Development of apparatus for permeability testing on pervious asphalt

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Abstract

This article aims to evaluate the performance of a prototype variable load permeameter developed with hydrosanitary pieces in order to measure the permeability coefficient of pervious asphalt, which is a mixture composed of mineral aggregates and pure or modified asphalt binders, having an air void content close to 20%. This material must have permeability and porosity characteristics that influence the hydrological behavior of the surface. Faced with the need to quantify the degree of permeability of specimens used in studies of pervious asphalt and the absence of a regulatory standard for this test, a permeameter was created from hydrosanitary pieces. It was observed that the operation was easy, the system had an excellent degree of tightness and that the results were coherent and aligned with literature. To enable the development of the mentioned permeameter, a laboratory study was carried out on a mixture of pervious asphalt with a binder modified by polymers and an air void content of 18.3%, in which the influence of the addition of four different levels of cellulose fiber was evaluated (0%, 0.25%, 0.50% and 0.75%). It was observed at the end of the study that the material with the addition of 0.50% fiber presented the best results in terms of permeability. It should be noted that the developed permeameter proved to be an efficient, simple and precise testing tool, consisting of the creation of a set capable of laterally surrounding a traditional test specimen and allowing water to pass only in a vertical direction.

Keywords: permeability test; pervious asphalt; testing apparatus.

1. Introduction

The concept of pervious pavement can be understood as the set of the pervious surface course and the structure beneath it. This system works by passing water through the surface course's pores and infiltrating the lower layers (Brown e Borst, 2014).

Pervious asphalt was the porous composite used in this study and was conceptualized by Wei and Jing-jing (2012) and Zhao *et al*. (2020) as a mixture with open grain size, high permeability, capable of promoting noise reduction and with the ability to offer good resistance to skidding, with an air void content greater than 18%.

Fwa *et al*. (2015) highlights that the high air void content allows the elimination of water layers on the surface course as the precipitated water is drained through the communicating voids.

Permeability or drainability of a porous asphalt is understood by Momm (2002) as the property of draining water from the surface into the openings between the roughness of the concrete.

Jiang *et al*. (2015) emphasize that factors like the air void content and its microscopic characteristics, such as their number, size and shape are important. Precisely because of the difficulty in analyzing such factors, a significant majority of researchers use only the void content of the mixture as the main parameter for pervious asphalt.

According to Anupam *et al*. (2016), the number of communicating or effective air voids can represent 90% of the total voids in the mixture, and the higher this percentage, the better the hydraulic behavior of the material.

Therefore, the permeability coefficient "k" represents one of the most significant characteristics when dealing with pervious asphalt concrete (Tennis *et al*., 2004; Acqua *et al*., 2012; Sañudo-Fontaneda *et al*., 2013) and its determination is fundamental for the understanding and functionality of this type of mixture.

In order to obtain this parameter, Carvalho (2015) and Garcia *et al*. (2019) both used in their studies a permeameter of variable load called LCS. This equipment is specified in the Spanish standard NLT327/000. As another example, Schneider (2016), a Brazilian author, made a variable load permeameter inspired on previous works and within the specifications of the european standard CEN PR-12697-19-A.

With that being said, it is evident that different studies resort to different permeameter settings. In the Brazilian research, the landscape still lacks a standard to guide both the methodology and the apparatus required to test pervious asphalt in regard to its permeability.

As it is, in this article, taking as guide the American standard ACI 522R – 06 (Pervious Concrete), a low cost permeameter was developed as a prototype that fits the boundary conditions of being able to test specimens made with the Marshall compactation methodology, assuring a water flow in the longitudinal direction and also enabling to state that, when the time starts on the clock, all the effective voids were already filled with water.

2. Materials and methods

This topic will present the characteristics of the materials used in the composition of the asphalt mixture (aggregates, binder and cellulose fibers) that served as the basis of laboratory studies to create the permeameter. The equipment development stages will also be shown, as well as the methodology for determining the permeability coefficient using the proposed equipment.

2.1 Materials used on the research

To evaluate the performance and applicability of the proposed permeameter, a laboratory study was carried out on a mixture of porous asphalt with a polymer-modified binder, in which the influence of the addition of four different cellulose fiber contents (0%, 0.25%, 0.50% and 0.75%) were evaluated.

The stone aggregates used in the composition of the pervious asphalt in this study were stone dust and fine gravel, of granite-gneissic origin, originating from the crushing process of a quarry in the city of Matias Barbosa, Minas Gerais.

The DNER-ES 386 (1999) standard, referring to the Porous Friction Course highlights particle size ranges for the aggregates used in this type of asphalt mix. This was chosen here to work with the limits of Range I, following recurrent particle size distributions cited in literature, such as in the research of Wei and Jing-jing (2012), Jiang *et al*., (2015) and Huang *et al*. (2020). For this, a proportion of 20% stone dust and 80% fine gravel was used, originating from the crushing process. The particle size distribution curve of the aggregates can be seen in Figure 1.

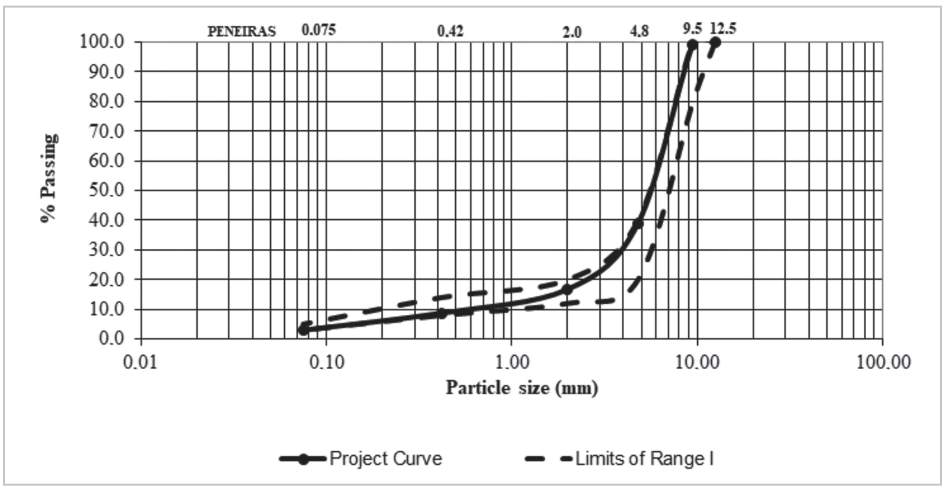

Figure 1 – Particle size distribution curve of the aggregate mixture used.

The use of polymer-modified binders reduces the potential for disintegration of surface materials, implies a more porous structure and protects the asphalt concrete from oxidation (Virgiliis, 2009). In this study, the polymer-modified binder CAPFLEX 60/85 E was used, whose characteristics are explained in Table 1.

Table 1 – Characteristics of the asphaltic binder.

TEST	STANDARD	UNIT	RESULT
Softening point	NBR 6560	°C	83.3
Penetration (100g, 25°C, 5s)	NBR 6576	0.1 mm	49
Flash point	NBR 11341	°C	>235
Elastic recuperation, 25°C, 200 mm	NBR 15086	%	92.0
Relative density	ASTM D70	NA	1.015
Brookfield Viscosity, SP21, 135°C	NBR 15184	Cp	1192
Brookfield Viscosity, SP21, 150°C			740
Brookfield Viscosity, SP21, 177°C			311

Source: Stratura Asfaltos (2021).

Cellulose fibers (Figure 2) with an approximate length of 45 µm and a thickness of 7.5 µm were used in percentages of 0%, 0.25%, 0.50% and 0.75% in relation to the weight of the binder mixture with aggregates.

For the DNER-ES 386 (1999) standard, the air void content in a porous friction course must be 18% to 25%; the French standard AFNOR NF P 98-134 (2000) determines the use of levels close to 20%. Therefore, the design binder content obtained by the Marshall dosing methodology was 4%, corresponding to a mixture with 18.3% voids.

The process of mixing the components began by adding the binder to the aggregates retained in the 2 mm sieve, then the aggregates passing through this sieve and finally the cellulose fibers. This order proved to be efficient in relation to the homogenization of asphalt concrete.

Compaction of the mixture followed the Marshall methodology with the application of 50 blows on each of the two faces of the specimen, in accordance with the prescription of DNER-043/95 (1995) for porous layers. After this process, the specimen (CP) was subjected to permeability tests (Figure 3).

Figure 2 – Cellulose fibers.

Figure 3 – Specimen.

2.2 The developed permeameter

Due to the absence of a standard regulating the permeability test for this type of material and based on an American standard of the American Concrete Institute, ACI-522R/06 (2006), for permeable Portland cement concrete, a variable load permeameter was created with the premise of eliminating air bubbles in the voids of the test piece, so as not to alter the true readings.

The purpose of the test is to measure the time elapsed between the passage of the water layer through the initial and final levels, with the test piece positioned in such a way so as to offer resistance to the flow of the liquid.

As regards to the material, the ideal is a transparente one, such as acrylic. However, the operation of connecting the specimen (CP) repeatedly, would compromise the integrity of the cylinder.

Furthermore, when carrying out market research, it was found difficult to acquire a hollow acrylic cylinder with a nominal dimension of 100 mm in diameter.

Therefore, it was decided to use PVC material, purchasing parts commonly used in hydraulic services, in order to be able to assemble a set whose configuration can be seen in Figure 4a.

To provide visual acuity when measuring the water depth, two cuts were made in the vertical cylinder with a nominal diameter of 100 mm. In order to ensure tightness during the test, the section close to each opening in the pipe was lined with the cylindrical part of a 2-liter PET bottle and then the junction was sealed with insulating tape (Figure 4b).

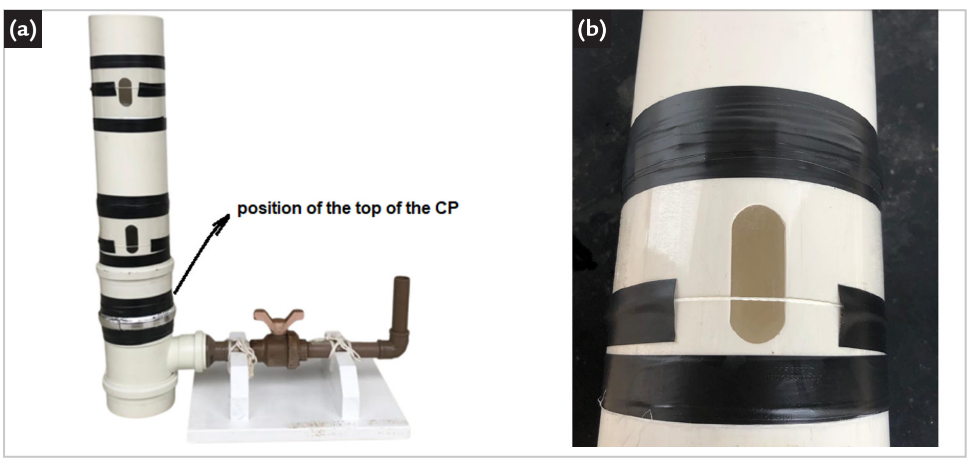

Figure 4 - (a) Equipment for permeability test; (b) Detail of the pipe opening.

The same water level values proposed by the American standard ACI- 522R/06 (2006) were used. The upper level is 290 mm above the top of the CP, while the lower one is 70 mm away, 220 mm apart (see Figure 5). The demarcation was made using string and insulating tape.

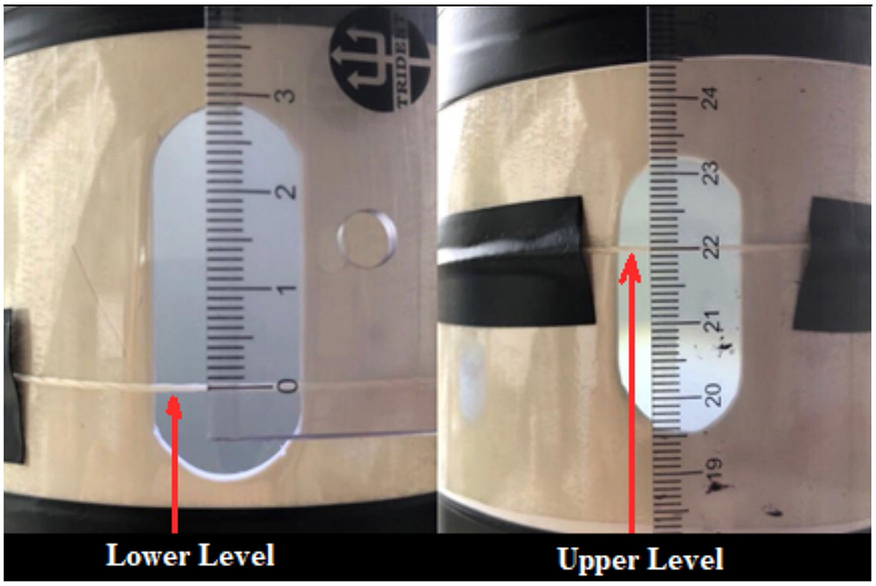

Figure 5 – Demarcation of upper and lower levels.

After marking the PVC pipe (part 1), it is ready to be connected to part 2 (Figure 6).

Figure 6 – Parts of the permeability test device.

As the exploded view of the permeameter is presented, it is important to identify the parts of the device, namely:

- 100 mm diameter PVC pipe (1);
- 100 mm PVC sleeve with rubber ring (2);
- 100 mm PVC T reduced to 50 mm and 100 mm PVC Cap (at the base of the T) (3);
- wooden board to support element 5, with the possibility of tying it (4);
- 50 mm reduction bushing for 25 mm, 25 mm PVC pipe, sphere valve and 90 degree elbow connected to another 25 mm PVC pipe (5).

2.3 The permeability determination

Having explained the circumstances that led to the development of the equipment for measuring the permeability coefficient, the methodology applied during the test itself is presented.

Initially, the specimen must be fitted into the 100 mm sleeve so that the top of the CP coincides with the PVC strip (Figure 7a); It was observed that the fit is extremely tight, a fact that limits the interference of water passing through the CP side on the results.

It was observed that the fit between the CP and both sleeve and T are extremely tight, requirering a lateral sealing with a water-based lubricating paste to make the fit even possible. The closeness between the CP and the internal surface of the pipe, and also the presence of the lubricant between them are characteristics that make it possible to state that the passage of water on the sides of the CP isn't considerable in the results.

To seal the junction between the PVC sleeve and the PVC T, used were three materials. First a plastic film, then an insulating blanket and finally an insulating tape as shown in Figure 8.

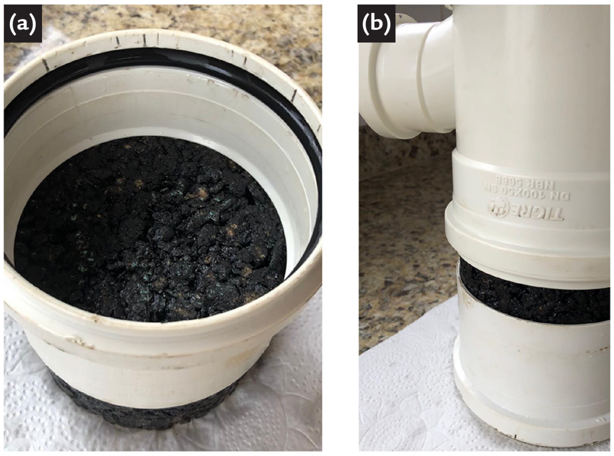

Figure 7 – (a)Fitting of the CP in the sleeve; (b) – Fitting of the CP in the T.

Figure 8 – Sealing procedure in the junction.

With the CP positioned and the sphere valve open, water is poured into the free end of the 25 mm tube (Figure 9a), so that it passes from bottom to top through the voids in the CP and stabilizes at a level of 1 cm above to the top of the specimen (Figure 9b). This pre-wetting is important, since it prevents air bubbles and water absorption by the material from interfering with the accuracy of the test.

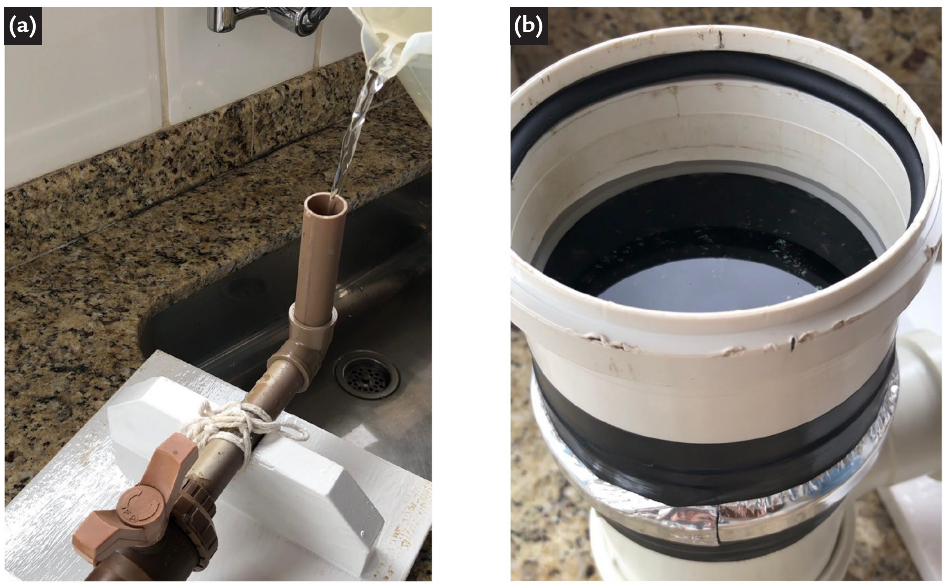

Figure 9 – (a) Water being poured into the end of the 25 mm pipe; (b) Film of water on the specimen.

Then, the 100 mm pipe is attached to the sleeve sealed with a rubber ring, the sphere valve is closed and the water is poured through the free end of the 100 mm pipe to create a water column whose level exceeds the upper mark. To standardize the initial level of the test, the blue thread was used to delimit the liquid layer (Figure 10a).

Next, the sphere valve is opened and the downward movement of the water level is observed, activating the stopwatch when the liquid reaches the upper level mark and ending the time measurement when the slide coincides with the lower level. In Figure 10b it is possible to observe the approach of the water in relation to the lower string marking.

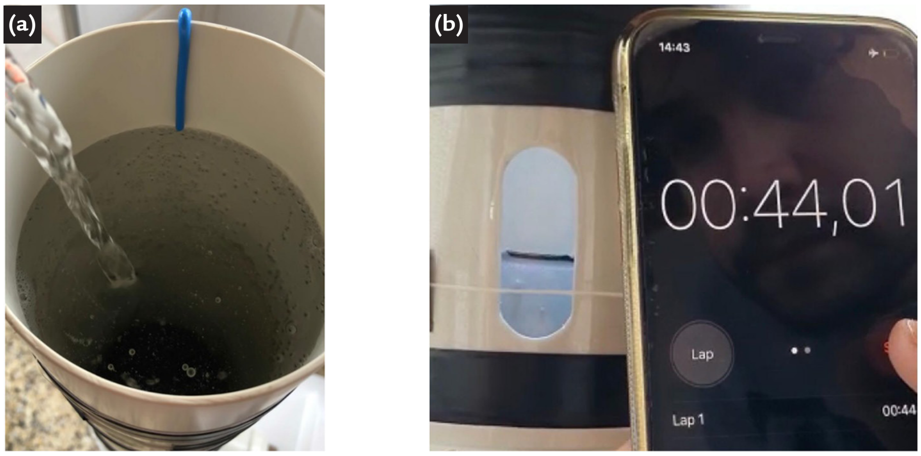

Figure 10 – (a) Detail of filling the 100 mm tube; (b) Water level in relation to the lower mark.

From the measured time, Darcy's Law is used to calculate the permeability coefficient k. For each specimen. Three measurements were taken, with the final result being the average of the three.

$$k = \frac{2.3 \times A_1 \times L \times \log(h_i/h_f)}{A_2 \times t} \qquad (1)$$

Where: • k is the coefficient of permeability, on m/s;

• A_1 is the transversal area of the pipe, on m²;

• A_2 is the transversal area of the specimen, on m²;

• L is the average of four measurements of the specimen's thickness, on m;

• t is the time interval between the measures, on s;

• h_i equals the initial height of 29 cm;

• h_f equals the final height of 7 cm.

The developed apparatus' efficiency will be verified with the aid of statistical analysis of the coefficient k obtained for 4 different materials with 9 samples each. The methodology used to carry out the analysis was the ANOVA.

3. Results and discussions

To demonstrate the good performance of the developed Permeameter, analyses of the results of the Permeability Coefficients (k) determined from the pervious asphalts from the developed laboratory study will be shown.

Three time readings were taken for each specimen and each of the four groups (based on the celulose fibers percentage) has three samples. Table 2 shows the 36 permeability coefficient values obtained as well as the statistical values of interest and Figure 11 shows the average values.

Table 2 – Results of the permeability test.

Cellulose fibers	0.00%	0.25%	0.50%	0.75%
Permeability Coefficient k (10^{-3} m/s)	1.66	2.13	2.25	2.01
	1.66	2.12	2.20	2.05
	1.63	2.13	2.22	2.01
	1.64	2.12	2.32	1.90
	1.67	2.14	2.28	1.89
	1.65	2.15	2.26	1.89
	1.69	2.17	2.25	1.80
	1.70	2.19	2.27	1.78
	1.72	2.19	2.25	1.77
Average (10^{-3} m/s)	1.67	2.15	2.26	1.90
Standard deviation	0.03	0.03	0.03	0.11
Coefficient of variation	0.02	0.01	0.02	0.06

The Figure 11 shows the average values as well as the standard deviations (represented with a vertical line). As can be seen, the addition of cellulose fibers at all levels resulted in k values higher than those obtained for the 0% mixture. For levels up to 0.50%, the higher the percentage of fibers used, the more pervious the asphalt. For the addition of 0.75%, the permeability coefficient suffered a reduction.

In order to analyze whether the results obtained are significantly different from each other, demonstrating unique behaviors in groups with different fiber contents, the GraphPad Prism software and the "ANOVA" variance assessment process were used.

With nine values per group, the number N was sufficient to perform the normality test, which verified that the four groups present values with characteristics of a Gaussian distribution (the graphs of the results have simetry and bell shapes). This statement means that the equipment developed, for each of the 4 types of pervious asphalt, made it possible to have the same probability to obtain values, both above or below the average. As such, it was possible to validate the behavior of the apparatus.

The ANOVA repeated measures test and the Tukey test criterion made it possible to state that, for all comparisons between the four types of pervious asphalt, the P values were lower than 0.05. Therefore, it can be concluded that, statistically, no group is similar to another, and the values of the permeability coefficient are significantly different from each other.

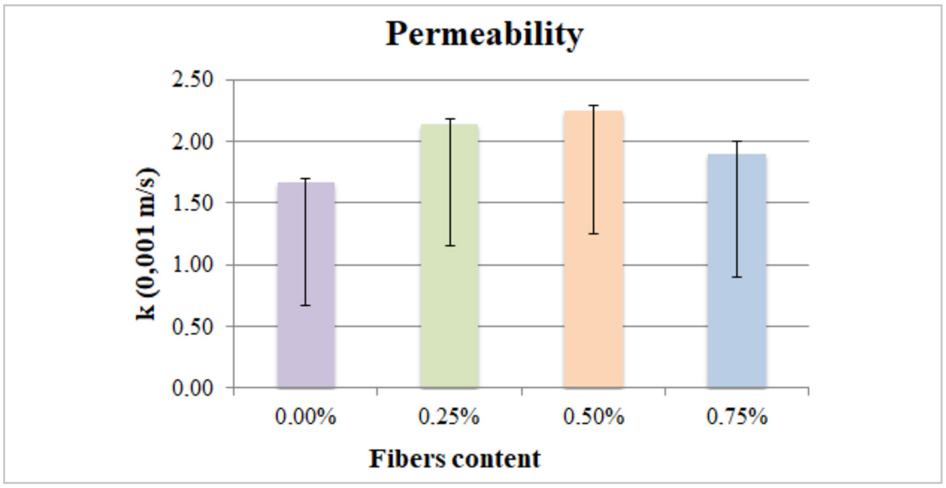

Figure 11 – Permeability Coefficient for pervious asphalts with different fiber contents.

Table 3 illustrates the comparison between values obtained in other studies and this one.

Table 3 – Comparison of permeability between studies.

Author	Asphaltic binder	Cellulose fibers	k (10^{-3} m/s)
Homem (2002)	With polymer	0.00%	1.2
Luo *et al*. (2015)	With polymer	0.00%	1.3
Schneider (2016)	With polymer	0.00%	1.4
Hsu *et al*.(2011)	Conventional	0.00%	1.6
Chen *et al*. (2012)	With polymer	0.30%	1.9
Ahmad *et al*.(2018)	Conventional	0.00%	2.0
Chen *et al*. (2016)	With polymer	0.30%	2.2
Lin *et al*. (2012)	Conventional	0.00%	2.3
Chen *et al*. (2016)	With polymer	0.00%	2.4
Present study	With polymer	0.00%	1.7
Present study	With polymer	0.25%	2.2
Present study	With polymer	0.50%	2.3
Present study	With polymer	0.75%	1.9
Limit according with NBR 16416 (2015)			1.0

The asphalt concrete with 0.25% of fibers in this study presented the same k value as the material from Chen *et al.* (2016) with the addition of 0.30% of fibers (although this has a higher air void content than the first – 20% and 18.3%, respectively).

A particularity observed is that, in Chen *et al.* (2016), the addition of 0.30% of fibers resulted in a 21% reduction in the k value, while the addition of 0.25% of fibers in the present work increased permeability by 45%.

The permeability coefficient for concrete with 0% fibers is higher than that obtained for the composite with conventional binder and without fibers produced by Hsu *et al.* (2011), even though this one had a higher rate of voids (20.3%).

The four coefficients presented values higher than the minimum limit of 1×10^{-3} m/s recommended by NBR 16416 (2015), a Brazilian standard referring to pervious asphalts.

5. Conclusions

After a series of experiments and tests, the equipment was finally created with hydrosanitary parts, constituting a permeameter with a variable load. As observed, the tightness fit between CP specimen and PVC pieces was such that the use of a lubricant was needed, assuring the lateral waterproofing of the specimen. To eliminate leakage, sealing with plastic film, an insulating blanket and insulating tape was proven to be totally effective, since no water was observed on the external surface of the PVC components throughout the entire set of tests.

The good performance presented by the permeameter encouraged the authors to apply to the INPI for a patent on the proposed process for carrying out the described permeability test, as well as the equipment developed. The impact of this study on the field is that it developed a low cost permeameter that provides reliable results, stimulating the study and application of pervious asphalt in Brazil – a material that can be an ally for modern engineering regarding sustainability.

The statistical ANOVA methodology showed that the equipment made it possible to obtain Gaussian distributions for the 4 different kinds of pervious asphalt, validating its efficiency to obtain permeability values that, statistically, could both be above or below the average value for each material tested.

Regarding the permeability coefficient results, the addition of fibers in all three percentages resulted in concretes with k values greater than that obtained without addition (1.7 x 10^{-3} m/s).

The highest k value was 2.3 x 10^{-3} m/s, obtained for the group with 0.50% fibers. Up to this content, the increase in the percentage of fibers corresponds to greater permeability, while for the addition of 0.75%, the value of k decreases to 1.9 x 10^{-3} m/s. Statistical analysis indicated that the four k values are significantly different from each other.

The four materials studied presented values higher than the minimum value of 1×10^{-3} m/s prescribed by NBR 16416 (2015).

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Authors' contributions

Gustavo Araujo Carvalho (Corresponding author): *conceptualization (equal), data curation (equal), formal analysis (equal), investigation (equal), methodology (equal), project administration (equal), resources (equal), software (equal), validation (equal), writing - original draft (equal), writing - review & editing (equal);* **Geraldo Luciano de Oliveira Marques:** *conceptualization (equal), data curation (equal), formal analysis (equal), investigation (equal), methodology (equal), project administration (equal): resources (equal), supervision (equal), writing - original draft (equal), writing - review & editing (equal);* **Thais Mayra Oliveira:** *project administration (equal), supervision (equal), validation (equal), writing - review & editing (equal).*

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Conflict of interests

The authors declare that there is no conflict of interest.

Data availability

Datasets related to this article will be available upon request to the corresponding author.

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