Performance of Permeable Pavement to Filter Stormwater Runoff for Non-Potable Uses in Buildings

By Liseane Padilha Thives[1], Enedir Ghisi[1], Gianfranco Longo[1], Gabriela Hammes[1], Thiago Belotto[1]

ABSTRACT

Permeable pavement benefits, besides stormwater runoff reduction and groundwater recharge, include stormwater harvesting. As an alternative to water resources scarcity, stormwater that reaches a permeable pavement could be filtered by the same pavement and then used for non-potable purposes in buildings. This work aims to evaluate some types of permeable pavements regarding their performance to remove pollutants from stormwater and decrease runoff. Analyses of infiltration capacity and pollutant concentrations were performed in four permeable pavement models with different types of permeable surface layer (porous asphalt mixture and porous interlocked concrete blocks). Then, the data were used to calculate the "stormwater credits" according to the Minnesota Stormwater Manual. The credits were calculated for volume of runoff, and concentrations of Total Suspended Solids (TSS) and Total Phosphorus (TP). As a result, the models proved adequate to decrease both stormwater runoff and TSS and TP concentrations. Moreover, models with the porous asphalt mixture as a surface layer were more efficient to reduce the concentration of pollutants. However, for the models evaluated in this work, additional treatment is recommended when stormwater harvested from permeable pavements is meant for non-potable uses in buildings.

Keywords: buildings, stormwater, credits, non-potable uses.

1. Introduction

In the last decades, the accelerated development and urbanisation experienced in the urban centres contributed significantly to the increasing of impermeable surfaces. Tataranni & Sangiorgi (2019) stated that paved areas such as streets, avenues, roads, sidewalks and parking lots could represent about 40% of the impermeable surfaces in urban centres. Consequently, the waterproofing surface associated with the inefficiency of urban drainage systems leads to high stormwater runoff volume, resulting in flooding, especially during heavy or long-term rainfall.

Rech, Pacheco, Caprario, Rech & Finotti (2022) asserted that stormwater runoff could be a source of pollution by emerging micropollutants and heavy metals such as lead and zinc. De Buyck, Matviichu, Dumoulin, Rousseau & Hulle (2021) added that samples of stormwater runoff that flows over impermeable pavements presented contamination by organic and inorganic pollutants, hydrocarbons, phthalates and pesticides.

Stormwater management is the primary of the Low Impact Development (LID) principles, in which permeable pavements have been used as an alternative to conventional impermeable ones (Agency of Natural Resources, 2013). Permeable pavements are structures composed of porous layers, able to infiltrate, filter and retain stormwater

|[1] Federal University of Santa Catarina, Department of Civil Engineering, Research Group on Management of Sustainable Environments, Laboratory of Energy Efficiency in Buildings, Florianópolis-SC, Brazil.

pollutants and provide groundwater supply. In addition, permeable pavements can contribute to reducing the incidence of flooding on public roads and the overloading of drainage systems (Kumar, Kozak, Hundal, Cox, Zhang & Granato, 2016).

Commonly, surface layers can be made of permeable concrete, porous asphalt, and permeable interlocked concrete blocks (Minnesota Stormwater Manual, 2021). Permeable pavement is designed so that the characteristics of the layers can allow stormwater filtering and pollutants retention and, if necessary, stormwater harvesting and storing. Depending on the purpose, the under layers vary and generally are the following: choker course, filter course, filter blanket, and reservoir course (University of New Hampshire Stormwater Center, 2016).

Wang, Ma, Yuan, Wang, Mu, Zuo, Zhang, Hong & Wang (2019) analysed the potential of permeable pavement application in sponge cities, that is, urban areas with the ability to integrate water cycle management into urban planning projects. The study compared a permeable pavement with a surface layer of permeable bricks and an impermeable concrete pavement. The results showed that permeable pavement presented an Emergency Sustainability Index about three times higher, contributing to rainwater management and water scarcity in urban areas.

Another benefit attributed to the use of permeable pavement is the possible temperature reduction in the urban environment. Santamouris (2013) stated that the ability to absorb water through permeable pavements is one of the factors responsible for keeping the low pavement's surface temperature, significantly reducing the impact of heat islands.

The capacity of permeable pavements to retain stormwater pollutants and collected stormwater for non-potable uses in buildings was also addressed in other studies (Antunes, Thives & Ghisi, 2016; Charlesworth, Beddow & Nnadi, 2017; Thives, Ghisi, Brecht & Pires, 2018; Nejad, Behfarnia, Abedi-Koupai & Mostafazadeh-Fard, 2018).

As a green infrastructure, permeable pavement can be a suitable option for the retention of stormwater runoff; and evaluating the permeable stormwater credits is possible. Credit refers to the quantity of stormwater or pollutant reduction achieved either at the Best Management Practice (BMP) or representing a tool for environmental authorities to make decisions and promote incentives for preserving natural areas (Minnesota Stormwater Manual, 2021).

This work aims to evaluate the performance of some permeable pavements in removing pollutants from stormwater and decreasing runoff. The stormwater infiltration capacity and the Total Suspended Solids (TSS) and Total Phosphorus (TP) concentrations were measured in four permeable pavement models, and the credits related to runoff volume and pollutants (TSS and TP) concentrations were calculated according to the Minnesota Stormwater Manual.

2. Permeable pavements credits

Due to the permeable characteristics of the layers in a permeable pavement, the stormwater runoff passes through the layers promoting pollutant removal and runoff volume reduction. The infiltrated stormwater can be stored in an underlying reservoir and captured by drains for further use or infiltrate slowly into the soil subgrade.

The credits are generally associated with two parameters to minimise the impact: runoff volume reduction and quality of filtered stormwater. Such credits represent a resource to measure the permeable pavement efficiency in terms of runoff reduction, filtering pollutants and storing stormwater. Such systems effectively reduce concentrations of pollutants such as nitrogen, metals, bacteria, and hydrocarbons. The Minnesota Stormwater Manual (2021) provides equations only to calculate credits for volume, Total Suspended Solids (TSS) and Total Phosphorus (TP).

Zhao, Fonseca & Zeerak (2019) added that the stormwater credit programme is shown as an incentive for adopting sustainable practices by reducing the burden of fees for water use in low-income populations and decreasing the overall cost of water management, as already implemented in Minneapolis (United States of America) by the local government. The credit systems have also been used in other North American states, such as Florida, Oklahoma and Ohio, to evaluate the stormwater volume retained to mitigate the impacts of surface runoff. In Florida, the volume of stormwater retained has generated 42% to 100% credits, while in Oklahoma and Ohio, between 50% and 60% (Doll, Scodari & Lindsey, 1999).

3. Methodology

A flowchart of the methodology to estimate the permeable pavement performance to filter stormwater runoff for non-potable uses in buildings is shown in Figure 1 and described in the following sections.
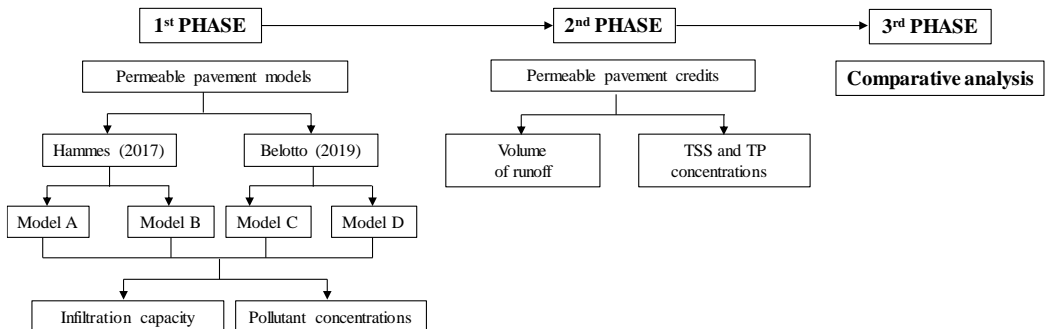

Figure 1. Flowchart of the methodology

3.1. Models infiltration capacity and pollutant concentrations

The infiltration capacity and pollutant concentrations were performed using data obtained from four permeable pavement models studied by Hammes (2017) (models A and B) and Belotto (2019) (models C and D), shown in Figure 2. The permeable pavement models, mounted into acrylic boxes, were exposed to 18 rain events to evaluate the infiltration capacity. In each rain event, the infiltrated rainwater height in the models was compared with the height of rainwater stored in an empty box (all boxes had the same size).

In order to evaluate the permeable pavement model filtering capacity, stormwater was collected from a street gutter (five stormwater samples), and then, the stormwater was spilt over the models. After that, the stormwater filtered by the models was analysed in the laboratory to measure the concentrations of Total Suspended Solids (TSS) and Total Phosphorus (TP). The methods employed at the laboratory were the colourimetric vanadomolybdophosphoric acid for TSS and the gravimetric for TP.
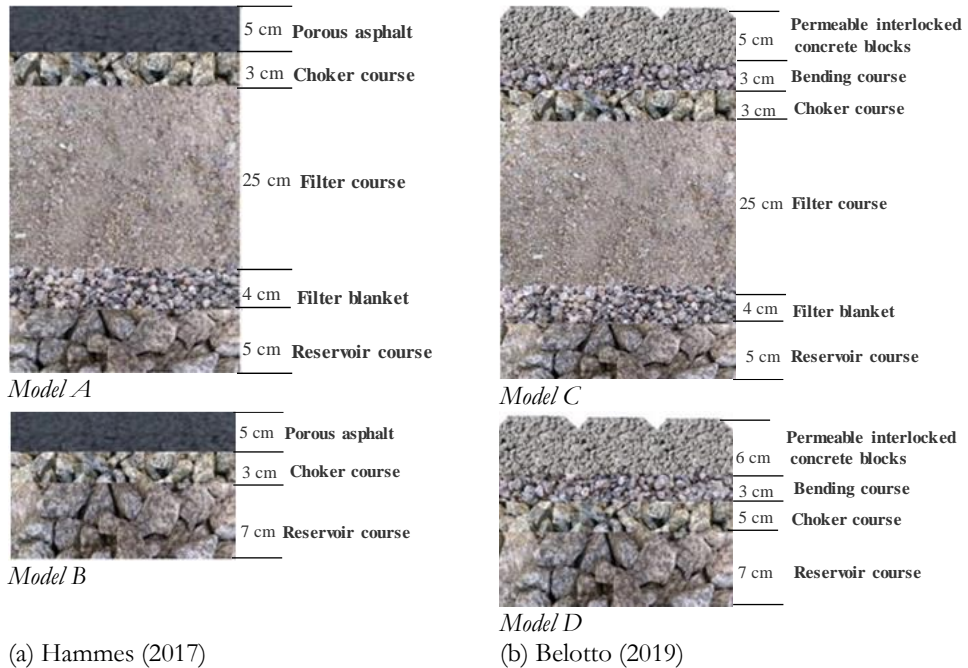

5 cm **Porous asphalt**	5 cm **Permeable interlocked concrete blocks**
3 cm **Choker course**	3 cm **Bending course**
	3 cm **Choker course**
25 cm **Filter course**	25 cm **Filter course**
4 cm **Filter blanket**	4 cm **Filter blanket**
5 cm **Reservoir course**	5 cm **Reservoir course**
Model A	*Model C*
5 cm **Porous asphalt**	6 cm **Permeable interlocked concrete blocks**
3 cm **Choker course**	3 cm **Bending course**
	5 cm **Choker course**
7 cm **Reservoir course**	7 cm **Reservoir course**
Model B	*Model D*
(a) Hammes (2017)	(b) Belotto (2019)

Figure 2. Permeable pavement models considered in the study

3.2. Permeable pavements credits

The permeable pavement credits were evaluated according to the Minnesota Stormwater Manual (2021) methodology, which comprises: (i) infiltrated volume; (ii) total suspended solids and total phosphorus. The infiltrated stormwater volume was calculated according to Eq. 1.

$$V_{tot} = V_s + V_d \tag{1}$$

Where: V_{tot} is the total credits of stormwater volume infiltrated (L); V_s is the stormwater volume infiltrated through the soil (L), given by Eq. 2, and V_d is the stormwater volume infiltrated by drains (L), calculated using Eq. 3.

$$V_s = 1,000 \times D_0 \times n \times (A_0 + A_i) \tag{2}$$

Where: V_s is the stormwater volume infiltrated through the soil (L); D_0 is the reservoir layer depth below the drain (m); n is the porosity of the reservoir layer material (dimensionless); A_0 is the bottom surface area of the permeable pavement system (m²); A_i is the area of the underside of the permeable pavement system (m²). Note: 1,000 was used as a conversion factor to litres.

$V_d = 1,000 \times A_i \times T \times IR$ (3)

Where: V_d is the stormwater volume infiltrated by drains (L); A_i is the area of the underside of the permeable pavement system (m²); T is the relegation time for water stored below the drain (h); IR is the infiltration rate, which depends on the soil subgrade type (m/h). Note: 1,000 was used as a conversion factor to litres.

For calculating TSS or TP mass removal by permeable pavements in kilograms per stormwater event, Eq. 4 was used. The credits of these pollutants for infiltrated and filtered runoff were calculated by using Eqs. 5 and 6, respectively.

$MT = M_i + M_f$ (4)

Where: MT is the total mass (mg); M_i is the mass removed by infiltration (mg); M_f is the mass removed by filtration (mg).

$M_{ri} = 1,000 \times V_i \times PR_i \times MC$ (5)

Where: M_{ri} is the mass removed by infiltrated runoff (mg); V_i is the stormwater volume infiltrated in the permeable pavement (L); PR_i is the pollutant removal fraction for infiltrated stormwater (dimensionless); MC is the average concentration of pollutants in the runoff (mg/L).

$M_{rf} = 1,000 \times V_f \times PR_f \times MC$ (6)

Where: M_{rf} is the mass removed by filtered runoff (mg); V_f is the stormwater volume filtered in the permeable pavement (L); PR_f is the pollutant removal fraction for filtered stormwater (dimensionless); MC is the average concentration of pollutants in the runoff (mg/L).

4. Results

4.1. Models infiltration capacity and pollutant concentrations

The permeable pavements infiltration capacity measured after 18 rain events resulted in: (i) model A: 70.1%; (ii) model B: 80.0%; (iii) model C: 78.1%; (iv) model D: 88.1%, demonstrating that the models were able to reduce runoff volume.

The TSS and TP stormwater concentrations retained by each model are shown in Table 1, and the results represent the average of five measurements. For non-potable purposes, the Brazilian Water Agency (ANA, 2005) limits TSS and TP concentrations at 5 mg/L and 0.1 mg/L, respectively. The results showed variations in the characteristics of the stormwater runoff once the collections and analysis were performed in 2017 (models A and B) and in 2019 (models C and D). On the other hand, despite the additional water treatment for non-potable uses, the efficiency of the filtering and retained TSS and TP obtained through the models can be proved.

Table 1. TSS and TP concentrations.

Hammes (2017)	Concentrations (mg/L)		Belotto (2019)	Concentrations (mg/L)	
	TSS	TP		TSS	TP
Stormwater	98	0.40	Stormwater	16	0.18
Model A	8	0.31	Model C	6	0.08
Model B	17	0.17	Model D	7	0.26

4.2. Permeable pavements credits

Table 2 shows the parameters for infiltration credits calculation and the results for the models. The porosity is related to the voids content of the pavement surface layer and the reservoir layer depth below the drain, depending on the model (Figure 2). The bottom and underside areas are the same, as the models have the same surface area. The stormwater volume infiltrated through the soil was calculated using Eq. 2. The relegation time for water stored below the drain was assumed at 48 hours, recommended by the Minnesota Stormwater Manual (2021).

From the models infiltration capacity and the infiltration rate of the pavement materials layer, available at the Minnesota Stormwater Manual (2021), the infiltration rates were: (i) 3.32 m/h for model A; (ii) 6.67 m/h for model B; (iii) 7.1 m/h for models C and D. The stormwater volume infiltrated by drains was calculated using Eq. 3. Finally, the infiltration credits were calculated using Eq. 1.

Table 2. Parameters of the models and for infiltration credits.

Model	Porosity	D_0 (m)	A_0 and A_i (m²)	V_s (L)	V_d (L)	Credits (L)
A	0.316	0.05	0.09	1.42	14.77	16.19
B	0.306	0.07	0.09	1.93	29.81	30.74
C	0.250	0.05	0.09	1.12	30.67	31.79
D	0.250	0.07	0.09	1.58	30.67	32.25

Note: D_0 is the reservoir layer depth below the drain; A_0 is the bottom surface area of the pavement; A_i is the area of the underside of the pavement; V_s is the stormwater volume infiltrated through the soil; V_d is the stormwater volume infiltrated by drains.

The higher concentrations in the samples evaluated at the laboratory tests were selected for the stormwater credits calculation related to TSS and TP credits concentration removal (Tables 3 and 4). Considering that the measurements were conducted in the models instead of in the field (lower stormwater volume), it was assumed that after passing through the models, the remaining stormwater infiltrated the soil and, in this case, it was not conducted to the drains. Thus, based on data from Tables 3 and 4 and using Eq. 5, TSS and TP removal rates and the credits were calculated, as shown in Table 5.

Table 3. Infiltration volume and pollutants concentrations for the models by Hammes (2017).

Sample	Infiltrated volume (L)	Model A		Model B	
		TSS (mg/L)	TP (mg/L)	TSS (mg/L)	TP (mg/L)
1	0.27	16.00	0.40	36.00	0.31
2	0.99	0.01	-	4.00	-
3	2.79	12.00	-	12.00	-
4	1.44	-	0.61	-	0.06
5	7.20	-	0.53	-	0.47

Table 4. Infiltration volume and pollutants concentrations for the models by Belotto (2019).

Sample	Infiltrated volume (L)	Model C		Model D	
		TSS (mg/L)	TP (mg/L)	TSS (mg/L)	TP (mg/L)
1	1.0	8.00	0.04	2.00	0.12
2	1.0	2.00	0.03	14.00	0.36
3	1.0	8.00	0.06	6.00	0.41
4	1.0	-	0.19	-	0.13

In general, the models seemed efficient in terms of TSS and TP concentration removal. Also, Table 5 shows that the total phosphorus retention rate of model B was higher than model A, which has a filter layer (Figure 2). TSS concentrations are associated with water turbidity, in which the solid particles can be removed by simple sedimentation (decanters) or dissolved air flotation. Stormwater runoff is one source of phosphorus, and high TP concentrations can be observed depending on the location. In excess, TP concentration can lead to water eutrophication, which is responsible for the appearance of cyanotoxins (microcystins) and poses a risk to public health (ANA, 2022). In this way, porous pavement models proved efficient in reducing TP concentrations, which was an advantage.

Table 5. Removal concentration rates and credits according to the Minnesota Stormwater Manual (2021) for TSS and TP.

Reference	Model	Removal rate (%)		Credits (mg)	
		TSS	TP	TSS	TP
Hammes (2017)	A	92.0	23.0	11.59	0.37
	B	83.0	48.0	13.03	0.70
Belotto (2019)	C	63.0	63.0	3.78	0.06
	D	44.0	44.0	3.21	0.01

4.3. Comparative analysis and discussion

Based on the data from the analyses performed herein and through the calculation of credits, it was possible to analyse and compare the results. As for decreasing runoff volume, expressed by infiltration credits, it can be seen in Figure 3(a) that models B, C and D obtained very close results. Regarding the permeable pavements infiltration (Figure 3(b)), models B and C are similar, while model A has the lowest and D has the highest infiltration capacity. The main difference was the surface layer type (models A and B contain porous asphalt mixture, and models C and D contain permeable interlocked blocks).

Arora, Chopra, Ngyyen, Fernando, Burns & Fletcher (2023) asserted that permeable pavement performance is significantly affected by the intensity and duration of the rainfall event. Depending on the rainfall intensity and duration, the pavement layers can be saturated, the infiltration capacity is reduced, and as a consequence, the runoff volume increases. In this case, knowing the rainfall regime is essential for the pavement hydraulic

design. Pavement layers have to be designed with the maximum possible permeability and porosity. Additional sub-drain installation can also relieve the layer's saturation.
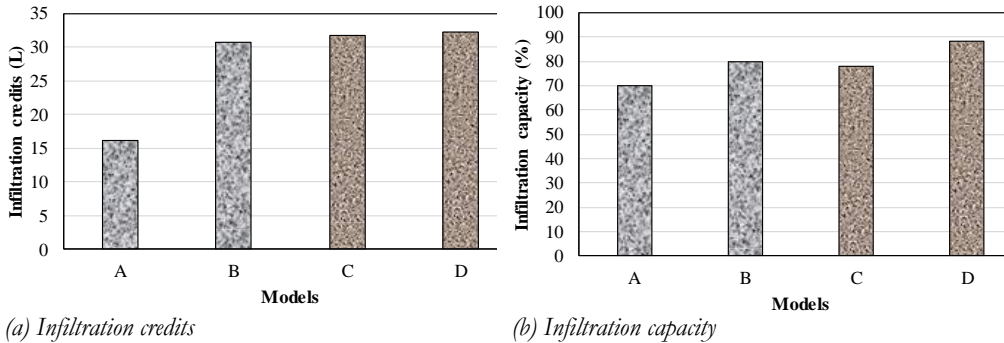

(a) Infiltration credits   *(b) Infiltration capacity*

Figure 3. Infiltration credits and infiltration capacity of the models

Garcia & Thives (2023) stated that permeable pavement advantages include the reduction of runoff and its pollutants. On the other hand, the porous layers' voids clog over time, and the permeable characteristics decrease. The authors found that when the interconnected void content reaches 12%, the porous mixture can be considered clogged and recommended that the surface be cleaned (with water and air jets) at least once a year. Lu, Liu, Wang, Faßbender, Wang & Oeser (2019) added that the layers are in constant moisture condition due to the high air void content, accelerating the binder ageing (porous asphalt mixtures) and causing early deterioration. Thus, permeable surface layers are generally designed for five years, with shorter lifespan compared to impermeable surfaces, generally for 10 to 20 years.

On the other hand, the models with porous asphalt mixture as surface layer, regardless of the under-pavement layers, were shown to be more efficient in removing TSS and TP pollutants expressed in credits, as shown in Figure 4.
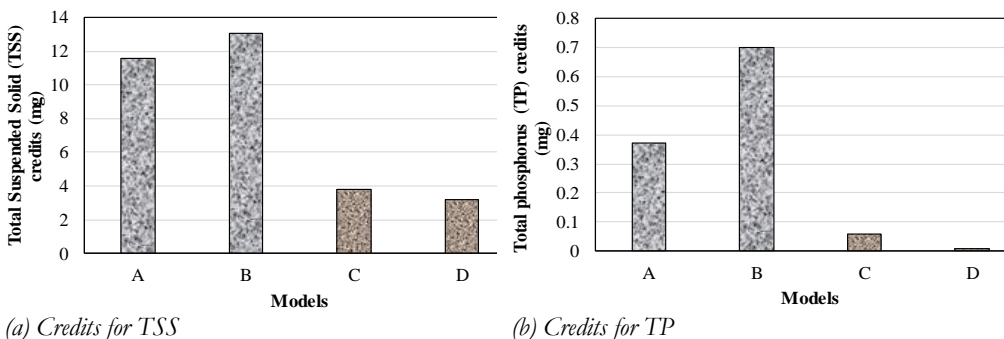

(a) Credits for TSS   *(b) Credits for TP*

Figure 4. Pollutants credits for each model

According to Minnesota Stormwater Manual (2021), for pollutant removal efficiencies, the minimum recommended figures are 74% for TSS and 41% for TP. Therefore, models A and B, which have porous asphalt mixture as a surface layer, achieved results higher than the minimum recommended for TSS, i.e. 92% and 83%, respectively; but only model B

achieved results higher than the minimum for TP, i.e. 48% (Table 5). On the other hand, models C and D did not reach the minimum recommended for TSS (63% and 44%, respectively, for models C and D), but both met the minimum recommended for TP (63% and 44%, respectively, for models C and D) (Table 5). The permeable pavement models evaluated herein proved that pollutants TSS and TP could be reduced from stormwater runoff (Figure 5). It was considered that a greater number of stormwater events should be evaluated in order to obtain a statistical analysis over the years. However, the results obtained indicated that the models are able to remove pollutants. The analysis has to be complemented, including more pollutants evaluation. In the case of stormwater harvesting, additional water treatment is required.
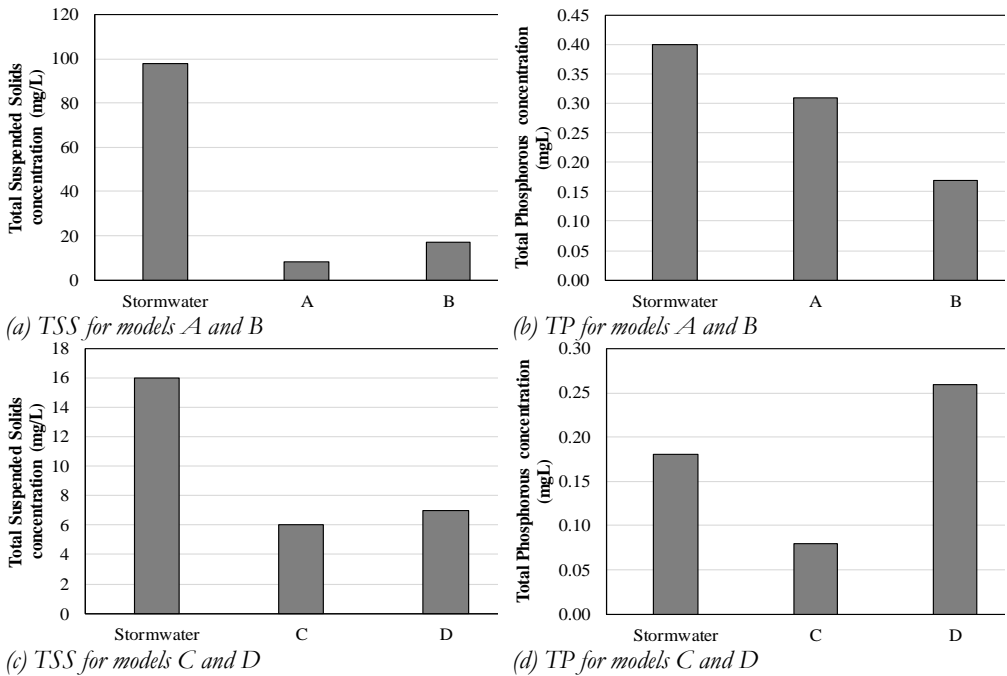

(a) TSS for models A and B

(b) TP for models A and B

(c) TSS for models C and D

(d) TP for models C and D

Figure 5. Comparison of pollutants removal for each model

5. Conclusion

This work evaluated the performance of permeable pavements in removing pollutants from stormwater and decreasing runoff. Four permeable pavement models were evaluated and exposed to stormwater events for infiltration and pollutants (TSS and TP) credit calculations. Also, the pollutants concentrations and infiltration capacity were measured.

The permeable pavement models studied herein reduced the pollutant concentrations and runoff volume. It was observed that the models with porous asphalt mixture as the surface layer, independent of the under-pavement layers, were more efficient in removing TSS and TP. On the other hand, the models with permeable interlocked blocks as the surface layer presented better infiltration capacity than the porous asphalt mixture.

The results obtained are preliminary, considering the short analysis period. A more significant number of stormwater events is needed for a complete evaluation of the models. Added to this is the need to assess the concentration of other pollutants to enable stormwater harvesting for non-potable uses in buildings.

The methodology for calculating credits was shown as an alternative for local authorities interested in encouraging best practices in rainwater management and meeting water quality objectives for non-potable uses in buildings. The results obtained in this work showed that permeable pavement application could be a suitable alternative contributing to the Low Impact Development (LID) principles.

Although the rainwater harvesting for non-potable purposes in buildings has been growing in Brazil, a few studies were performed considering permeable pavements. Also, there is no stormwater credits programme in the country, and this study contributed to disseminating stormwater management practices and the credits from different permeable pavement structures evaluation.

Acknowledgments

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