UFSM

CIÊNCIA e NATURA

ISSN 2179-460X
OPEN ACCESS

Ci.e Nat., Santa Maria, v. 45, spe. n. 1, e84089, p. 01-27, 2023 • https://doi.org/10.5902/2179460X84089
Submitted: 14/06/2023 • Approved: 04/07/2023 • Published: 02/10/2023

Special edition

Field investigation of clogging with different sediment types in a permeable pavement system with low-cost maintenance

Investigação a campo da colmatação com diferentes tipos de sedimentos em um sistema de pavimentos permeáveis com baixo custo de manutenção

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ABSTRACT

Maintenance has a significant impact on permeable pavements' service life. Proper cleaning procedures include pressure washing and heavy-duty wet/dry vacuum to remove accumulated sediment and maintain permeability. Aiming to analyze the influence of sediment type and size on the clogging process and the importance of preventive maintenance, six experimental permeable pavement modules were assessed. Pairs of in-situ Pervious Concrete (PC), Permeable Interlocking Concrete Pavement (PICP) and Permeable Interlocking Pervious Concrete Pavement (PIPCP) were monitored over two consecutive periods: i) under natural clogging process; ii) accelerated clogging under sand and clay sediment types. At the end of both periods, all modules received maintenance through water pressure washing. The results showed a reduction of up to 80% in the surface infiltration capacity during the natural clogging period, but that most of it could be recovered using pressure washing. Result in all situations also reinforced that periodic cleaning every 4-6 months, even with just pressure washing, as a key factor to extend permeable pavements' life cycle.

Keywords: Pervious concrete; Infiltration; Life cycle

RESUMO

A manutenção tem um impacto significativo na vida útil dos pavimentos permeáveis. Os procedimentos de limpeza adequados incluem lavagem sob pressão e aspiração a vácuo molhada/seca para remover sedimentos acumulados e manter a permeabilidade. Com o objetivo de analisar a influência do tipo e tamanho do sedimento no processo de entupimento e a importância da manutenção preventiva, foram avaliados seis módulos experimentais de pavimento permeável. Pares de Concreto Permeável In-situ (PC), Pavimento de Concreto Intertravado (PICP) e Pavimento de Concreto Permeável Intertravado (PIPCP) foram monitorados em dois períodos consecutivos: i) sob processo natural de colmatação; ii) entupimento acelerado com sedimentos de areia e argila. No final de ambos os períodos, todos os módulos receberam manutenção por meio de lavagem com pressão de água. Os resultados mostraram uma redução de até 80% na capacidade de infiltração da superfície durante o período de colmatação natural, mas a maior parte pode ser recuperada com a lavagem sob pressão. O resultado em todas as situações também reforçou que a limpeza periódica a cada 4-6 meses, mesmo com apenas lavagem sob pressão, é um fator chave para prolongar a vida útil dos pavimentos permeáveis.

Palavras-chave: Concreto permeável; Infiltração; Ciclo de vida

1 INTRODUCTION

Due to the increasing urbanization and impermeability in urban areas, techniques that promote the infiltration and retention of surface runoff have gained attention in the last years (Eisenberg; Lindow; Smith, 2015; Tong, 2011). Permeable pavements, are one of these techniques, that can be designed to meet stormwater management requirements for water quantity and quality control, besides groundwater recharging (Hu et al., 2020; Antunes; Ghisi; Thives, 2018; Hein; Dougherty; Hobbs, 2013; Kayhanian et al., 2012; Chopra et al., 2010; Zhang et al., 2018; Rama; Shanthi, 2018; Razzaghmanesh; Beecham, 2018; Kia; Wong; Cheeseman, 2018; Tong, 2011; Schaefer; Kevern; Wang, 2011; Deo; Sumanasooriya; Neithlath, 2010).

During rainfalls, the surface runoff is totally or partially directed to the pervious pavement lower layers through its porous surface, providing filtration, temporary storage, and its gradual infiltration into the soil (Antunes; Ghisi; Thives, 2018; Eisenberg; Lindow; Smith, 2015; Urbonas; Stahre, 1993). Over this process, solids such as soil particles (sand, silt, clay) eroded from surrounding areas, debris from other surfaces, small particles originating from the pavement itself, and organic matter from surrounding vegetation can be carried by the runoff, wind and precipitation becoming trapped in the pervious pavement's pores leading to the loss of the in-situ permeability over time, in a phenomenon known as clogging (Lin et al., 2016; Deo; Sumanasooriya; Neithlath, 2010; Zhang et al., 2018).

Due to the reduction of surface infiltration rates over the years, there is a need for cleaning and maintenance of those pavements. To date, procedures such as vacuum hose/sweeper, pressure washing, regenerative air sweeper, and their combination have been used as maintenance measures to restore the permeability of pervious pavements improving its durability (Hu et al., 2020; Hein; Dougherty; Hobbs, 2013). In the literature, recommendations for cleaning frequency vary between one and four annual cleanings, being the aggressiveness of the environment and traffic on the pavement are the main external elements that should be taken into account to set this periodicity (Razzaghmanesh; Beecham, 2018; Kia; Wong; Cheeseman, 2017).

Therefore, there is not an agreement about the most suitable procedure for pervious pavement maintenance, especially because the clogging effect is not well-understood (Tong, 2011; Mishra; Zhuge; Karunasena, 2013) due to the huge variability of external factors such as the degree of clogging and the effect of periodic clogging process (HU et al., 2020), the type of the pervious pavement and the size of the solid particles (Coughiling et al., 2012; Deo; Sumanasooriya; Neithlath, 2010; Schaefer; Kevern; Wang, 2011), and climatic conditions (Yong; Mccarthy; Deletic, 2013; Watson-Craik; Jones, 2020). In this sense, studies on (i) how different particles clog in the system, (ii) which method(s) is(are) best to reverse this process and (iii) how often to execute it (them) (Kia; Wong; Cheeseman, 2017; Lin et al., 2016; Tong, 2011; Chopra et al., 2010) can provide different findings.

This research sought to evaluate the effects of different kind of sediments (sand and clay) on clogging and the recovery efficiency in experimental open-field 1m² pavement modules, paved with Pervious Concrete (PC), Permeable Interlocking Concrete Pavement (PICP) and Permeable Interlocking Pervious Concrete Pavement (PIPCP). The monitoring was accomplished during 17 months under natural and accelerated clogging process followed by cleanings, and surface infiltrations tests, which enabled to assess the loss of surface infiltration capacity as well the recovering capacity after the cleaning.

2 METODOLOGY

Superficial runoff drained from each module and the water levels within these modules were measured along the monitoring period. Surface infiltration rates at different periods were assessed through the single-ring infiltration test (ASTM, 2017; ABNT, 2015). The clogging effect on reducing surface infiltration was evaluated by combining the results.

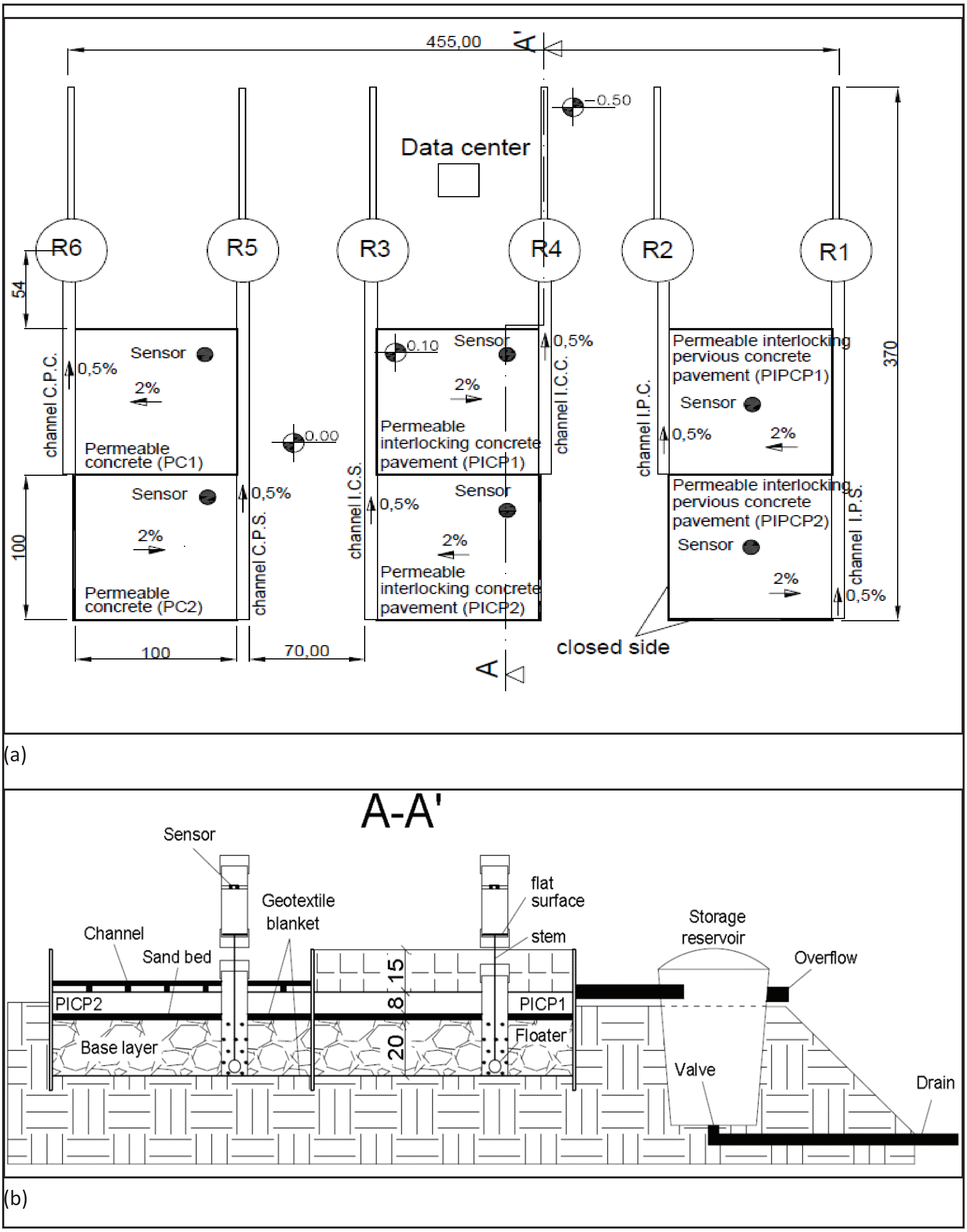
2.1 Experimental setup

The six modules were placed in the countryside of Itaara, in the central region of Rio Grande do Sul, the Southernmost State in Brazil. The region is characterized by regular rainfall throughout the year, with annual average rainfall between 1,500 mm and 1,600 mm. The climate is humid subtropical according to the Köppen classification, with average temperatures ranging from 12 ºC during winters to 27 ºC during summers.

To determine soil permeability at the site, infiltration tests with concentric rings (ASTM, 2018) were carried out at three points. The initial average infiltration rate was 203.65 $mm.h^{-1}$ while saturated average infiltration rate was 8.75 $mm.h^{-1}$. The six $1m^2$ area modules were individually built on the non-compacted soil and assembled in pairs according to the pervious surface used. The pairs with the same type of pervious surface were placed side by side and were sealed laterally from each other by a wall, avoiding entry or loss of water volumes. To compose the modules, three pervious surfaces were used: in-situ Pervious Concrete (PC), Permeable Interlocking Concrete Pavement (PICP) and Permeable Interlocking Pervious Concrete Pavement (PIPCP) (Figure 1).

For the in-situ PC a dosage was determined using local materials (shown in Table 1) and evaluated in laboratory for mechanical and hydraulic characterization. Tests of resistance to axial compressive strength, flexural strength, diametral compression, abrasion mass loss, unit weight, porosity, and permeability by means of constant and falling head permeameters were accomplished according to ACI (2010), and results are presented in Table 2.

Figure 1 – (a) Design of the experimental modules and (b) AA ’cross-section



Source: Authors (2023)

Table 1 – Physical properties and proportion of pervious concrete

Materials	Water	Cement	Coarse aggregate 1*	Coarse aggregate 2*	Fine aggregate
Specific gravity ($g.cm^{-3}$)	1.00	2.93	2.44	2.50	2.64
Mixture proportions	0.36	1.00	3.04	0.76	0.20
Mixture proportions ($kg.m^{-3}$)	116.82	324.49	986.44	246.61	64.90

* Granitic rock passing 12,5 mm and retained on 4,75 mm sieve

** Granitic rock passing 25 mm and retained on 9,5 mm sieve

Source: Authors (2023)

Table 2 – Mechanical and hydraulic results of the pervious concrete

Test	Pervious concrete	Minimum values NBR 16416 (2015)
28-day compressive strenght (MPa)	15.50	-
28-day flexural strenght (MPa)	3.07	2.00
28-day diametral compression (MPa)	2.01	2.00
Abrasion mass loss (%)	27.50	-
Unit weight ($kg.m^{-3}$)	1779.70	1600 ± 80
Porosity (%)	30.41	-
Permeability (constant head method) ($cm.s^{-1}$)	0.97	0.1
Permeability (falling head method) ($cm.s^{-1}$)	0.65	0.1

Source: Authors (2023)

Each PICP module was built by using 16-sided concrete pavers or blocks with eight centimeters high. The PICP were purchased from a commercial supplier in the nearby city of Santa Maria/RS and had resistance characteristic of 35 MPa. The PIPCP havers had a similar shape as the PICP, including the same eight centimeters height, 17.17% average voids, however, the resistance was estimated in 25 MPa. These PIPCP pavers were acquired from a commercial supplier specialized in SUDS.

From the bottom to surface (Figure 1b), the modules' layers were composed by a geotextile blanket, 20 cm coarse aggregate, geotextile blanket and finally the pervious pavement. CP modules were in situ produced with a height of 10 cm and placed directly on the geotextile blanket. PIPCP and PICP paver blocks were laid over a thin layer of sand bed placed above the second layer of geotextile blank. Sand was also used to fill the pavers' joins. The geotextile blanket was used to reduce the migration of sediment particles into the deeper pavement layers, making the process of cleaning and recovering the infiltration rate more efficient (Kia; Wong; Cheeseman, 2017; Kayhanian et al., 2012; Lucke; Beecham, 2011), although the infiltration may be reduced more quickly due to the accumulation of particles in this blanket.

The slope length of each module was 2% towards the gutter for runoff collection, as shown in Figure 1 (a). The runoff drained from each module was stored in individual reservoirs (R1 to R6) and after each precipitation event, the amount of runoff collected in each storage reservoir was manually measured and reservoirs were emptied and cleaned.

The water levels fluctuation inside the modules were evaluated by monitoring with an ultrasound sensor at each module. Due to the environment and sensors requirement (Minetto; Allasia; Tassi, 2021), water levels were not directly monitored, but instead a floating system was inserted in a perforated PVC pipe, as shown in Figure 1(b) and the movements of this floating device triggered by the water level changes were monitored instead. This monitoring system was validated in Minetto (2018) and included an ultrasonic sensor of the HC-SR04, connected to an Arduino UNO rev. 3 Microcontroller boards and shields data-logger with 20 seconds recording time-step on an SD memory card. Also, at the center of the monitoring site and 1.60 m above the ground, a 20 second time-step recording rain gauge was installed. To validate the precipitation, a non-recording rain gauge was also installed close to the site at the same height and measurements were additionally compared to a nearby Brazilian National Meteorological Institute rainfall station.

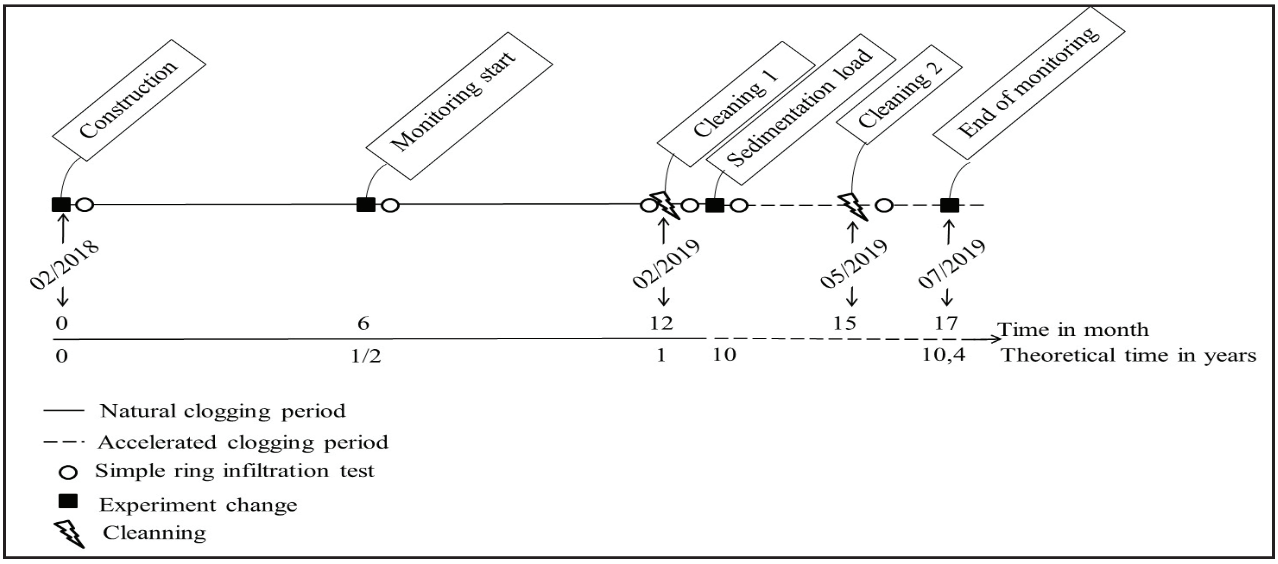
The hydraulic/hydrological design of pavements, gutters and storage reservoirs were carried out for 10 years return period rainfall and 60 minutes duration, following the requirement of Brazilian technical standards NBR 16416 (ABNT, 2015). The rainfall intensity-duration-frequency (IDF) equation from the nearest city (<20 km) of Santa Maria/RS was adopted (Roman, 2015), and envelope curve method was used for designing the pavements storage depth (Urbonas; Stahre, 1993). In this process, the infiltration capacity of the local soil was reduced by 1.5, as recommended by Ballard et al. (2015).

2.2 Periods and procedures for clogging analysis and maintenance

The construction of the six modules ended in February of 2018, however the monitoring period effectively started 6 months later, as early data were discarded due to problems related to malfunctional sensors that were initially used, that were later mitigated by customization of the monitoring system with a floating device as previously described (Figure 2). Manual readings were adopted to measure the runoff collected at the storage reservoir.

A year after construction, a pressure washing cleaning was accomplished (Cleaning 1) and the accelerated clogging process under different sand and clay sediments sizes (sedimentation load) was performed from February 2019 to May 2019, when a new pressure washing cleaning (Cleaning 2) was executed. Between these periods the surface infiltrations were assessed by using a single ring infiltration test (ASTM, 2017; ABNT, 2015) at ages of 6 and 12 months to evaluate the loss of surface infiltration capacity as well the recovering capacity after the cleaning. Each test was repeated at least five times.

Figure 2 – Timeline of the clogging analysis



Source: Authors (2023)

The natural clogging process performed over almost one year can be considered aggressive, because the experimental area was placed close to an unpaved road which releases a large amount of dust, especially during dry periods. Additionally, the experimental area is bounded by short vegetation, which does not create natural conditions for avoiding the particulate material to reach the modules. In this step of the analysis, the pairs of sets were named with the acronyms that describe them followed by a number (i.e. PC1 and PC2; PIPCP1 and PIPCP2; PICP1 and PICP2).

During the later accelerated clogging processes, it was attempted to reproduce a clogging period of 10 years due to sedimentation of sand and clay. To accomplish this, one module of each paired pavement type was simulated receiving sand (S) while the another under clay (C) sediment. Therefore, in this period, the modules were labeled according to the sediment that they were receiving, thus modules ending in 1 were renamed with C and modules ending in 2 were renamed with S (i.e. PC-S and PC-C; PIPCP-S and PIPCP-C; PICP-S and PICP-C).

The establishment of the sediment load for the accelerated clogging assessment was based on previous works of Kia et al. (2018), Schaefer, Kevern and Wang (2011) and Tong (2011), who applied an amount equivalent to 0.63 $kg.m^{-2}.year^{-1}$ of sediment in 10x20 cm cylindrical specimens over 20 steps to simulate 20 years of clogging. This way, it was used a local clayish material passing through a 0,075 mm sieve and a commercial sandy material passing through sieves between 2 mm and 0,075 mm. To simulate 10 years of clogging, a total of 6.36 kg sediment (sand and clay) was added to each module. To accomplish this addition, 2.12 kg of sediment was dissolved in 18 liters of water, mixed with a mixer for 2 minutes and evenly released over the entire area of the module. This process was repeated three times during the accelerated clogging period to totalize the 6.36 kg of sediment.

To evaluate possible benefits related to the pavements' maintenance on the recovering surface infiltration capacity, the method of pressure washing was used. A nozzle with 6 liters. $minute^{-1}$ flow rate capacity and 7 MPa (70 bar) working pressure was adopted, which was kept at 10 cm from the pavement surface for 3 minutes in each module, passing in lines systematically. After the maintenance, the surface infiltration test by using single ring was performed again, according to the timeline previously described.

2.2.1 Infiltration rate

Infiltration test results were evaluated through the natural and accelerated clogging periods for each module and were compared against the initial values and the minimum requirement established by the Brazilian Standards (ABNT, 2015). During the natural clogging period, infiltration was compared against the measured values immediately after construction (month 0) and during accelerated clogging, against the initial surface infiltration in this step, i.e. the infiltration after cleaning 1 (month 12).

2.2.2 Pavement's behavior at the rainfall events

The runoff coefficients of the modules (C, varying from 0 to 1) were individually calculated for each event as the quotient between the runoff depth and the total depth of precipitation. The runoff coefficients for each module were analyzed chronologically searching for statistical differences during the natural and accelerated clogging periods, using the non-parametric Mann-Whitney test at a significance level of 5%. This statistical test was chosen because it is more appropriate when comparing small samples of different sizes.

The maximum water levels (Hmax) inside each module were related to the total precipitation of the events (P) and return times (Tp). The determination coefficients (R^2) represented the points plotted in the relationship between levels against precipitation and levels against return time (on a logarithmic scale).

3 RESULTS AND DISCUSSIONS

Initially, the results of the infiltration rate test estimated by the single ring method are analyzed and discussed (ASTM, 2017; ABNT 2015). Then, the results related to the pervious pavement behavior under real precipitation events.

3.1 Infiltration rate assessment

The infiltration rate by the single ring method (ASTM 2017; ABNT 2015) was performed in two different periods: during natural (Table 3) and accelerated (Table 4) clogging. The Figure 3 also presents the percent change against the initial values of each period.

Table 3 – Infiltration rate of the experimental pavements in the natural clogging period

Module	Infiltration rate (cm.s-1)					
	0 month	6 months	12 months	Percent of initial infiltration (%)	After cleaning 1	Percent of initial inf. after cleaning (%)
PIPCP1/PIPCP-C	0.030	0.014	0.008	26.7	0.025	83.3
PIPCP2/PIPCP-S	0.024	0.020	0.014	58.4	0.024	100.0
PICP1/PICP-C	0.012	0.008	0.003	25.0	0.006	50.0
PICP2/PICP-S	0.013	0.009	0.003	23.1	0.004	30.8
PC1/PC-C	0.202*	0.160*	0.152*	75.3	0.155*	76.7
PC2/PC-S	0.184*	0.090	0.040	21.7	0.070	38.0

* Value above the standard requirement (NBR 16416, 2015)

Source: Authors (2023)

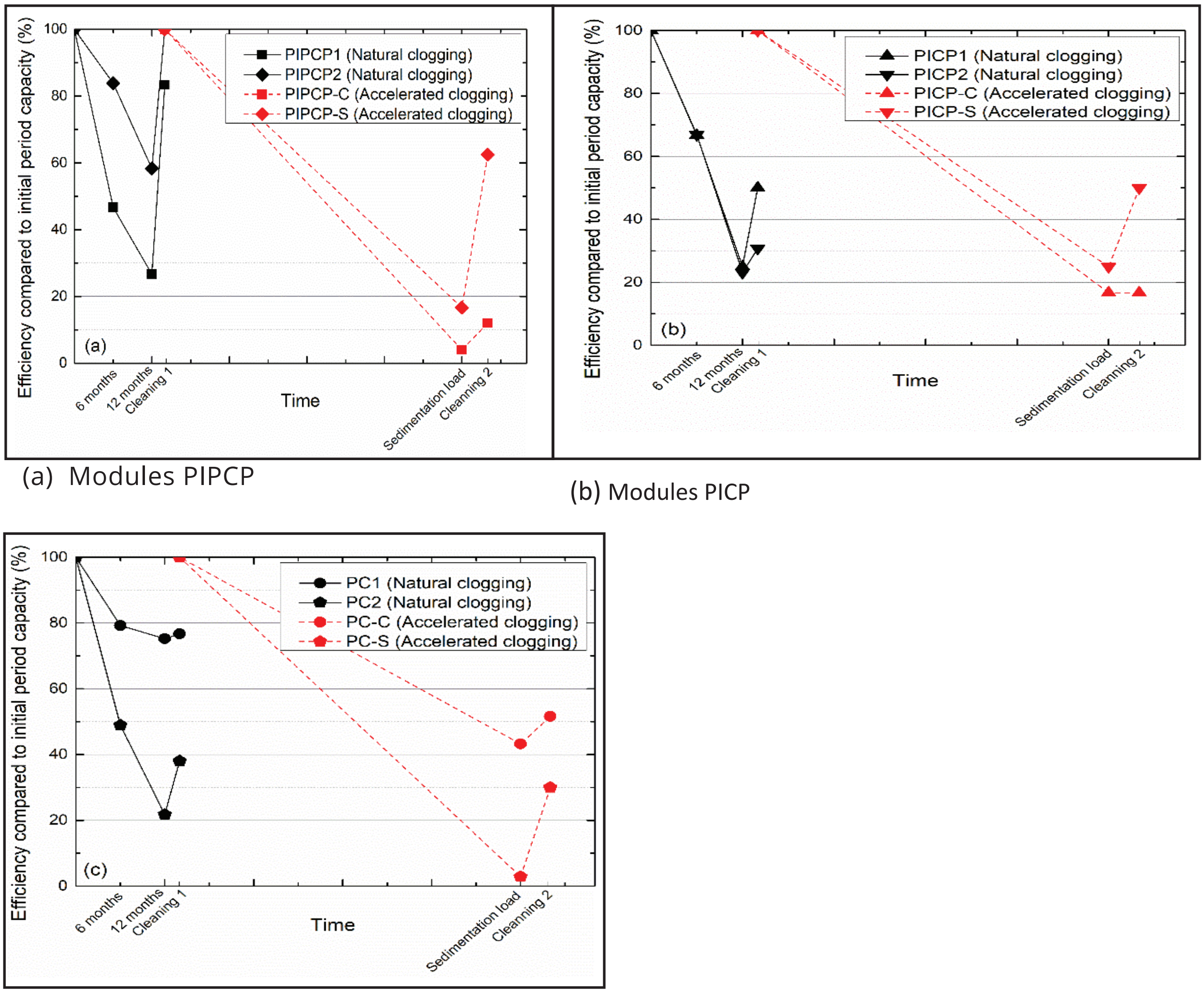
Table 4 – Infiltration rate of the pavements in the accelerated clogging period

Module	Infiltration rate (cm.s^{-1})			
	After cleaning 1	Percent of initial infiltration period (%)	After cleaning 2	Percent of initial inf. after cleaning 2 (%)
PIPCP1/PIPCP-C	0.025	4.0	0.003	12.0
PIPCP2/PIPCP-S	0.024	16.7	0.015	62.5
PICP1/PICP-C	0.006	16.7	0.001	16.7
PICP2/PICP-S	0.004	25.0	0.002	50.0
PC1/PC-C	0.155*	43.2	0.080	51.6
PC2/PC-S	0.070	2.9	0.021	30.0

* Value above the standard requirement (NBR 16416, 2015)

Source: Authors (2023)

Figure 3 – Reduction of the surface infiltration capacity of the modules in relation to the initial condition



(a) Modules PIPCP

(b) Modules PICP

(c) Modules PC

Source: Authors (2023)

3.1.1 Natural clogging period

Only the pervious concrete modules (PC) that were built under strict researchers' supervision had an infiltration rate exceeding 0.1 $cm.s^{-1}$, as recommended by NBR 16416 (ABNT, 2015) in newly built conditions (month 0). This implies that the commercial pervious concrete solutions available in the region fail to follow the Brazilian national standards. At the end of the first 12 months under natural clogging condition, with exception of PC1, all modules showed a reduction between 73.3% and 78.3% of the infiltration rate in the four modules (PIPCP1; PICP1; PICP2; and PC2) and well below standards' minima. The two modules with the lowest relative infiltration rate reduction were PIPCP2 (41.6%) and PC1 (24.7%).

After the cleaning procedure by pressure washing, PIPCP modules recovered 83.3% and 100% of the initial infiltration rate (Figure 3a), however, the other modules did not recover as much as these specific modules. It is believed that the pore size affected the sediment removal process: smaller pores, predominant in PIPCP, kept the sediments close to the surface and did not allow the sediments to pass to lower layers; the larger pores and joints between pavers had the opposite effect, directing part of the sediments to the internal structure, being more difficult to remove with just pressure washing.

3.1.2 Accelerated clogging period

After Cleaning 1, the sedimentation process was modified to simulate 10 years of clogging either with sand or clay as previously described in the methods section (Table 4), remembering that reference or initial infiltration is, in this case, that measured immediately after cleaning 1. In general, the simulated 10-year sediment deposition promoted a reduction between 56.8% and 97.1% in the infiltration rate of the modules, which reached infiltration rates close to zero, highlighting the importance of the maintenance practices.

The pervious concrete had a void ratio of 30.41% and this allowed a large part of the clay material to pass through the pervious surface and accumulate in the geotextile blanket. However, the sand accumulated more superficially significantly reducing the value of the PC-S more than clay in the PC-C module, in agreement with reports by Kia et al. (2017) and Kayhanian et al. (2012).

The modules with permeable interlocking pervious concrete (PIPCP-C and PIPCP-S.), with an average void ratio of 17.17%, had larger sediment retention close to the surface – for both sand and clay. The clay material filled the upper pores and reduced the module's surface infiltration capacity (PIPCP-C) in 96%. The sandy material reduced 83.3% the infiltration capacity of the initial value of this module (PIPCP-S).

After the second cleaning (first one corresponding to the accelerated clogging process), none of the modules returned close to their initial rate of permeability, once again, showing the importance of maintaining the pavement over the years. The PIPCP-S module presented the best recovery proportional to the initial infiltration capacity, returning to 62% of the initial infiltration.

The destructive testing after the experiment, showed that the geotextile blanket retained the small sediments that passed through the different pervious surface and this played a key role in reducing the surface infiltration capacity, as the blanked finished almost totally clogged. However, it plays an important role in the long run, as it prevents these sediments from reducing the volume of voids available in the reservoir layer where rainwater is stored before infiltrating. In this light, it is possible to restore the initial conditions combining the cleaning of the voids in the pavement, even with low-cost solutions as pressure washing with the replacement of the geotextile blanket after a certain period of use in agreement with observations from (Kia et al., 2017; Kayhanian et al., 2012; Lucke; Beecham, 2011).

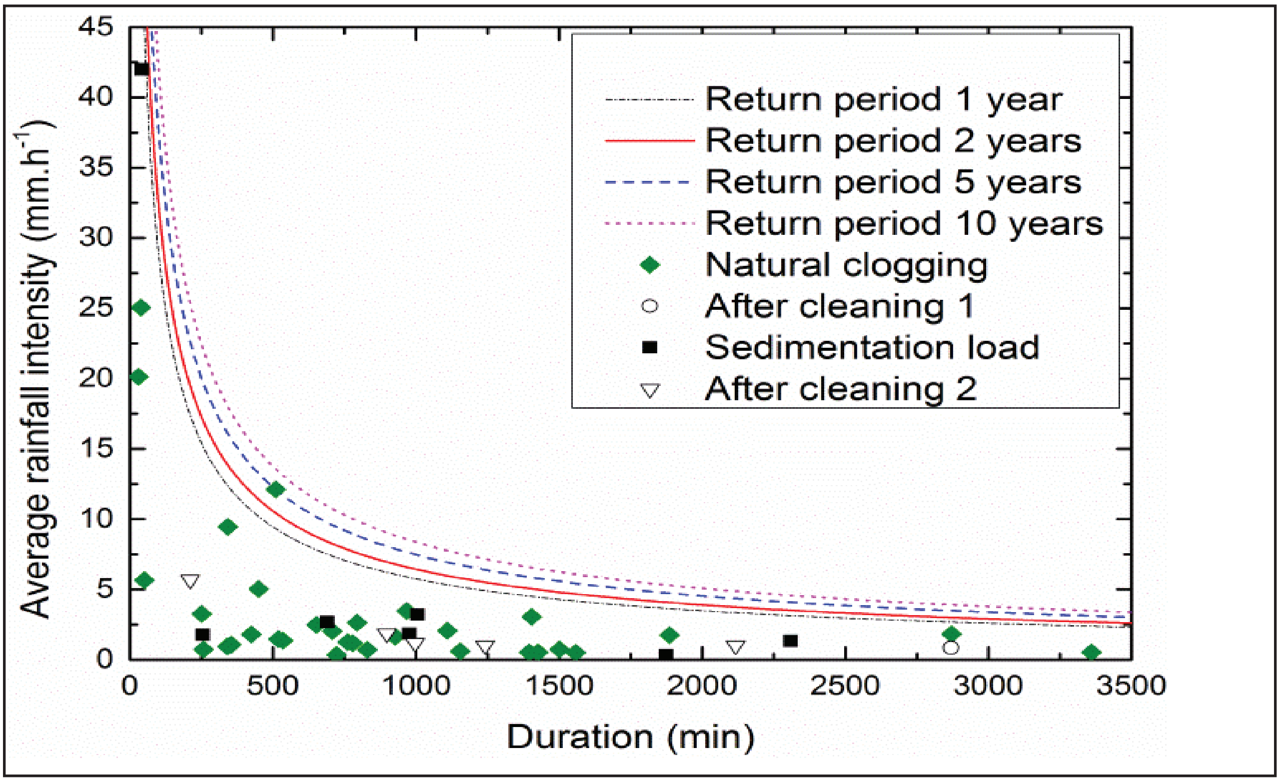
3.2 Pavement's behavior during rainfall events

As mentioned, a total of 51 events were monitored with precipitation volumes between 3.2 mm and 114.0 mm, with temporal distribution shown in Table 5. When comparing the observed events against Tp as estimated from IDF, it can be seen that most of the events had a return period of less than one year, with the exception of an event with a five-year return period, that was monitored during the natural clogging period (Figure 4).

Table 5 – Rainfall events monitored over the survey according to month and period

Period	Stage	Year	Month	Number of events	Total rainfall (mm)
Natural clogging	Before cleaning 1	2018	August	3	148.4
		2018	September	9	194.8
		2018	October	5	103.4
		2018	November	5	197.8
		2018	December	5	169.9
		2019	January	6	163.0
Accelerated clogging	After cleaning 1	2019	February	1	65.0
	Before cleaning 2	2019	February	1	15.0
		2019	March	4	196.0
		2019	April	3	135.4
		2019	May	4	77.8
	After cleaning 2	2019	May	2	57.0
		2019	June	2	40.0
		2019	July	1	28.0

Figure 4 – Characterization of the events monitored from the Santa Maria IDF

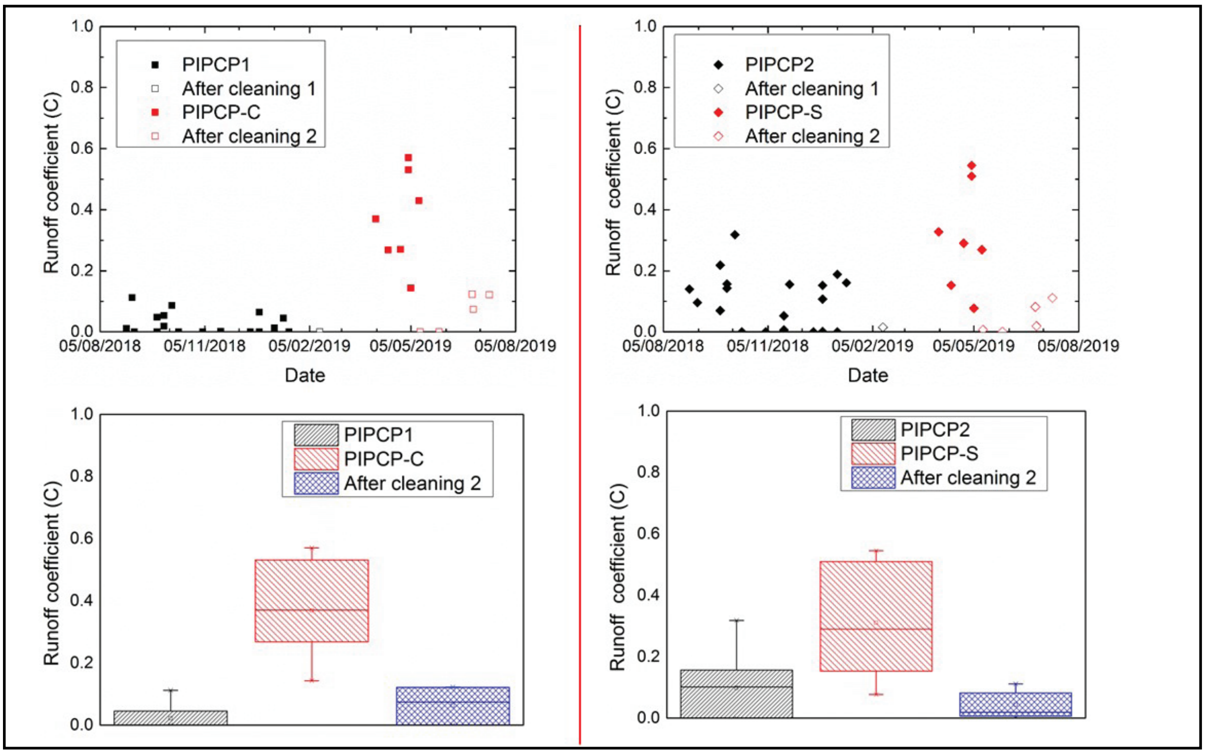


Source: Authors (2023)

3.2.1. Natural clogging period

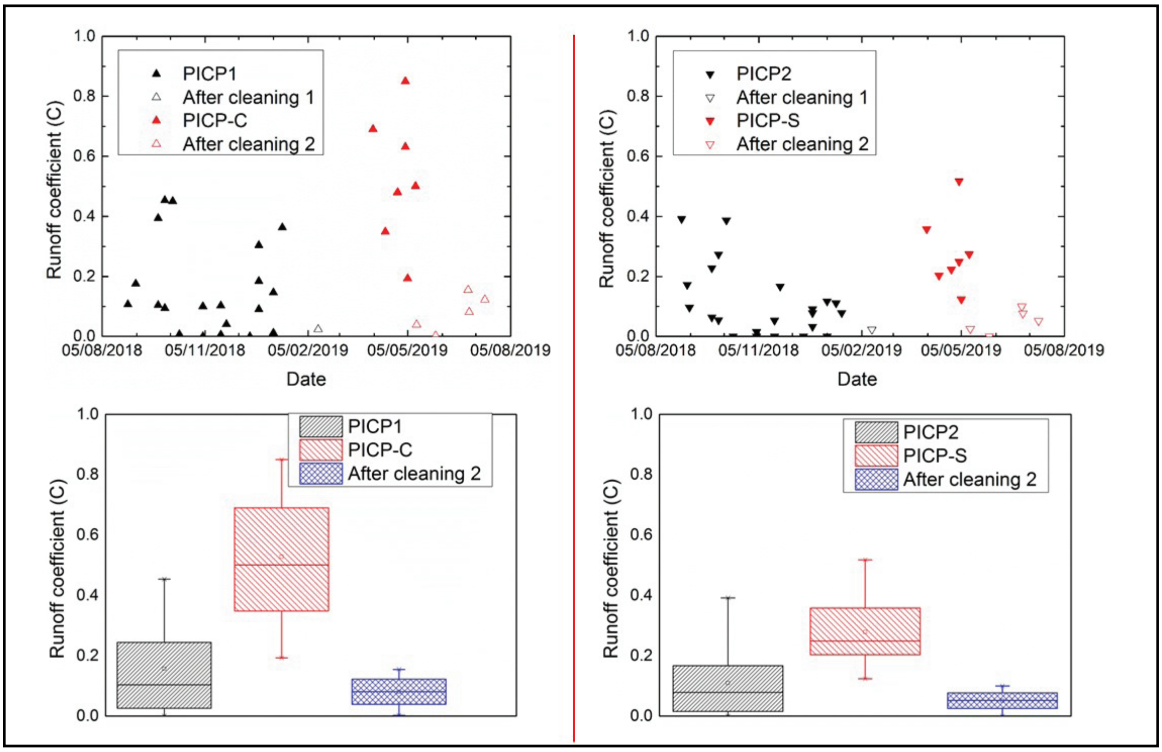
The superficial runoff generated by each precipitation event over the study periods was verified indicating no significant increase in runoff coefficient over this 1-year period in any module. In the permeable interlocking modules (Figure 5), the PIPCP1 module showed a maximum runoff coefficient of 0.11 and the PIPCP2 presented a maximum value of 0.32 before undergoing the accelerated clogging process. The behavior of the two modules with conventional interlocking paver blocks (PICP) (Figure 6) in the period of natural clogging was similar. In this period, the results of superficial runoff coefficient were higher than those found by Collins, Hunt and Hathaway (2008), that mentioned values below 0,10 for events up to 89 mm. The two PC modules (Figure 7) presented similar results to those reported by Collins, Hunt and Hathaway (2008) in the natural clogging period – averages of 0.01 on the PC1 pavement and 0.02 on the PC2 pavement.

Figure 5 – PIPCP modules events chronological analysis



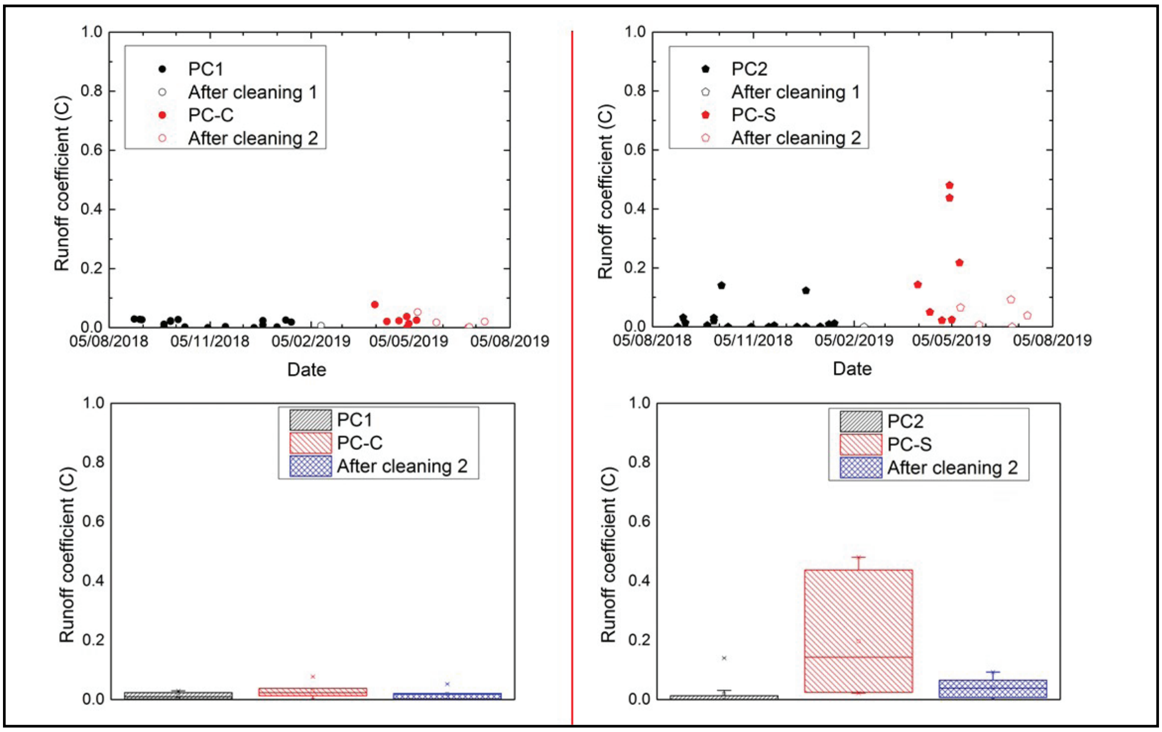
Source: Authors (2023)

Figure 6 – Chronological analysis of the PICP modules events



Source: Authors (2023)

Figure 7 – Chronological analysis of the PC events



Source: Authors (2023)

3.2.2. Accelerated clogging period

During the accelerated clogging period, in the PIPCP-C module the runoff coefficient varied between 0.14 and 0.53 while in the PIPCP-S between 0.08 and 0.54 showing no statistically significant differences along the period. On the other hand, clogging with clay proved to be more harmful to the infiltration capacity of PICP than sand, in agreement with the results previously discussed and observed during the infiltration tests (KIA et al., 2017; TONG, 2011), owing this to the larger clogging at the joints between the pavers blocks. The clay-clogged module (PICP-C) showed surface runoff coefficients values between 0.19 and 0.85, whereas the sand-clogged module (PICP-S) had a surface runoff coefficient between 0.12 and 0.52.

The PC-S results largely varied after being sand-clogged between a minimum of 0.02 and maximum of 0.48. Unlike the other five modules, PC-C showed little variation in the results after accelerated clogging. The largest runoff coefficient went from 0.03, observed during the natural clogging, to 0.08 in accelerated clogging. After cleaning 2, the two porous interlocking modules showed similar recovery. The PIPCP-C pavement showed superficial runoff ranging from 0 to 0.12 and the PIPCP-S pavement presented values from 0 to 0.11.

By using the Mann-Whitney method (Table 6) runoff coefficient were compared in-between modules and phases. It is clear from the results, that all paired modules (PIPCP1 & 2; PICP1 & 2; PC1 & 2) performed statistically similarly on the natural clogging phase, even if runoff coefficient were slightly different among paired modules. Other result shows that there is almost no statistical difference in the runoff coefficients at the end of a 12-month natural clogging phase or after 10-year simulated clogging (except for PC-C). This means that just one year of lack of maintenance, is enough to take out of service a permeable pavement. However, that even with pavement that have not suffered maintenance for a long while (10-year sediment simulation) can be recovered with just pressure washing, even if not to pristine conditions.

Table 6 – Results of Mann-Whitney test comparing runoff coefficients for each module at different stages

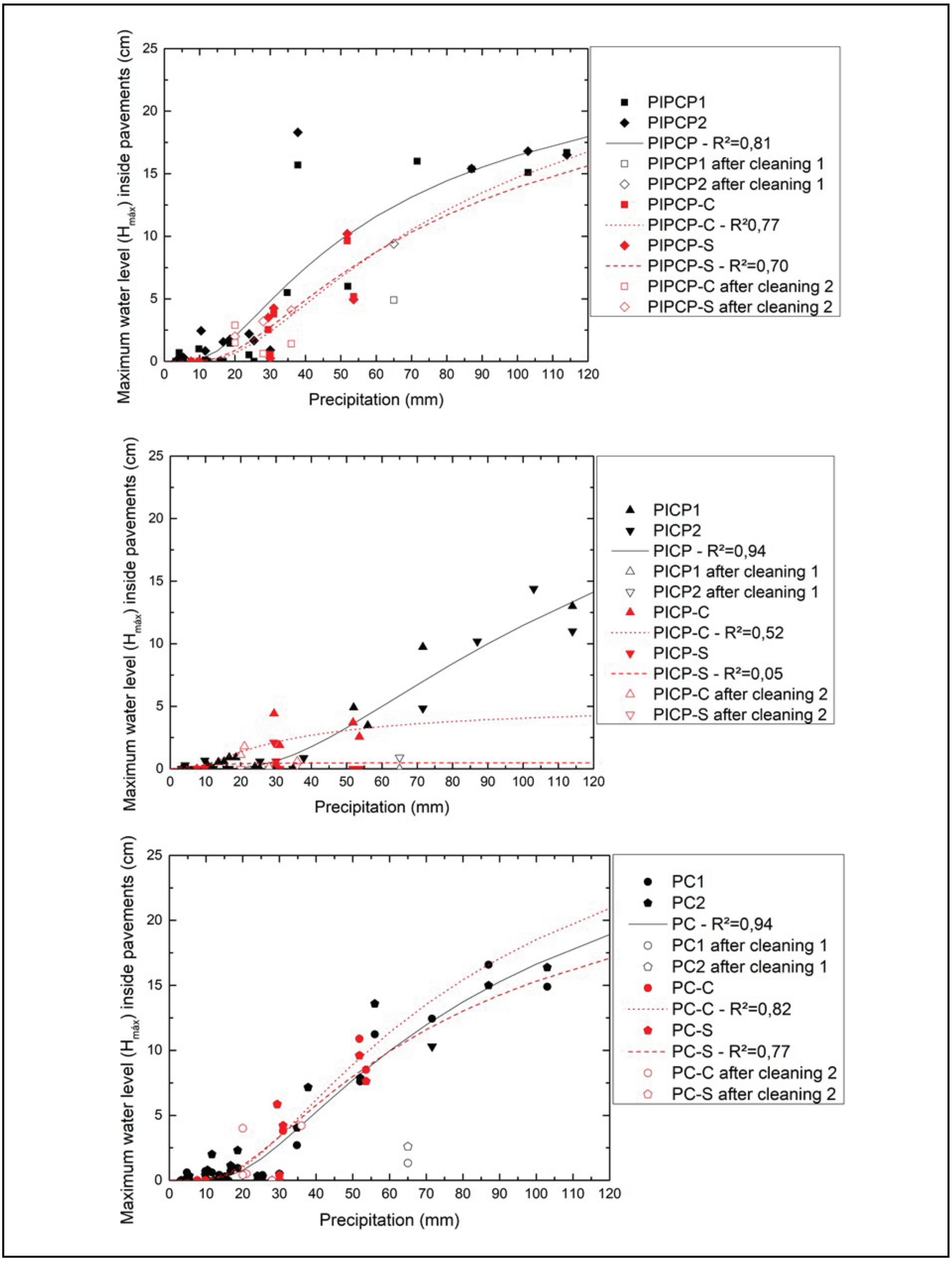
Period comparation	Sample		Compared against		p-value
	Module	Stage	Module	Stage	
Natural clogging	PIPCP 1	Before cleaning 1	PIPCP 2	Before cleaning 1	0.07
Natural clogging x accelerated clogging	PIPCP 1	Before cleaning 1	PIPCP-C	Before cleaning 2	**0.00**
	PIPCP 2		PIPCP-S		**0.01**
	PIPCP 1		PIPCP-C	After cleaning 2	0.08
	PIPCP 2		PIPCP-S		0.83
Natural clogging	PICP 1	Before cleaning 1	PICP 2	Before cleaning 1	0.20
Natural clogging x accelerated clogging	PICP 1	Before cleaning 1	PICP-C	Before cleaning 2	**0.00**
	PICP 2		PICP-S		**0.01**
	PICP 1		PICP-C	After cleaning 2	0.47
	PICP 2		PICP-S		0.47
Natural clogging	PC 1	Before cleaning 1	PC 2	Before cleaning 1	0.14
Natural clogging x accelerated clogging	PC 1	Before cleaning 1	PC-C	Before cleaning 2	0.33
	PC 2		PC-S		**0.00**
	PC 1		PC-C	After cleaning 2	0.78
	PC 2		PC-S		0.07

Source: Authors (2023)

P-value ≤ 0.05 indicates that the null hypothesis is rejected and that the samples are statistically different

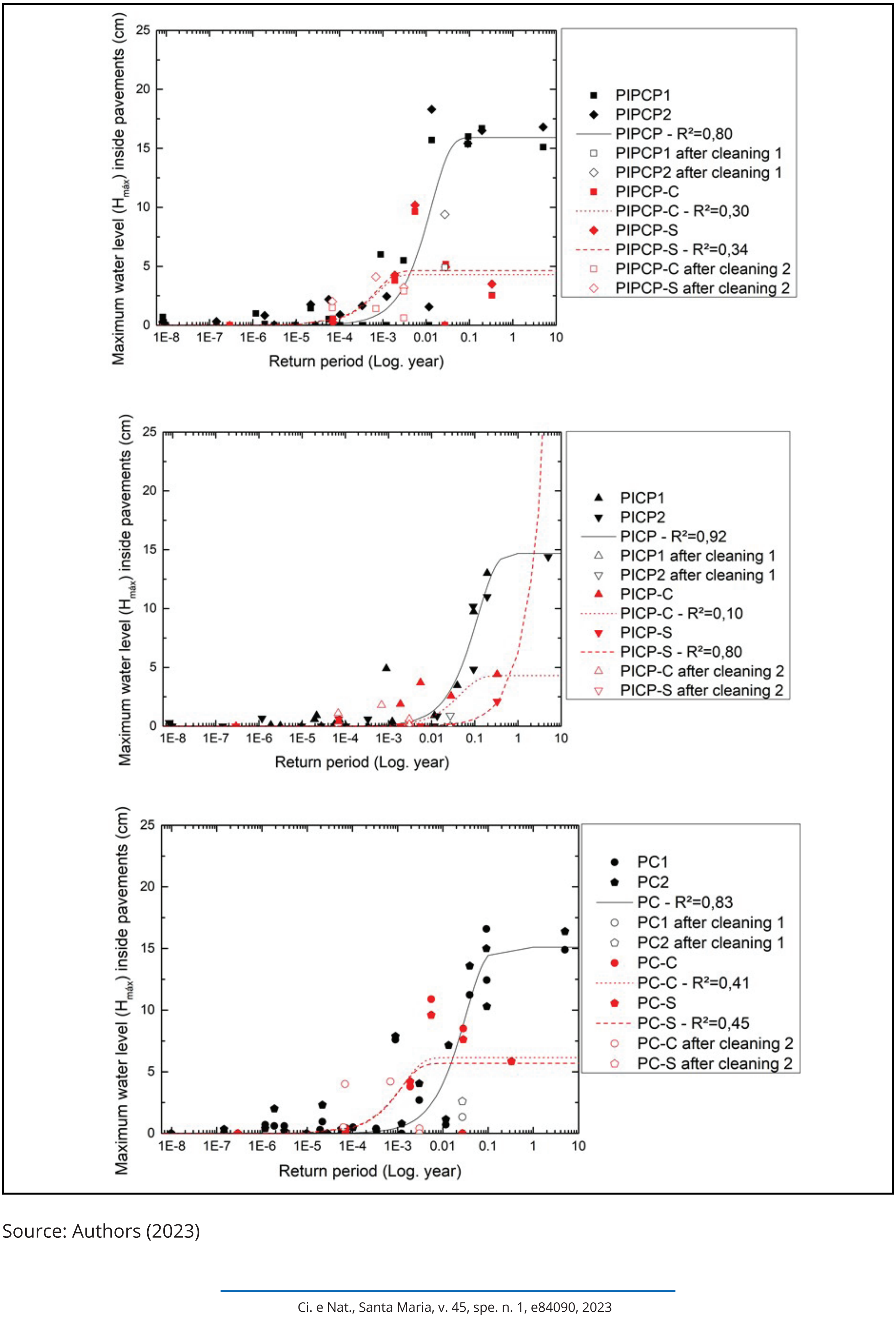
The maximum water levels (Hmáx) in the reservoir within each module, were related to the rainfall depth (P) (Figure 8) and return times (Tp) (Figure 9). To facilitate data analysis, trend curves were adjusted to the points at each period (natural and accelerated clogging) with determination coefficients (R^2) above 0.5 (Figure 8).

Figure 8 – Correlation between precipitation and maximum level of the modules



Source: Authors (2023)

Figure 9 – Correlation between return time and maximum level of the modules



Source: Authors (2023)

It is observed that the water levels in the six modules in natural clogging period had a similar behavior, with the beginning of water level rise withing the storage reservoir after 15 mm of rain. The interlocking concrete pavement (PICP) reached lower levels than the other pervious surfaces, which was expected by the lower infiltration rate of this pavement, and, consequently, more superficial flow.

In accelerated clogging process, there was a small reduction in Hmáx of the modules with permeable interlocking (i.e. PIPCP-C and PIPCP-S compared against PIPCP1 and PIPCP2), due to less infiltration and a higher percentage of superficial flow. In the PICP modules, this trend is not so clear just looking the observed data, but noticeable from the trend lines. The PC modules showed similar results to PIPCP.

Because few events were monitored immediately after each cleaning, trend lines were not drawn in this situation. However, Hmáx after cleaning 1 showed a clear decrease compared to values observed during the natural clogging period. This could be explained by the fact that local soil is a clay based soil, and as already observed in this work and by other authors such as Kia et al. (2017) and Kayhanian et al. (2012), clay tends to penetrate more within the permeable pavement systems, eventually clogging the lower layers. Due to this, more water tend to accumulate within the reservoir until cleaned.

On the other hand, after the accelerated clogging that represent 10 years of filling within the structure, Hmáx seemed larger after cleaning, meaning that water pressure is successful to unclog superficial pores, but fails to clean a 10-year worth of sediments accumulated at the bottom of the structure. In other words, more water can infiltrate from the surface, but faces difficulties draining in the bottom, accumulating withing the structure. However, if we consider that the hydraulic/hydrological failure of the pavement as the total saturation of the structure, this did not happen during the monitored events and could be stated that the pavements performed satisfactorily within its life span (10 years), but this assertion is not definitive as results are influenced by the lack of a larger number of extreme events.

4 CONCLUSIONS

At the end of the 12 months of natural rate clogging in a region with a soil mainly composed by clay, the infiltration rate of the modules was reduced between 24% and 79%. The infiltration rate reduction was due to natural factors, such as sediment deposition by the action of wind and vegetation development. The experiment site proved to be quite aggressive in terms of sedimentation, and due to its clay contents, penetrated deep within the structure, showing the importance of understanding regional soils to characterize expected sediments. Despite the reduction in the infiltration capacity of the modules over 12 months, modules still performed satisfactorily as water was still allowed to infiltrate within the reservoir and do not saturated the structure. The method of pavement cleaning by pressure washing was able to recover, partially the infiltration capacity of the modules.

In accelerated clogging (10-year simulation), it was found that the clay caused a larger increase in runoff coefficient in the interlocking modules (PIPCP and PICP) than the sand. In the case of pervious concrete modules (PC), the opposite occurred, and the sand caused larger runoff coefficient increase than the clay and this was linked to grain and pore size relationships in agreement to other studies. This also explained the better recovery of infiltrations in the sand-clogged modules using pressure washing techniques.

Observing the infiltration trends over time and the results, it is clear the cleaning the surface every 4-6 months, even with just pressure water cleaning is enough to keep permeable pavements in working conditions. Also, that regions subject to sandy sediments are easier to maintain through this technique.

ACKNOWLEDGEMENTS

The authors thank the continuous support of the Federal University of Santa Maria (Rio Grande do Sul, Brazil), Ecotechnologies Research Group and the Post-Graduate Program in Civil and Environmental Engineering.

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how to cite this article

Lamberti, L., Piccilli, D. G. A., Minetto, B., Perius, C. F.,& Tassi,R. Field investigation of clogging with different sediment types in a permeable pavement system with low-cost maintenance. *Ciência e Natura,* Santa Maria, v. 45 (spe 1), e84089, 2023. DOI 10.5902/2179460X84089. Available from: https://doi.org/10.5902/2179460X84089. Accessed in: em: day month abbr. year.