Journal of Water Process Engineering 53 (2023) 103658

Contents lists available at ScienceDirect

Journal of Water Process Engineering

journal homepage: www.elsevier.com/locate/jwpe

Influence of sediment characteristics on long-term hydrology and water quality behaviour during the clogging process of a permeable asphalt

Eduardo García-Haba [a,*], Juan Naves [b], Carmen Hernández-Crespo [a], Angélica Goya-Heredia [b], Joaquín Suárez [b], Jose Anta [b], Ignacio Andrés-Doménech [a]

[a] *Instituto Universitario de Investigación de Ingeniería del Agua y del Medio Ambiente (IIAMA), Universitat Politècnica de València, Camí de Vera s/n, 46022, Spain*
[b] *Universidade da Coruña, Water and Environmental Engineering Research Team (GEAMA), Center for Technological Innovation in Construction and Civil Engineering (CITEEC), Campus de Elviña, 15071 A Coruña, Spain*

ARTICLE INFO

Keywords:
Permeable pavement
Sustainable urban drainage systems
SUDS
Runoff pollution
Rainfall simulation

ABSTRACT

Sustainable urban drainage systems (SUDS) are common solution to address flow discharges, runoff volumes and pollutant concentrations caused by urban expansion and climate change trend. Among them, permeable pavements (PP) effectively manage and treat stormwater. The clogging process of PP has been addressed in previous studies but there is still room for improvement the knowledge about how it affects to their performance in terms of hydrological behaviour and pollutant removal and how it depends on sediment properties. The present study simulates and analyses the behaviour of a permeable asphalt through 47 sediment loading steps tested for six different sediment classes under laboratory conditions. The experiments were performed using permeable asphalt slabs in two laboratory rainfall simulators, measuring reductions in permeability, filtered and runoff flows, and water quality variations in effluents according to sediment loads and rainfall events. The results showed significant reductions of permeability (22–99 %) for sediment surface loads from 1 kg/m^2 onwards, except for very fine sediments (<125 μm) (1 %). Permeability recovery after vacuum cleaning varied between 8 % and 100 % of original permeability. Sediment particle size distribution, organic matter content and rain events sequence were key variables influencing the permeability loss and its recovery, and quality of filtrated water. The hydraulic efficiency was high, filtrating almost 100 % of the applied rainfall, whenever the sediment surface load was below 4 kg/m^2, above which surface runoff was produced. The efficiency of the slab for pollutant retention was 96 % for COD, 76 % for TN, 79 % for TP, and 98 % for TSS.

1. Introduction

Sustainable urban drainage systems (SUDS) are becoming a common solution to address the increase in flow discharges, runoff volumes and pollutants concentrations caused by urban expansion [44]. Among them, the use of permeable pavements (PP) is nowadays wide-spreading due to their demonstrated effectiveness in managing and treating stormwater at source. Porous asphalt is a common material that performs the surface layer of PP structures, which is successfully tested to implement this type of SUDS [39]. Even though in many countries SUDS are more and more being integrated into the usual urban drainage scheme [20]. However, technical challenges related to clogging and water quality aspects need to be further studied in order to achieve a successful city-wide implementation of PP and SUDS in general, ensuring a high social acceptance [3,19].

Clogging is the process by which PP lose its capacity for rainwater infiltration, due to the interception and accumulation of solid particles within the pavement layer. Solid particles can be sediments eroded from surrounding areas or from the pavement itself, debris from road surfaces or from other areas and carried by vehicles, organic matter from vegetation, etc. [27]. In addition, some fluids, such as hydrocarbons and oils, or biofilm growth, can accelerate the clogging process. Furthermore, clogged PP deteriorate at a faster rate than those remaining unclogged [21]. Different methods can be used for clogging evaluation, including the measurement of permeability with standard permeameters [40], the measurement of porosity in core samples [26], and full-scale infiltration methods [4]. The previous methods are usually employed in full-scale PP, whereas at lab-scale, the use of physical models with rainfall

---

* Corresponding author.
E-mail addresses: edgarha@iiama.upv.es (E. García-Haba), juan.naves@udc.es (J. Naves), carhercr@upvnet.upv.es (C. Hernández-Crespo), angelica.goya@udc.es (A. Goya-Heredia), joaquin.suarez@udc.es (J. Suárez), jose.anta@udc.es (J. Anta), igando@hma.upv.es (I. Andrés-Doménech).

https://doi.org/10.1016/j.jwpe.2023.103658
Received 9 January 2023; Received in revised form 3 March 2023; Accepted 11 March 2023

simulators and road-deposited sediments dosage is a well-established practice to assess clogging processes and their influence on hydraulic efficiency and water quality of filtrated water [25,28].

The novelty of this article is the strengthened role of real sediment used under laboratory conditions. Previous studies focusing on the water quality of filtrated flows, usually introduced pollutants through the application of synthetic rainwater or runoff on the PP [22,25,48]. However, in many cases, the accumulation of pollutants occurs directly on the own pavement surface and not through runoff from impervious pavements. In this case, the application of real sediments collected from urban areas and non-polluted rainwater, simulates a more realistic scenario to improve knowledge about the influence of rainfall intensity on pollutants mobilisation [17]. In this sense, it is interesting to check potential different behaviours of filtrated water considering sediments collected from different urban areas which can present different properties (such as particle size distribution, organic matter content or pollutant concentration), and accordingly, to suggest appropriate cleaning strategies. Most studies generally use synthetic runoff or prepared sediments with clay, sand and mixtures of them [41], while very few studies use real samples of sediment or runoff, or even different gradation openness of the pavement to evaluate clogging in PP [1,41,6]. The present study aims at covering this gap of knowledge.

Therefore, the objective of this research is to improve the knowledge about how porous asphalt behaves as it becomes clogged with different particle size distributions, with a special emphasis on real sediments. Under a holistic approach, the research looks at the hydraulic performance but also at the filtrated water quality and runoff when it may occur, under synthetic rainfall laboratory-controlled conditions. The hypotheses set to develop the research are: experimental setups built in different universities can be used in a coordinate way to obtain complementary information; sediments taken from different urban areas have different properties and can affect differently to the hydraulic and water quality performance of porous asphalt; and, the study of filtrated water quality in clogging experiments can provide decisive information for recommendations on cleaning and maintenance frequencies. Section 2 describes the experimental setup and the procedure followed during the tests. The tests carried out at the Universidade da Coruña (UDC) focus on analysing the influence of granulometry on the clogging of the permeable pavement, while the experiments carried out at Universitat Politècnica de València (UPV) aim to evaluate in detail the behaviour of the porous asphalt in terms of pollutant reduction for different degrees of clogging. Section 3 presents and discusses results, focusing on the permeability evolution of porous asphalt and its reduction by clogging; the hydraulic efficiency of the pavements in terms of volume and flow rates managed; the water quality of filtrated water; and, finally, the mass balance analysis of sediment masses within the different flow components.

2. Materials and methods

The experimental setup is introduced in Section 2.1, first by describing the rainfall simulators in Section 2.1.1. The porous asphalt slabs and the variable head permeameter are described in Sections 2.1.2 and 2.1.3. Then, the characteristics of the different sediment classes distributed over the asphalt slabs are presented in Section 2.1.4. Finally, the procedure followed during the tests is explained in detail in Section 2.2.

2.1. Experimental setup

2.1.1. Rainfall simulators

Two rainfall simulators have been used to assess the hydrological performance of the permeable pavement. First, a tailored rainfall simulator of 1 m^2 (Fig. 1a) was built in the hydraulics laboratory of CITEEC at Universidade da Coruña (UDC). It consists of a drippers-based rainfall simulator that can generate uniform and realistic rainfalls as described in Naves [34,35]. A rainfall intensity of 80 mm/h was simulated in this work, with an associated value of the Christiansen's uniformity coefficient of 93.5 %. Then, the permeable pavement is installed below the drippers over an impervious surface with a 2 % slope [44].

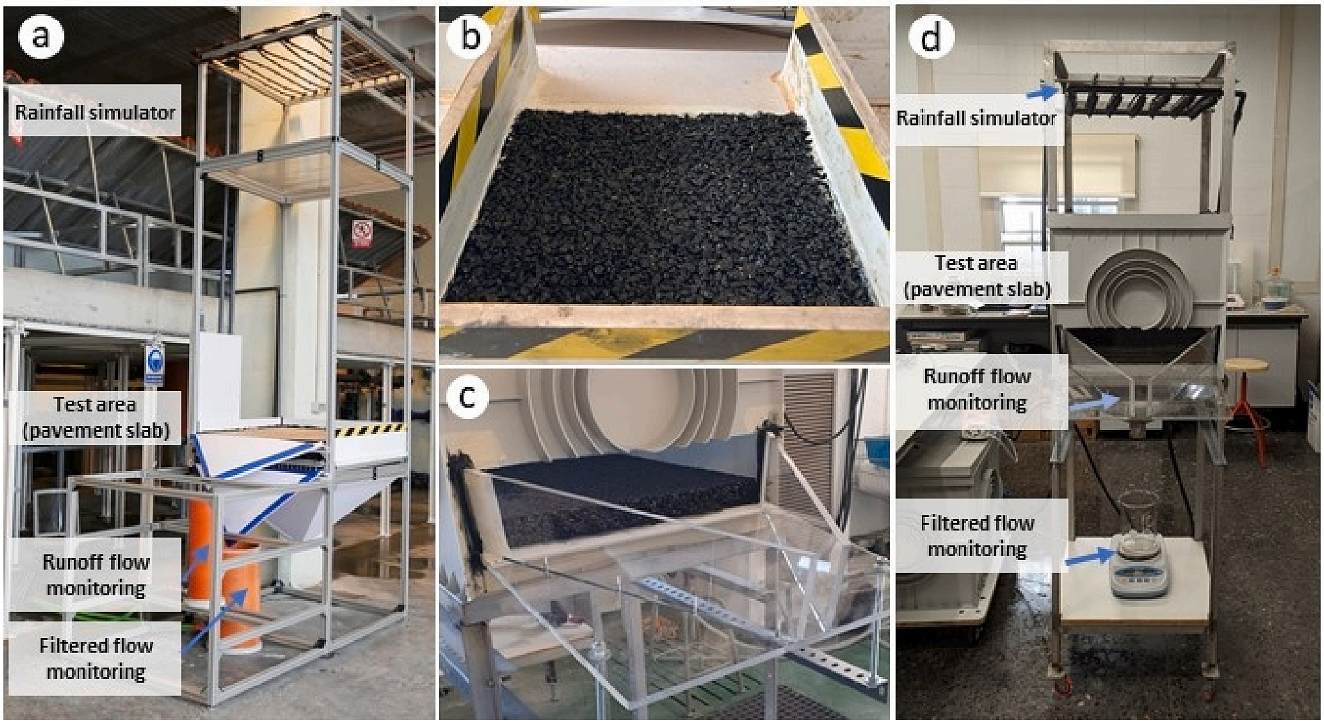

Fig. 1. General views of the UDC (a) and UPV experimental setup (d). Detail of the asphalt slab installed in the test area of each rainfall simulator and including the runoff collection system (b and c, respectively).

The rainwater that is filtered through the system is collected in a circular tank at the lateral of the experimental bench through a collecting funnel for online measuring of water discharge. In the same way, as the pavement gets clogged by sediment, runoff is generated and conducted to a second tank (Fig. 1b). Both filtered and runoff flow discharges are estimated from the level variation in the tanks using SN-SR04T ultrasonic probes previously calibrated.

A second rainfall simulator is placed at Universitat Politècnica de Valéncia (UPV). This facility uses the same methodology to simulate rain over a surface of 0.25 m^2, and the filtrated water is collected vertically below the pavement with a funnel and weighted in a precision balance (Fig. 1d). The surface runoff generated when the asphalt starts clogging, is collected laterally and monitored in an additional tank in the same way that the first facility at UDC (Fig. 1c). A detailed description of this rainfall simulator can be found in Fernández-Gonzalvo [17]. The tests carried out at UDC focus on analysing the influence of sediment particle size distribution on the clogging of permeable pavement, while the experiments carried out at UPV aim to evaluate in detail the behaviour of pavements in terms of pollutant reduction for different degrees of clogging.

2.1.2. *Porous asphalt*

The permeable pavement used in this investigation is a Spanish PA-16 porous asphalt use (Fig. 1b). Pavement slabs with 22.6 % void-ratio, 4.03 % of bitumen, and dimensions of 0.44 m × 0.40 m × 0.06 m in case of tests performed at UDC and 0.49 m × 0.49 m × 0.04 m for UPV tests. This pavement has been used because it is standardized in the Spanish national road design instructions [33]. The slabs were installed in the rainfall simulators with the perimeter completely sealed to force rain and sediment loads to pass through the pavement or be drained laterally with the runoff flow generated once the slab becomes clogged. At UDC tests, a two-centimetre-height slot has been left along the bottom part of one side of the slab to allow lateral drainage of the filtered flow over the impervious base into the corresponding tank. Above this open boundary condition, the slab was kept sealed to force rainfall vertical infiltration in the vicinity of that side. A new asphalt slab was used for each of the three tests carried out at UDC where the influence of particle size distribution on the clogging process was studied. After testing the possibility of recovering the initial conditions of the slab by washing it thoroughly between tests, an asphalt slab was used for the remaining three tests carried out at UPV to evaluate the pollutant reduction capacity for different levels of clogging and different sediment classes.

2.1.3. *Variable head permeameter*

A variable head permeameter has been used to measure the permeability of the porous asphalt for different grades of clogging during the tests following the Spanish standard NLT-327/00 [8], similar to EN 12697-40 [16]. This standardized variable head permeameter estimates permeability in one point of the surface from the time it takes the water level in a vertical cylinder to descend between two marks as the pavement drains. A single permeability measurement was made instead of the two indicated by the standard because it has been observed that the pulse of water generated by the permeameter can partially flush the sediment trapped in the PP, disturbing the second measurement. The procedure indicated in the standard is motivated to moisten dry pavements in field measurements. In our tests, measurements were performed 30 min after the end of the rain event once the slab has completely drained water, but the pavement is still wet. Three points separated 75 mm between them were marked on the centre of the asphalt slabs to be used as control points to monitor the variations on permeability produced by the different sediment loads and sediment classes distributed during the tests.

2.1.4. *Sediment classes*

Three sediment classes have been used first to investigate the influence of particle size distribution on the long-term hydraulic performance of the porous asphalt as it progressively clogs. These sediments were obtained from road dust collected from parking lots in the UDC campus. The sediment was first calcined at 550 °C and prepared to be classified into three different sediment classes: fine (UDC-1), coarse (UDC-2), and realistic (UDC-3). The calcination aims to remove organic matter reducing the uncertainty that cohesivity may introduce in the process and focusing this part of the research in the influence of particle size distribution on the clogging process. UDC-1 (63–125 μm) and UDC-2 (250–500 μm) have a uniform particle size distribution with a mean diameter d_{50} of 104 μm and 391 μm, respectively. UDC-3 represents a realistic graded road deposit sediment with a d_{50} of 282 μm. This third sediment class was created by sieving the road dust using blind, 63, 125, 250 and 500 μm sieves and composing it in a proportion of 10 %, 15 %, 25 % and 30 % following the particles size distribution found in Deletic and Orr [11], Vaze and Chiew [42], Viklander [43], and Zafra [46]. In this process, the coarser fraction retained in the sieve of 1 mm was not considered since it was preliminary observed that these particles cannot be introduced into the pavement due to the pore size of the asphalt and thus, they do not contribute to the clogging process of slabs [32]. Fig. 2a shows the particle size distribution of these three sediment classes measured using a laser coulter counter (Beckam-Coulter LS 13 320) and compared to literature values.

Three additional sediment classes have been tested at UPV facility to assess in detail variations in pollutant removal efficiency as pavement gets clogged. First, as the content of organic matter has been removed in the previous sediment classes and considering that cohesivity may play an important role in both the water quality of the effluents and the clogging of permeable pavements, the realistic graded sediment class (UDC-3) was replicated without calcinating (UDC-4). The behaviour of this material was then compared with two additional sources of sediments collected from the UPV campus and from a residential area in the Benicalap district of València (BEN). Sediments UPV and BEN were collected by mechanical vacuum-sweepers [45] and sieved to a size of 5 mm. In this case, particles larger than 1 mm have been considered because, although they do not contribute to the clogging process due to the maximum pore size of the pavement, they may be of interest because they can contain contaminants that are washed during rain events [7,14,15,24]. Fig. 2b shows the particle size distribution of the three sediment classes tested in this part of the research at UPV. Note that the maximum size of 1 mm has been maintained for UDC-4 sediment to compare with previous tests analysing the influence of cohesivity on the clogging process. UPV and BEN sediments presented a lower content of fine material despite being collected with an effective technique for the finest fraction [23], probably since these sediments were sieved at 5 mm. Table 1 includes a summary of all sediment classes used in this work indicating the rainfall simulator where the sediment class was used and its main characteristics. The influence of sediment characteristics on the results is analysed in next section.

2.2. *Experimental and analytical procedures*

A total of 45 sediment load steps have been tested for 6 different sediment classes evaluating the variations of permeability and changes in the quantity and quality of drained hydrographs as the pavement becomes gradually clogged. Every load step represents the accumulation of sediment in time with no cleaning or maintenance. For each sediment class, the porous asphalt slabs are loaded by means of cyclical build-up and rainfall events. Deionised water (electrical conductivity [EC] of 10 μS/cm and pH of 7.1) is used to simulate rainwater. In each step of this procedure, a certain amount of the sediment tested was distributed homogeneously over the slab surface and a constant 80 mm/h and 30 minute rainfall was simulated, waiting 24 h until the next step of load to allow the system to dry. The rainfall intensity used was chosen as the highest and most unfavourable in terms of clogging that the rainfall simulator is able to generate [17,18,24], with a duration enough to achieve a steady flow regime and to ensure that the material is able to

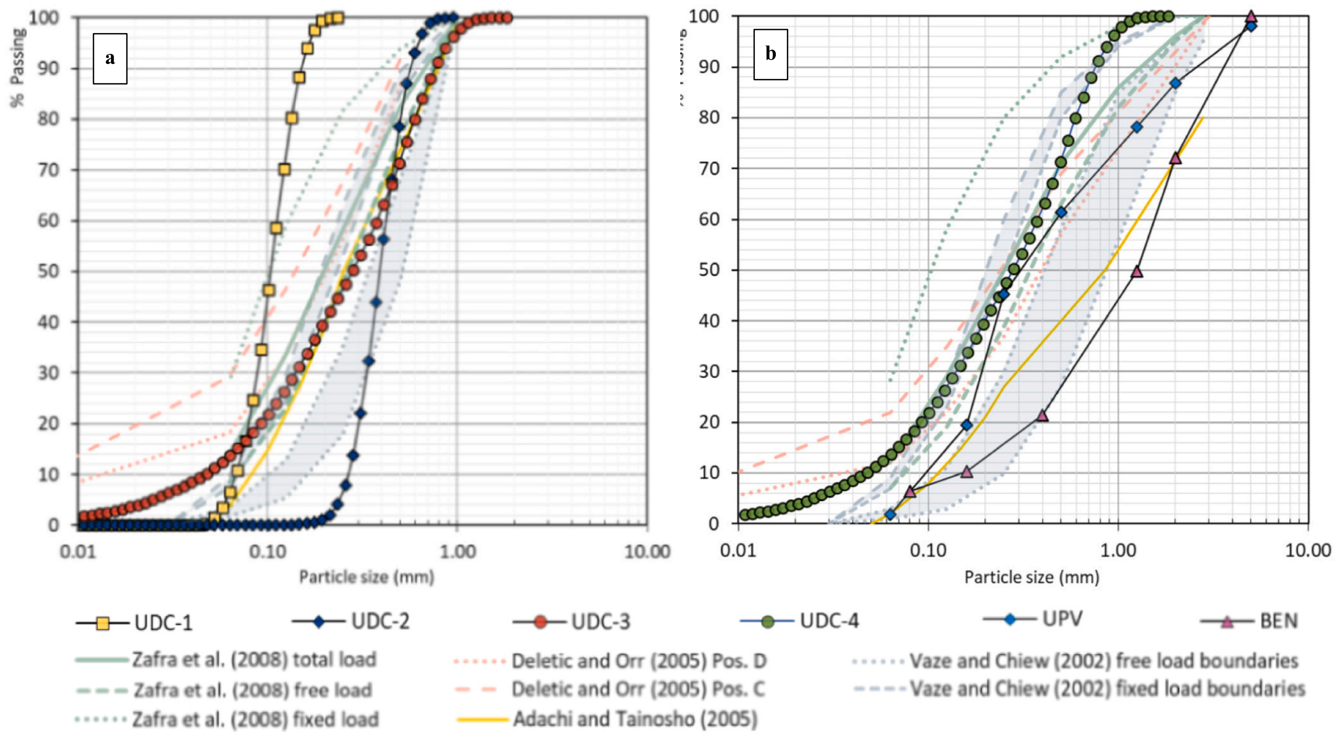

Fig. 2. Particle size distribution of the six sediment classes analysed compared to reference values found in the literature [2,11,42,46]. The left graph (a) includes the sediment classes used to analyse in detail the effect of particle size on the clogging process (UDC-1, UDC-2 and UDC-3), which are limited to a maximum size of 1 mm. The remaining sediment classes (UDC-4, UPV and BEN) are shown on the right graph (b). Only the fraction <1 mm of the literature references has been considered in the left graph to be compared.

Table 1
Summary of sediments characteristics. Note: d.w.: dry weight; NA: not analysed; LOI: loss-on-ignition; Org. C: organic carbon; TN: total nitrogen; TP: total phosphorus.

Sediment class	d_{50} (μm)	d_{min}-d_{max} (μm)	Real density (kg/m^3)	LOI (% d.w.)	Org. C (% d.w.)	TN (g/kg d.w.)	TP (g/kg d.w.)
UDC-1	104	63–125	2931 ± 5	0	NA	NA	NA
UDC-2	391	250–500	2652 ± 4	0	NA	NA	NA
UDC-3	282	0–1000	2929 ± 4	0	NA	NA	NA
UDC-4	282	0–1000	NA	4.7	2.2 ± 0.3	0.2	0.05
UPV	300	0–5000	NA	8.2	2.4 ± 0.4	0.9	0.30
BEN	1125	0–5000	NA	33.2	4.9 ± 0.5	1.3	0.20

penetrate the pavement as far as possible. Filtered and runoff drained flows were online monitored during the simulated rain events. The permeability of the slab was measured 30 min after the end of the rain at certain load steps using the variable head permeameter. The measurement was made at the three control points marked on the asphalt without any sediment load (blank), after 1 kg/m^2 cumulative load and with the maximum load tests to consider the heterogeneities of the slab. For the rest of measurements, only one of the three control points has been used each time alternatively so that the flush flow generated by the permeameter has the minimum effect on the slab clogging and thus on subsequent measurements. When the proposed maximum load stablished for each sediment class has been reached, the surface of the pavement was cleaned using an 1600 W industrial vacuum cleaner (UDC) and 110 W handheld vacuum cleaner (UPV) until it was observed that no more particles were able to enter the device. Then, an additional rain event was simulated the following day, measuring permeability and drained flow rates again to assess the potential recovery of initial conditions. Table 2 summarizes the load steps tested for each sediment class indicating the cumulative sediment load distributed on the slab from the start of each test and the steps where permeability measurements and vacuuming were made. At the end of each battery of experiments, a mass balance was carried out by weighting the sediment load vacuumed from the surface of the slab and quantifying the mass of sediment dragged into the filtration and surface runoff tanks.

Beyond this general procedure, in the tests using the realistic continuous granulometry within the analysis of the influence of particle size on the clogging process (sediment class UDC-3), the particle size distribution of the sediment collected at the end of the experiments for the mass balance was analysed by a laser coulter particle size analyser (Beckam-Coulter LS 13 320) to be compared with the sediment initially distributed and to assess the behaviour of the different particle sizes through the permeable pavement tested. In the case of the experiments that aimed at analysing in detail the quality of the effluents for different degrees of clogging (UDC-4, UPV and BEN), the drained mean concentration of different water quality variables was analysed. These variables were chemical oxygen demand (COD), biological oxygen demand at 5 days (BOD$_5$), total and volatile suspended solids (TSS and VSS), ammonium, nitrites, nitrates, total nitrogen (TN), phosphates, total phosphorus (TP), aluminium (Al), turbidity, hydrogen potential (pH), electric conductivity (EC), dissolved oxygen (DO), saturation percentage (%sat DO) and temperature. For sediments, humidity, apparent and real density, organic matter (loss-on-ignition (LOI) and oxidable carbon), total nitrogen (TN) and total phosphorus (TP) were also analysed. The standardized methods used for these physicochemical analyses are listed in Table S1 (Supplementary material).

Table 2
Cumulative sediment load tested in each step of each battery of experiments.

Sediment class	Cumulative sediment load (kg/m^2)													
	D0	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12	D13
UDC-1	0[a]	0.1	0.3	0.6	1.0[a,b]	V[a]	–	–	–	–	–	–	–	–
UDC-2	0[a]	0.1	0.3	0.6	1.0[a,b]	V[a]	–	–	–	–	–	–	–	–
UDC-3	0[a]	0.1	0.3	0.6	1.0[a]	1.5	2.0[a]	2.5	3.0[a]	3.5	4.0[a,b]	V[a]	4.5	5.0
UDC-4	0[a]	0.1	0.4	1.0	2.0[a]	3.5	5.5[a,b]	–	–	–	–	–	–	–
UPV	0[a]	0.1	0.4	1.0	2.0[a]	3.5	5.5[a,b]	–	–	–	–	–	–	–
BEN	0[a]	0.1	0.4	1.0	2.0[a]	3.5	5.5[a,b]	–	–	–	–	–	–	–

V new rain event after vacuuming the surface at the end of the previous day.

[a] Variable head permeameter measurement.

[b] Vacuuming of the surface at the end of the test.

3. Results and discussion

3.1. Permeability of porous asphalt and reduction by clogging

Permeability was measured by the variable head permeameter in the sediment load steps indicated in Table 2. The results obtained for the initial permeability, 23,559 ± 5034 mm/h (Fig. 3), fall around the upper limit of the range reported for porous asphalt in a recent review study (300–30,000 mm/h) [38]. As sediment load was increased on the system surface, the permeability was exponentially reduced for the different sediment classes, as showed in Fig. 3. Similar decreasing patterns have been observed by other studies, in which the decrease has been related with pavement age [38] or with the number of cycles of clogging assays [28].

Despite this significant reduction of permeability, it remained above the simulated rainfall intensity (80 mm/h) even after the maximum surface sediment dosing, when sediments UDC-4, UPV and BEN were used. Concretely it remained at 583 ± 567, 286 ± 56 and 860 ± 527 mm/h for UDC-4, UPV and BEN respectively. This may be the reason why no runoff was generated in the experiments with UPV and BEN sediments, as explained in the next section.

Focusing on the experiments performed to assess in detail the effect of particle size distribution (UDC-1, UDC-2 and UDC-3), a different behaviour was obtained for the granulometries tested, with the finest granulometry (UDC-1) being the one that least clogged the slabs, while the real granulometry (UDC-3) was the most unfavourable for a cumulative sediment load of 1 kg/m^2. We can also observe that finer sediment (UDC-1) was much less harmful to the pavement than the coarser one (UDC-2) and the realistic one (UDC-3), as the former can restore permeability to almost 100 % of the original (Fig. 3). The fine material was able to pass through the asphalt slab, percolating with the rainwater, while the larger grain size material was trapped, causing a greater loss of permeability. Nevertheless, not only sediment diameter affects to clogging process of PP. The tests also shown the importance of using graded sediments instead of uniform particle size distribution. Thus, uniform UDC-2 distribution has a d_{50} of 391 μm while graded UDC-3 sediments of about 282 μm, but the percentage of clogging is much higher for the realistic sediment (78 % vs. 53 %). It is possible that the latter material had a grain size similar to that of pore size of the porous asphalt, resulting in a higher potential for clogging. A literature review concluded that findings from clogging studies are not always consistent with each other, since differences in the clogging material used, pore structure of the pavement, exposure conditions and other variables can influence the results [27]. Neupert [36] highlighted that using small diameter sediments ($d_{50} \sim 63$ μm) to analyse permeable pavement performance as in some German standardized procedures, may lead to underestimation of the actual road sediment deposits load. In our work it is shown that the reduction in permeability is also underestimated.

The effect of organic matter can be observed by comparing the experiments performed with UDC-3 and UDC-4. It can be observed that UDC-4 caused a larger loss of permeability, which could be related to the higher content of organic matter (UDC-4).

After different sediment loading steps, the porous asphalt was vacuum-cleaned, and the recovery of permeability was checked (Fig. 3). The experimental batteries with UDC-1 and UDC-2 recovered the most permeability after vacuum cleaning, followed by UDC-4 and BEN, while the battery with UDC-3 recovered the least permeability, both in absolute and relative terms. UDC-1 and UDC-2 were subjected to four rainfall

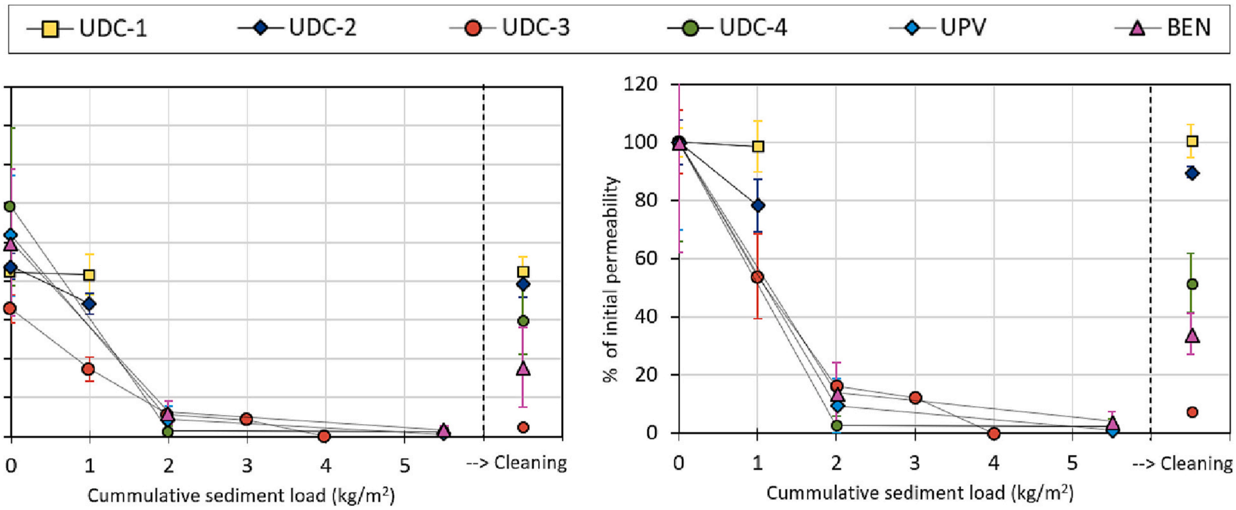

Fig. 3. Reduction of permeability observed for different sediment loading steps over the porous asphalt for each sediment class tested. The results are presented in mm/h (left) and in relative terms with respect to the initial permeability (right).

events, UDC-4 and BEN to six and UDC-3 to eleven (Table 2). From these results, one can deduce that, for similar sediment loads, the number of rainfall events has a negative influence on the potential permeability recovery. Therefore, the frequency of rainfall events should also be considered when establishing maintenance protocols.

3.2. Flow rates drained

The hydraulic efficiency, measured as the percentage of rainfall volume that is infiltrated through the porous asphalt, was very high for loading steps up to 1 or 4 kg/m^2 when sediments UDC-1, UDC-2 and UDC-3 were used, with a negligible runoff flow (Fig. 4). It was 100 % for all the sediment loads when UPV and BEN sediments were used. The filtration flow rate was very similar among the different experiments for sediment loadings below 4 kg/m^2, almost equal to the applied rainfall (80 mm/h), despite the loss of permeability shown in the previous section. This can be explained by the fact that the permeability, despite the reduction, was still higher than the applied rainfall intensity, as well as the possible existence of unclogged areas and the occurrence of preferential flows through them.

UDC-3 total clogged for 5.0 kg/m^2 as seen in Fig. 4. The effect of clogging was noted from a cumulative load of 4.5 kg/m^2, when rainwater can no longer be drained completely through the slabs and generates runoff. The runoff generated was collected, increasing runoff discharge and decreasing filtered discharge. Initial measured runoff showed in Fig. 4 was due to splashing of raindrops on the lateral runoff collection funnel, so the runoff caused by clogging for 4.5 kg/m^2 was 0.0027 L/s, which was increased up to 0.0039 L/s for 5.0 kg/m^2 of cumulative load as more percentage of the surface slab becomes clogged. However, looking at the third test (UDC-3), where the realistic granulometry was distributed, we observed a reduction of the filtered flow and an increase of runoff at roughly 3.5 kg/m^2 of accumulated load. This indicates that some parts of the slabs are starting to clog at a sediment load between 3.5 and 4.0 kg/m^2.

The tests performed with UDC-4, which is the same sediment as UDC-3 but not calcined, presented a filtration rate lower than those performed with UDC-3. This decrease of infiltration rate, as in the case of loss of permeability, could be related to the presence of organic matter, which confers cohesivity to the sediment. The runoff generated at a cumulative load of 2 kg/m^2 is very similar in both cases, varying between 1 and 2 mm/h, and total volumes between 0.10 L/m^2 (UDC-3) and 0.32 L/m^2 (UDC-4) (3 % of the rainfall depth). At the top sediment load tested (5.5 kg/m^2), the runoff flow was significantly higher (54 mm/h for UDC-4) as well as its volume (24.4 L/m^2; 61 % of the rainfall depth applied).

In contrast, UPV and BEN sediments did not generate runoff for any of the sediment loading steps. These sediments have a less proportion of fine material, so they hardly led to physical clogging. Instead, UPV and BEN have a higher potential to induce clogging due to biofilm growth, also known as bioclogging [37], as they have a larger content of organic matter and nutrients, or even, chemical clogging, as they have more substances able to react and precipitate with others. Probably, a longer period would have been necessary to detect this clogging mechanism.

As shown in Fig. 4, the vacuuming of the pavement surface produces a moderate recovery (25 %) of the filtration capacity for the realistic granulometry (UDC-3), which is in line with the low recovery of

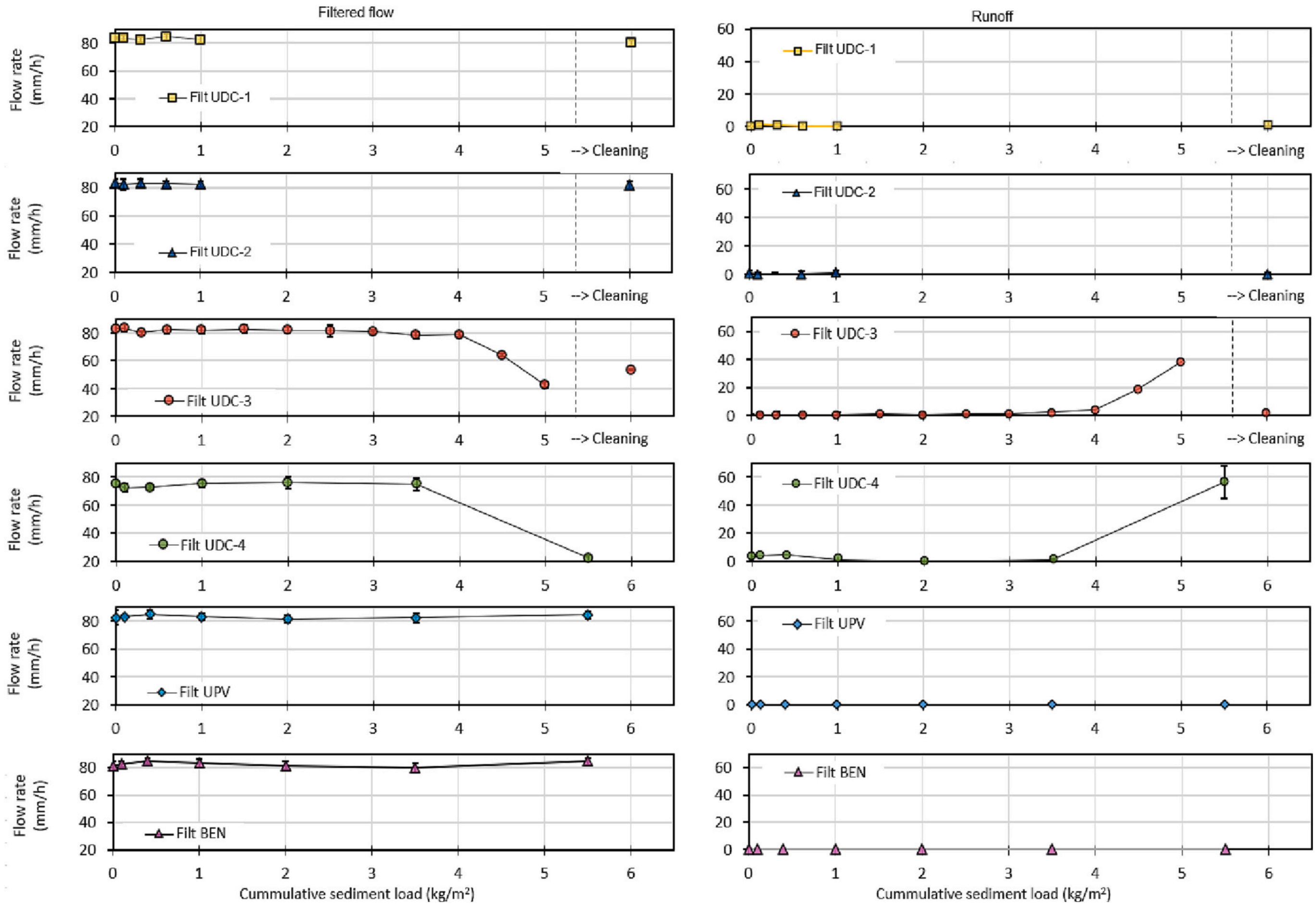

Fig. 4. Mean of the filtered (left column graphs) and runoff (right column graphs) flow rates drained for each sediment class and different grades of clogging when the hydrograph reached stationary condition between 900 and 1500 s from the beginning of the experiment. Standard deviation represented with error bars.

permeability for this sediment and within the range reported in literature [27]. These authors concluded that the recovery rate depends on several factors, such as porosity, pore size and connectivity of the porous pavement, and on the properties of the sediments that clog the pavement, mainly on its grain size.

3.3. *Water quality of filtrate and surface runoff flows*

Water quality (WQ) of the filtrate and runoff flows was analysed for the experiments using real sediments (UDC-4, UPV and BEN) (Fig. 5).

In general, all the WQ variables increased as the cumulative sediment load increased. For all variables except TSS, UDC-4 was the sediment that contributed the least pollutant load to the filtered water, followed by UPV; BEN was the sediment that leached more nutrients and organic matter. These results are related to the higher content of organic matter and nutrients of BEN sediments (Table 1). However, UDC-4 added more TSS to the filtered water, because of its higher proportion of fine material (Table 1). After 1 kg/m^2 of cumulative sediment load, COD, TSS and TP reached concentrations higher than the discharge limits for treated wastewater [12] for at least one kind of sediment. Other WQ indicators to consider are those included in the regulation on the protection of groundwater against pollution and deterioration [13], which establishes quality standards for nitrates and pesticides, and call upon the European Union Member States to establish threshold values for additional WQ variables. Among all these variables, the ones analysed in the present study and their indicator value are nitrates (11.3 mg N/L), ammonium (1.91 mg N/L) and phosphates (0.52 mg P/L) [9]. The concentration of filtered water is below the nitrate standard and the ammonium threshold for any of the sediment classes and their cumulative loads, even total nitrogen is below the standard. Although a low risk of nitrate pollution can be considered, measures such as water detention inside the PP are recommended to favour denitrification, and thus, to reduce pollution risk [10]. However, phosphates exceed the threshold from a cumulative sediment load of 1 kg/m^2. When the sediment characteristics are similar to those used in this study and considering all these indicator values, a maximum allowable sediment load on permeable pavements of 1 kg/m^2 could be established to avoid negative impacts on the receiving waters. According to previous studies [17,24], this could be equivalent to a period of around six months of pollutant build-up in urban road surfaces. Therefore, the obtained results are in line with the recommendations given in previous studies for establishing a monthly cleaning frequency for the routine maintenance tasks [18], which is more frequent than maintenance usually recommended in other studies (1 to 4 times per year, [27]).

If the total content of organic matter and nutrients in the sediments deposited on the pavement surface is considered, the relative release of these substances are, on average, 4 % for COD (estimated from organic carbon in Table 1), 23 % for TN and 21 % for TP. This release percentage decreased as the sediment load increased, likely because rainwater is not able to mobilise all the pollutant mass accumulated on the pavement surface when the sediment load is large (Table 3). Previous studies also pointed out this trend [18]. Complementary, the relative proportion retained on the surface or inside the porous asphalt may be considered as an indicator of the PP performance, which gives, on average, 96 % for COD, 76 % for TN and 79 % for TP. The efficiency obtained is among the highest values reported in the literature. For instance, Liu [30] reported mean load reductions around 59 % for TP and 43 % for TN by permeable bricks and 43 % (TP) and 52 % (TN) for porous concretes. Kamali [25] and Mahmoud [31] obtained removal performances of 100 % and 77 % respectively for TSS, and Braswell [5] found load reductions of 95 % for TSS and TP, and 70 % for TN.

The leaching capacity of organic matter and nutrients increased with sediment concentrations. Concretely, BEN sediments leached more organic matter and nutrients than UPV and UDC-4 sediments (Table 3). It is also remarkable that leachability decreases with the cumulative sediment mass deposited on the surface, as commented previously. The values obtained in this study are in the same order of magnitude that those obtained in previous studies [34]. These results are useful to assess the pollution potential of each sediment class. It is important to emphasize that physical characteristics of PP such as roughness and porosity allow pollutant retention so that they can be easily removed later, and do not reach the environment. By contrast, accumulated pollution on impervious surfaces, with a low void-ratio, is likely to be washed during rain events. In consequence, less quantity of contaminants can be removed, and end up affecting the environment.

3.4. *Fate of sediments at the end of the tests*

Finally, the mass balance shows how much and what type of sediment has been retained for each test in the surface, dragged to the runoff tank or filtered through the asphalt slab (Table 4). Overall, a 98 % of the sediments remains accumulated over the surface and inside the porous asphalt, meanwhile just roughly a 2 % is mobilised by surface runoff or filtrated water.. This result demonstrates that physical interception is a major mechanism for solid removal, which coincides with previous studies [24,29]. The sediment with finer granulometry (UDC-1) was mainly retained inside the porous asphalt, while coarser sediments (UPV and BEN) remained mainly on the surface. Sediment UDC-2, which is slightly coarser than sediment UDC-1, was retained on the surface to a greater extent than sediment UDC-1. Sediment UDC-2 clogged the upper pores of the asphalt largely and therefore did not allow more sediment to pass through it. This result is consistent with the fact that sediment caused a greater loss of permeability of the asphalt slab (Fig. 3) and with the conclusions reached by other studies [28,47].

Sediment UDC-4 was retained on the surface in higher proportion than UDC-3. This fact that can be explained by the higher organic matter content of UDC-4, which could have become more cohesive on the surface, trapping more fine particles. Additionally, UDC-4 received less rain events than UDC-3, thus having less probability of penetrating inside the porous asphalt.

Fig. 6 shows the particle size distribution of the sediments collected from the surface, from the runoff or filtered through the pavement at the end of the tests for sediment class UDC-3, which is the one with a realistic inorganic granulometry. Comparing initially distributed granulometry and particle size distribution of sediment present at filtered flow, it can be seen that only the finest material was able to pass through the slab (approximately d_{50} 75 μm), with coarsest sediments (approximately d_{50} 300–400 μm) being retained on the pavement surface. It can also be seen that sediment washed into the runoff tank, either by saltation by raindrops or when runoff is generated, is similar to that on the surface. This is in line with and reinforces the conclusions drawn from the mass balance and stated previously.

4. Conclusions

Porous asphalt is one feasible solution for continuous surfaces of permeable pavements. Although it has been widely used, there is still a lack of knowledge on mechanisms influencing the clogging process and how this problem affects the water quality of filtrated water. This research developed in two different laboratories an experimental strategy to analyse the influence of sediment particle size distribution on the clogging of the permeable pavement and, to evaluate in detail the behaviour of the porous asphalt in terms of pollutant reduction for different degrees of clogging. From the tests carried out and the results obtained, the following conclusions can be drawn:

- The use of two different facilities managed by two independent teams demonstrates the transferability of the methodology proposed in this study, the comparability of the results obtained and the possibility to obtain complementary results.
- Testing different sediment materials provide valuable information to evaluate the clogging process, the water quality of filtrated water

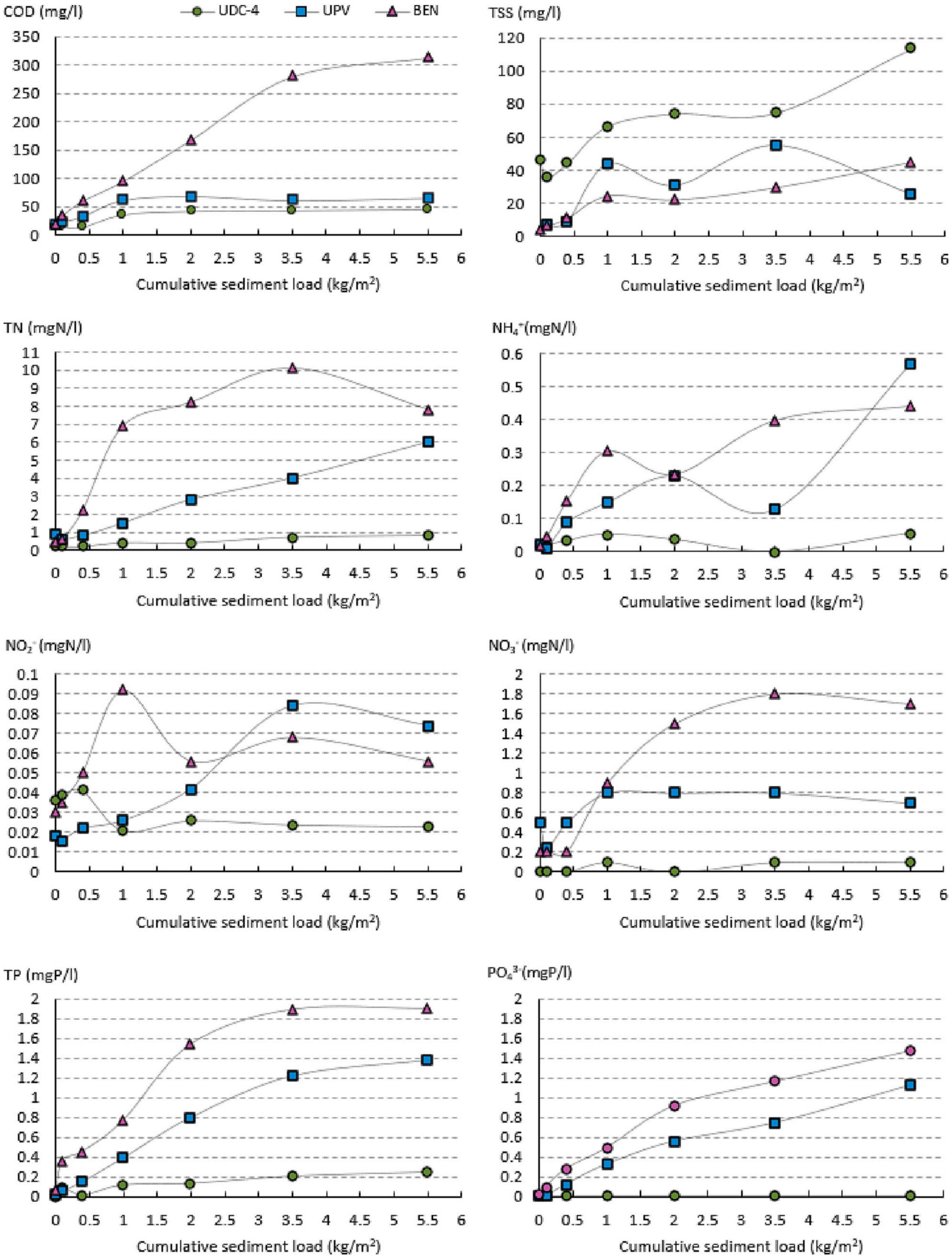

Fig. 5. Water quality results of filtrated water under increasing sediment load using different sediments (UDC-4, UPV and BEN).

Table 3
Organic matter and nutrients released from the sediment deposited on the surface of porous asphalt to the filtrated water, expressed as percentage (%) relative to the accumulated mass on the surface, and leaching capacity expressed as mg per kg of sediment and L of rainwater applied (mg/kg/L). Note: (*) indicates nutrients released by the surface runoff; NA: not available.

Sediment class	Sediment loading (kg/m^2)	COD (% released)	COD (mg/kg/L)	TN (% released)	TN (mg/kg/L)	TP (% released)	TP (mg/kg/L)
UDC-4	0.1	7.6 %	439.9	58 %	13.0	65 %	3.1
	0.4	2.0 %	113.2	22 %	4.9	19 %	0.2
	1.0	2.3 %	130.7	15 %	3.4	16 %	0.4
	2.0	1.3 %	73.7	11 %	2.4	13 %	0.2
	3.5	0.8 %	44.1	9 %	2.1	12 %	0.2
	5.5	0.2 %	9.6	7 %	1.5	8 %	0.1
	5.5 (*)	NA	NA	4 %	1.0	11 %	0.6
UPV	0.1	14.1 %	893.4	64 %	58.2	18 %	2.4
	0.4	5.1 %	322.4	25 %	22.5	12 %	1.6
	1.0	3.8 %	243.6	16 %	15.0	13 %	1.6
	2.0	2.1 %	132.7	14 %	12.9	14 %	1.6
	3.5	1.1 %	67.1	13 %	11.8	15 %	1.4
	5.5	0.7 %	46.6	13 %	11.8	15 %	1.0
BEN	0.1	9.7 %	1264.9	32 %	42.8	53 %	14.4
	0.4	4.4 %	570.4	24 %	32.0	27 %	4.5
	1.0	2.8 %	371.7	30 %	40.1	21 %	3.1
	2.0	2.4 %	313.6	26 %	35.5	19 %	2.9
	3.5	2.3 %	297.4	23 %	31.0	18 %	2.0
	5.5	1.6 %	213.1	19 %	25.0	15 %	1.3

Table 4
Fate of sediments at the end of the tests for each battery of experiments. Sediment applied on the surface and contained in runoff and filtered flows are measured data. The sediment load retained in the asphalt slab is estimated through a mass balance from the total mass distributed over the pavement and the previous values.

Sediment class	Sediment mass (%)			
	Surface	Runoff	Retained	Filtered
UDC-1	0.1	1.6	97.8	0.5
UDC-2	20.7	0.8	75.9	2.6
UDC-3	12.8	2.3	84.7	0.2
UDC-4	31.6	0.5	67.5	0.3
UPV	80.7	0.0	19.0	0.3
BEN	92.9	0.0	7.0	0.1

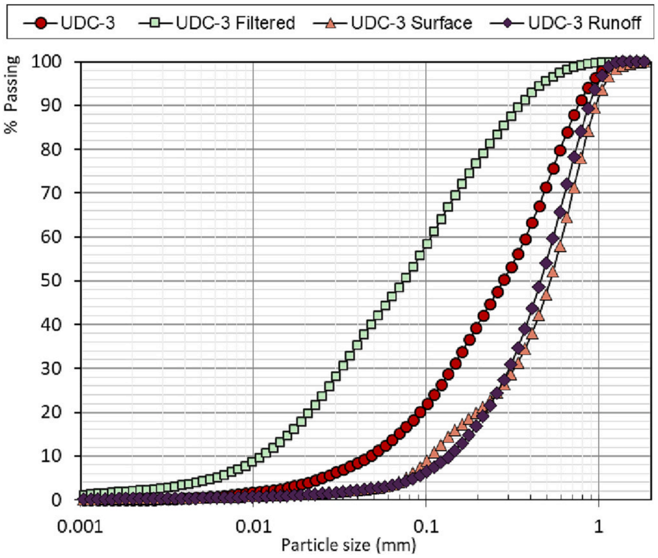

Fig. 6. Particle size distribution of sediment collected at the end of the experiments in the different parts of the rainfall simulator compared to the sediment initially distributed.

and, consequently, establish recommendations for PP cleaning maintenance protocols. Therefore, when a PP is designed, it is highly recommended to characterize the potential for sediment production within the catchment and to propose cleaning and maintenance frequencies adapted to local conditions. In addition, the quality of filtrated water should be analysed whenever possible, as it can determine the frequency of sediments cleaning needed to avoid negative impacts on the receiving waters.

- Fine sediments with a maximum diameter lower than 125 μm cause a lower permeability loss than sediments with a wider minimum-maximum diameter range (250–500 or 0–1000 μm), so standardized methods for assessing clogging potential should consider this fact. The number of rainfall events (or clogging cycles) influences negatively on permeability recovery by vacuum cleaning, thus the rainfall frequency is an important variable to consider when cleaning methods are going to be tested and proposed.
- The porous asphalt tested in this study has shown an elevated hydraulic efficiency and high capacity to retain sediments and pollutants, thus installing this kind of infrastructures in urban areas makes a significant contribution to the environment and the sustainability of urban drainage.

It must be considered that the sediments used in the experiments were collected from parking lots and residential sites. Nevertheless, a wider range of land uses can be identified within the urban environment, such as commercial or industrial among others. According to the site and the urban activities that take place, pollutant composition and concentration can vary significantly. For this reason, it is suggested to widen consider additional types of sediments generated at more diverse sites to complete this experience. It might be suggested that future research lines focus on the development of site-based maintenance and cleaning procedures of permeable pavements, according to the direct influence of the sediment characteristics and the rainfall conditions on the clogging process.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jwpe.2023.103658.

CRediT authorship contribution statement

Eduardo García-Haba and Angélica Goya-Heredia with the help of Joaquín Suárez performed the experiments, interpreted the results, and prepared the original draft with the supervision of Juan Naves, Carmen Hernández-Crespo, José Anta, and Ignacio Andrés-Doménech, who conceptualized the study. All the authors critically revised the final version.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Eduardo García-Haba reports financial support was provided by Spain, Ministry of Science and Innovation (MCIN). Ignacio Andrés-Doménech reports financial support was provided by Spain, Ministry of Science and Innovation (MCIN).

Data availability

Data will be made available on request.

Acknowledgments

This research is developed within the framework of the Spanish “Plan Estatal de Investigación Científica y Técnica y de Innovación 2017–2020”, project HOFIDRAIN (Holistic characterization of filtering sections for smart and sustainable management of urban drainage systems at city scale), through the sub-projects ENGODRAIN (grant number RTI2018-094217-B-C31) and POREDRAIN (grant number RTI2018-094217-B-C33) funded by MCIN/AEI/10.13039/501100011033 and by “ERDF A way of making Europe”. Eduardo García-Haba appreciates the pre-doctoral contracts funding received for doctors training (Ref. PRE2019-089409) funded by MCIN/AEI/10.13039/501100011033 and by “ESF Investing in your future”.

References

[1] J. Aberle, C. Rennie, D. Admiraal, M. Muste, Experimental hydraulics: methods, in: Instrumentation, Data Processing and Management: Volume II: Instrumentation and Measurement Techniques, CRC Press, 2017.

[2] K. Adachi, Y. Tainosho, Single particle characterization of size-fractionated road sediments, Appl. Geochem. 20 (2005) 849–859, https://doi.org/10.1016/j.apgeochem.2005.01.005.

[3] I. Andrés-Doménech, J. Anta, S. Perales-Momparler, J. Rodríguez-Hernández, Sustainable urban drainage systems in Spain: a diagnosis, Sustainability (Switzerland) 13 (5) (2021) 1–22, https://doi.org/10.3390/su13052791.

[4] F. Boogaard, T. Lucke, Long-term infiltration performance evaluation of dutch permeable pavements using the full-scale infiltration method, Water 11 (2) (2019) 320, https://doi.org/10.3390/w11020320.

[5] A.S. Braswell, R.J. Winston, W.F. Hunt, Hydrologic and water quality performance of permeable pavement with internal water storage over a clay soil in Durham, North Carolina, J. Environ. Manag. 224 (2018) 277–287, https://doi.org/10.1016/J.JENVMAN.2018.07.040.

[6] M. Burgin, M. Marchioni, G. Becciu, F. Giustozzi, E. Toraldo, V. Andrés-Valeri, Clogging potential evaluation of porous mixture surfaces used in permeable pavement systems, Eur. J. Environ. Civ. Eng. 24 (5) (2017) 2020, https://doi.org/10.1080/19648189.2017.1411834.

[7] G.A. Burton R. Pitt 2002. Stormwater Effects Handbook: A Toolbox for Watershed Managers, Scientists, and Engineers. CRC Press LLC. doi:10.1201/9781420036244.

[8] CEDEX, Normas NLT I.- Ensayos de Carreteras, Centro de Estudios y Experimentación de Obras Públicas. Ministerio de Transportes, Movilidad y Agenda Urbana. Gobierno de España, 2000. ISBN: 84-7790-361-1.

[9] CHJ, Plan Hidrológico de la Demarcación Hidrográfica del Júcar. Memoria – Anejo 12. Evaluación del estado de las Masas de agua superficial y Subterránea. Confederación Hidrográfica del Júcar. Ministerio de Agricultura, Alimentación y Medio Ambiente. Gobierno de España. https://www.chj.es/es-es/medioambiente/planificacionhidrologica/Documents/Plan-Hidrologico-cuenca-2021-027/PHC/Documentos/PHJ2227_Anejo12_Estado_20220329.pdf, 2022.

[10] J. Drake, A. Bradford, T. Van Seters, Stormwater quality of spring-summer-fall effluent from three partial-infiltration permeable pavement systems and conventional asphalt pavement, J. Environ. Manag. 139 (2014) 69–79, https://doi.org/10.1016/j.jenvman.2013.11.056.

[11] A. Deletic, D.W. Orr, Pollution buildup on road surfaces, J. Environ. Eng. 131 (1) (2005) 49–59, https://doi.org/10.1061/(ASCE)0733-9372(2005)131:1(49).

[12] Directive 91/271/CEE, Council Directive 91/271/EEC of 21 May 1991 concerning urban waste-water treatment. http://data.europa.eu/eli/dir/1991/271/oj.

[13] Directive 2006/118/EC, Directive of the European Parliament and of the Council of 12 December 2006 on the protection of groundwater against pollution and deterioration. http://data.europa.eu/eli/dir/2006/118/oj.

[14] T.T.T. Duong, B.K. Lee, Determining contamination level of heavy metals in road dust from busy traffic areas with different characteristics, J. Environ. Manag. 92 (2011) 554–562, https://doi.org/10.1016/j.jenvman.2010.09.010.

[15] C. Durand, V. Ruban, A. Amblès, B. Clozel, L. Achard, Characterisation of road sediments near Bordeaux with emphasis on phosphorus, J. Environ. Monit. 5 (2003) 463–467, https://doi.org/10.1039/b300695f.

[16] European Standard, BS EN 12697-40:2020 Bituminous Mixtures. Test Methods in Situ Drainability, BSI Standards Publication, 2020.

[17] M. Fernández-Gonzalvo, C. Hernández-Crespo, M. Martín, I. Andrés-Doménech, Comparison of permeable pavements effluent under Atlantic and Mediterranean rainfall regimes: a mid-term laboratory experience, Build. Environ. 206 (2021), 108332, https://doi.org/10.1016/J.BUILDENV.2021.108332.

[18] M. Fernández-Gonzalvo, C. Hernández-Crespo, M. Martín, I. Andrés-Domenech, Influence of pollution build-up and pavement cross-section on permeable pavements under extreme rainfall events, WIT Trans. Ecol. Environ. 242 (2020) 161–171, https://doi.org/10.2495/WP200141.

[19] E. García-Haba, J. Rodríguez-Hernández, I. Andrés-Doménech, C. Hernández-Crespo, J. Anta, M. Martín, Design of permeable pavements in Spain: current situation and future needs, Ing. Agua 26 (4) (2022) 279–296, https://doi.org/10.4995/Ia.2022.18290.

[20] M. Gimenez-Maranges, J. Breuste, A. Hof, Sustainable drainage systems for transitioning to sustainable urban flood management in the European Union: a review, J. Clean. Prod. 255 (2020), 120191, https://doi.org/10.1016/j.jclepro.2020.120191.

[21] W.S. Guthrie, C.B. DeMille, D.L. Eggett, Effects of soil clogging and water saturation on freeze-thaw durability of pervious, Concrete 2164 (2010) 89–97, https://doi.org/10.3141/2164-12.

[22] S. Han, Y. Yang, S. Liu, M. Lu, Decontamination performance and cleaning characteristics of three common used paved permeable bricks, Environ. Sci. Pollut. Res. 28 (12) (2021) 15114–15122, https://doi.org/10.1007/S11356-020-11706-Y/FIGURES/9.

[23] H.M. Haynes, K.G. Taylor, J. Rothwell, P. Byrne, Characterisation of road-dust sediment in urban systems: a review of a global challenge, J. Soils Sediments 20 (12) (2020) 4194–4217, https://doi.org/10.1007/S11368-020-02804-Y/FIGURES/13.

[24] C. Hernández-Crespo, M. Fernández-Gonzalvo, M. Martín, I. Andrés-Doménech, Nitrogen in infiltrated water from pervious pavements under different rainfall regimes and pollution build-up levels, in: Green Energy and Technology, 2019, https://doi.org/10.1007/978-3-319-99867-1_5.

[25] M. Kamali, M. Delkash, M. Tajrishy, Evaluation of permeable pavement responses to urban surface runoff, J. Environ. Manag. 187 (2017), https://doi.org/10.1016/j.jenvman.2016.11.027.

[26] M. Kayhanian, H. Li, J.T. Harvey, X. Liang, Application of permeable pavements in highways for stormwater runoff management and pollution prevention: California research experiences, Int. J. Transp. Sci. Technol. 8 (2019) (2019) 358–372, https://doi.org/10.1016/j.ijtst.2019.01.001.

[27] A. Kia, H.S. Wong, C.R. Cheeseman, Clogging in permeable concrete: a review, J. Environ. Manag. 193 (2017) 221–233, https://doi.org/10.1016/J.JENVMAN.2017.02.018.

[28] A. Kia, H.S. Wong, C.R. Cheeseman, Defining clogging potential for permeable concrete, J. Environ. Manag. 220 (2018) 44–53, https://doi.org/10.1016/J.JENVMAN.2018.05.016.

[29] H. Li, Z. Li, X. Zhang, Z. Li, D. Liu, T. Li, Z. Zhang, The effect of different surface materials on runoff quality in permeable pavement systems, Environ. Sci. Pollut. Res. 24 (26) (2017) 21103–21110, https://doi.org/10.1007/s11356-017-9750-6.

[30] W. Liu, Q. Feng, W. Chen, R.C. Deo, Stormwater runoff and pollution retention performances of permeable pavements and the effects of structural factors, Environ. Sci. Pollut. Res. 27 (24) (2020) 30831–30843, https://doi.org/10.1007/S11356-020-09220-2.

[31] A. Mahmoud, T. Alam, A. Sanchez, J. Guerrero, T. Oraby, E. Ibrahim, K.D. Jones, Stormwater runoff quality and quantity from permeable and traditional pavements in semiarid South Texas, J. Environ. Eng. 146 (6) (2020), https://doi.org/10.1061/(ASCE)EE.1943-7870.0001685.

[32] K. Mishra, Y. Zhuge, K. Warna, Clogging mechanism of permeable concrete: a review, Available at, in: Understanding Concrete conference, Gold Coast Australia, 2013, pp. 16–18, http://eprints.usq.edu.au/24554.

[33] Ministerio de Fomento, Pliego de Prescripciones Técnicas Generales para obras de carreteras y puentes (PG-3), Ministerio de Transportes, Movilidad y Agenda Urbana. Gobierno de España, 2019. https://www.mitma.gob.es/carreteras/normativa-tecnica/17-pliegos-de-prescripciones-tecnicas-generales.

[34] J. Naves, J. Anta, J. Suárez, J. Puertas, Development and calibration of a new dripper-based rainfall simulator for large-scale sediment wash-off studies, Water 12 (1) (2020) 152, https://doi.org/10.3390/w12010152.

[35] J. Naves, J. Anta, J. Suárez, J. Puertas, Hydraulic, wash-off and sediment transport experiments in a full-scale urban drainage physical model, Sci. Data 7 (1) (2020) 1–13, https://doi.org/10.1038/s41597-020-0384-z.

[36] J.W. Neupert, P. Lau, D. Venghaus, M. Barjenbruch, Development of a new testing approach for decentralised technical sustainable drainage systems, Water 13 (2021) 722, https://doi.org/10.3390/w13050722.

[37] N. Perujo, A.M. Romaní, X. Sanchez-Vila, A bilayer coarse-fine infiltration system minimizes bioclogging: the relevance of depth-dynamics, Sci. Total Environ. 669 (2019) 559–569, https://doi.org/10.1016/J.SCITOTENV.2019.03.126.

[38] M. Razzaghmanesh, S. Beecham, A review of permeable pavement clogging investigations and recommended maintenance regimes, Water 10 (3) (2018) 337, https://doi.org/10.3390/W10030337, 2018, Vol. 10, Page 337.

[39] J. Rodríguez-Hernández, V.C. Andrés-Valeri, M.A. Calzada-Pérez, A. Vega-Zamanillo, D. Castro-Fresno, Study of the raveling resistance of porous asphalt pavements used in sustainable drainage systems affected by hydrocarbon spills, Sustainability 7 (12) (2015) 16226–16236, https://doi.org/10.3390/SU71215812.

[40] L.A. Sañudo-Fontaneda, V.C. Andres-Valeri, C. Costales-Campa, I. Cabezon-Jimenez, F. Cadenas-Fernandez, The long-term hydrological performance of permeable pavement Systems in Northern Spain: an approach to the "End-of-life" concept, Water 10 (2018) 497, https://doi.org/10.3390/w10040497.

[41] S. Tan, T. Fwa, C. Han, Clogging evaluation of permeable bases, J. Transp. Eng. 129 (3) (2003), https://doi.org/10.1061/(ASCE)0733-947X(2003)129:3(309).

[42] J. Vaze, F.H.S. Chiew, Experimental study of pollutant accumulation on an urban road surface, Urban Water 4 (2002) 379–389, https://doi.org/10.1016/S1462-0758(02)00027-4.

[43] M. Viklander, Particle size distribution and metal content in street sediments, J. Environ. Eng. 124 (8) (1998) 761–766, https://doi.org/10.1061/(ASCE)0733-9372(1998)124:8(761).

[44] B. Woods-Ballard, Wilson, H. Udale-Clarke, S. Illman, T. Scott, R. Ashley, R. Kellagher, The SuDS manual. www.ciria.org, 2015. ISBN: 978-0-86017-760-9.

[45] Q. Yang, Z. Gao, S. Beechman, A sustainable approach to cleaning porous and permeable pavements, Sustainability 14 (21) (2022) 14583, https://doi.org/10.3390/su142114583.

[46] C.A. Zafra, J. Temprano, I. Tejero, Particle size distribution of accumulated sediments on an urban road in rainy weather, Environ. Technol. 29 (2008) 571–582, https://doi.org/10.1080/09593330801983532.

[47] J. Zhang, R. She, Z. Dai, R. Ming, G. Ma, X. Cui, L. Li, Experimental simulation study on pore clogging mechanism of porous pavement, Constr. Build. Mater. 187 (2018) 803–818, https://doi.org/10.1016/J.CONBUILDMAT.2018.07.199.

[48] M. Zheng, W. Chen, Q. Gao, S. Liu, C. Deng, Y. Ma, G. Ji, Research on the reduction performance of surface runoff pollution through permeable pavement with different structures, Water Air Soil Pollut. 233 (4) (2022) 1–16, https://doi.org/10.1007/S11270-022-05619-4/TABLES/5.