This paper is part of the Proceedings of the 3rd International Conference on Design, Construction, Maintenance, Monitoring and Control of Urban Water Systems (UW 2016)
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Laboratory study on the rainfall influence over the sediment transport dynamics on pervious pavements' discharge

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Abstract

Infiltration capacity reduction due to the progressive clogging of land surfaces is the most important feature controlling pervious pavement life use. It is influenced by material and local characteristics. The rainfall regime can be influenced by water volume and rainfall intensity. A laboratory study was conducted to analyze the influence of the rainfall intensity on the sediments dynamics on pervious pavements. Three different rainfall intensities were settled using a rainfall simulator: 50 mm/h, 100 mm/h and 150 mm/h. Pervious concrete (PC) and porous asphalt (PA) slabs of 50 x 26 x 5 cm, with void contents of 15%, 20% and 25% were tested. They were clogged using sediments containing mostly sand and an assembled PSD (particle size distribution) that fall within the range of real case scenarios. The sediments were applied over the slabs on aerial loadings of 0.5 kg/m^2, 1.0 kg/m^2 and 2.0 kg/m^2. Using a falling head permeameter discharge measurements were made over the samples in newly built conditions, after clogging and after rainfall simulation. The obtained results showed that in most cases the rainfall intensity does not produce significant differences in discharge time. The information obtained through this study provides better understanding of sediments transport mechanisms on pervious pavements and could lead to customized maintenance routines.
Keywords: pervious pavement, clogging, rainfall simulation, sustainable urban drainage.

www.witpress.com, ISSN 1743-3509 (on-line)
doi:10.2495/UW160151

1 Introduction

Pervious pavements are part of sustainable drainage systems (SUDs) and promote storm water volume and pollutants control (Marchioni and Becciu [1]). The open porosity matrix allows water to infiltrate although at the same time it behaves like a filter, promoting particulate matter (PM) separation. Although this particular feature is essential to promote water quality improvement, it also reduces the infiltration capacity of the pavement at the point that maintenance or rehabilitation is needed (Sansalone *et al*. [2]).

The infiltration capacity reduction of pervious pavement systems will basically depends upon the material characteristics (void content, hydraulic conductivity, pore size distribution – $PSD_{(pore)}$, effective porosity, tortuosity) and the clogging sediment properties (loading, particle size distribution – PSD). There is also local influence of local features, like the average daily traffic, the rainfall regime and presence of vegetated areas (Li *et al*. [3]). Depending on the rainfall characteristics, the sediments deposited over the pavement surface could be washed off, partially recovering the infiltration capacity, or consolidated due to the impact of the rain drops, decreasing the infiltration capacity of the pavement. Accurately knowing how long it takes for the pavement to fall below an accepted level of infiltration allows for better scheduling of maintenance and better evaluation of costs over the service life.

2 Objective

The objective of this study is to investigate the rainfall intensity influence over pervious surfaces using a laboratory rainfall simulation device.

3 Materials and methods

3.1 Pervious concrete

Nine pervious concrete slabs were produced with 50 x 26 x 5 cm of dimension. The concrete mix design was obtained according to a previous study from (Bonicelli *et al*. [4]). The mix design contained a 2–12 mm limestone coarse aggregate, and 5% by weight of coarse aggregates of quarry sand. It was used a type II CEM II 42.5R A-LL Portland cement with limestone addition with a water to cement ratio (*w/c*) of 0.27 and a cement to aggregate ratio (*a/c*) of 0.2. Three different admixtures were used: high range water reducer, air-entraining admixture and viscosity-modifying admixture with the dosages recommended by the manufacturers. The slabs were manually compacted with the help of a Marshall test device. By controlling the mass of concrete in a specific volume three slabs were produced for each void content: 15%, 20% and 25%.

3.2 Porous asphalt

We also produced nine slabs of porous asphalt with 50 × 26 × 5 cm of dimensions. The porous asphalt mixture contained 4.1% by weight of mixture of SBS (Styrene-

Butadiene-Styrene) modified bitumen and the slabs were compacted using a wheel tracking device to obtain the void contents of 15%, 20% and 25%.

3.3 Clogging sediments loadings

Sand and recovery filler were mixed to achieve a PSD distribution with maximum density according to particle size packing theories. This PSD distribution was then compared to dry deposition PSD obtained in the literature (Deletic and Orr [5]) (Zafra *et al*. [6]) (Bian and Zhu [7]) to guarantee that the material fell within their limits.

3.4 Falling head permeameter

A falling head permeameter according to EN 12697-19 was used to measure the water flow on the slabs. A similar device, the LCS (*Laboratorio de Caminos de Santander*) permeameter have already been used to investigate the decaying of infiltration capacity on pervious surfaces (Jimenez and Perez [8]) (Sañudo-Fontaneda *et al*. [9]). This field falling head permeameter measures drainage capacity (dm^3/min) and is not suitable to obtain the hydraulic conductivity using Darcy's Law (Ranieri *et al*. [10]). In this work the discharge time was measured, i.e., the time the falling water column falls 20 cm, to obtain a qualitative analysis of the behaviour of the slab regarding infiltration capacity. When the discharge time reach 300 s the slab was considered fully clogged and the test stopped. All tests were conducted on three points of the slabs.

3.5 Rainfall simulator

A rainfall simulator was developed to investigate the behaviour of runoff over the pervious surfaces under clogged conditions. The device consisted of a 3 m high steel structure with 30 droppers placed on top. The slabs were placed 60 cm over the ground and in between the droppers and the slabs were placed framed nets to distribute the raindrops. The droppers were feed by a plastic tube connected to a flow meter with 2–30 l/h capacity. The rainfall simulator allows to simulate rainfall intensities ranging from 25 mm/h to 200 mm/h. The flour pellet method was used to measure the drop distribution and assure they respect the dimension of natural rainfall drops (Hudson and Rhodesia [11]).

3.6 Rainfall simulation tests

Using the rainfall simulator the 18 slabs of pervious concrete and porous asphalt were tested using rainfall intensities of 50 mm/h, 100 mm/h and 150 mm/h and aerial loading of sediments of 0.5 kg/m^2, 1.0 kg/m^2 and 2.0 kg/m^2 in a total of 162 tests. The test consisted in placing the slab on the rainfall simulator, manually adding the load of sediment over the slab and starting 15 minutes of rainfall on the chosen intensity. After the 15 minutes the rainfall stopped, the runoff mass was collected on a small container and the discharge time was measured with the falling head permeameter.

4 Results and discussion

4.1 Preliminary results

Prior of conducting rainfall simulation tests the discharge times were measured with and without load of sediments according to Figure 1 for PC and Figure 2 for PA. As expected for a heterogeneous material the discharge time results were highly disperse, as can be observed through the overlapping errors bars in Figures 1 and 2 and in Table 1.

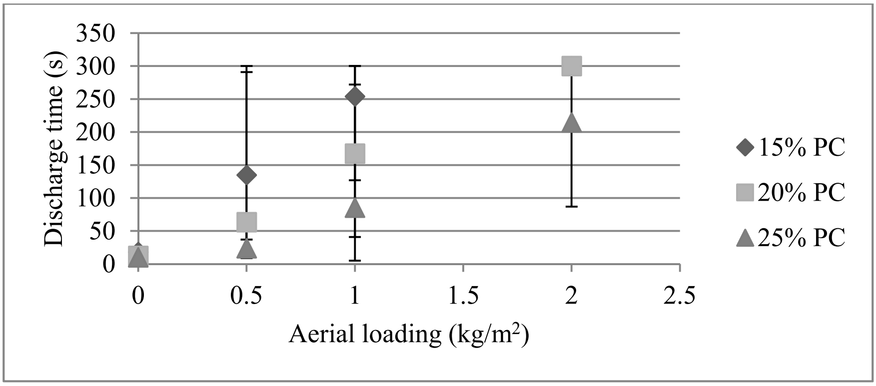

Figure 1: PC initial discharge times.

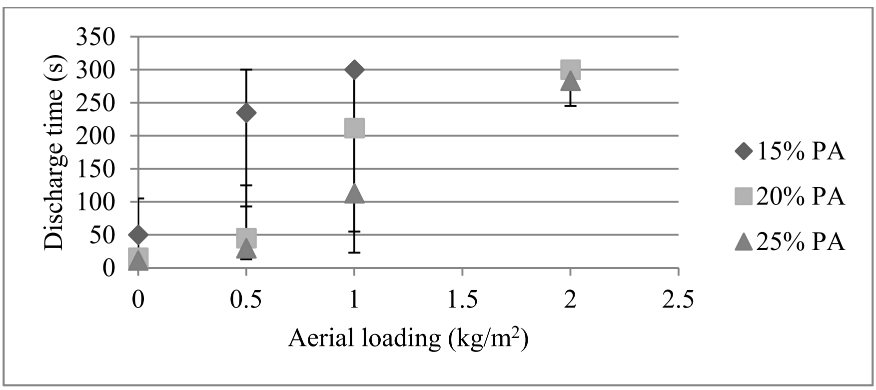

Figure 2: PA initial discharge times.

For this reason the results obtained were analysed in order to assess the statistical significance of the differences observed depending on the void contents of the materials for the different clogging scenarios. The non-parametric Kruskal–Wallis H-test was used to compare the PC and PA discharge time results for the three void contents. The results of this test showed that there were significant differences among the discharge times measured for the different air void contents for both pervious concrete (p-value=0.0014) and porous asphalt (p-value= 3.68×10^{-5}) considering a 99% confidence level. Therefore a statistically significant difference was observed for discharge times when varying the void content.

Table 1: Initial discharge times for the PC and PA slabs.

Type	Void content	Aerial loading (kg/m^2)	AVR(1) (s)	STD(2) dev(s)	Maximum value (s)	Minimum value(s)
PC	15	0	18	2	21	15
	15	0.5	135	108	300	37
	15	1	254	60	300	127
	15	2	300	0	300	300
	20	0	12	2	16	9
	20	0.5	63	83	291	20
	20	1	167	103	300	41
	20	2	300	0	300	300
	25	0	10	3	14	5
	25	0.5	24	12	50	9
	25	1	85	85	272	5
	25	2	215	90	300	87
PA	15	0	50	24	105	20
	15	0.5	235	92	300	41
	15	1	300	0	300	300
	15	2	300	0	300	300
	20	0	15	3	19	10
	20	0.5	45	29	125	22
	20	1	211	86	300	55
	20	2	300	0	300	300
	25	0	11	3	18	8
	25	0.5	30	25	93	13
	25	1	113	102	300	23
	25	2	283	24	300	245

(1)Average; (2)Standard deviation.

An exponential behaviour was observed for the average discharge as function of the sediments aerial loadings. To model that behaviour a first order exponential model was used (eqn (1)), where d is the discharge, l is the sediments aerial loadings, and a and b are constants. The coefficients of determination R^2 for the PC samples of 15%, 20% and 25% of void content are respectively of 0.74, 0.93 and 0.98. For the PA samples of 15%, 20% and 25% of void content the R^2 is respectively of 0.53, 0.82 and 0.97.

$$d(l)=a^x.e^{b.x} \tag{1}$$

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The modelled equation was used to quantify the sediments loads necessary to fully clog the slabs. It was obtained that to reach fully clogged stage on PC it was necessary 1.8 kg/m^2 of loadings for the 15% void content, 2.0 kg/m^2 for 20% void content and 2.3 kg/m^2 for 25% void content. For the PA it was necessary 1.01 kg/m^2 of loadings for the 15% void content, 1.95 kg/m^2 for 20% void content and 2.04 kg/m^2 for 25% void content.

On this study the PC showed a higher infiltration capacity in general when compared with the PA. This difference can be result of the difference on PSD of the aggregates used and the compaction methods. Further analysis is needed to investigate the pore properties of the materials (total porosity, effective porosity, $PSD_{(pore)}$, pore connective, tortuosity) to understand the difference on the results.

4.2 Rainfall intensity impact on sediment transportation

4.2.1 PC results

In Figure 3, the PC tests held with the rainfall simulator in comparison with the initial test without rainfall are plotted. The data plotted is average and the error bars shown the maximum and minimum values. Statistical analysis was held to confirm if there were statistically significant different for the results obtained for each aerial loading group by using the Kruskal-Wallis H-test (Table 2). For the void contents of 20% and 25%, and aerial loading of 0.5 kg/m^2 and 1.0 kg/m^2 there were not significant difference between samples with 99% of confidence level. That means that for these tests the rainfall intensities did not produce significant changes on sediment transportation and did not result on significant changes on discharge times. For the samples that result different, multiple pairwise comparison were performed by using the non-parametric Mann–Whitney U-Test (Wilcoxon Rank Sum Test) with a confidence level of 95% (Table 3).

Analysing the PC results it can be observed a significant variation of the discharge time for all tests with rainfall of 150 mm/h and aerial loadings of 2 kg/m^2. For that sediment loadings the surfaces were completely clogged for the 20% and 25% void content and after the rainfall simulations they shown a reduction on discharge time going from 300 s to 125 s and 201 s (33% and 58% of reduction) respectively, on average. For the 25% void content the reduction was from 215 s to 72 s, 66% of reduction on average. Therefore a rainfall effect over the sediments transportation is clearly notice on high intensities rainfall and clogged or almost clogged situation. In Milan's case (North of Italy) a rainfall with 150 mm/h of intensity and 15 minutes of duration will have a return period of 50 years (Becciu and Paoletti [12]).

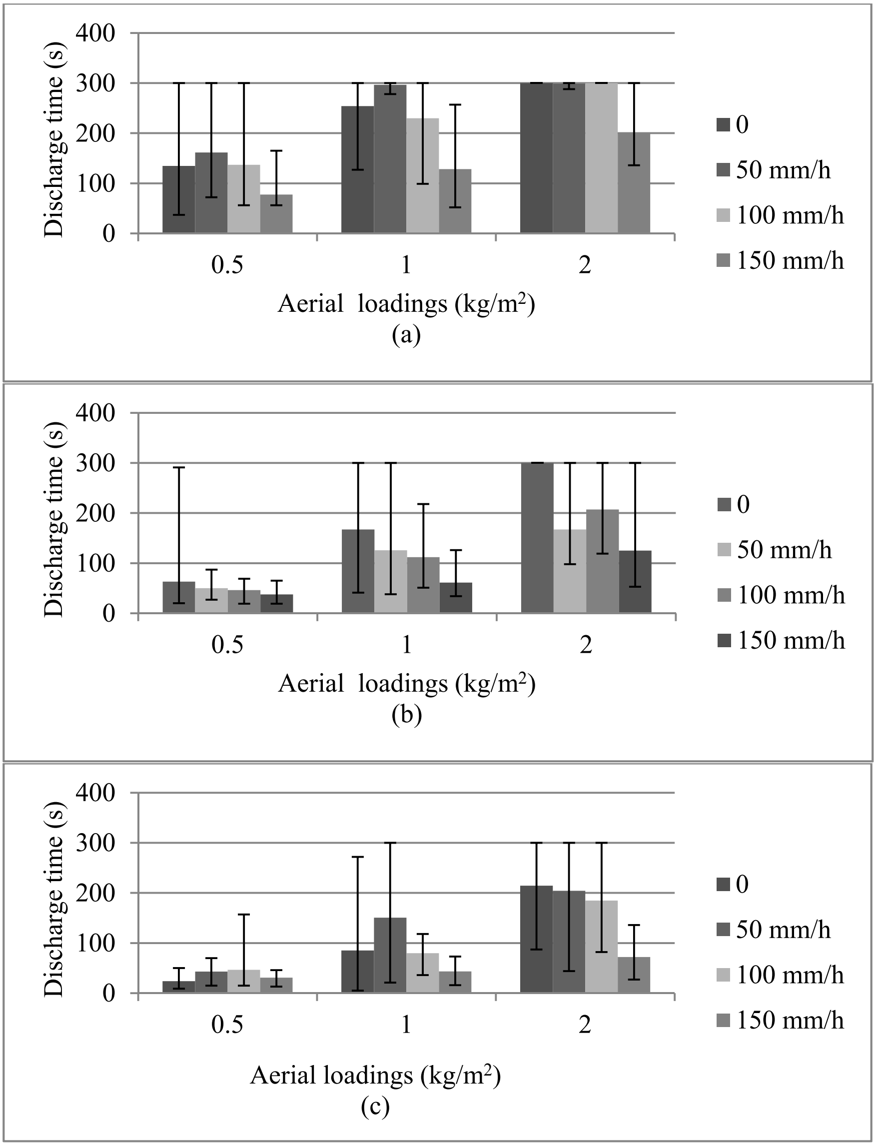

Figure 3: PC discharge time measured after rainfall simulation tests with aerial loadings ranging from 0.5 kg/m^2 to 2.0 kg/m^2 and rainfall intensities ranging from 50 mm/h and 150 mm/h compared to the preliminary tests without rainfall. (a) = 15% void content, (b) = 20% void content and (c) = 25% void content.

Table 2: PC statistical analysis on the same void content and aerial loading group.

Void Content (%)	Aerial Loading (kg/m^2)	p(1)	$p > 0.01$
15	0.5	0.005	false
15	1	0.001	false
15	2	0.003	false
20	**0.5**	**0.409**	**true**
20	**1**	**0.048**	**true**
20	2	0.001	false
25	**0.5**	**0.121**	**true**
25	**1**	**0.180**	**true**
25	2	0.003	false

(1)p-value for the null hypothesis that the tested data comes from the same distribution, using a Kruskal-Wallis test. The alternative hypothesis is that not all samples come from the same distribution.

Table 3: PC statistical analysis comparing discharge time for different rainfall intensities.

Void content (%)	Rainfall intensity (mm/h)	Aerial loading (kg/m^2)	p(1)	$p > 0.05$	Rank sum
15	0 × 50	0.5	0.339	true	74
15	0 × 100	0.5	0.055	true	64
15	0 × 150	0.5	0.983	true	87
15	0 × 50	1	0.164	true	72.5
15	0 × 100	1	0.520	true	92.5
15	**0 × 150**	**1**	**0.002**	**false**	**119**
15	0 × 50	2	1.000	true	90
15	0 × 100	2	0.082	true	103.5
15	**0 × 150**	**2**	**0.002**	**false**	**117**
20	**0 × 50**	**2**	**0.002**	**false**	**117**
20	**0 × 100**	**2**	**0.009**	**false**	**112.5**
20	**0 × 150**	**2**	**0.000**	**false**	**121.5**
25	0 × 50	2	0.675	true	90.5
25	0 × 100	2	0.468	true	94
25	**0 × 150**	**2**	**0.001**	**false**	**121.5**

(1)p = Rank sum test returns the p-value of a two-sided Wilcoxon rank sum test. The null hypothesis is that the two samples data are from continuous distributions with equal medians, against the alternative that they are not.

4.2.2 PA results

The same analyses were held for the PA data. In Figure 4 the discharge times varying the rainfall intensities for each group of void content and aerial loadings are shown. Then in Table 4 the groups with the same void content and aerial loading were compared using the Kruskal–Wallis H-test to inquiry if they were significant different with 99% of confidence level.

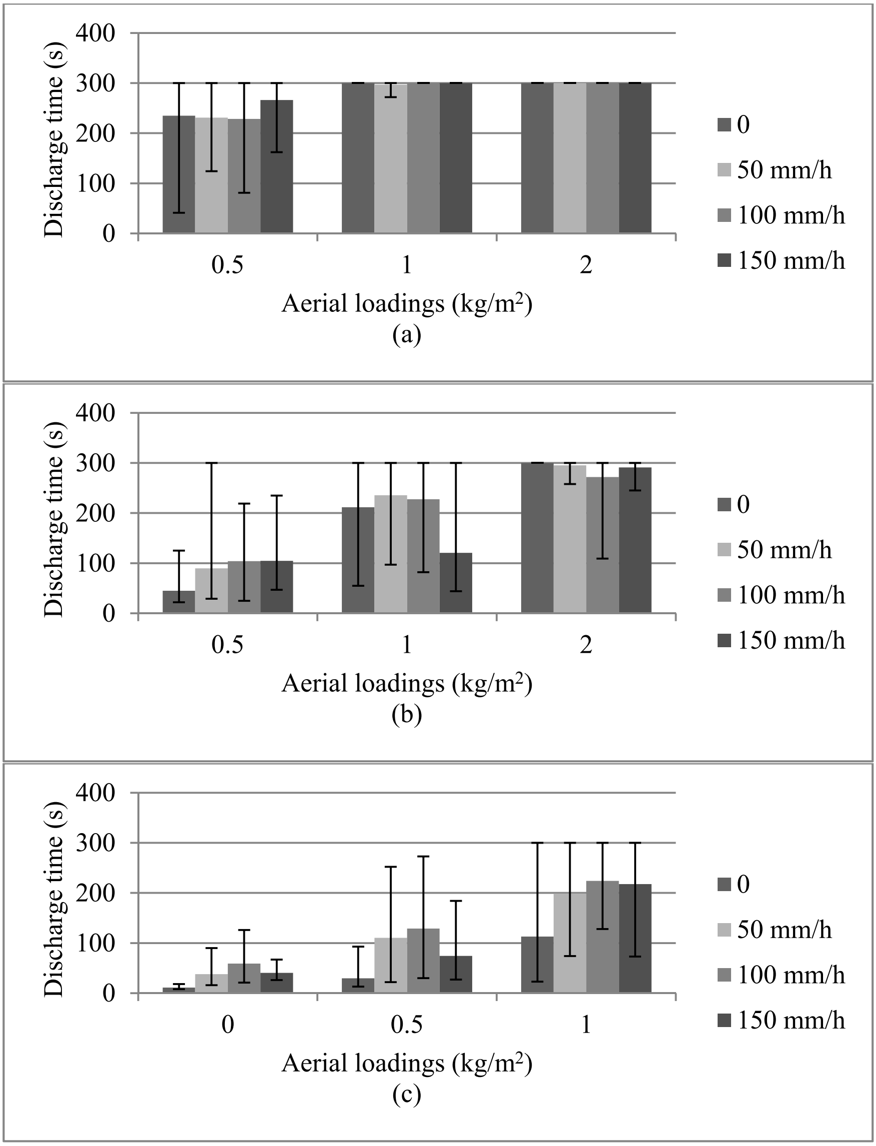

Figure 4: PA discharge time measured after rainfall simulation tests with aerial loadings ranging from 0.5 kg/m^2 to 2.0 kg/m^2 and rainfall intensities ranging from 50 mm/h and 150 mm/h compared to the preliminary tests without rainfall. (a) = 15% void content, (b) = 20% void content and (c) = 25% void content.

Table 4: PA statistical analysis on the same void content and aerial loading group.

Void content (%)	Aerial loading (kg/m^2)	p[1]	p > 0.01
15	0.5	0.883	true
15	1	0.392	true
15	2	- [2]	-
20	0.5	0.022	true
20	1	0.040	true
20	2	0.457	true
25	0.5	0.057	true
25	1	0.371	true
25	2	0.107	true

[1]p-value for the null hypothesis that the tested data comes from the same distribution, using a Kruskal–Wallis test. The alternative hypothesis is that not all samples come from the same distribution.
[2]For the 15% void content with 2.0 kg/m^2 of sediments all the discharge times reached the maximum limit of 300 s.

The analysis on the PA samples did not find statistically significant difference between the discharge time when varying the rainfall intensities for the same void content and aerial loading of sediments. Therefore the event of rainfall does not produce visible differences on discharge on the PA slabs. This result, which does not follow what was observed on the PC, can also be explained for the differences on the porous properties and further analysis should be conducted.

4.3 Runoff coefficient

The runoff coefficient was also analysed after all rainfall simulation tests. On PC the maximum value for runoff was 1.78% for a slab with 15% void content clogged with 2 kg/m^2 of sediments under a 150 mm/h rainfall intensity. On 69% of PC rainfall simulation tests any runoff was not observed (runoff coefficient = 0).
For the PA the maximum value of runoff was 12.64% for a slab with 15% void content, clogged with 2 kg/m^2 of sediments under a 100 mm/h rainfall intensity. For 38% of PA tests, there was no observed runoff (runoff coefficient = 0) and 74% of the tests showed runoff coefficients below 1.0%.

In both cases the value for runoff coefficient is significantly lower than a conventional pavement, which can reach over than 90% runoff coefficient (de Araújo *et al.* [13]). It was observed that even in the cases that the slabs were completely clogged, i.e., showing a 300 s discharge time, the runoff coefficient remained low, meaning that the pervious pavement was still functional. The probable reason is that the rough surface reduced the runoff velocity at the point that allowed infiltration as it was observed on previous research (Rodriguez-Hernandez *et al.* [14]). All the tests were conducted with a 2.5% slope and an increase on slope could eventually lead to higher runoff. The variations held on the tests (void content, rainfall intensities, sediments concentration) did not produce significant differences on the runoff results.

5 Conclusions

Under the conditions of this study the rainfall intensity had no or little effect on the sediments transportation over the surface of the pervious pavement and therefore does not produce significantly different effects on the pavement. Additionally, when modelling the infiltration capacity decay, in this case represented by the increase of discharge time, the effect of rainfall intensity may be disregarded within the constraints present here. However, being the sediment PSD and pervious surfaces $PSD_{(pore)}$ the main elements of influence on the clogging process, variation on these elements could lead to changes regarding the influence of rainfall.

One interesting point on this study was that even during fully clogged discharge times the runoff volume was significantly low, hence the pavement was still functional for the runoff reduction volume property.

This project following steps consists on evaluate the pore properties of both PC and PA samples and determine the hydraulic conductivity (K_d) through the Darcy's Law, to be able to model the hydraulic and pollution removal. Also by relating the sediments loadings with real case scenarios the discharge decay can be related with a time period and provide a maintenance schedule under the materials and local conditions.

Acknowledgements

We appreciate the efforts of the engineer Matteo Brugin with the rainfall simulation tests and the support of the "Gaudenzio Fantoli" Hydraulics Laboratory and the Experimental Roadway Laboratory of the Politecnico di Milano and their staff. Mariana Marchioni would like to thanks Capes for funding this work through the scholarship number BEX 9224/13-0 as part of the *Ciências sem Fronteiras* program. Valerio C. Andrés-Valeri would like to thanks the Spanish Ministry of Economy and Competitiveness, funding for his research activity in the Politecnico di Milano through the PhD fellowship (BES-2013-062604), and the mobility grant (EEBB-I-15-10095).

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