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Permeable pavement efficiency under clogging conditions Efficacité de la chaussée perméable dans des conditions de colmatage

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RÉSUMÉ

Les systèmes de chaussée perméable fournissent un stockage temporaire des eaux de pluie favorisant la gestion des eaux pluviales sur place dans les zones qui, autrement, contribueraient à l'augmentation du ruissellement. La surface de la chaussée gère le débit de pointe du ruissellement en infiltrant rapidement l'eau de pluie et fonctionne comme un filtre, retenant les particules qui s'accumulent à la surface. Lorsque cela est acceptable pour les conditions du site, l'afflux peut être stocké dans les réservoirs de base et infiltré sur le sol sous-jacent gérant le volume de ruissellement, où l'excès d'eau est évacué par des drains souterrains ou des étangs. Au cours de la durée de vie de la chaussée, les sédiments piégés en surface ont tendance à diminuer la capacité d'infiltration et constituent le principal facteur à prendre en compte dans l'évaluation de la fonctionnalité de la chaussée. Cette recherche a porté sur la fonctionnalité des systèmes de chaussées perméables avec des surfaces perméables en asphalte et en béton sur le débit de pointe du ruissellement, le volume et l'élimination de la charge dans des conditions de colmatage. L'efficacité moyenne de la surface poreuse sur le débit et la charge de pointe a été mesurée dans diverses conditions avec une simulation de précipitations, puis le devenir des particules a été estimé avec un modèle mécaniste utilisant des paramètres de pores obtenus par microtopographie aux rayons X. L'efficacité du réservoir dans la gestion du volume a été évaluée avec une simulation continue, et une équation a été proposée pour estimer la probabilité de débordement à partir des processus hydrologiques impliqués et des caractéristiques des précipitations.

ABSTRACT

Permeable pavement systems provide rainwater temporary storage promoting on-site stormwater management in areas that otherwise would generate runoff. The pavement surface manages runoff peak flow by infiltrating promptly rainwater and function as a filter, retaining particulate matter that accumulates on the surface. When acceptable for the site conditions, inflow can be storage in the base reservoir and infiltrated on the underlying soil managing runoff volume, where excess water is discharged through underdrains or ponding. Over the pavement life use, sediments trapped on the surface tend to decrease infiltration capacity and are the main factor to be considered in pavement functionality assessment. This research investigated the functionality of permeable pavement systems with pervious asphalt and concrete surfaces on runoff peak flow, volume, and load reduction under clogging conditions. Surface porous media efficiency on peak flow and load were measured on various conditions with rainfall simulation, and then particulate matter fate was estimated with a mechanistic model using pore parameters obtained with X-ray microtomography. The reservoir efficiency in managing volume was evaluated with continuous simulation, and an equation was proposed to estimate overflow probability from the hydrological processes involved and rainfall characteristics.

KEYWORDS

(permeable pavement, BMPs, hydraulic risk, probabilistic approach, particulate matter)

1 INTRODUCTION

Permeable pavement system (PPS) promotes runoff peak flow, volume and load reduction delivering Best Management Practices (BMPs) on stormwater management while easily adapted to high density urban contexts (Elliott and Trowsdale, 2007). The system, often installed on parking lots, consists of a highly permeable surface that promptly absorbs rainwater avoiding runoff generation. Rainwater is then conveyed to the sub-base layer functioning as a storage reservoir, releasing slowly the inflow through infiltration on the underlying soil or through an underdrain (Andrés-Valeri et al., 2016; Brugin et al., 2020; Marchioni et al., 2022, 2021). Porous surfaces function also as a filtering media, retaining particulate matter (PM) accumulated on impermeable surfaces during dry periods and washed off by stormwater runoff. PM trapped on the pore structure of the surface layer ultimately lead to infiltration capacity reduction, requiring performance evaluation methods to assess ordinary and extraordinary maintenance procedures.

This research investigated PPS performance on managing runoff peak flow, volume, and PM load control under clogging conditions (Marchioni et al., 2022, 2021). Runoff peak flow was evaluated considering the runoff generated under clogging from pervious asphalt (PA) and concrete (PC) surfaces through laboratory experiments, using a rainfall simulator developed specific for the project. Runoff volume control was investigated by looking on the performance of the base layer reservoir with a rainfall-runoff continuous simulation and a probabilistic approach to estimated overflows. Filtration mechanism involved on the PM load removal present on urban surfaces was investigated with laboratory experiments and then model relating PM removal from the relation between pore media characteristics and PM particle size distribution. Pore parameters to apply the model were obtained using X-Ray microtomography (XRT). While runoff peak flow and volume reduction are main aspects to consider when analyzing PPS, measuring runoff is complex on a regular basis and assessment is ordinarily held measuring HC using permeameters and infiltrometers, therefore the hydraulic conductivity (HC) was measured using a falling head permeameter. The obtained HC data was compared with volumetric runoff coefficient (C) obtained from the rainfall simulation verifying the adequacy of using HC as an indirect way of assessing PPS performance.

2 METHODOLOGY

Runoff and PM fate were estimated simulating rainfall on PA and PC slabs loaded with PM. For the rainfall simulation tests 18 PA and PC specimens with ΦT (total porosity) of 0.15, 0.20 and 0.25 respectively were produced with a mix design from a previous study (Bonicelli et al., 2015). A granular mixture of sand with particle size distribution ranging from 75 to 2,000 μm and a small fraction of filler was assembled to simulate PM that accumulates on pavement surfaces clogging the surface porous media. Tests were carried with rainfall intensity of 50 mm/h, 100 mm/h and 150 mm/h and PM load concentrations of 0.5 kg/m²; 1.0 kg/m² and 1.5 kg/m² for a total of 285 tests measuring after each test runoff volume, PM load fate and HC. The European Standard CEN 12697-40:2020 test method was implemented to determine HC. The used falling head permeameter consisted of a 125 mm diameter tube and a weighted base plate with a clear plexiglas tube height of 560 mm with a 48 mm outflow orifice through the permeameter base plate sealed to the specimen and ensured that all flow was discharged into the PP test specimens. The test consisted of measuring the outflow time (OT), i.e., the time (s) that elapses for an outflow of 4.0 liters (L) through the PP specimen. Further details are reported on (Andrés-Valeri et al., 2016; Brugin et al., 2020; Marchioni et al., 2021).

Under the hypothesis that the surface performs correctly, promptly infiltrating rainfall, the volume control depends upon the storage capacity of the reservoir on limiting overflows to an acceptable level. An independent event-based continuous simulation describing the hydrological process on a PPS estimated the overflows frequency for a certain reservoir maximum depth (h_{max}) using a rainfall series recorded at the Station ID 273 in San Paolo (Brazil) from 2007-2017 with 10 minutes interval time supplied by *Fundação Centro Tecnológico de Hidráulica* (FCTH) and typical soil saturated hydraulic conductivity (f_c) from sandy loamy soil (SM, SC from Soil-USCS) ($f_c = 1 \times 10^{-7}$ m/s). No contribution area was considered ($r = 0$). The analytical probabilistic method using derived probability distribution theory was then used to obtain an equation to estimate the overflows probability (Raimondi et al., 2022). The overflows probability was compared with the event-based continuous simulation using the San Paolo data. PM fate was model considering filtration mechanisms on the porous media through a mechanistic model considering the ratio of the average pore diameter (d_m) to PM particle diameter (d_p) (McDowell-Boyer et al., 1986; Teng and Sansalone, 2004). Three main mechanisms of transport can be identified: formation of a *schmutzdecke* also known as a surface (cake) generated by surficial straining for d_m/d_p

< 10 , deep-bed filtration within the pore space leading to a reduction in porosity for a range of approximately $10 < d_m/d_p < 20$, and physical-chemical filtration when $d_m/d_p > 20$, where the fine suspended PM attaches to the pore surfaces in the PP but do not generate a significant reduction in porosity. The d_m was estimated from the pore particle size distribution (Pore_{PSD}) obtained from the XRT analysis. Pore parameters were estimated through XRT using a NSI X25 system (NSI Inc., Rogers, MN, USA) equipped with a Dexela detector with 75 μm pixel pitch allowing for the acquisition of 1536 x 1944-pixel radiographies at full-binning with 16 bit encoding. Samples were extracted from the PA specimens to fit the XRT equipment. Further details can be found at (Marchioni et al., 2022).

3 RESULTS

The volumetric runoff coefficient was the efficiency indicator on reducing runoff peak flow under clogging conditions. From the global results of rainfall simulation tests, the C mean was 0.07 with standard deviation of 0.11 and median of 0.014, where 47% of the tests did not generate runoff ($C = 0$) assessing the efficiency on reducing runoff and conveying rainwater towards the base layers even when loaded with PM (Figure 1-a). Runoff volume reduction would then depend on the storage efficiency of the base reservoir. From the event-based continuous simulation, a PPS reservoir with $h_{\text{max}} = 300$ mm resulted on an overflow frequency of 0.02, corresponding to a return period of 50 years ($T = 50$ years). The analytical equation obtained from the probabilistic approach estimated the overflows frequency with a R-squared of 0.706 and can be used as a design tool (Figure 2-b).

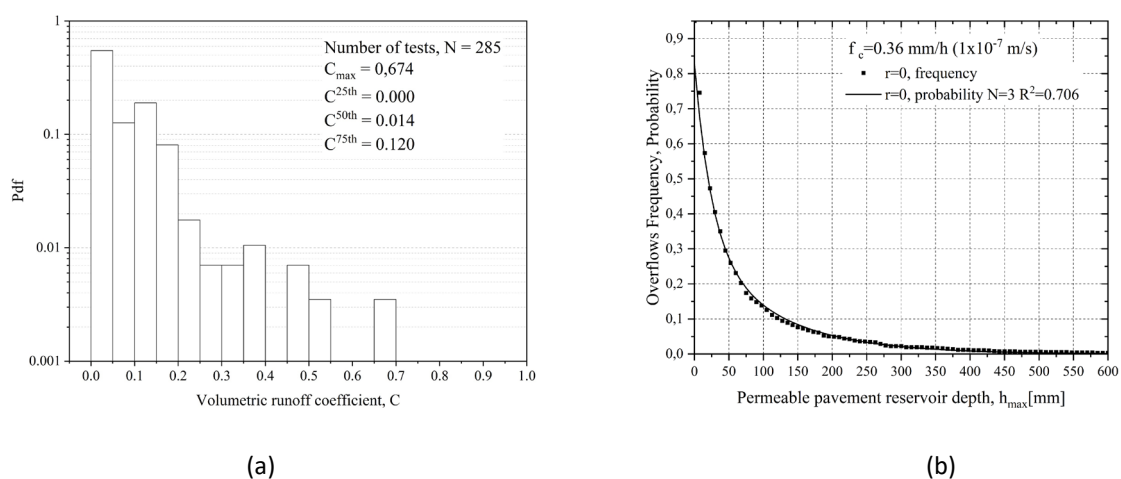


Figure 1 – Efficiency on managing runoff peak flow and volume: a - volumetric runoff coefficient, b – reservoir depth overflows frequency and probability.

For the rainfall simulation tests the majority ($> 85\%$) of the PM load was retained on the specimen surfaces as a schmutzdecke and within the pore matrix. Less than 15% was exfiltrated through the specimens and consisted of fine suspended PM, where a geotextile could retain these exfiltrated particles if required. A nominal fraction of PM ($< 2\%$ on a gravimetric basis) was washed off with runoff indicating that for the test conditions that the use of PA reduce PM loads that reach the drainage system assessing PPS performance on runoff sediment load removal (Figure 2 – a). The measured and modeled data presented a maximum of 8% relative percent difference, with 83.1% to 88.5% PM mass retained on the PA surface forming a schmutzdecke, 3.8% to 5.6% trapped on the pore matrix and 7.6% to 11.3% potentially leaching. More information can be found at (Marchioni et al., 2022). Assessing PP functionality by measuring runoff is complex to adopt on a regular basis, where PP evaluation is normally facilitated by measuring HC, leading to the assessment of an acceptable range of results. A combined consideration of HC, in this case represented with the OT index, and C showed that C is not as sensitive to variation on the surface conditions under clogging as HC, with a Spearman correlation coefficient between HC and C indicating a weak correlation ($\text{RHO } 0.2578$ and $p < 0.001$). For the tests where the cutoff limit was reached ($\text{OT} = 300$ s) the maximum runoff measured was 0.67, the maximum result for the entire test matrix and the minimum was zero ($C = 0$, no runoff) with mean of 0.05 and standard deviation of 0.15 (Figure 2 – b). HC can be used as a tool to assess PPS performance with attention to test method and site conditions, where for the method adopted in this study a cutoff limit of $\text{OT} = 300$ s could be an indicator for proceeding with maintenance. Further information can be found at (Marchioni

et al., 2021).

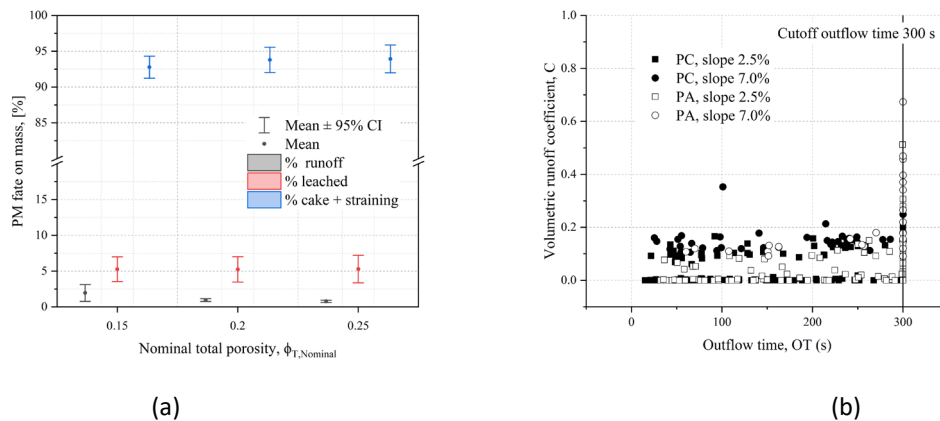


Figure 1 – Efficiency on managing runoff PM load and PPS functionality evaluation: a – PM fate on mass, b – volumetric runoff coefficient and outflow time (index for HC).

4 CONCLUSION

Part of the BMPs, PPS can use paved areas to manage runoff peak flow, volume and PM load adapting to dense urban areas. Functioning as a filter for PM accumulated on paved surfaces the capacity of infiltration rainwater decreases over time requiring maintenance procedures. Hydraulic aspects of PPS functionality were investigated through laboratory experiments and modelling assessing an adequate performance under clogging conditions, where PPS surface layer manages runoff peak flow and load removal while the base reservoir manage volume. HC is the main indicator for PPS functionally assessment although a weak correlation was found when compared with C results.

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