Permeable Asphalt Pavement as a Measure of Urban Green Infrastructure in the Extreme Events Mitigation

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***Abstract*—**Population growth in cities has led to an increase in the infrastructures construction, including buildings and roadways. This aspect leads directly to the soils waterproofing. In turn, changes in precipitation patterns are developing into higher and more frequent intensities. Thus, these two conjugated aspects decrease the rainwater infiltration into soils and increase the volume of surface runoff. The practice of green and sustainable urban solutions has encouraged research in these areas. The porous asphalt pavement, as a green infrastructure, is part of practical solutions set to address urban challenges related to land use and adaptation to climate change. In this field, permeable pavements with porous asphalt mixtures (PA) have several advantages in terms of reducing the runoff generated by the floods. The porous structure of these pavements, compared to a conventional asphalt pavement, allows the rainwater infiltration in the subsoil, and consequently, the water quality improvement. This green infrastructure solution can be applied in cities, particularly in streets or parking lots to mitigate the floods effects. Over the years, the pores of these pavements can be filled by sediment, reducing their function in the rainwater infiltration. Thus, double layer porous asphalt (DLPA) was developed to mitigate the clogging effect and facilitate the water infiltration into the lower layers. This study intends to deepen the knowledge of the performance of DLPA when subjected to clogging. The experimental methodology consisted on four evaluation phases of the DLPA infiltration capacity submitted to three precipitation events (100, 200 and 300 mm/h) in each phase. The evaluation first phase determined the behavior after DLPA construction. In phases two and three, two 500 g/m^2 clogging cycles were performed, totaling a 1000 g/m^2 final simulation. Sand with gradation accented in fine particles was used as clogging material. In the last phase, the DLPA was subjected to simple sweeping and vacuuming maintenance. A precipitation simulator, type sprinkler, capable of simulating the real precipitation was developed for this purpose. The main conclusions show that the DLPA has the capacity to drain the water, even after two clogging cycles. The infiltration results of flows lead to an efficient performance of the DPLA in the surface runoff attenuation, since this was not observed in any of the evaluation phases, even at intensities of 200 and 300 mm/h, simulating intense precipitation events. The infiltration capacity under clogging conditions decreased about 7% on average in the three intensities relative to the initial performance that is after construction. However, this was restored when subjected to simple maintenance, recovering the DLPA hydraulic functionality. In summary, the study proved the efficacy of using a DLPA when it retains thicker surface sediments and limits the fine sediments entry to the remaining layers. At the same time, it is guaranteed the rainwater infiltration and the surface runoff reduction and is therefore a viable solution to put into practice in permeable pavements.

***Keywords*—**Clogging, double layer porous asphalt, infiltration capacity, rainfall intensity.

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I. Introduction

THE evolution of urbanization in recent years has generated major concerns about the occupation of urban spaces by infrastructures that waterproof the soils. The major consequences associated with this are flooding aggravated by changes in precipitation patterns and, consequently, the reduction of rainwater infiltration to the soils and the increase in the volume of surface runoff [1], [2]. Therefore, control of the amount of water drained and infiltrated in urban roads is fundamental. Thus, the implementation of urban green infrastructures (GI) has been a solution in mitigating the effects of climate change in the planning of cities regarding the management of rainwater [3], [4]. One of the elements of GI that can be integrated into road construction includes the use of porous materials on street pavements and parking lots. The GI allied to Sustainable Urban Drainage Systems (SUDS) leads to the development of more natural urban environments [5].

Permeable bituminous pavements are among the various techniques developed in SUDS systems and also follow the trend of environmentally friendly solutions like GI. Its structure consists of an aggregate reservoir with uniform granulometry and with 40% voids that temporarily stores the water until it infiltrates the soil, followed by a thin layer of aggregates to stabilize the surface, which consists of one or more mixtures of PA with a high void content of 16-22% [6]. These pavements are an effective measure to control rainwater runoff and allow water infiltration into soils [7]. In addition, other advantages have already been studied, such as the reduction of pollutants in the surface runoff and infiltration, absorption of noise, mitigation heat islands effects, minimization of tire spray and hydroplaning, leading to safer driving [8], [9].

The introduction of sediments and pollutants through the pores of the surface layers of the permeable pavements has been one of the most questioned subjects in the use of these pavements, since the capacity of infiltration of the bituminous mixtures is questioned when they are clogged [10]. The clogging process begins with the displacement of larger particles like sands into the pores of the surface layer. The space between these is quickly filled with fine particles that are able to move in the structure. These particles come from the very wear of the surface (tire contact with the pavement) and sediment suspended in rainwater [11]. The infiltration capacity decreases with years of service until it forms an impermeable surface. Therefore, the development of clogging is characterized by an increased amount of material retained in the surface.

Several studies have evaluated the behavior of permeable pavements to clogging [12]-[15]. In 1996, Legret et al. [8] analyzed a permeable bituminous pavement with reservoir structure in France. After a period of four years, during which the structure was in experiments, it was shown that the rainwater of 30 precipitation events that crossed the pavement contained a markedly lower pollutant load than in the reference basin. The analysis of the reservoir and soil materials showed that pollutants from runoff water accumulated mostly on the surface of the PA mixture. In a laboratory simulation, Yong et al. [16] studied PA mixtures for the precipitation conditions in the cities of Melbourne and Brisbane, which only filled after 8.5 and 17 years of service. Hassan et al. [17] simulated the clogging of PA mixtures with sealing materials obtained from a main road and a residential area, the latter tending to obstruct the empty spaces of the mixture.

The development of a DLPA has been a good practice in solving problems caused by clogging in PA pavements [18]. The surface layer of the pavement is formed by uniform aggregates of finer size, while the lower layer contains uniform aggregates of thicker size. The first layer acts as a sieve that limits the entry of sediments to the second layer. Both PA mixtures used have a high void content to guarantee the drainage of rainwater to the lower layers, consisting of loose aggregates of uniform granulometry, with a reservoir function [19].

In order to limit the risk of clogging and allow infiltration of rainwater into the soil, it is necessary to prevent clogging and sweep the pavements, which are the most important tasks associated with regular inspections and maintenance on permeable pavements [6]. High pressure jet washing is the most effective maintenance technique in the process of preventing and restoring the function of permeable pavements [20]. However, sometimes this technique is not available to the city cleaning sectors and the most common maintenance techniques are mechanical street sweeping and vacuum street sweeping.

Permeable bituminous pavements play an essential role in urban drainage systems, representing a technique of interest to researchers and practitioners. However, there are some uncertainties about its hydrological performance, clogging and maintenance. Thus, the objective of this investigation is the study of the evaluation of the infiltration capacity of a square section of DLPA. Said DLPA was built in laboratory, along with a rain simulator capable of simulating real precipitation intensities. The influence of three precipitation intensities on the response to DLPA infiltration capacity was analyzed after construction, clogging and simple maintenance.

II. Materials and Methods

The following section presents the materials used to carry out the experimental tests and the adopted methodology.

A. DLPA

The application of a DLPA in permeable bituminous pavements aims to minimize the effect of clogging in urban areas, improving the function and durability of the draining bituminous mixtures employed. This type of surface is an improvement of the single layer PA mixture. The composition of the DLPA produced in this study includes a top layer of bituminous drainage (PA1) with aggregates of fine granulometry (up to 10 mm) and a lower layer of bituminous drainage (PA2) with aggregates of large granulometry (up to 15 mm). The PA1 layer acts as a filter that holds the coarse dirt at the surface, while the fine dirt moves to the lower layer PA2, thus the clogging of subsequent layers is minimized. Tiles of pavement were produced in a laboratory with a square section of 0.30 x 0.30 m and thicknesses of 3 and 4 cm for PA1 and PA2, respectively. The composition of the draining bituminous mixtures followed the formulation developed in the study of Afonso et al. [21], which evaluated the addition of cellulosic fibers in these mixtures. The initial porosities obtained for each tile were 17.2% for PA1 and 22.6% for PA2.

B. Clogging Material

The performance of a permeable floor depends on local conditions, including the particle size distribution of the materials in the surrounding area, and the resulting clogging hazards, including the quantities and the mode of action of the sediments [22]. The sediments used in simulations may be from actual samples or obtained artificially [23] and its application can be done manually [15], [24], dissolved in precipitated water [12] or added to superficial runoff [13]. Sand is the most used clogging material in laboratory simulations in the study of the effects of clogging. The sand used, of mostly granite origin, was physically characterized by granulometric analysis (Table I), guaranteeing a predominance of fine material and maximum size smaller than 2 mm.

TABLE I
CLOGGING MATERIAL PARTICLE SIZE

Sieve size (mm)	Cumulative Percentage Passing (%)
2	100,00
1	75,10
0,5	54,01
0,25	38,52
0,125	26,13
0,063	18,05

C. Rainfall Simulator

Portable rainfall simulators are essential study tools for understanding the hydrological processes [25], [26]. In this study, a rain simulator with its own characteristics was developed to simulate three precipitation intensities: 100, 200, and 300 mm/h. This was instrumented with a sprinkler nozzle (Fulljet B3/8HH-9.5) and a pressure gauge that regulated the amount of water pumped from a 1000-l reservoir. In the laboratory, a modular structure (Fig. 1 (a)) with dimensions of 0.50 m in height and 0.30 m in width and length was constructed to support the DLPA's plates and with capacity to collect the surface runoff and water Infiltrated. In each test, the superficial and infiltration flows were monitored using the weight of water in containers placed in the outlet tubes.

Several configurations were studied to standardize the precipitation applied to the DLPA, in terms of sprinkler height, pressure and positioning of the modular structure. The method of flow measurement was used to calibrate the desired precipitation intensities. This consisted in registering the time required to collect a certain volume of water in the study area, with different pressures. The best configuration was obtained with a height of 2.60 m from the surface of the DLPA to the sprinkler and a pressure of 2.6 bar. While the position of the modular structure for each intensity was achieved at three points, duly tested, along the center line of the sprinkler nozzle

The Christiansen uniformity coefficient (CUC) was calculated to obtain uniformity of precipitation distribution for each intensity by the collecting cups method. The minimum value of CUC in the literature is 70% [27]. The values obtained in this study for the intensities of 100, 200, and 300 mm/h were 78.84, 72.24, and 68.51%, respectively. The results were considered adequate, since they are close to or higher than the reference.

D. Evaluation Methodology for the Infiltration Capacity

The experimental procedure involved the completion of four phases of evaluation of infiltration capacity, according to the schematic diagram presented in Fig. 1 (b). In each test phase, the three precipitation intensities were applied in periods of 50 minutes. Each test phase was performed independently with pre-wetting before the start of each precipitation intensity, except in the last maintenance phase. Repeating preliminary trials to test the experiment revealed a good trend in the rain simulator's responsiveness and modular structure to the purpose of the study.

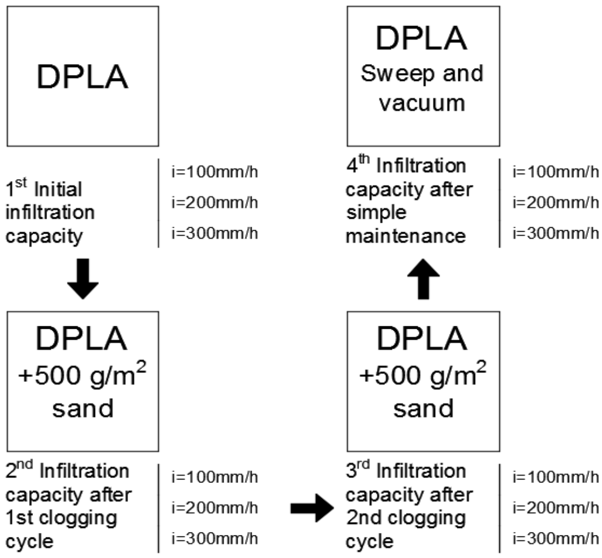
The sequence of the four test phases was as follows: the first test phase was performed after construction without any clogging, corresponding to the initial infiltration capacity of the DLPA; the 2nd phase refers to the 1st clogging cycle with the application of 500 g/m^2 of sealing material, manually placed on the surface of the PA1 layer followed by a slight compacting with a steel roller; in the 3rd phase, the second clogging cycle was applied with further 500 g/m^2 of sealing material, totaling 1000 g/m^2 (characteristic value of the laboratory simulations in the clogging analysis); after a drying period of one week at room temperature (24 °C), the fourth phase was performed with the DLPA cleaning using the sweeping process followed by vacuum, simulating the most common road maintenance technique. It should be noted that successive trials were carried out with the three precipitation intensities in the four evaluation phases. The methodology used also weighed the paving stones between the test stages.

III. Results and Discussion

A. Initial Infiltration Flow Rate

In Fig. 2, the accumulated infiltration flow hydrographs as well as the precipitation intensities recorded at the sprinkler outlet of 100, 200, and 300 mm/h are shown. The flow rates used in the tests for the square section of the DLPA under analysis were 9, 18, and 27 l/h for the intensities of 100, 200, and 300 mm/h, respectively. In general, the curves follow the same trend for the three precipitation intensities. It was verified in all the hydrographs that the infiltration rate measured in the first minutes increased until reaching the flow rate corresponding to the intensity tested, with a delay between the in and out flow. This lag at the start of the test is defined as the time required for the precipitation to penetrate through the pavement structure until it reaches the free drainage point, i.e. when flow is observed at the outlet. The decrease in the delay over the three cycles of precipitation intensity can be explained by the fact that the level of water retention in the pavement structure increased in consecutive rain events, causing a reduction in travel time across the pavement thickness. This analysis is in line with findings from other studies [2].

(a)



(b)

Fig. 1 Infiltration capacity test: a) DLPA modular support structure; b) Schematic diagram

The flow rate of DLPA infiltration with the intensity of 100 mm/h exceeded, in about 5%, the flow rate corresponding to that precipitation from the 30-minute test. The justification for this is due to the fact that the paving stones are only wet due to pre-soaking and for the first few minutes they fill their pores with water. This water was subsequently drained after increasing the hydraulic load inside the pavement when the saturation point was reached during the rainfall. Thus, it was found that the initial moisture conditions of the draining bituminous mixtures influenced their drainage water storage capacity before a precipitation event occurred, as found in the study by Alsubih et al. [2].

At the other intensities, this did not occur, because the paving stones already contained their pores fully filled with water from the previous test. In this first test phase, no runoff occurred, so all the precipitated water was infiltrated by the DLPA.

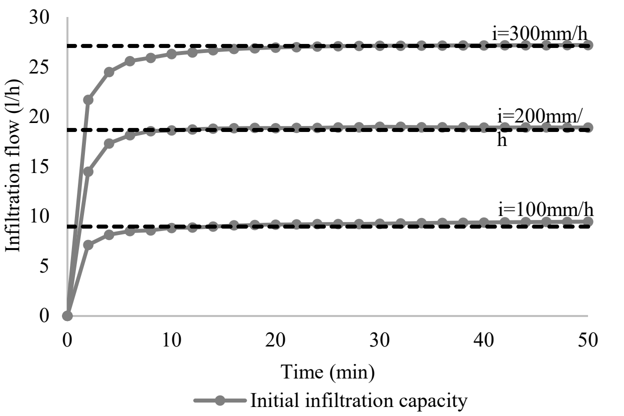


Fig. 2 Initial Infiltration Capacity (first phase) related to the infiltration rate corresponding to the three precipitation intensities

B. Infiltration Capacity after Clogging

Fig. 3 illustrates accumulated infiltration flow hydrographs after the two clogging cycles for the precipitation intensities of 100, 200, and 300 mm/h. For a better visualization of the results, the vertical axis presents different maximum limits in each hydrograph. As can be seen, the shape of the curves for infiltration flow rates after the clogging cycles shows a similar behavior throughout the tests. At the three intensities, a delay of the infiltration flow rate was again observed in the first few minutes of the clogging test phase in relation to the initial infiltration rate.

For the three precipitation intensities, the infiltration rate after the first clogging cycle practically reached the initial infiltration rate. Therefore, the application of 500 g/m^2 to the surface of the DLPA only influences the hydrological performance in the initial minutes, with a recovery of infiltration capacity over time.

After the second clogging cycle was applied, the infiltration rate decreased by about 12% from the initial flow rate to the intensity of 100 mm/h. However, for the intensities of 200 and 300 mm/h the infiltration rate only decreased by about 5%, which means an improvement of about 50% with respect to the intensity of 100 mm/h. It was concluded that the application of 1000 g/m^2 of clogging material affected the performance of DLPA, but its influence is reduced as the intensity of precipitation increased. This behavior is considered to result from washing of the fine filler material within the structure of the DLPA, which provides an increase in the infiltration rate.

C. Recovery of Infiltration Capacity

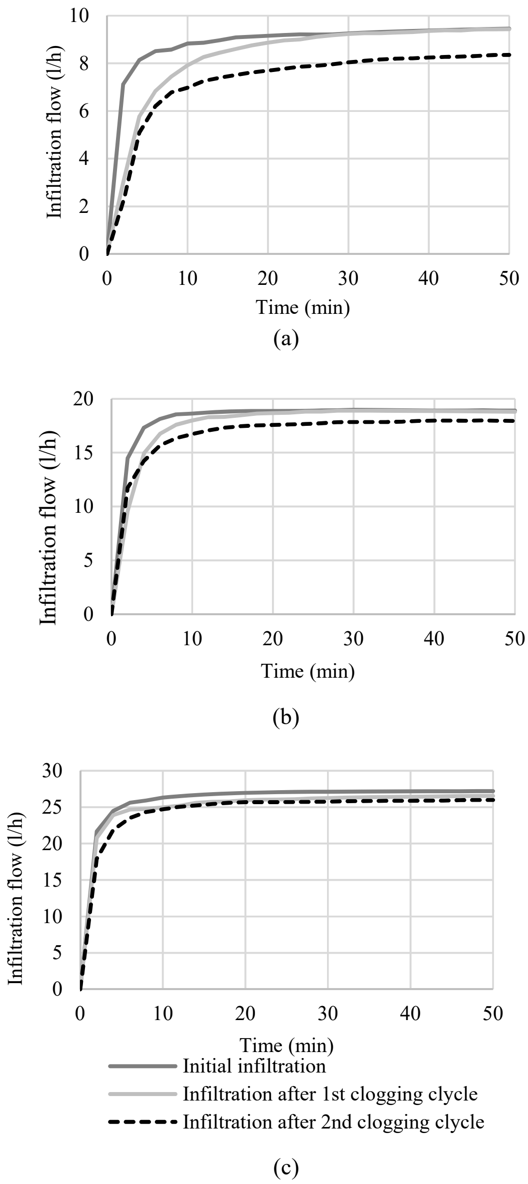


Fig. 3 Initial infiltration capacity, after clogging and maintenance. a) 100 mm/h, b) 200 mm/h, c) 300 mm/h

The recovery of the infiltration capacity of the DLPA was evaluated by comparing the results of the initial infiltration flow and after simple maintenance. By observing the curves shown in Fig. 4, the higher the precipitation intensity, the greater the capacity of the pavement to recover infiltration over time. For the precipitation intensities of 200 and 300 mm/h, the simple maintenance allowed the DLPA to reestablish the initial infiltration rate, with deviations of less than about 1%. However, for the intensity of 100 mm/h and under the same conditions, a deviation of about 8% was obtained.

The hydrological performance of the different precipitation intensities is comparable, although there are differences of 100 mm/h between them. This indicates that increasing the precipitation intensity above 100 mm/h without increasing its duration causes an increase in the water attenuation within the pavement structure, highlighting its recoverability after simple maintenance.

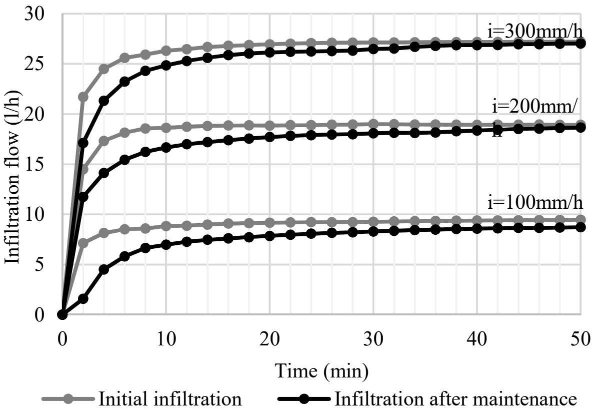


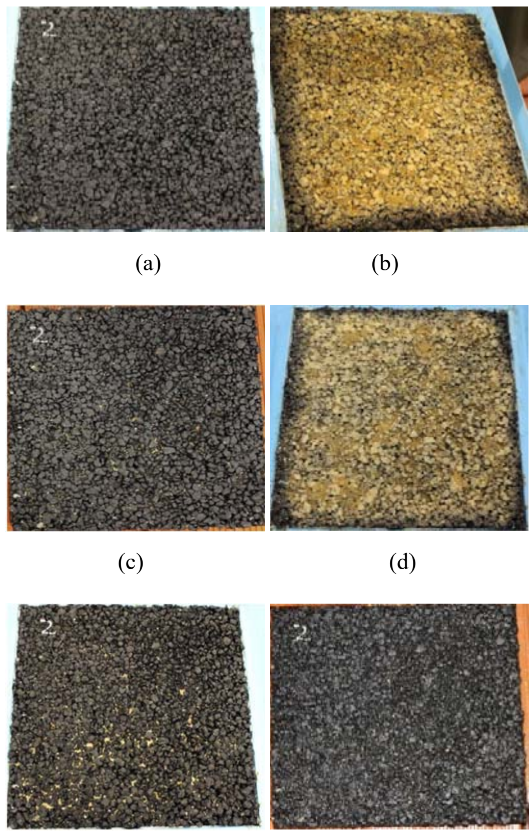
Fig. 4 Relation between the initial infiltration capacity and after simple maintenance

In Table II, the percentage change in mass of the two layers (PA1 and PA2) that form DLPA between the beginning and the end of the evaluation phases under wet and dry conditions is presented. Analyzing the mass percentage values of the DLPA relative to the wet conditions, it is verified that the set of the two layers gained mass after the two cycles of clogging, being able to recover after cleaning of the superficial layer. In this way, the maintenance contributes to the performance of the DLPA regarding the infiltration capacity. However, analysis under wet conditions does not allow accurate quantification of the retained material in the DLPA due to the presence of imprisoned water in the pores. In dry conditions, the mass increase between the beginning of the tests and after the maintenance is less than 1%, revealing an excellent result. This indicates that the simple technique of sweeping and vacuuming the surface of the DLPA applied to permeable bituminous pavements is sufficient for them to increase their rainwater infiltration capacity.

The accumulation of sediments in the DPLA occurred mainly in the upper PA1 mixture, indicating the formation of a layer of sealing on the surface. This observation is in agreement with the studies of Kayhanian et al. [14] who verified that most of the sediments settle on the surface of permeable pavements. Baladès et al. [20] also suggested that the depth of clogging is limited to the first centimeters of the permeable floor. In Fig. 5, the appearance of the PA1 layer can be visually observed during the evaluation phases, in which the clogging material was deposited and maintained. A more detailed inspection of the two independent layers (PA1 and PA2), after the clogging cycles, showed accumulated sediments on the surface of PA1 and the absence of them in PA2. This aspect proves the effective performance of the draining double layer, since the bituminous mixture with finer aggregates at the surface (PA1) retained the sediments and prevented them from passing to the lower layer with thicker aggregates (PA2). Thus, the PA2 layer played its role in the infiltration of the water to the lower layers without impediments caused by the concentration of sediments in the surface layer PA1.

TABLE II
PERCENTAGE BY MASS OF DLPA

Wet conditions	DLPA (% by mass)
Before and after 1st clogging cycle	0.69
Before and after 2nd clogging cycle	0.81
Before and after maintenance	-1.58
Dry conditions	(% by mass)
Initial and after maintenance	0.40
Initial and after maintenance followed by infiltration	0.30



(a) (b)

(c) (d)

(e) (f)

Fig. 5 Appearance of the layer PA1 in the different test phases: (a) 1st phase, after construction; (b) 2nd phase, applying of clogging material for the 1st cycle; (c) After the 1st cycle of clogging and simulation of rainwater; (d)3rd phase, applying of clogging material for the 2nd cycle; (e) After the 2nd cycle of clogging and simulation of rainwater; (f) 4th phase, after simple maintenance process

IV. Conclusion

GI allied to SUDS have, as one of their main purposes, to reduce the surface runoff and increase the capacity of infiltration of rainwater to the soil or its storage for future uses. The present research aimed to study the behavior of a DLPA to be applied to permeable pavements when clogged in two cycles and subject to three precipitation intensities. The objective was to evaluate the infiltration capacity after construction, clogging and after a simple maintenance applying different successive precipitations. The evaluation phases were performed with laboratory experiments through a rain simulator and a modular structure. The main conclusions obtained in the study are:

- Infiltration flow data show that DLPA performance can effectively reduce runoff from rainwater resulting from intense rainfall events.
- DLPA infiltration capacity varied according to the conditions it was subjected to. Under clogging conditions with 1000 g/m^2 of filler material the infiltration capacity was reduced, but this was restored after simple maintenance.
- Simple maintenance is an efficient technique as it has properly restored DLPA's hydraulic functionality.
- The accumulation of thicker sediments occurs in the surface layer, while the lower layer ensures drainage of rainwater, fulfilling the purpose of DLPA functionality.

The results of the study prove that DLPA provides infiltration capacity and at the same time helps to restore its function under clogging and maintenance conditions. Therefore, DLPA permeable bituminous pavements are efficient, effectively responding to a wide variety of rainwater when properly designed and maintained. Further studies are needed to examine the functionality of DLPA with different sediments and their effect on water quality.

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