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Use of permeable pavement as a compensatory alternative for urban drainage in Recife-PE

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ABSTRACT
The accelerated process of urbanization in recent decades changes the global population organization and brings modifications to cities, directly affecting the environment. The emergence of alternative solutions, such as permeable pavements, incorporate sustainable concepts and reshape the drainage system to adapt to faster and more critical flood hydrographs, aiming to reduce the impacts of urbanization. This study aimed to analyze the feasibility of using a permeable pavement, performed at the Polytechnic School of the University of Pernambuco (POLI-UPE), as a compensatory alternative in urban drainage, assessing the system and its hydraulic behavior. The methodology followed the stages of subgrade characterization; characterization and compliance analysis of the materials of the pavement layers; and evaluation of the hydraulic performance of the permeable pavement, conducting permeability tests, hydraulic simulations of precipitation, and evaluation of the largest rainfall event, in the analyzed period from March to May 2023. The results indicated a subgrade soil of good quality and base layer material in normative compliance. On the other hand, the material used in the laying and the compressive strength of the coating blocks were non-compliant, but without negative influence on usage for the period. The hydraulic performance of the pavement was analyzed, presenting a high permeability coefficient recently built (3.26×10^{-3} m/s) and good behavior in the simulations of intense rainfall and in the natural rainy event. The permeable pavement allowed infiltration and, consequently, reduction of the total runoff volumes, characterizing itself as a potential mitigation of urban flooding

KEYWORDS: Compensatory techniques. Infiltration. Stormwater management.

1 INTRODUCTION

The world, in recent decades, has observed a marked urban growth and, according to the report of the United Nations (UN), in 2018, the urban population already represented 55.3% of the world population (4.220 billion in urban area and 7.633 billion in total) (UN, 2019). According to the last census conducted by the Brazilian Institute of Geography and Statistics (IBGE), in 2010, urban population rates were even higher than the global scenario, representing 84.4% of the Brazilian population (IBGE, 2010). Considering the global and national projections, these values point to even higher indexes for the year 2023.

Regarding urban drainage, the classic solutions adopted for management are limited, as they are based on sanitary and hygienist concepts, aiming only to drain water. In contrast, alternative solutions incorporate sustainable concepts and aim for a balance between water retention and drainage (SCHREIBER, 2022). Some of these solutions seek to reclaim the characteristics existing during pre-urbanization in basins and are called compensatory measures, BMP (Best Management Practices), or LID (Low Impact Development). For this, they use more comprehensive mechanisms, such as Sustainable Drainage Systems (SUDS), Blue-Green Infrastructure (BGI), and Water Sensitive Urban Design (WSUD) (TANG *et al*., 2018).

The compensatory infiltration devices aim to facilitate water retention and, consequently, the reduction of direct surface runoff, in addition to runoff volumes through water infiltration in the soil, reducing the intensity of flooding (FERREIRA; BARBASSA; MORUZZI, 2018). Among the devices are rain gardens, infiltration trenches, and permeable pavements; all promote source control of stormwater where the precipitation occurred, aiming to reduce the imbalance in the natural cycle of infiltration, percolation, and water runoff caused by urbanization and high rates of impermeabilization (BEZERRA *et al*., 2022).

Permeable pavements can be defined as structures that have voids in their layer composition, which allow the passage of air and water (DEBNATH; SARKAR, 2020). Their coating layer should be constructed with the intention of allowing the quick passage, through

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infiltration, of water, which will be stored for a certain period in the base layer until it percolates to the subgrade soil (SILVA, 2019). Marchioni (2018) highlights that the level of compaction of the layers is reduced, allowing the accumulation of water in the existing voids and also that the surface of the pavement, direct recipient of the mechanical loads related to traffic, enable rapid infiltration of water. The permeable pavement has a surface, like porous asphalt, permeable concrete, or permeable pavement, and multiple permeable layers to store rainwater until it infiltrates into the underground soil or is collected by a drain (WEISS *et al*., 2019). Thus, this study aimed to analyze the feasibility of using permeable pavement as a compensatory alternative in urban drainage, assessing the system and its hydraulic behavior. In an effort to address one of the gaps highlighted by Weiss et al. (2019), by providing data on the permeability of the pavement and its newly constructed coating as a comparative parameter of durability over time, incorporating the analyses of the pavement, both of materials and hydraulic, on a real scale, of a project carried out at the Polytechnic School of the University of Pernambuco (POLI-UPE).

Permeable pavement can also be studied alongside other techniques. A recent study, conducted in Wuhan, China, showed that the combination of low-impact techniques, such as bioretention cells, permeable pavements, and green roofs, achieved good runoff control performance for a densely populated site (Shang et al., 2022). Therefore, the present work analyzed the compensatory drainage alternative from the use of permeable pavements, as a viable solution part of Sustainable Drainage Systems (SUDS), and its possible impacts on reducing the damage caused by urbanization and the consequent soil sealing, aiming to increase the capacity for infiltration and retention of rainwater and reduce direct surface runoff, mitigating urban flooding.

2 METHODOLOGY

This section presents all the steps developed during the analyses of the permeable pavement executed at the Polytechnic School – POLI – of the University of Pernambuco – UPE, in Recife, Brazil. These include: the characterization of the soil of the experimental area; the characterization of the materials that make up the layers of the permeable pavement; and the analyses of hydraulic performance, through evaluations of permeability, field rain hydraulic simulations, and precipitation data, occurred during the observation period from March to May 2023.

2.1 Study area

The permeable pavement was executed at the Polytechnic School of the University of Pernambuco (POLI-UPE), located in the neighborhood of Madalena, in the city of Recife, capital of the State of Pernambuco, represented by geographic coordinates: latitude 8 9 03'34"S and longitude 34 54'12"W. According to Cabral and Alencar (2005), the city is situated on a large low-lying plain, with elevations ranging from 1 m to 10 m above sea level, surrounded by a chain of low hills with elevations up to 150 m.

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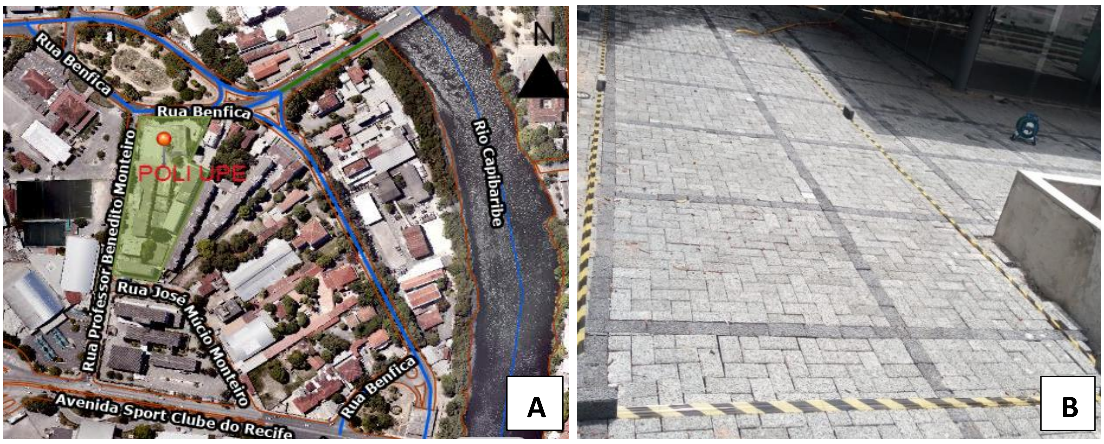
The city is located in the physiographic zone of the coastal-Atlantic forest, with a hot and humid climate and abundant rainfall, compared to the Northeast region of Brazil, presenting its rainiest period between the months of March and August. Regarding the hydrographic aspect, it is bathed by the Capibaribe, Beberibe, and Tejipió rivers, all with various tributaries and interconnection channels, forming a shared estuarine region (CABRAL; ALENCAR, 2005).

The choice of this experimental field occurred through the adaptation of an ongoing reform in the area, aiming at the redesign of part of the external floor of POLI, designated for pedestrian use, where previously, conventional paving would have been used, changing it to permeable paving. This study also sought to scientifically justify this choice and ratify it as a good alternative compared to the original project of conventional paving.

Figure 1 (A) indicates the location of POLI, delimited by urban roads: Rua Prof. Benedito Monteiro and Rua Benfica, and (B) shows the permeable pavement executed, with the demarcation of the rectangular area of 27 m² (2.7 m x 10 m) studied. It is noteworthy that the project was responsible for the reform of a total area of 470 m² of permeable paving, but this study was carried out in this module of 27 m².

Figure 1 - Area of POLI-UPE (A) and permeable pavement executed (B).



Source: Authors. (A) - Elaborated from ESIG - Geographic information of Recife (2022).

2.2 Description of the experimental module

The section of pavement implemented in the renovation was pre-dimensioned and predetermined due to preexisting studies on experimental permeable pavements conducted at POLI by Almeida (2017) and Silva (2022). The experimental module that composes the pavement has its section presented in Figure 2, per meter of pavement width. In ascending order of depth, the surfacing consists of: rectangular permeable interlocking concrete blocks, 8 cm thick; a 5 cm thick layer of stone dust; a layer of non-woven geotextile blanket (commercially known as Bidim); the base layer with 19 mm gravel, 30 cm thick; another layer of non-woven geotextile blanket (Bidim); and the supporting subgrade with the natural material of the land.

The complete section of the experimental pavement is 43 cm thick, typology of use for pedestrians, as previously highlighted, and with the total infiltration system, that is, all precipitated water infiltrates to the subgrade without the use of drains. It is noteworthy that the

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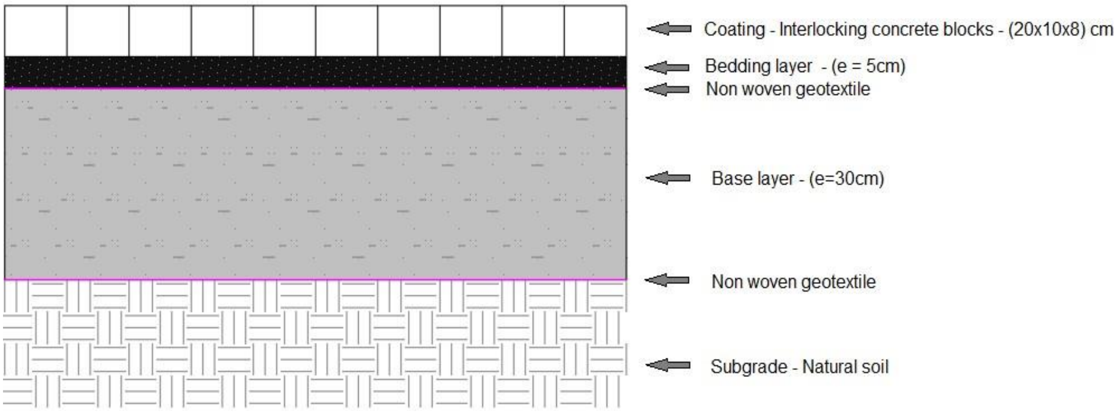
executive process with the coating in blocks of permeable concrete is without the extended joints, being of the dry joint type (without grouting) and the infiltration occurs through the permeable parts themselves.

Figure 2 - Section of experimental permeable pavement



Source: Authors.

2.3 Soil characterization of the experimental area

The characterization of the soil in the experimental area was based on a depth of 0.45 m precisely because this is the interface where the base ends and the natural soil subgrade begins, thus necessitating its characterization. With the intention of analyzing the soil characteristics, before the pavement execution, the level of the water table was assessed through an investigative borehole to the depth where water presence was found; laboratory tests were carried out for soil characterization by granularity, using the California Bearing Ratio (CBR) and the permeability of the subgrade; in addition to the field test of soil permeability, with the single ring infiltrometer test.

For the execution of the laboratory tests, a deformed soil sample was collected at a depth of 0.45 m (subgrade of the permeable pavement), and then, subdivided and prepared for each test carried out, in accordance with ABNT NBR 6457 (2016) – Soil Samples – Preparation for compaction tests and characterization tests.

2.4 Characterization and requirements of materials composing the pavement layers

To characterize the layers of the experimental permeable pavement, the national standard for permeable concrete pavements of ABNT NBR 16416 (2015) was adopted, since it is important to analyze the criteria established by the national regulations and whether they actually produce a satisfactory result. With this objective, in each component layer (base, bedding, and covering), the acceptability of the materials used was verified, considering the criteria and normative values for each necessary property to be evaluated.

For the 19 mm gravel stone that makes up the base layer, the following were evaluated: granulometric distribution, voids index, material passing through the 0.075 mm sieve, and Los Angeles abrasion. As for the stone dust of the bedding layer, all the properties of

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the base layer were observed, plus the characteristic maximum dimension. For all properties, 3 samples were tested, whose final result was the average between them. The coating blocks, in a total batch of 24, respecting the ABNT NBR 16416 (2015), were evaluated through visual inspection, dimensional evaluation with caliper and compressive strength, and the permeability coefficient was analyzed in hydraulic performance.

2.5 Analysis of hydraulic performance

In the performance assessement, permeability tests of the pavement and two hydraulic simulations of rainfall were carried out in the field. To determine the pavement's permeability coefficient, the methodology of ABNT NBR 16416 (2015) was followed, using the infiltration ring in the field (a hollow cylinder of 300 mm in diameter and 50 mm in height). The test was conducted at 3 different points, with one repetition at each, and were performed more than 24 hours after the last precipitation at the location. The tests were repeated on 3 different days and the final result of the permeability coefficient of the newly constructed pavement took into account all the measurements taken.

The procedure indicates the positioning of the infiltration ring and its sealing in the part in contact with the pavement using caulking mass. To begin, the time of a pre-wetting is timed, with clean water, starting the test up to 2 minutes after the beginning of this process, with a water volume of 3.6 L if the pre-wetting time is more than 30 seconds; otherwise, 18 L are used, pouring the water into the infiltration ring with sufficient speed to maintain the water level between the ring's internal markings of 10 mm and 15 mm in height. It is emphasized that the timing should start as soon as the water touches the pavement surface and should end when there is no more free water on the surface.

Hydraulic simulations in the field were conducted using a defined quantity of water and a delimited test area, establishing the water blade height, which represents precipitation, in millimeters. Two reservoir tanks with a capacity of 1,000 liters (1 m³) each were employed. The first simulation was performed across the entire experimental module area of 27 m² (2.7 m x 10 m), and the second was conducted in a reduced area of 9.45 m² (2.7 m x 3.5 m), aiming to assess the behavior of the experimental pavement under a more critical scenario (equal water volume and smaller test area).

In the hydraulic simulations, an automatic water level meter (equipment produced by the company AMPEQ) was used, which was inserted into one of the piezometers installed in the experimental pavement (a 100 mm diameter PVC pipe, driven to a depth of 2 meters and perforated along its entire length). Consequently, readings of the water levels reached in the piezometer were automatically and consecutively taken through the sensor every minute, recording the values in the datalogger data storage device.

The rainfall simulations conducted on the experimental permeable pavement aimed to assess its behavior during two induced intense precipitation events. To achieve this, the water level values related to the complete permeable system, consisting of the permeable pavement itself and the subgrade soil, were evaluated in conjunction with the generated rainfall intensity. It was also performed the evaluation of the conditions prior to the execution of the tests, allowing the understanding of the behavior of the water level, justified by the conditions of soil

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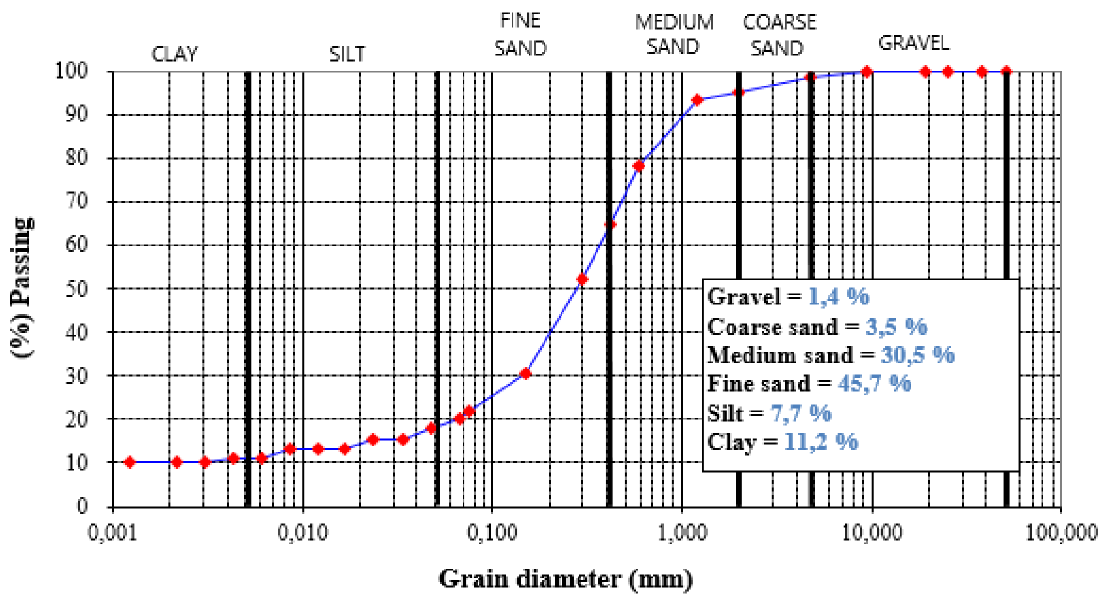
saturation. In addition, soil moisture was evaluated through data derived from the rainfall events to which the system was exposed prior to the performance of simulations Regarding the conditions after the tests, the analyzes aimed to understand: the recovery mode of the system at the initial condition, before the test; the time for this to occur; and the factors that influence this process. The results and the system's behavior during the actual tests allowed for the assessment of the performance of the experimental permeable pavement in the face of simulated intense precipitation events. Furthermore, the largest natural daily rainfall event was evaluated for the period from March to May 2023, in a manner similar to the simulations, using precipitation data from the Pernambuco Agency of Water and Climate (APAC, 2023) for the nearest rain gauge station to the study area, located in the Santo Amaro neighborhood.

3 RESULTS

3.1 Soil of permeable pavement subgrade

From the analysis of soil behavior (experimental permeable pavement subgrade, with depth of 0.45 m), it is possible to observe the particle size curve of the sample, as shown in Figure 3, in which there is a predominance of the sand fraction, approximately 80% of the soil composition, classified as a free sand, according to the textual triangle. As for the consistency limits, the soils presented low plasticity, being classified as nonliquid (NL) and nonplastic (NP).

Figure 3 -Granulometric curve of the subgrade soil.



Source: Authors.

The California Bearing Ratio (CBR) is an important test for any type of pavement as it represents the load-bearing capacity of the subbase. Through the conducted test, which evaluates penetration pressure, a CBR value of 34% was determined. Another parameter

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obtained during the test was the expansion, measured using a deflectometer over four consecutive days while the specimen was submerged in a water tank, with a value of 0%.

The determination of the subbase coefficient of permeability was carried out using a permeameter test at a constant load due to the granular nature of the soil. When conducting the test, it was necessary to find the input data for the equation to obtain the coefficient of permeability, taking into account the subgrade's compaction degree, determined *in situ*, by the studies of Almeida (2017) and Silva (2022) for areas adjacent to the experimental pavement, which was considered to be 90%. By applying Equation 1, based on Darcy's law, it was possible to find the coefficient of permeability of the subgrade to be equal to 6.38 x 10^{-3} cm/s.

$$K = \frac{V \, x \, L}{A \, x \, h \, x \, t} \quad \text{(Equation 1)}$$

Where:
K = Coefficient of permeability (cm/s);
V = Volume of water that passes through the sample (cm^3);
L = Thickness of the soil layer in the permeameter, measured in the direction of flow (cm);
A = Area of the soil sample in the permeameter (cm^2);
h = Hydraulic load (cm); e
t = Time interval (s).

This permeability value differs from that established by ABNT NBR 16416 (2015), adopting the total infiltration system, as was executed, because the minimum normative value indicated for such a system is 10^{-3} m/s. The national standard sets a very restrictive minimum coefficient; however, the American standard ACI 522 R (2010) recommends that the minimum coefficient of soil permeability for total infiltration systems should be greater than 3.60 x 10^{-6} m/s, provided that this soil extends to at least 1.20 meters from the surface.

As a result of this, in order to assess the suitability of choosing the total infiltration system, a constant load permeability test was also conducted for a soil sample at a depth of 1.20 meters, which was also characterized as granular. The value of the permeability coefficient (K) was 8.76 x 10^{-6} m/s, which is higher than the minimum value defined in the American standard, thus supporting the choice of the total infiltration system.

The infiltration test, conducted in the field using a single-ring infiltrometer, was performed at three different points within the subgrade area and provided soil infiltration results under field conditions, aiming for a more comprehensive analysis in addition to the laboratory test for soil permeability coefficient. Figure 4 shows the infiltration curves of the points, highlighting that the maximum and minimum values (tending to constancy) of the infiltration rate were, respectively: for point 1, 925.99 mm/h and 111.2 mm/h; for point 2, 702.48 mm/h and 118.44 mm/h; and for point 3, 885.73 mm/h and 82.48 mm/h. These values, according to ABNT NBR 16416 (2015), are for an average degree of soil permeability (>36 mm/h and ≤ 3600 mm/h).

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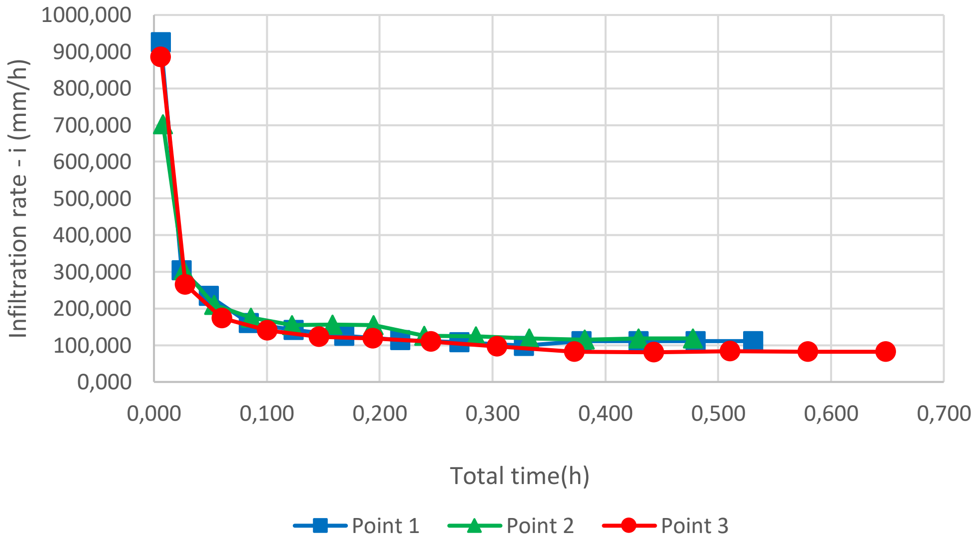
Therefore, in relation to the subgrade soil of the permeable pavement at a depth of 45 cm, after the tests carried out, it can be said that there are good conditions for the implementation of compensatory infiltration techniques, given the characterization of its composition, as sand loam, low percentage of fines and low plasticity, in addition to also presenting good load-bearing capacity, through the CBR equal to 34%, and a permeability condition compatible with the needs of the total infiltration system adopted for the permeable pavement.

Figure 4 - Subgrade soil infiltration curves



Source: Authors.

3.2 Materials composing the pavement layers

The suitability of the 19 mm gravel used in the pavement base, the stone dust in the bedding layer, and the permeable concrete blocks in the surface layer was assessed through laboratory tests and compliance with the criteria of ABNT NBR 16416 (2015), the Brazilian standard for permeable pavements, by means of the necessary analyses. Table 1 presents a summary of the results obtained for each tested property and the compliance analysis for the aggregate used in the base (19 mm gravel), highlighting that the material meets all the requirements specified by the standard.

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Table 1 - Tests of the permeable pavement base layer.

Property	Result - Tests	Normative specification - ABNT NBR 16416 (2015)	Compliance with the standard
Los Angeles Abrasion	26,81%	< 40%	YES
Material passing through the sieve 0.075 mm	0,57%	≤ 2%	YES
Void ratio	42,77%	≥ 32%	YES
Granulometric analysis	% retained accumulated on the sieves: 37,5mm, 25mm, 19mm, 12,5mm, 4,75mm, 2,76mm		YES

Source: Authors

Similarly to Table 1, Table 2 shows the results and compliance analysis for the stone dust used in the bedding layer. It is noteworthy that the material used had a finer particle size distribution than it should have, an aspect that was pointed out before execution but was still used by the responsible parties. In fact, the material did not meet any of the requirements specified by the standard, and it's mentioned that the Los Angeles Abrasion test did not yield results due to the impossibility of execution by fine grain.

Table 2 - Tests of the permeable pavement bedding layer.

Property	Result - Tests	Normative specification - ABNT NBR 16416 (2015)	Compliance with the standard
Los Angeles Abrasion	-	< 40%	NO
Material passing through the sieve 0.075 mm	5,84%	≤ 2%	NO
Maximum characteristic dimension	4,75 mm	9,5 mm	NO
Void ratio	27,89%	≥ 32%	NO
Granulometric analysis	% retained accumulated on the sieves: 12,5 mm; 9,5 mm; 4,75 mm; 2,36 mm; e 1,76 mm		NO

Source: Authors.

For the permeable concrete blocks of the coating, the visual inspection verified the absence of defects and significant delaminations of the concrete, being the homogeneous parts with regular edges. The dimensional evaluation of compliance with the 3 mm tolerance showed that only 3 of the 24 blocks showed variations slightly above the allowed in one of the dimensions. When performing the simple compressive strength test to evaluate whether the blocks exhibited at least 20 MPa, an average of 10.68 MPa was obtained, which does not comply with the standard.

It should be noted that the non-conforming conditions of the bedding layer material and the coating blocks did not have an impact on the use of the pavement, possibly due to its low pedestrian traffic load, but it could eventually have an impact on the frequency of maintenance and the useful life of the pavement.

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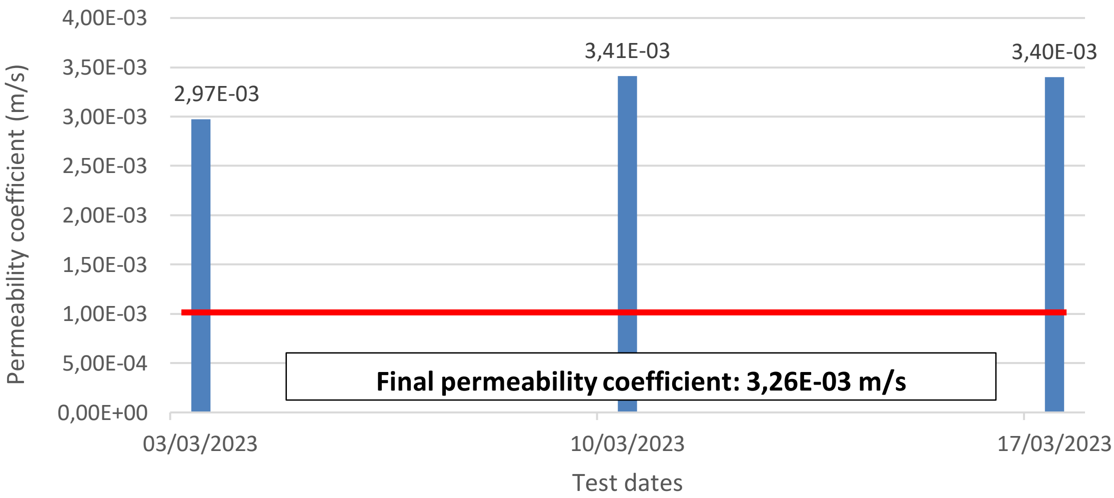
3.3 Pavement permeability coefficient

Through the execution of the infiltration ring test, following the methodology proposed in Annex A of ABNT NBR 16416 (2015), an important parameter of the permeable pavement's infiltration efficiency, the permeability coefficient, was determined. It should be noted that values above 10^{-3} m/s are required for a newly constructed pavement. The tests were conducted over three days (03/03/2023, 10/03/2023, and 17/03/2023), with the choice of dates being due to the assessment of permeability in the newly constructed pavement, which was completed in February 2023.

For each day, 3 points were tested with a repeat measurement, resulting in 6 valid measurements per day. All the calculated values were higher than 10^{-3} m/s, as can be seen in Figure 5, which shows the average coefficients for each date tested, as well as indicating the normative limit of 10^{-3} m/s with a red line and highlighting the final permeability value, calculated as the average between the 3 measurement days.

The permeability value of the pavement obtained was 3.26 x 10^{-3} m/s, indicating high permeability. This suggests that, by this analysis criterion, the pavement exhibits good hydraulic performance in terms of its capacity to infiltrate rainfall water that falls on it. Another interesting way to express the permeability of the pavement is to state it as 3.26 mm per second.

Figure 5 - Permeability of the newly constructed permeable pavement.



Source: Authors

3.3 Hydraulic simulations of precipitation and natural rainfall event.

The first simulation was performed on 25/02/2023, using the complete area of the experimental floor (27 m²). The 2000 liters (1 m³ of each tank) were placed in this area, but due to the unevenness and some irregularities in the total area, the area of the blade where water infiltration actually occurred and the test was approximately 16.4 m², value calculated by marking the wet area, which is after the test and was confirmed with the filming of the test. The blade was visible while the pavement was still receiving water, being completely infiltrated even before the tanks emptied completely, as the outflow of water reduces as time passes.

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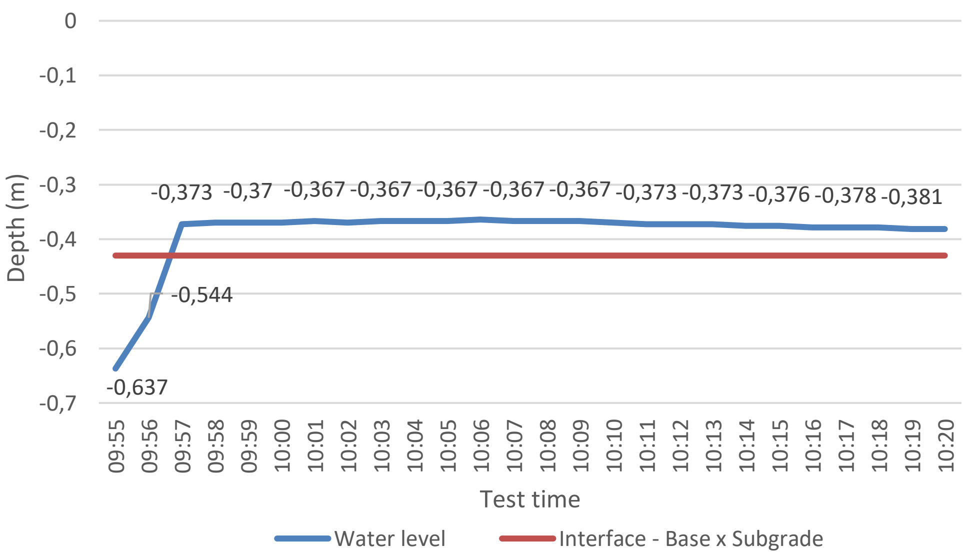
The conditions prior to the test were analyzed, noting that from February 24 (prior to the test) until the start of the test at 09:55 on February 25, the permeable sidewalk received precipitation, one of which occurred one hour before the test, raising the water level from 0.892 m to 0.390 m. After this rainfall, the system, in its process of recovery by infiltration, lowered the water level to a depth of 0.637 m, where the simulation test began.

The variation in the behavior of the pavement is noticeable depending on whether it receives rainfall or not. In other words, the water level in the system rises when it rains, leading to contact with water, followed by infiltration, and consequently, a rise in the water level. The process is reversed when the infiltrated volume ceases, allowing the infiltrated water in the system to continue its course, thereby lowering the water level. The greater the amount of rainfall, the deeper the water penetrates into the soil, causing greater soil saturation, which gradually slows down the infiltration process.

The first rain simulation, conducted with 2 m³ of water on the effective area of 16.4 m², resulted in a simulated precipitation of 121.95 mm. This test lasted for 25 minutes: with complete emptying of the reservoirs in 14 minutes followed by continuous evaluation for an additional 11 minutes. Throughout the period, individual readings per minute of the water level were performed. The behavior of the system during the test can be observed in Figure 6, in which, as in other similar graphics, the Base x Subgrade interface matches the depth of 0.430 m at the end of the base layer of the pavement, presenting only a few values graphically, due to the large number of data (readings/min), choosing the representative ones to understand the behavior.

Figure 6 - Intense rain simulation nº 01



Source: Authors

The test began with a water level at a depth of 0.637 meters, and after a rapid increase, it remained relatively stable until the end. From time 0 to 2 minutes, there is a rapid rise in the water level, with the water level being maintained within the base layer of the permeable pavement reservoir (depth of 0.430 meters) from the first minute onwards until the end of the

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test. This behavior indicates that the pavement maintained, during the test, its infiltration rate similar to the rate of water entry into the system after the first minutes, resulting in a good hydraulic infiltration performance, considering the high volume of water in the short time (simulated rain of approximately 121,95 mm), even though the system is at a certain level of saturation due to precipitation occurring on site in the hours prior to the start of the test.

The analysis of the condition of recovery of the permeable pavement verified the time that the system took to return to the initial condition of the pre-test, that is, to the same water level value. This evaluation began at 09:55h on 25/02/2023, with the rise of the water level, resulting from the beginning of the test, and finished when the water level returned to its initial condition, equal to 0.637 m deep, occurring on average, 2h after, at 11:58h. The recovery of the pavement for the simulated intense rain was fast, highlighting that there was no natural precipitation in this recovery time interval analyzed.

The second simulation, conducted on March 4, 2023, aimed to assess the behavior of the permeable pavement under a more intense simulated precipitation and a different pre-test condition. For this purpose, a rectangular area of 9.45 m² was defined, and the same 2000 liters of water used in the first simulation were applied, resulting in a simulated rainfall of approximately 211.64 mm.

In addition to the difference in the intensity of the simulated precipitation, the response of the pavement under a condition of no prior natural rainfall was also evaluated. In other words, the system was nearly unsaturated. According to APAC (2023), there was no rainfall in the 4 days leading up to the test (Santo Amaro rain gauge).

The test started at 09:22 am on March 4, 2023, with a water level of 1.310 meters. Similarly to what happened in the first simulation, the first few minutes saw a rapid rise in the water level, reaching a minimum depth of 0.317 meters after 5 minutes from the start of the test. Subsequently, the system had its water level lowered during the test, unlike what occurred in the first simulation. This can be attributed to the more favorable soil infiltrability condition and the lower saturation of the soil and system compared to the first test. Figure 7 illustrates the behavior of the graph during the test period.

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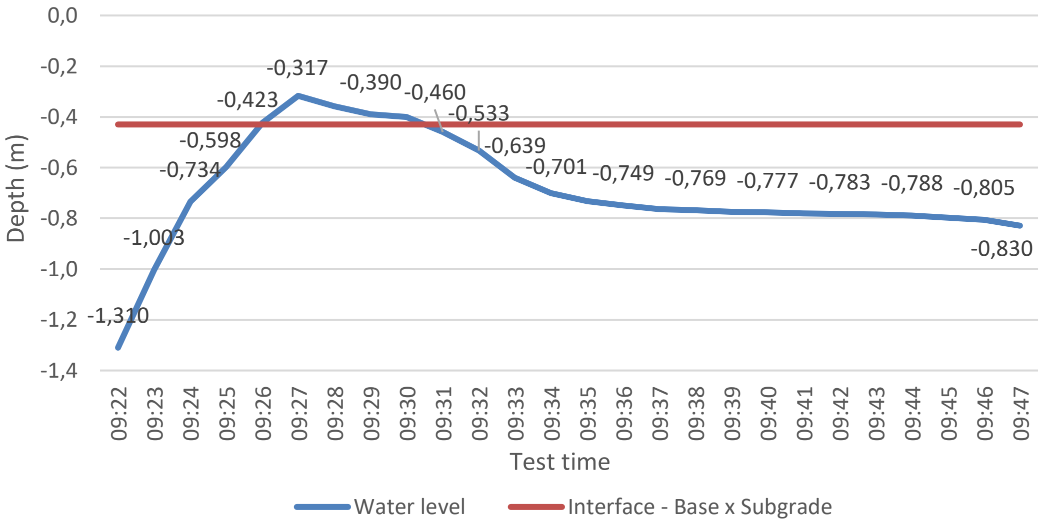
Figure 7 - Intense Rainfall Simulation No. 02.



Source: Authors

The permeable pavement once again demonstrated good hydraulic performance when subjected to a simulated intense rainfall of 211.64 mm. It's worth noting that the water layer formed was completely infiltrated before the total emptying of the reservoirs, similar to what happened in the first simulation. Regarding the recovery of the pavement after the test, it was necessary more time for the system to return to the pre-test condition than the 2h required in the first simulation, occurring around 24h later, with water level measured at 08:43h (day 05/04/2023) at 1,310 m depth, equal to the value in the initial test condition at 09:22h (04/04/2023 day). There was no natural rain in the period of analysis of the recovery of the pavement.

On April 9, 2023, the cumulative rainfall reached 76 mm at the Santo Amaro rain gauge (APAC, 2023). Since there was no water overflow in the system, it was possible to estimate the volume retained by the pavement during the natural rainfall event, resulting in 2.05 m³ retained through infiltration for the area of 27 m², all in a single day. It's worth noting that the simulations, due to the high volume of water in a short time interval, experienced rapid ascent and subsequent continuous recovery, unlike natural rainfall, which is distributed over time.

Therefore, it was possible to identify the movements of rising and falling water levels, but the permeable system consistently responded satisfactorily to each new need for receiving rainwater, confirming its good hydraulic performance. Figure 8 illustrates the system's behavior throughout April 9, 2023, noting that the soil saturation level was low, considering the three previous days with precipitation values of 0 mm or 1 mm (APAC, 2023).

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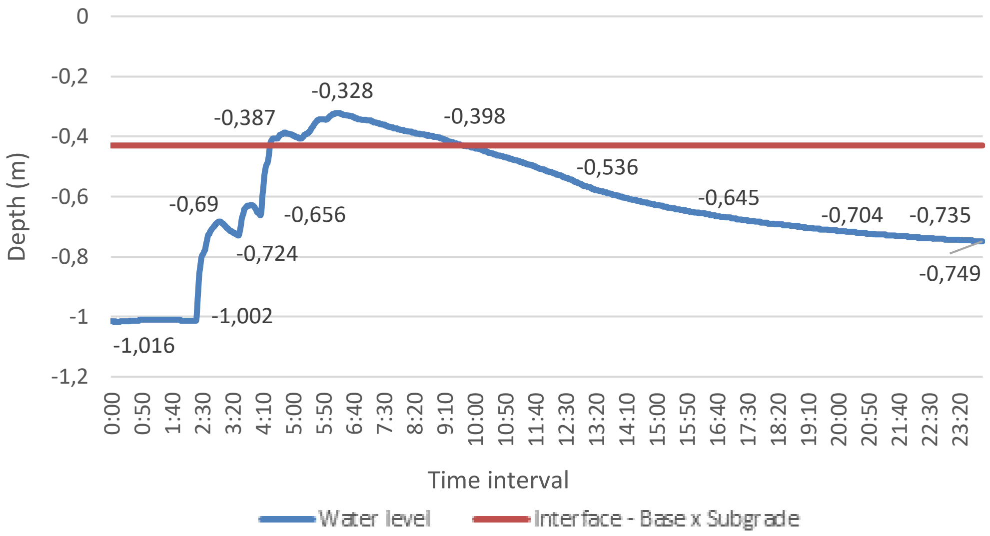
Figure 8 - Permeable System Behavior - April 9, 2023.



Source: Authors

The hydraulic performance of the pavement was defined as good after conducting two hydraulic simulations of intense rainfall and the largest daily natural rainfall event for the analyzed period. The permeable response of the pavement was observed, evaluating the system's behavior for simulated rainfalls with values of 121.95 mm and 211.64 mm, as well as for natural rainfall of 76 mm. It's important to highlight that the conditions included varying levels of soil saturation and moisture, and the permeable pavement responded positively to all events with high volumes of water and in the recovery to the pre-rain conditions.

4 CONCLUSIONS

The present research aimed to assess the feasibility of using an experimental permeable pavement as a compensatory alternative for urban drainage. The study evaluated the subgrade soil supporting the pavement, the layers, and the materials composing it, with the goal of analyzing the entire permeable system and its hydraulic performance.

The evaluation of the hydraulic behavior of the pavement was important to find answers regarding the increase in volumes of infiltrated water due to the permeable system, how this system responded to simulated rains and natural precipitation, and its coefficient of permeability.

The theme addressed is relevant for urbanized cities with high rates of waterproofing, because it presents a device that can be deployed aiming at more sustainable and resilient environments to water, highlighting that the greater the number of sustainable devices executed, reductions in the effects of extreme rainfall events.

The experimental permeable pavement proved to be a satisfactory compensatory infiltration technique, capable of reducing surface runoff and volumes discharged through infiltration, with real potential for mitigating urban flooding.

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