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LABORATORY ANALYSIS OF THE INFILTRATION CAPACITY OF INTERLOCKING CONCRETE BLOCK PAVEMENTS IN CAR PARKS

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ABSTRACT
Interlocking Concrete Block Pavements (ICBPs) have been widely used in car parks to reduce runoff. Researches have demonstrated that clogging is the most influential factor in the reduction of the infiltration capacity of this type of permeable pavement. Nevertheless, there is no laboratory study of the infiltration performance of ICBPs that combines clogging levels with variables related with the topography of car parks such as runoff surface length (R_{SL}) and surface slope (S_S). This paper studies the infiltration behaviour of ICBP during their operational life in a car park using an improved version of the Cantabrian Fixed (CF) Infiltrometer. This laboratory device simulates direct rainfall and runoff from adjacent impervious areas over an ICBPs surface of 0.25m^2 for different slopes (0, 3, 5, 7 and 10%) and three scenarios of clogging (surface newly built, surface clogged and surface clogged with maintenance). This paper presents the results of the tests and a statistical analysis based on three regression models (corresponding to each clogging scenario) depending on the R_{SL} and S_S variables. All models passed a confidence level of 95%, presenting high R^2 values and showing that R_{SL} is a more influential variable than the S_S for all clogging scenarios.

KEYWORDS: SUDS; BMP; stormwater; permeable surfaces; clogging; statistical analysis.

1. INTRODUCTION

Rapid urban development and paving of extensive areas of cities together with large amounts of water from heavy rainfall create serious problems of flooding (Ferguson, 2005) and diffuse pollution (Gilbert and Clausen 2006). Permeable surfaces have been developed as a solution to these problems, reducing runoff by increasing infiltration in urban areas (Dietz 2007). Nowadays, car parks designed and constructed with permeable pavements occupy large urban areas, helping to reduce surface runoff and pollutant loads in cities (Rushton 2001).

A typical permeable surface has a surface layer of permeable pavement that enables the infiltration of stormwater, reducing runoff flow rates and volumes (Schlüter and Jefferies 2002), and retaining oils and other pollutants (Brattebo and Both 2003), usually in a geotextile layer that separates the surface layer from a permeable pavement sub-base layer (Gómez-Ullate et al. 2010).

Many field and laboratory researches on the infiltration capacity of ICBPs have been carried out in the last decade, taking into account the influence of surface runoff due to rainfall intensities and sediments that clog the permeable surfaces of ICBPs (Davies et al. 2002; Haselbach et al. 2006; Collins et al., 2008; Pezzaniti et al, 2009; Lucke and Beecham, 2011). However, there is a lack of a comprehensive laboratory study that takes into account the influence of direct rainfall together with surface runoff from adjacent impervious areas over a permeable surface. There is also a lack of a laboratory study of the infiltration behaviour of ICBP surfaces on car parks during their operational life when the topographic variables such as surface slope and flow distance are likely to have an important influence.

The main aim of this paper is to develop three regression models (each one corresponding to the three different clogging levels chosen for the study) based on the topographic variables such as runoff surface length (R_{SL}) and surface slope (S_S). These relationships will define the infiltration behaviour of ICBPs during their operational life in a car park bay in terms of their cumulative infiltration rates (C_{IR}). The analysis determines the most influential topographic variable, taking into account the effecte of clogging. To achieve this aim, the authors developed an Infiltration Capacity Test (ICT) using the Cantabrian Fixed (CF) Infiltrometer of Rodriguez et al. (2005), modified in two stages by: Castro et al. (2007) and González-Angullo et al. (2008).

2. RESEARCH METHODOLOGY

2.1. Cantabrian Fixed (CF) Infiltrometer

The CF Infiltrometer is a laboratory device that allows testing any kind of permeable pavement surface using a $0.25m^2$ test specimens under rainfall intensities in the range of 10-150mm/h for any storm duration and slopes between 0% and 10%. The size of the test pieces was chosen to make specimens as manageable as possible in the laboratory. The previous researches of Davies et al. (2002), Castro et al. (2007), González-Angullo et al (2008) and Rodriguez-Hernandez et al. (2012) used the same surface size.

The CF Infiltrometer is connected to an intake that provides water to the system. There is a hose section that divides the water flow and directs it to a five lines of 75 adjustable drippers (0-40l/h) with a drop diameter of 3.5mm and a kinetic energy of $5.6 \cdot 10^{-4}$J (direct rainfall simulator) and to a perforated pipe (runoff simulator) (Rodriguez-Hernandez et al., 2012) as it can be observed in the Figure 1. Each pipe has a flow meter to control the simulated rainfall intensity and the runoff rate during the tests. Once the water touches the permeable surface, it can infiltrate through or flow off to become residual runoff.

The test pieces were formed in three layers with infiltration rates increasing from the top to the bottom layers. They have the following characteristics (Figure 1):

- A top layer of ICBP precast concrete blocks of impervious material with a rectangular shape of 20cm x10cm that is 10cm thick with six elliptical vertical slots that allow the infiltration of stormwater through an open area of 6cm^2 in each block. There are no aggregates placed in the paver joints.
- A base layer 50mm thick of limestone aggregate with a particle size between 4 and 6mm, 50% voids and 1.354g/cm^3 apparent density.
- A bottom layer of polyester nonwoven geotextile with a mass of 150g/m^2 and a water permeability flow rate of 110l/m^{2}s.

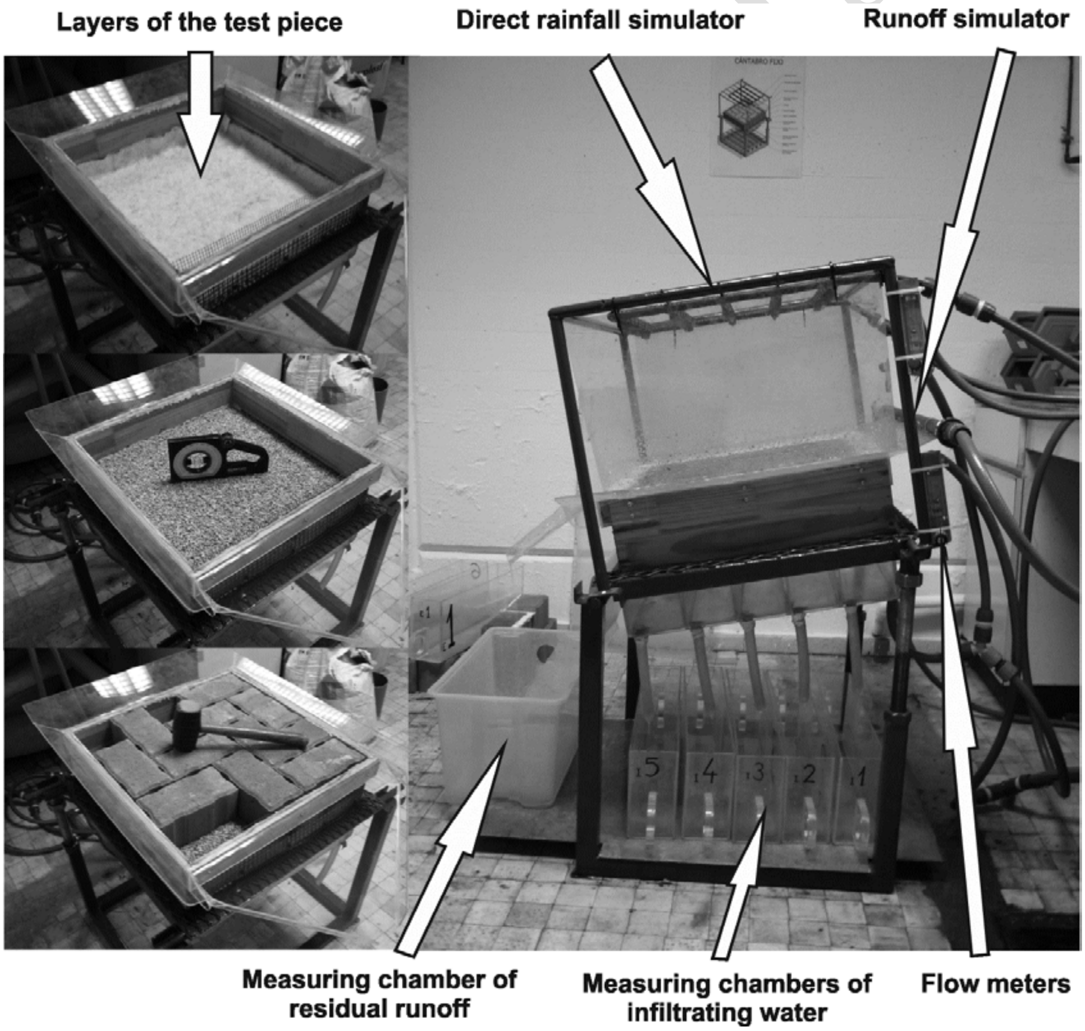

Figure 1. Scheme of the improved CF Infiltrometer of the University of Cantabria with the layers of the test piece.

The high permeability of all layers avoids saturation of the test specimen. Therefore, the base layer of aggregates is a porous media non-saturated in which the Darcy's Law can be applied based on the assumption that steady-state flow through this porous media is governed by the Navier-Stokes equations (Sansalone et al. 2008; Charbeneu et al. 2010; Rodriguez-Hernandez et al. 2012). However, the permeable surface of ICBP is made of impervious concrete blocks. The water infiltrates through the joints of the blocks, not through the blocks. Accordingly, the hydraulic phenomena inside the test specimens can be explained directly by the hydraulic characteristics of the layers and the rainfall intensity used in the tests. The volume of the slots is $60cm^3$, consequently without sediments, it requires a volume of water greater than $60cm^3$ to generate runoff and change the physical infiltration process inside the tests. The rainfall intensity needed to reach this volume with the CF Infiltrometer is 432mm/h. Therefore, the physical process is always the same in the tests and the measurements indicates the hydraulic conductivity of the surface facing the rainfall intensity simulated by the CF Infiltrometer. Taking into account the theoretical hydraulic phenomena, the most influential variables in the infiltration capacity study were the topographic variables S_S and R_{SL}.

2.2. Infiltration Capacity Test (ICT)

It is necessary to develop laboratory models to analyze the infiltration capacity behaviour of the ICBP surfaces under different scenarios of clogging. Each scenario represents a period of the operational life of ICBP surfaces. The three scenarios are:

- <u>Newly built surface</u>. This level of clogging corresponds to a newly laid surface of concrete blocks, free from any kind of sediments.
- <u>Clogged surface</u>. This second scenario represents a completely clogged ICBP surface simulating its worst infiltration capacity behaviour, at the end of its operational life.
- <u>Clogged surface, with maintenance</u>. Finally, this scenario corresponds to a clogged ICBP surface after maintenance. In the laboratory, maintenance was carried out by light brushing, simulating sweep machines to clean sediments from urban surfaces.

Also, it is necessary to define the variables of the ICT to be included in the statistical models in each scenario of clogging. These variables were chosen after a study of the variables that may influence the infiltration capacity behaviour of ICBP surfaces, taking into account previous studies in the United Kingdom (Davies et al. 2002), United States of America (Collins et al., 2008), Australia (Lucke and Beecham, 2011) and Spain (Rodriguez et al. 2012). The variables chosen were:

- <u>Runoff surface length</u> (cm)-(R_{SL}). This is the first independent topographic variable studied. It is the distance measured from the top part of the permeable surface test piece of the CF Infiltrometer, where the runoff simulator is placed (50cm maximum). Five infiltration chambers collect the infiltration water every 10 cm along the test piece (Figure 1).
- <u>Surface slope</u> (%)-(S_S). This is the slope of the test piece of ICBP. It is the second independent topographic variables of the study (Figure 1).
- <u>Cumulative infiltration rate</u> (%)-(C_{IR}). This is the dependent variable of the infiltration capacity study. It is the cumulative percentage of infiltration at each

measuring chamber.

All the tests were carried out with the same direct rainfall and runoff flow. A heavy rainfall of 60mm/h, corresponding to a 50-year return period rainfall over a duration of 30 minutes in the cities of London (United Kingdom), Los Angeles (United States), Wellington (New Zealand) and Santander (Spain) was simulated in order to check the suitability of the ICBP for catching and infiltrating stormwater in extreme conditions of rainfall intensity and clogging. Each test was carried out for thirty minutes and the laboratory conditions were always controlled during the tests with temperatures between 16ºC and 20ºC and 70-80% of humidity. The duration of the tests was divided into two stages:

- Steady-state stage. To reach the steady state of water flow inside the CF Infiltrometer, a period of about ten minutes was necessary. This time enables the wetting of the ICBP surface, the base layer of aggregates and the geotextile layer inside.
- Measuring stage. The remaining time of the test was used to measure the amount of infiltrated water and residual runoff water collected in the chambers.

Tests of ICBPs were performed with three test specimens. Each one was tested with three clogging levels and five surface slopes. Thus, there were fifteen different scenarios for each test piece combining all the independent variables of the tests. Consequently, forty-five tests were performed in the CF Infiltrometer. The main reason to use three identical test specimens of ICBP was to improve the subsequent statistical analysis of the results. Previous researches of Davies et al. (2002) identified high percentages of organic matter as one of the most important reason for decreasing infiltration capacity of ICBP surfaces. Therefore, to achieve the two clogging states in the concrete blocks test pieces (surface clogged and surface clogged with maintenance) limestone silt with 14% of organic matter was used with the size distribution shown in Figure 2a. Sawdust was employed to simulate the organic matter and replaced limestone silt in the particle size diameter ranges of 250-500μm and <80μm. The average amount of sediments used to clog the treated ICBP surface was 3900gr/m^2, lower than the 4000gr/m^2 used by Castro et al. (2007) with the same ICBP surface and particle size distribution of the sediments. This fact can be explained by the higher percentage of organic matter used, which has less density than the limestone silt sediments, as demonstrated Pratt (1990). The way in which the sediments were applied into the concrete blocks surface was very important (Figure 2b). They were firstly introduced into the gaps of the permeable surface and then slightly hand-compacted. The other key question to consider in the test performance was the simulation of the surface maintenance. This was simulated by a light brushing, taking away part of the sediments from the concrete blocks. There are better methods of maintenance, but this method was chosen because it was the easiest way to model the maintenance carried out by the sweep machines used to clean urban surfaces. The objective was to define the infiltration behaviour recovery of ICBP surfaces to develop practices that require as little maintenance as possible.

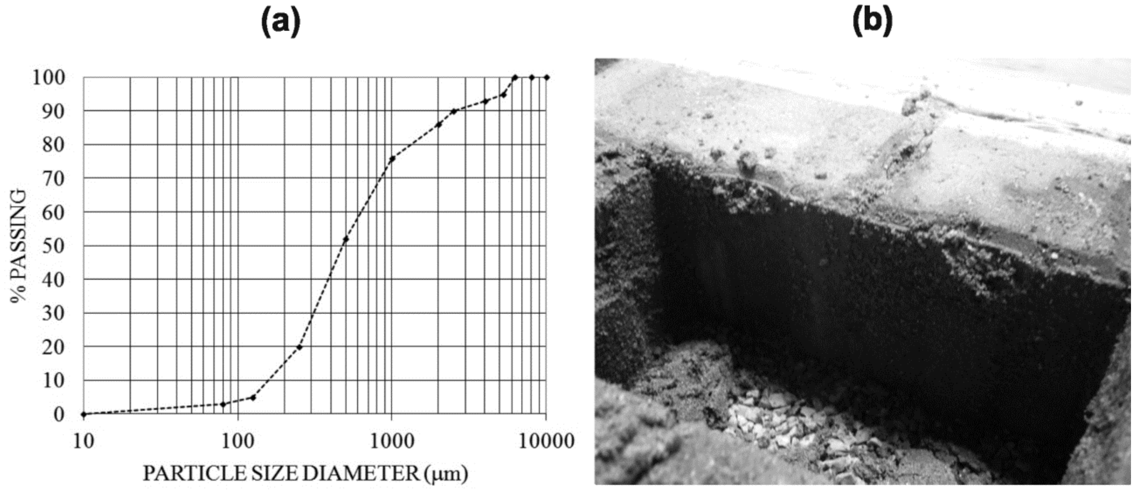

Figure 2. (a) Particle size diameter distribution of the sediments used to clog the ICBP surface. (b) Sediments clogging the slots between blocks in the clogged surface scenario.

The majority of the sediments in terms of mass were retained in the paver joints. Fine particle sediments were trapped by the base layer and the geotextile, specially the organic matter (Figure 2b). This fact confirmed previous researches on the clogging of ICBPs by Pratt (1990) and Lucke and Beecham (2011).

3. RESULTS AND DISCUSSION

The computer program used to create the linear regression models and analyze the infiltration behaviour of ICBP was IBM SPSS Statistics 19. Statistical criteria for the verification of the correct use of linear regression were established and verified in all models (analysis of collinearity, independence of observations, normality of the standardized residues of the dependent variable, and homocedasticity)

The sample size for the statistical analysis was 75 in each study case (scenario of clogging) corresponding with the 5 measuring infiltration chambers values obtained for each test and the 15 scenarios existing in each test piece. All models of infiltration rates of ICBP were obtained for a 95% confidence level (as shown in Table 1) under the laboratory and clogging conditions specified previously.

Table 1. Regression models based on the topographic variables R_{SL} and S_S and values of the β coefficient and Student's t obtained for each level of clogging in the statistical analysis.

SCENARIO OF CLOGGING	REGRESSION MODEL	R^2	Student's t		
			C	R_{SL}	S_S
Newly built surface	$C_{IR} = 10.256 + 2.049 \cdot R_{SL} - 3.255 \cdot S_S$	0.95	4.265	34.015	-13.001
Clogged surface	$C_{IR}^{1/2} = 1.336 + 0.156 \cdot R_{SL} - 0.368 \cdot S_S$	0.87	3.716	18.125	-9.865
Clogged surface with maintenance	$C_{IR} = 11.191 + 1.257 \cdot R_{SL} - 3.629 \cdot S_S$	0.76	2.887	12.657	-8.599

The infiltration behaviour of ICBP surfaces during their operational life varies depending on their clogging level. This can be verified from the three regression models of C_{IR} corresponding to the each scenario of clogging (Table 1). The increase of the independent variable R_{SL} produces an increase in the dependent variable C_{IR} rate in all the regression models proposed. The negative sign of the independent variable S_S in the equations shows that an increase of its value produces a decrease of the C_{IR}. Moreover, it can be observed from the Student's t values in Table 1 that the most influential variable in all models is the R_{SL} compared to the S_S. The influence of the constant in all the equations of the models is quite low, giving greater credence to the models obtained.

The lack of sediments in the test piece surface corresponding to the first scenario of clogging produces low variability of the tests results and a high efficiency of prediction through the linear regression model, as can be seen by its high R^2 value (Table 1). This linear regression model represents the best infiltration behaviour of ICBP permeable surfaces during their operational life (surface newly built). It is important to limit the range of validity of this model from a hydrological point of view to avoid the mathematical possibility of a negative cumulative infiltration rate. This occurs when the independent variables reach their extreme values in the ICT, combining higher values of S_S and lower values of R_{SL}.

On the other hand, the clogged surface shows a R^2 value lower than for newly built model, increasing the variability of the test results (Table 1). This can be explained by the sediments that fill the slots of the ICBP (Figure 2) over the permeable surface modifying its infiltration rate behaviour and decreasing the C_{IR} values. In this case, the variable's outcomes not satisfy the conditions indicated previously to obtain a regression linear model due to this variability. Therefore, a transformation of the C_{IR} variable was necessary. This transformation was calculated using the scatter diagrams of the dependent variable (C_{IR}) in each independent variable (R_{SL} and S_S) and consisted of the square root of the dependent variable.

Maintenance increases the variability of the tests results (Table 1). Its R^2 is the lowest value in comparison with those for the other clogging levels due to the combined influence of the sediments and maintenance. These external factors modify the C_{IR} behaviour of the ICBP surface. In this case, there are negative mathematical values of C_{IR} when the R_{SL} has low values in the tests (0-10cm) and there are high values of S_S (7%-10%). It is also observed that for low R_{SL} values, newly built ICBPs have similar infiltration rate behaviour to clogged ICBP surfaces with maintenance for all types of S_S. This means that correct maintenance for ICBPs restores infiltration rates to those occurring at the beginning of their operational life.

Residual runoff is the runoff that cannot infiltrate into the ICBP surface and flows into the measuring chamber of residual runoff as it can be seen in Figure 3. This residual runoff represents the reduction of the infiltration capacity of the ICBP surface. The infiltration capacity of newly built surfaces is above 90% for all S_S, being 99.5% for slopes close to 0%. However, the infiltration capacity decreases drastically in a clogged surface when $S_S \geq 3\%$. Maintenance operations allow recovery of about 10% of the infiltration capacity of ICBPs in almost all cases. When the surface slope is close to 0%, the maintenance is very effective in the recovery of the initial infiltration capacity behaviour. The influence of the S_S is quite low when the slope is above 7%, because there is no significant increase of the residual runoff (Figure 3).

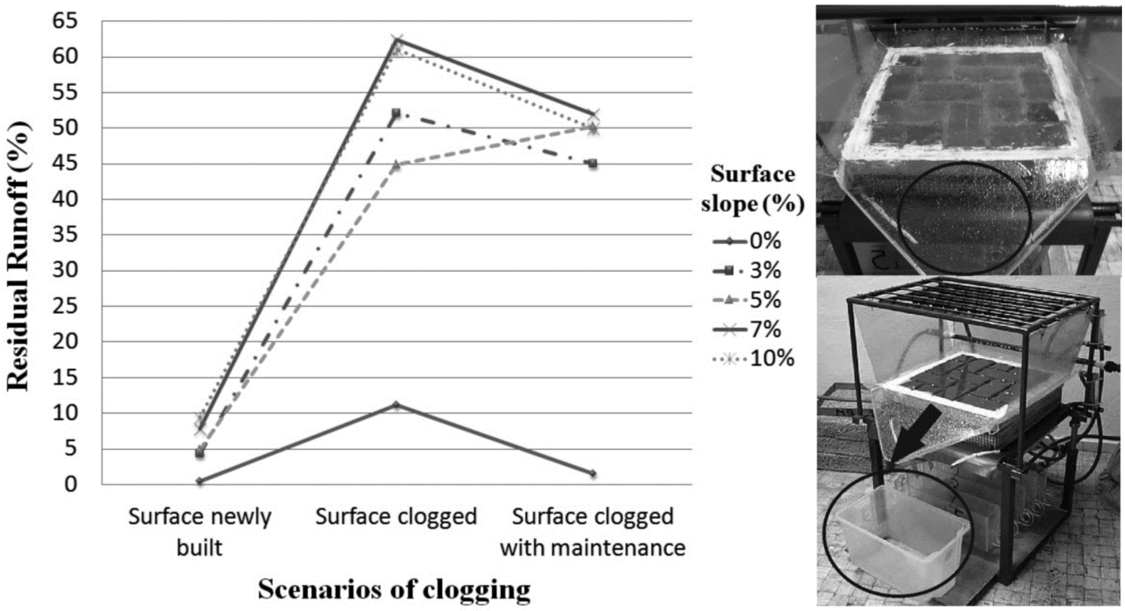

Figure 3. Infiltration capacity of the ICBP surface in terms of its residual runoff depending on the surface slope and the scenario of clogging.

As can be seen in Figure 3, the runoff surface flow started from 3% of S_S in all clogging scenarios, except in the surface clogged scenario where the flow started with 0% due to the low permeability. The strange outcome in the residual runoff flow for S_S=3%, being higher than for 5% (Figure 3), can be explained by the maintenance operations. They not only removed a small part of the sediments from the joints of the blocks, but also compacted the sediments inside the joints, reducing the permeability. Conversely, the kinetic energy of the drops impacting on the surface helped to recover the permeability by removing sediments from the joints and dragging them away when the S_S increased to above 5%.

4. CONCLUSIONS

The regression models predict the infiltration behaviour of the treated ICBP well, with R^2 values above 0.76 in all cases, with R^2=0.95 for newly built surfaces.

Uncertainty of the regression models increases in the second scenario, with the sediments used in this research clogging the ICBP surface, and also with its subsequent maintenance.

R_{SL} is the most influential topographic variable on the infiltration behaviour of the ICBP surface as showed by Student's t values obtained in the statistical analysis of the regression models.

The infiltration capacity of newly built ICBPs is above 90% for all S_S, being 99.5% for slopes close to 0%. Nevertheless, the infiltration capacity decreases markedly for clogged surfaces and clogged surfaces with maintenance when $S_S \geq 3\%$.

Suitable maintenance of ICBP surfaces with slopes close to 0% enables the recovery of 99% of the infiltration capacity at the beginning of their operational life. However, maintenance only achieves a 10% recovery of the infiltration capacity for $S_S \geq 3\%$.

In the future, field tests will be developed to validate the regression models obtained in the laboratory. Also, further tests will be conducted on other permeable surfaces applying the same laboratory and statistical methodology, with the aim of characterizing the infiltration behaviour of the most used permeable pavements across the world during their operational life.

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