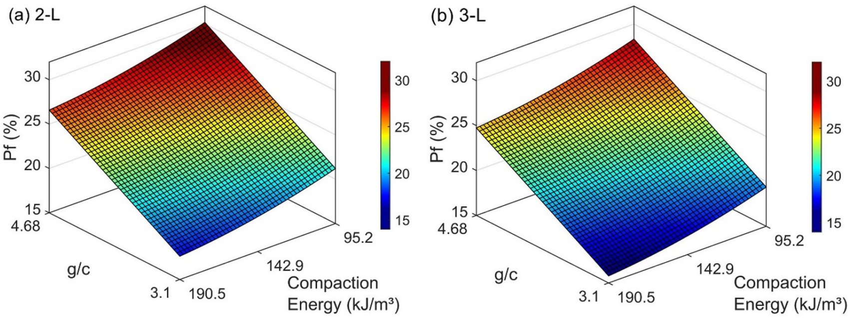

Figure 7. Fresh state porosity regression model for (a) two-layer compacted concrete and (b) three-layer compacted concrete

In the pervious concrete mixture design, porosity is usually adjusted by controlling the cement paste content in the mixture. The model developed in Equation 1 demonstrates that the compaction energy is a variable that may also be considered in the design of pervious concrete mixtures. Figure 7 shows that mixtures with different g/c ratios can result in the same porosity by controlling the compaction energy. In this way, it is possible to design mixtures with a lower cement paste content, increasing the efficiency of pervious concrete mixture design.

3.2 Compressive Strength

Figure 8 shows compressive strength of pervious concrete as a function of compaction energy. The results were submitted to an ANOVA followed by Tukey's test. In the figure, means sharing the same letter do not differ statistically at a 5% significance level. The pervious concrete compressive strength was directly influenced by the compaction energy employed. This might be mainly ascribed to the porosity reduction caused by the mixture compaction (Figure 3) and the increased bond between aggregates [2], [15]. This effect was more significant in the Mix A. Pervious concrete produced with 142.9 kJ/m^3 energy presented around 35% more strength than those produced with 95.2 kJ/m^3 energy. For Mix B the increase in strength was only 15%. Mixtures with higher cement paste content require less compaction energy to reach maximum compactness [61], which explains the higher compaction efficiency in Mix A. However, neither of the mixtures showed significant variation in the compressive strength when the energy was increased to 190.5 kJ/m^3, even though the porosity reduced. In this case, the energy of 190.5 kJ/m^3 may have caused over compaction of the mixture, causing the breakage of the coarse aggregate. Chandrappa and Biligiri [42] reported that the compaction energy produced by the Proctor Hammer can cause the coarse aggregate breakage in pervious concrete, especially in the top surface layers. This effect is affected by the shape of the coarse aggregate, with flat and elongated particles being more susceptible to fracture [62], [63]. This may justify the reduction in compressive strength and porosity for this compaction energy [63]. Thus, the effect of compaction energy has a limit for each pervious concrete mixture. An optimum energy can be defined to maximize the mechanical performance of the mixture without causing excessive compaction.

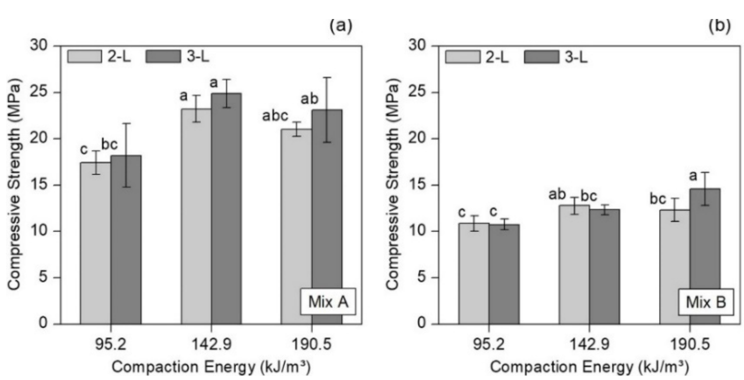

Figure 8. 28d compressive strength of (a) Mix A and (b) Mix B

Although the number of compaction layers influenced the porosity, there was no significant variation in the compressive strength of the two and three-layer compacted concretes. The 3-L samples were expected to result in higher compressive strength since the vertical porosity distribution was more homogeneous. However, the 3-L samples still showed higher porosity in the bottom layer of the specimen (Figure 6), limiting the overall compressive strength.

Compressive strength was affected by the g/c ratio and the compaction energy similarly to the fresh state porosity, confirming its importance in the pervious concrete mixture design. The relation between these variables and the compressive strength (f_c) may be described by the multiple linear regression model ($R^2 = 0.86$) presented in Equation 2.

$$f_c = 14.30 - 5.68 \cdot g/c + 0.33 \cdot E_n - 1.02 \times 10^{-3} \cdot E_n^2 \quad (2)$$

Figure 9 shows that the compressive strength increased with the reduction in the g/c ratio. Such effect results from the increase in the cement paste content in the mixture along with porosity reduction. The increase in compaction energy also caused an increase in the compressive strength. However, a possible saturation was observed regarding the compaction energy applied (evidenced by the non-significant statistical difference between the compaction energies 142.9 kJ/m^3 and 190.5 kJ/m^3 for all samples).

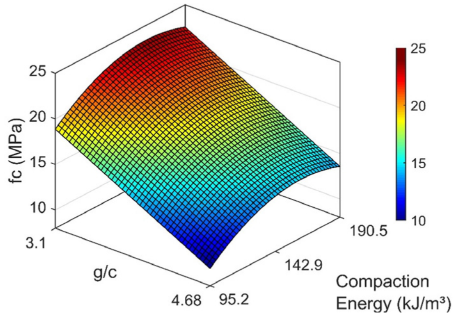

Figure 9. Compressive strength model as a function of g/c ratio and compaction energy

The g/c ratio effect was more significant, becoming a predominant factor in the compressive strength. Although reducing the g/c ratio results in improved compressive strength, it is not the most cost-effective option. With the adjustment of the compaction energy, it was possible to increase the mechanical strength while maintaining the same aggregate/cement ratio.

The model illustrated in Figure 9 demonstrates that optimization of pervious concrete mixtures can be accomplished by controlling both g/c ratio and compaction energy. A target compressive strength can be obtained by using an optimal compaction energy, resulting in mixtures with the most efficient g/c ratio. Although increasing the compaction energy above the optimum level provides a reduction in porosity, the compressive strength is not improved. Therefore, defining the optimum compaction energy is a fundamental step to increase the efficiency of the mixture design.

3.3 Tensile Strength

Figure 10 shows tensile strength of concrete as function of compaction energy. The tensile strength results were submitted to an ANOVA followed by Tukey's test. In the figure, means sharing the same letter do not differ statistically at a 5% significance level. The mean tensile strength ranged from 2.4 to 3.6 MPa in mixture A and from 1.4 to 1.9 MPa in mixture B. In mixture A, the minimum tensile strength occurred with the lowest compaction energy (90.2 kJ/m^3). In the three-layer samples, an increase in the compaction energy up to 142.9 kJ/m^3 resulted in higher strength. However, when compaction energy further increased no significant variation was observed in mechanical performance. Regarding mixture B, the compaction energy did not influence indirect tensile strength. This might indicate that in that mixture the compaction saturation already occurred when the 95.2 kJ/m^3 energy was applied. The number of compaction layers was not significant in the indirect tensile strength.

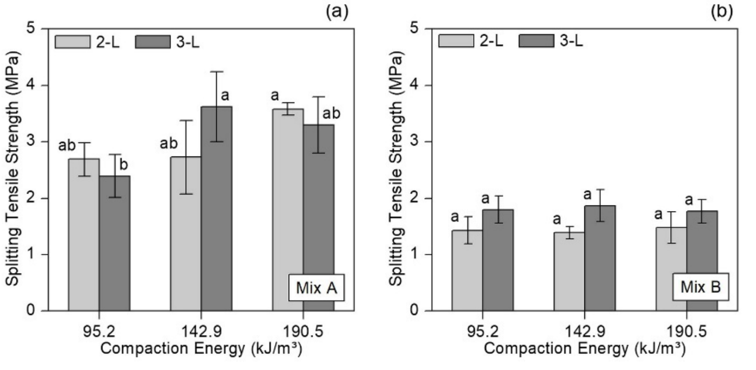

Figure 10. 28d indirect tensile strength of the (a) Mixture A and (b) Mixture B

Both the g/c ratio and the compaction energy affected the pervious concrete tensile strength. However, a distinct behavior was noticed between mixtures A and B, evidencing some interaction between the two variables. The relation between indirect tensile strength (f_t), g/c ratio and the compaction energy ($R^2 = 0.77$) is described in Equation 3.

$$f_t = 1.98 - 0.09 \cdot g/c + (26.81 \times 10^{-3} - 5.65 \times 10^{-3} \cdot g/c) \cdot E_n \quad (3)$$

Figure 11 shows that the indirect tensile strength increased with the g/c relation reduction, regardless of the compaction energy applied, similarly to the compressive strength findings. For the g/c ratio 3.10, the compaction energy increase also promoted an increase in the tensile strength. Regarding the g/c ratio 4.68, however, no influence of the compaction was noticed. This behavior indicates that the cement paste volume affects the mixture compaction. Therefore, each mixture might present distinct saturation energy.

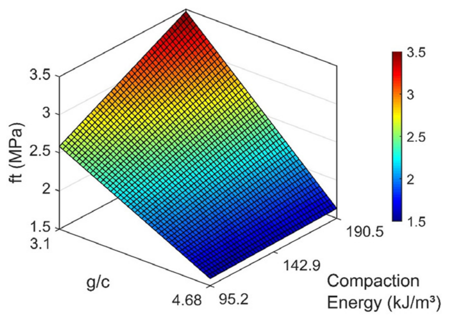

Figure 11. Indirect tensile strength model as a function of g/c ratio and compaction energy

Therefore, the model developed demonstrates that for the improvement of tensile strength both g/c ratio and compaction energy should be evaluated. In mixtures with low cement paste content (e.g., Mix B) the reduction of the g/c ratio will be more efficient in increasing the tensile strength. In mixtures with high cement paste content the compaction energy becomes more influential in the mechanical performance.

3.4 Hydraulic conductivity

Figure 12 shows hydraulic conductivity of pervious concrete as a function of compaction energy. The results were submitted to an Analysis of Variance (ANOVA) followed by Tukey's test. In the figure, means sharing the same letter do not differ statistically at a 5% significance level. As expected, the pervious concrete hydraulic conductivity was inversely proportional to the compaction energy.

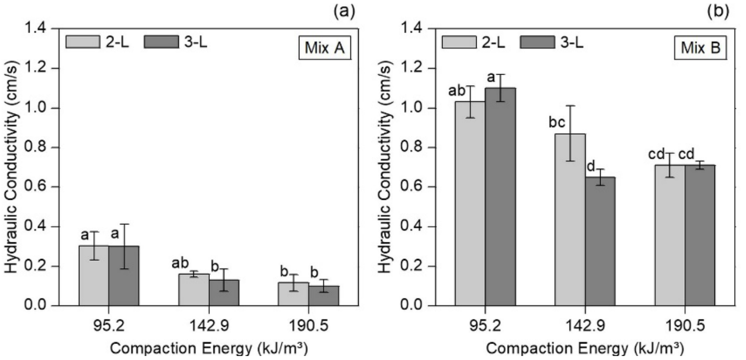

Figure 12. Hydraulic conductivity of the samples produced with (a) Mixture A and (b) Mixture B

In mixture A, the compaction with 190.5 kJ/m^3 energy resulted in a hydraulic conductivity close to the minimum limit recommended for pervious pavements, 0.10 cm/s [64]. An increase in the compaction energy could have compromised the hydraulic performance of the mixture, restricting its application. Compaction, in addition to reducing the pervious concrete total porosity, might originate closed pores, which do not contribute to hydraulic conductivity.

Figure 4b shows a significant reduction in open porosity proportional to the compaction energy, thus evidencing the formation of closed pores. Due to the lower cement paste content, mixture B kept a high hydraulic conductivity, even for the highest compaction level.

The number of compaction layers did not present a significant effect on hydraulic conductivity. Even though the number of compaction layers resulted in different porosities, the hydraulic conductivity did not vary significantly between 2-L and 3-L samples. As presented in Figure 6, the vertical porosity distribution was distinct for the 2-L and 3-L compaction. According to Martin et al. [40], the minimum porosity of pervious concrete has a greater impact on hydraulic conductivity than the global porosity. In all mixtures the top layer corresponded to the minimum porosity of the vertical profile. Thus, even though the specimens compacted with 2 layers showed higher overall porosity, the hydraulic conductivity was limited by the minimum porosity layer.

In addition to g/c ratio and compaction, fresh state porosity was also significant for the pervious concrete hydraulic conductivity (k), according to the linear regression model ($R^2 = 0.95$) shown in Equation 4.

$$k = 0.25 + 0.22 \cdot g/c - 1.6 \times 10^{-3} \cdot E_n - 0.07 \cdot P_f + 2.34 \times 10^{-3} \cdot P_f^2 \tag{4}$$

Figure 13 shows the hydraulic conductivity regression model as a function of fresh state porosity and compaction energy. In both mixtures, the fresh state porosity was observed to affect more significantly the hydraulic conductivity. The compaction energy also influenced the pervious concrete hydraulic conductivity, which was justified by the reduction in the open porosity (Figure 3).

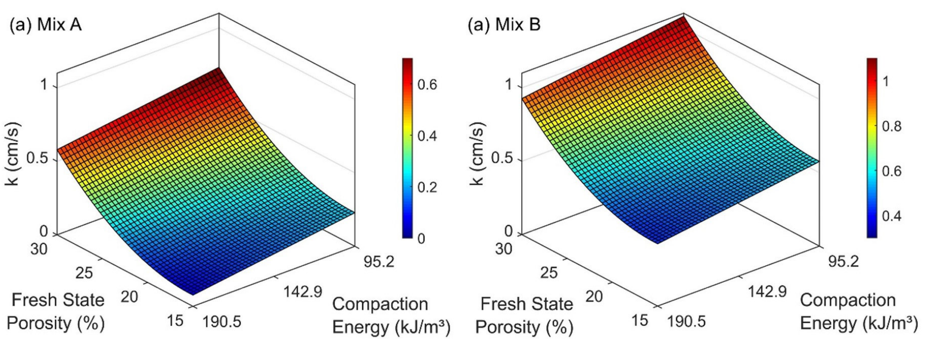

Figure 13. Permeability coefficient regression model for (a) Mixture A and (b) Mixture B

In addition to ensuring good mechanical performance, the pervious concrete mixture design must ensure sufficient hydraulic conductivity. As discussed earlier, increasing the g/c ratio is one of the options to increase the mechanical performance of pervious concrete. However, this is accompanied by a significant reduction in hydraulic conductivity. Compaction energy remains a viable variable in the control of pervious concrete mixtures. While maintaining the same g/c ratio, increasing the compaction energy results in mechanical improvement with less impact on hydraulic conductivity.

3.5 Influence of Compaction Energy in Mixture Design Parameters

According to the results obtained in this study, the compaction energy and the g/c ratio are parameters that allow the control of the pervious concrete physical, mechanical and hydraulic properties. By applying the regression models developed, it was possible to relate the variables involved in the pervious concrete mixture design, as illustrated in Figure 14.

For a constant g/c ratio, the compressive strength depends mainly on the compaction energy. Thus, by using the model described in Equation 2, it is possible to analyze the pervious concrete mechanical behavior in a compaction energy range of interest. Each pervious concrete mixture presents an optimal compaction energy, from which the mechanical improvement is only possible with the reduction in the g/c ratio (e.g., from 4.68 to 3.10).

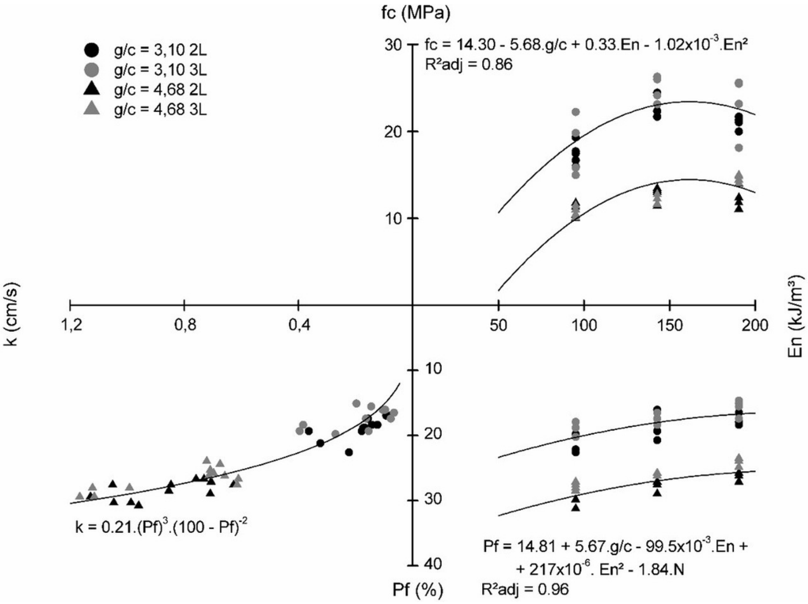

Figure 14. Relation between the pervious concrete compaction energy, porosity, compressive strength and hydraulic conductivity

The compaction energy also influences the material porosity and, consequently, the hydraulic conductivity. Figure 14 shows that for a certain mixture, the porosity can also be estimated by the compaction energy (Equation 1). Porosity, in turn, is the parameter that most affects the pervious concrete hydraulic conductivity [65]. Although Equation 4 may be used to describe the material hydraulic behavior, the relation between porosity and hydraulic conductivity may be represented by a simpler regression model, based on the Kozeny-Carman equation [34], [66], presented in Equation 5.

$$k = 0.21 \frac{{P_f}^3}{\left(100 - P_f\right)^2} \quad (5)$$

As shown in Figure 14, the hydraulic conductivity of the mixtures may be represented by a single model, involving only the pervious concrete porosity. Therefore, from the relations developed in this study, the use of compaction energy as a variable for the design of pervious concrete mixtures was seen to be possible. The compaction energy may be used to control directly the mechanical and hydraulic properties of pervious concrete, while maintaining the same aggregate/cement ratio. Thus, by defining the optimal compaction energy it is possible to select the most efficient mixture to meet the pervious concrete design criteria.

4 CONCLUSIONS

Pervious concrete compaction is a phase in the production of this material that affects its mechanical and hydraulic performance. An increase in compaction energy implies higher compressive strength. However, its improvement is limited to intermediary energy. Therefore, not only does the cement paste volume interfere with its mechanical properties, but also with its compaction degree, and this is one of the ways to control the pervious concrete characteristics, even if the mixture proportion is not altered. Tensile strength was also significantly affected by aggregate/cement ratio and compaction energy. However, the effect of compaction was more effective in the mixture with higher cement paste content. The hydraulic conductivity presented an inverse behavior with the compaction energy increase. Hydraulic conductivity reduction occurred due to the total porosity reduction and pore isolation, that is, an increase in closed porosity. The experimental data obtained in this study led to the following conclusions:

- Among the compaction methods investigated, samples produced with more compaction layers resulted in a more homogeneous vertical porosity distribution profile. Consequently, global porosity reduction occurs. However, the mechanical strength was still limited by the most porous layer.
- The number of compaction layers does not have a significant effect on compressive strength, tensile strength or hydraulic conductivity.
- Even if the aggregate/cement ratio is kept fixed, the pervious concrete porosity may be reduced by the compaction energy increase.

- Compaction provides a way to improve the mechanical properties of pervious concrete without changing the mix proportion. However, compaction efficiency reduces with increasing compaction energy. The closer the aggregate gets to its maximum compactness, the more difficult the compaction process becomes. Therefore, there is a saturation energy limit and from that point onwards, an increase in the compaction level does not improve the properties of pervious concrete. Excessive compaction can further reduce mechanical performance because of coarse aggregate breakage. The compaction saturation energy is also influenced by the amount of cement paste used.
- Both the aggregate/cement ratio and the compaction energy may be used to control the pervious concrete properties. Although the aggregate/cement ratio is more influential, its adjustment impacts the hydraulic conductivity and the cement content in the mixture. However, adjusting the compaction energy may result in mechanical improvement with less impact on hydraulic conductivity.

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