Laboratory Analysis of Stormwater Runoff Hydraulic and Pollutant Removal Performance of Pervious Concrete Based on Seashell By-Products

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***Abstract*—**In order to solve problems associated with stormwater runoff in urban areas and their effects on natural and artificial water bodies, the integration of new technical solutions to the rainwater drainage becomes even more essential. Permeable pavement systems are one of the most widely used techniques. This paper presents a laboratory analysis of stormwater runoff hydraulic and pollutant removal performance of permeable pavement system using pervious pavements based on seashell products. The laboratory prototype is a square column of 25 cm of side and consists of the surface in pervious concrete, a bedding of 3 cm in height, a geotextile and a subbase layer of 50 cm in height. A series of constant simulated rain events using semi-synthetic runoff which varied in intensity and duration were carried out. The initial vertical saturated hydraulic conductivity of the entire pervious pavement system was 0.25 cm/s (148 L/m^2/min). The hydraulic functioning was influenced by both the inlet flow rate value and the test duration. The total water losses including evaporation ranged between 9% to 20% for all hydraulic experiments. The temporal and vertical variability of the pollutant removal efficiency (PRE) of the system were studied for total suspended solids (TSS). The results showed that the PRE along the vertical profile was influenced by the size of the suspended solids, and the pervious paver has the highest capacity to trap pollutant than the other porous layers of the permeable pavement system after the geotextile. The TSS removal efficiency was about 80% for the entire system. The *first-flush* effect of TSS was observed, but it appeared only at the beginning (2 to 6 min) of the experiments. It has been shown that the PPS can capture *first-flush*. The project in which this study is integrated aims to contribute to both the valorization of shellfish waste and the sustainable management of rainwater.

***Keywords*—**Hydraulic, pervious concrete, pollutant removal efficiency, seashell by-products, stormwater runoff.

I. Introduction and Background

As early as the 1960s, the waterproofing of soil has accelerated with increasing urbanization. The multiplication of urban flooding by runoff and/or by networks overflow resulted in a change of strategy in urban stormwater management. A new vision of rainwater emerges; this is called Sustainable Drainage Systems (SuDs). The SuDs strive to mimic the natural movement of water from a development, reducing the risk of flooding and improving water quality. They also often provide attractive features that can make towns and cities more desirable places to live in. Permeable Pavement Systems (PPSs) are one of the most techniques used in SuDs. A PPS generally consists of pervious concrete on top, one or more layers of varying gravel sizes, and an underlying subbase. With its high porosity, pervious concrete can be used for concrete flatwork applications, that allow water from precipitation and other sources to pass directly through, thereby reducing the runoff from a site and allowing groundwater recharge [1]. Previous studies have also shown that PPSs using pervious concrete are effective in reducing the pollutants concentrations contained in runoff [2], [3]. It has even reported that pervious concretes are able to capture and treat *"first-flush"* pollutants [4]. The "*first-flush*" is a phenomenon in which about the first 25 to 30% of runoff is particularly polluted. This phenomenon often occurs during a rainy event following a long period of dry weather by the resuspension of a high concentration of pollutants that have accumulated during dry periods. After heavy rains, the "*first-flush"* sends surface toxins and pollutants along the pavement's horizontal surface and into the nearest drainage outlet. With a PPS, the water and surface toxins drain through the pervious concrete, then into the subbase and eventually into the soil below where further filtration may take place. Currently, pervious concretes are widely used in parking areas, areas with light traffic, residential streets, pedestrian walkways, and greenhouses [1], [4].

In metropolitan France, the annual aggregate production is estimated at 400 million tons, i.e. 6 tons per inhabitant according to the French Union of Aggregate Producers [5]. Aggregates are classified as the second most used resource after water. On another side, France is the leading producer in Europe of shellfish waste with almost 200 000 tons of shells from shellfish breeding and nearly 50 000 tons of shellfish per year from fishing [6]. These activities engender several thousands of tons of seashell by-products (SBPs) to be discharged, because they are considered as waste. All these figures give an idea of the economic and environmental stakes that involved the management of aggregates consumption and the management of shellfish waste. Moreover, environmental regulations, land use policies, and urban/suburban construction and expansion are further limiting access to many natural aggregate resources. One of the original and creative solutions that meet to both of these issues is the incorporation of shells in building materials. Currently, there are already various studies on the valorization of shells by incorporating them into building materials, which include some early

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examples: in the cement matrix [7], in the composition of the plain concrete and mortar [7], [8] and in the composition of the pervious concrete [9]-[11].

Let us focus on this last point, i.e. the use of SBPs in pervious concrete mix. These works [9]-[11] confirmed the feasibility of the use of the SBPs as a substitution in the composition of pervious concrete by experimental tests. The hydro-mechanical properties of pervious concrete based on SPBs were tested and compared with those of pervious concrete without SBPs. Generally, these tests showed that [9]-[11] the mechanical strength of pervious concrete based on SBPs is comparable to that of raw pervious concrete without SBPs, pervious concrete based on SBPs has high water permeability due to the presence of an interconnected porous system, and there is a relation between mechanical strength, porosity, and water permeability.

The project in which this work is registered follows the studies established in a previous project [9]-[11], from the stage of technical development and characterization of eco-pervious concrete based of SBPs (patented) and industrial production to their use in the field. Thus, a first industrial manufacture of pervious concrete based on SBPs was made by an industrial partner (Point P) within the framework of this project. A real building site which is 12-seaters car park has been recently constructed and monitored to study the long-term performance of a PPS using pervious concrete based on SBPs in terms of flood reduction, its pollutant reduction capabilities, and durability in service. Another larger site is also under construction. These two sites are located in the Normandy region (France).

The main objective of this study is to evaluate both the hydraulic performance and the removal pollutant efficiency of PPS using pervious concrete based of SBPs in order to better understand the behavior and the functioning of the field structures. This evaluation is based on 1D measurements (vertical) of the hydraulic responses of the structure under various types of stress as well as the measurement and analysis of some quality semi-synthetic runoff parameters, using an experimental test bench of reduced size but with the same characteristics in terms of composition of layers than those of the field structures.

These measurements consist of:

1) Hydraulic experiments: the characterization of the physical properties of the components of the structure and those of the entire structure and the assessment of the hydraulic performance of the structure in terms of water quantity reduction
2) Qualitative experiments: the assessment of the spatial (vertical) variability of the PRE of the structure and the study of the temporal variability of the PRE of the whole structure.

For this purpose, synthetic runoff was simulated (mixtures of tap water and added pollutant). For pollutants, the study focused on TSSs. TSS is a predominant parameter because they are the main vector of all pollutants in runoff [12], especially nutriments, heavy metal, and hydrocarbons, in particular as the pollution discharged into runoff is essentially in the form of solids particles (more than 90%). Several studies [13]-[17] showed that they are also responsible of the physical clogging of PPSs, including those using pervious concrete. Clogging is a common phenomenon that may occur in any filtration system. It can be defined as the formation of semi-pervious layer throughout a range of depths due to the combined effect of mechanical or physical, biological, and chemical processes [13], [14]. It has also showed that physical clogging caused by TSS is the main contributing factor to clogging [14]-[16]. The particle size distribution of TSS was also investigated.

This work provides data that will allow long-term modeling of the hydraulic functioning of the structure and the dynamic pollutant fate. The originality of the project which integrates this study resides in the incorporation of SBP in the formulation of pervious concrete by substituting some of the aggregates. Indeed, it takes up a triple environmental challenge: the limitation of the overconsumption of aggregates in France, the valorization of empty shells (that are now considered as waste), and the improvement of sustainable rainwater management.

II. Material and Methods

A. Description of the Experimental Test Bench

The experimental test bench was invented and designed to meet several objectives mentioned above. It is a square column of 25 cm of side and 75 cm of height (Fig. 1). These dimensions have been chosen with the aim of ensuring the vertical homogeneity of the flow and the pollutant mass associated with that volume throughout the structure. This apparatus is manufactured by Plexiglas on the two observation faces and waterproof particle panels on the other two faces. All sides are reinforced by the aluminum angles. A removable rain simulator is installed on the top of the system. A pump is used to introduce and control the targeted flow rate of the synthetic runoff influent into the column.

As a reminder, the composition of the layers of the porous structure of the experimental test bench was chosen to approach as well as possible that of operational structures within the framework of this project. From the surface, it consists in (Fig. 1):

- four pervious concretes based on SBPs having dimensions of (B x W x H) 125 mm x 125 mm x 8 mm.
- a gravel bedding layer (3 cm in height) with a fine particle size (2 mm/6 mm),
- a geotextile layer. It is a non-woven polyester of 330 g/m^3, a water permeability flow rate of 0.030 m/s and a filtration opening size of 60 µm.
- a subbase gravel layer (50 cm in height) of variable particle size (4mm/25 mm).

The geotextile is used as a separation, filter and even reinforcement [18], [19]. The location of the geotextile layer between the bedding layer and the subbase was chosen for increasing the pollutant retention capabilities of the PPS [20].

An underdrain is located at the bottom of the subbase to collect the outflow water. There is no soil subgrade (no infiltration) under the subbase, the bottom of the structure consists of waterproof particle panels. Fig. 1 shows the picture and the complete schematic diagram of the laboratory test bench.

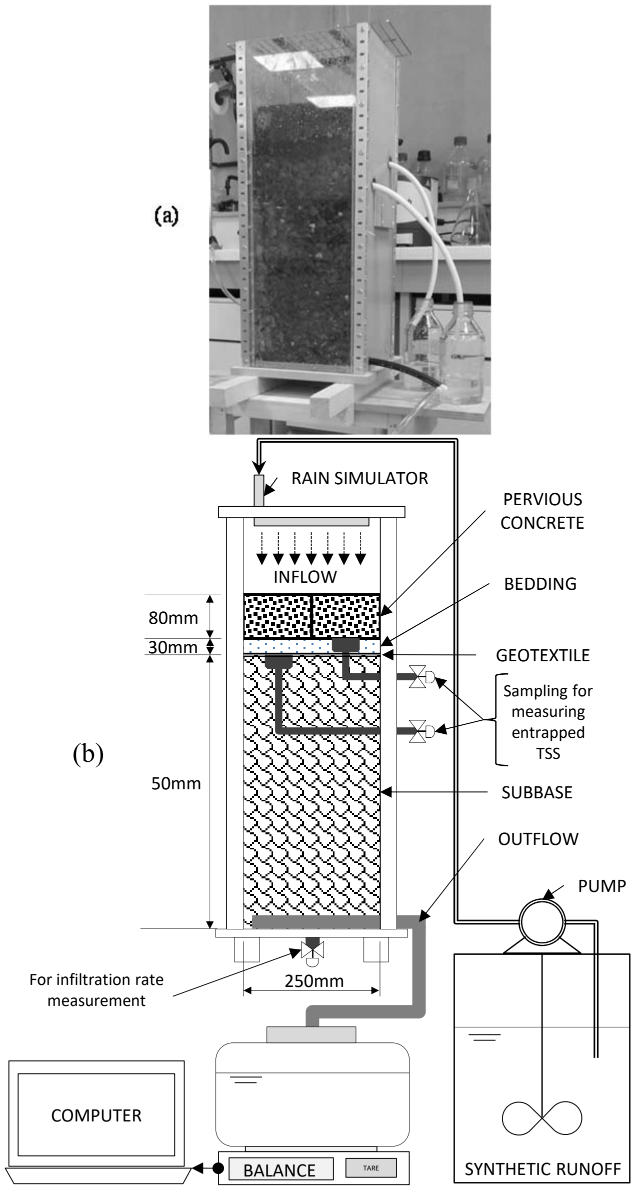


Fig. 1 The laboratory test bench: (a) Picture in an experimental stage; (b) Complete schematic diagram of the apparatus

B. Pervious Concrete Based on SBP

The pervious concrete used in this study is from the same series as those produced industrially. Among the crushed seashell tested (crepidula, scallops, queen scallops), the pervious concrete [11], which used scallops in its composition, were chosen for industrial manufacture and therefore for this study. The physical and chemical properties of the scallops are presented in the Table I [11].

The mix design of pervious concrete used in this research is based on a previous study [10], [11] with some slight adjustments for industrial manufacture. The industrial basic formulation of the pervious concrete based SBP and its target characteristics are summarized in the following Table II. It should be noted that, in France, there are no specific recommendations or design criteria on pervious products, although some countries, such as Belgium (PTV 122) [21] and Germany (FGSV 947) [22], already have standards and recommendations. Existing European standards (NF EN 1338 [23] for concrete paving blocks and NF EN 1339 [24] for concrete paving flags) do not cover permeable pavements. The compressive strength target is greater than 14 MPa. Values ranging between 15.2 and 18.6 MPa were found [11]. These values are included in the range (3.5 MPa to 28 MPa) for which the pervious concrete is suitable for a wide range of applications [1], [4]. The infiltration rate target is greater than 0.2 cm/s, comparable with the typical flow rates for water through pervious concrete: 0.2 cm/s to 0.54 cm/s [1]-[4].

TABLE I
PHYSICAL AND CHEMICAL PROPERTIES OF THE SCALLOPS

PARAMETER	Value
Specific gravity	2523
Bulk density, uncompacted (kg/m^3)	1061
Bulk density, compacted (kg/m^3)	1253
Water absorption (%)	2.93
Chloride ion content (%)	0.055
Organic matter content (%)	1.01
Surface area (mm^2/g)	1078

TABLE II
FORMULATION AND CHARACTERISTIC FOR INDUSTRIAL MANUFACTURE OF THE PERVIOUS CONCRETE

FORMULATION	Gray cement 52.2 N Gravel 4/10 mm Rolled sand 0/4 mm Scallop shells 2/6 mm Water
Gravel substitution rate 2/4 mm by shells	40%
Infiltration rate	> to 0.2 cm/s
Compressive strength	> to 14MPa

All tests were carried out in a room where the conditions are the following: 30% of relative humidity with an average temperature of 20 °C.

C. Hydraulic Experimental Methods

1. Physical Characteristics

The knowledge of the physical characteristics of the pervious concrete and aggregate layers is critical because the storage capacity base and thus the hydrological behavior of the system depends on it [4]. The following parameters were measured for all components of the structure: density, effective porosity, total water absorption, and the initial vertical infiltration rate for the entire structure. All tests were replicated five times for each material to ensure reproducibility and representativeness of the results. The retained values were therefore the average values. All materials were thoroughly washed with water before all measurements and their installation in the column. The aim was to eliminate cement pastes attached to the materials that may impact the results, including quantitative measurements.

The bulk density, the effective porosity, and the total water absorption were determined according to the European Standard NF EN 1097-6 [25] for the aggregate layers (bedding and subbase). These methods are similar to that described in ASTM C29M [26]. For the concrete pavers, these parameters were determined using the ASTM C1688/C1688M test procedure [27].

The bulk density was determined in an oven-dry (OD) condition according to:

$$\rho = \frac{W_{OD}}{Vol} \tag{1}$$

where: ρ = bulk density (kg/m^3), W_{OD} = mass in OD state (kg), Vol = nominal sample volume of the sample (m^3), The effective porosity it is calculated according to (2):

$$\phi = \left(1 - \frac{W_2 - W_1}{\rho_w Vol}\right) \times 100 \tag{2}$$

where: ϕ = the effective porosity (%), W_1 = weight immersed (kg), W_2 = dry weight (kg), Vol = nominal sample volume based on dimensions of the sample (m^3), ρ_w = density of water = 1000 kg/m^3.

The total water absorption (TWA) was measured by taking into account of the surface moisture when the materials were in the wet state (all pores completely filled with water with a film on the surface). It was calculated from the difference in weight between the wet (W) and oven-dry (OD) states, expressed as a percentage of the OD weight:

$$TWA = \left(\frac{W_W - W_{OD}}{W_{OD}}\right) \times 100 \tag{3}$$

where: W_W = weight in the wet state (kg), W_{OD} = weight in oven-dry state (kg).

The initial vertical saturated hydraulic conductivity or vertical infiltration rate (K_{sat}) of the whole system is determined from hydraulic experiments using Darcy's law. To do these tests with the experimental bench, the drain was closed and the hole at the bottom of the system was used. The Darcy's equation is given as:

$$K_{sat} = \frac{V' \times L}{A \times t \times \Delta H} \tag{4}$$

where: K_{sat} = vertical saturated hydraulic (m/s), A = the area of the column (m^2), ΔH = hydraulic head loss (m), L = total length of porous materials (m), V'= volume of the test water that flows through the system during time t (s).

2. Hydraulic Behavior and Performance

For the first time, the hydraulic performance was analyzed independently of the PRE. For this, only the tap water was used as synthetic runoff and the holes allowing the water sampling along the wall of the column were closed. Before the beginning of the test (i.e. when the rain simulator is not yet installed on the system), the simulated rain intensity was previously controlled by the control valve. The test starts at time t = 0 when the rain simulator is installed on the system. The infiltration behavior and capability of the PPS was studied with three inlet flow rates (3.75 L/min, 7.5 L/min, 15 L/min) and two rainfall durations (10 and 20 min). The inlet flow rate is kept constant throughout each test. The total inlet water volume (Vt_{in}) may be calculated as the product of inlet flow rate (product of the rainfall intensity to the total area) and the duration according to:

$$Vt_{in} = 60 \times A \times I \times t \tag{5}$$

where: Vt_{in} = the inlet water volume (l), I = the rainfall intensity (mm/h), t = duration (min), 60 = conversion factor

A plastic tray was used to collect the water infiltrated. No flowmeter was used. The volume of the outlet or drained water (V_{out}) was continuously measured using a balance directly connected with a computer. Thus, the flow rate at any time can be calculated by two independent measurements of the drained volume. This also allows understanding the behavior and the functioning of the PPS by analyzing the evolution of coefficient of restitution (CR), called also the outflow yield or drainage efficiency which is the ratio of the volume or flow rate of drained water to the inlet volume or flow rate generating this drainage, as a function of time.

$$CR = \frac{V_{out}}{V_{in}} = \frac{Q_{out}}{Q_{in}} \tag{6}$$

where: CR = coefficient of restitution (%), Q_{in} = inlet flow rate, Q_{out} = outlet flow rate or drained water flow rate.

The hydraulic performance of the structure in terms of water quantity reduction was assessed by the balance sheet of the total inlet water volume (Vt_{in}) and the cumulative volume of drained water (Vt_{out}). Knowing that the hydrological response depends on the initial hydric state of a catchment or a structure [28], [29], it is essential to know the initial humidity conditions of the pervious concrete and other porous layers in the column. Thus, in order to simplify the assessment of the influence of intensity variations and simulated rain duration on the hydrologic response, all materials were oven dried and then were driven to the same hydric conditions (same relative humidity) before each test.

D.Qualitative Experimental Methods

This study has always been combined with hydraulic measurements. Indeed, since water is the vector of pollutants, it is essential to have precise measurements of flows [30] and volumes to evaluate the polluting flows and therefore the PRE of the system. This time, the used semi-synthetic rainwater is a mix of tap water and pollutants. The pollutants used are mixtures of clay, agricultural soil, and medium sand. The idea is to have a wide range of particle size distribution. Semi-synthetic runoff water is continuously mixed with a stirrer during the experiments. By referring to the quality of runoff in urban areas [31], a TSS concentration of 150 mg/l was chosen for the semi-synthetic runoff. With this concentration, the following configurations were assessed: 3.75 L/min for 10min, 7.5 L/min for 10min, 15 L/min for 10min, 3.75 L/min for

20min, and 7.5 L/min for 20min. The studied parameters are the concentration of TSS and its particle size distribution.

The concentration of TSS was determined by filtration (according to the method described in NF EN 872 standard [32]) through a 0.45 µm pre-dried and pre-weighed glass fiber filter, dried at 105 °C and weighed on a precision balance. The volume of filtered sample is a variable according to the concentration of TSS. The samples are sieved before filtration (to 2 mm) in order to remove the coarse debris whose representativeness is not assured because of the small filtered volumes (10 to 100 mL for our experiments). The concentration of TSS is calculated by:

$$TSS = \frac{(m'-m)}{V} \quad (7)$$

where: TSS = concentration of total suspended solids (mg/L), m': mass of the filter after filtration and drying (mg), m: mass of the filter before filtration (mg), V: volume of the sample (L).

The study of the particle size distribution of particles smaller than 2 mm was carried out with a LS I3 320 Laser Diffraction Particle Size Analyser.

This qualitative study combines itself two objectives:

1) Study of the temporal variability of pollutants at the drain outlet. The pollutant removal performance of the whole structure was determined by the balance sheet of the pollutant flows at the inlet and at the drain outlet. Samples were taken every 2 min up to 20 min (maximum duration of the experiments) and then every 5 min up to 40 min assuming that the TSS concentration remained the same for more than 40 min until the end of the drainage. The PRE of the whole system is quantified by comparing the inlet pollutant flow with the average outlet pollutant flow.

The PREt of the whole system was calculated with:

$$PREt = \frac{TSS_{in} \times Vt_{in} \times TSS_{out} \times Vt_{out}}{TSS_{in} \times Vt_{in}} \times 100 \quad (8)$$

where: PREt = total PRE (%), TSS_{in} = TSS concentration of the inlet water (= 150 mg/L), TSS_{out} = mean TSS concentration of the outlet water (mg/L), Vt_{in} and Vt_{out} are respectively the inlet and outlet total water volume (L).

2) Study of the vertical variability of the PRE of the structure. For this, four water sampling points were noted: at the inlet, at the paver-bedding interface, and at the drain outlet. Samples for inlet and outlet water were taken directly. For sampling water on the paver-bedding and geotextile-subbase interfaces, two valves are placed at the side of the column. Water samples were collected every 2 min at these two sampling points. The average value was used for determining the TSS trapped. It should be noted that the volumes taken for these analyzes are taken into account in the calculation of the PREt.

The PREs along the vertical profile were calculated with:

$$PREs_i = \frac{TSS_{in} \times Vt_{in}(\%) \times TSS_i \times Vt_i(\%)}{TSS_{in} \times Vt_{in}(\%)} \times 100 \quad (9)$$

where: $PREs_i$ = PRE at a “i” location (%), i = the vertical measurement point: pervious concrete, geotextile, and subbase. TSS_i = average TSS concentration at “i” (mg/L), Vt_i (%) = the percentage of total water volume infiltrated at “i” location (%). Vtin (%) = the percentage of total inlet water volume (100%)

III. Results and Discussions

A. Hydraulic Experimental Results

1. Physical Properties of Porous Materials Layers

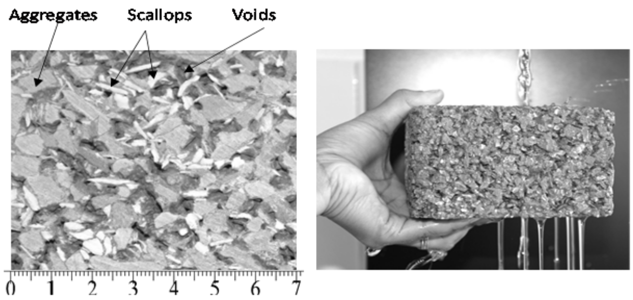
Table III contains the average values with standard deviations of the physical characteristics of the pervious concrete and the other porous layers. The average density and effective porosity were respectively 1883 kg/m^3 and 20% for the pervious concrete. These results are included in the range values (respectively 1600 kg/m^3 to 2000 kg/m^3 and 18 to 35%) found in literature review [1]-[4]. For aggregate layers, the densities decrease with the gravel size. It is the same for the porosities, they are respectively 47% and 38% for the bedding (2 to 6 mm) and the subbase (4 to 25 mm). The total water absorptions are respectively 8% for the pervious concrete, 5% for the bedding, and 2% for the subbase. The porosity and the absorption capacity values are used to estimate the total amount of water that can be stored when the structure is saturated and the amount of remaining water in the wet state. For the laboratory test bench, the total water absorption is 2040 mL. This value is useful for the calculation of the balance of hydraulic performance and the PRE of the system either for the laboratory and field investigations.

Fig. 2 represents pictures of the pervious concrete based on SBP cutting picture. It can be seen clearly on Fig. 2 (a) the internal structure of pervious concrete. Unlike aggregates (light gray) which have more or less rounded shapes, the scallops (white) have flattened shapes when crushed. As a result, the mixture is irregular in shape and improperly interlocked, thereby increasing the porosity and connection of the voids (darker gray), or the possibility of forming a continuous path between the pores.

TABLE III
PHYSICAL CHARACTERISTICS OF SYSTEM COMPONENTS

Parameter	Pervious concrete	Bedding	Subbase
Density (kg/m^3)	1883 (± 7)	1430 (± 9)	1321 (± 18)
Effective porosity (%)	20 (±1.8)	47 (±2.6)	38 (±1.6)
Total water absorption (%)	8% (±0.2)	5% (±0.4)	2% (±0.1)

The average value of the initial vertical saturated hydraulic conductivity of the entire pervious pavement system was 0.25 cm/s (148 L/m^2/min or 214 m/j or 351 in/h), more than 100 times the infiltration rates of most natural, saturated sands. This value is much higher than the minimum recommended value in Germany (0.027 cm/s) according to the memorandum for permeable constructions (FGSV 1998) [28] (cited by [2]). It is included in the typical value range for pervious concrete found in literature (80 to 720 L/m^2/min, 120 to 700 L/m^2/min) [1].



(a) (b)

Fig. 2 Pictures of the pervious concrete based on SBP: (a) cutting picture, (b) under water infiltration demonstration

2. Hydraulic Behavior and Performance

To illustrate the hydraulic behavior of the system under various stress, the cumulative volume of water drained and the coefficient of restitution as functions of time are plotted on logarithmic graph in the Fig. 3 for three different experiment conditions. For the same value of the inlet flow rate (7.5 L/min) but with different durations (10mn and 20min), it can be observed that the cumulative volumes of drained water show a similar trend evolution and also for the coefficients of restitutions. The differences reside in the values of the total cumulative volume of drained water and the time elapsed from the beginning of drainage, which are normal because the test times are different. For Qin = 7.5L/min and 20 min and Qin = 7.5 L/min and 10 min, drainage period lasted respectively 9100 s and 8530 s, the total cumulative volume of drained water was respectively about 134.2 L and 68 L. For the same duration (20 min) but with different inlet flow rates (3.75 L/min and 7.5 L/min), it can also be seen that the trend evolution of the cumulative volumes and the coefficients of restitutions are similar for the two experiments. And this time, the differences lie in the drainage response time and the total cumulative volumes of drained water. The response time is shorter (38 s), for the higher flow (7.5 L/min) and the total cumulative volume (Vt_{out}) is 132.3 L, if drainage only begins after 70 s and Vt_{out} is 60.1 L (a little less than half) for the lower flow (3.75 L/min).

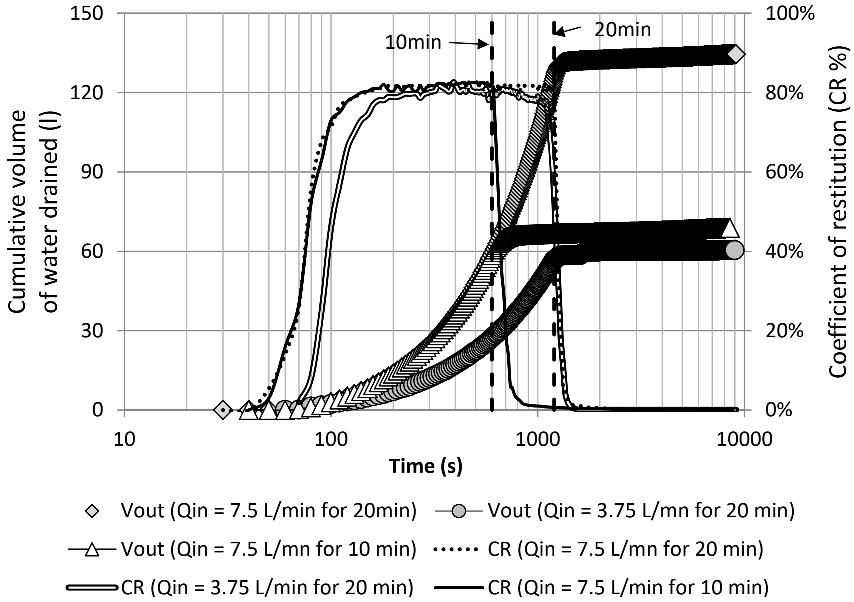


Fig. 3 Evolution of the cumulative volume of water drained and the coefficient of restitution as functions of time

In all cases, the graphs of coefficients of restitution and the drained volumes as a function of time (Fig. 3) have revealed three successive periods, explaining the hydraulic behavior of the system under various stress (runoff):

1) Initiation period of drainage: at the beginning of the experiment, the materials are dry, the inlet water is gradually absorbed by the materials (pervious concrete and the other porous layers), the drainage rate is still zero. After a certain time (response time) depending on the inlet flow rate, the drainage starts and the coefficient of restitution increases gradually;
2) Period of intense drainage: the materials are saturated, the received water flows into the drain, the coefficient of restitution is very large (around 80%);
3) Drying period: this period starts from the end of the test period (i.e. at the end of the rain in the real case), water losses by evaporation are greater than the inflows of the inlet water. The water reserve is gradually emptied and the materials become desaturated, the coefficient of restitution suddenly decreases and then tends to zero until drainage is stopped.

Table IV contains the results of the various experiments carried out to understand the hydraulic behavior of the PPS using the laboratory test bench and to assess its drainage performance. It can be observed that, for the same inlet flow rate, the longer the test duration, the lower the outflow yield, however the difference was not large. For example, the outflow yield was 83.2% for Qin = 3.75 for 10 min, whereas it is 80.1% for 20 min. This may be due to the fact that the losses by evaporation are greater when the duration of the test is longer. For the same duration, the outflow yield is greater for a higher inlet flow rate. For all tests, the losses range between 8.9 % and 19.9%. In these results, losses combine surface moisture and water losses by evaporation. However, it is pointed out that this study did not claim to make precise measurements of evaporation.

TABLE IV
RESULTS OF HYDRAULIC EXPERIMENTS

Flow rate (L/min)	3.75	7.5	15	3.75	7.5
Test duration (s)	600 (10 min)	600 (10 min)	600 (10 min)	1200 (20 min)	1200 (20 min)
Vt_{in} (L)	37.5	75	150	75	150
Drainage period (s)	8270	8530	8430	8920	9100
Vt_{out} (L)	31.2	68	136.7	60.1	132.3
CR (%)	83.2%	90.7%	91.1%	80.1%	88.2%
Losses	16.8%	9.3%	8.9%	19.9%	11.8%

A. Qualitative Experimental Results

1. Temporal Variability of Pollutant Removal Capability

Fig. 4 illustrates the temporal evolution of the concentration of TSS of the outlet water for 3.75 L/min, 7.5 L/min and 15 L/min flow rates for 10 min. Table V summarizes results of all experiments. It compares the mean concentrations of TSS with standards deviation of the outlet water for four intervals: 0 to 10 min, 10 to 20 min, 20 to 30 min, and 30 min to the end of the drainage (tf = final time). For all experiments, results (Fig. 4 and Table V) showed that the highest TSS concentrations were observed in the first minutes (2 to 6 min) regardless the duration and intensity of the experiments. This finding shows the *first-flush* effect. Then, the TSS concentrations decreased up to a relatively consistent baseline (from the end of the experimental period). The concentrations of TSS during the first 10min segment of the outlet water were, on average, a factor of 2.5 times than concentrations during 20-30 min and 30min-tf segment.

On one hand, the mean TSS concentrations of the outlet water and the extent of the *first-flush* effect were inversely correlated with the inlet flow rates. For example, the TSS concentrations during the 10-min synthetic runoff decreased from 41.9 mg/L in 3.75 L/min to 38.1 mg/L in 7.5 L/min, and to 35.9 mg/L in 15 L/min, i.e. higher intensities produced decreased concentrations. On the other hand, for the same inlet flow rates, it can be observed that the shorter the duration of the experiment, the greater is the concentration. An explanation for these findings may be the washoff of the suspended solids.

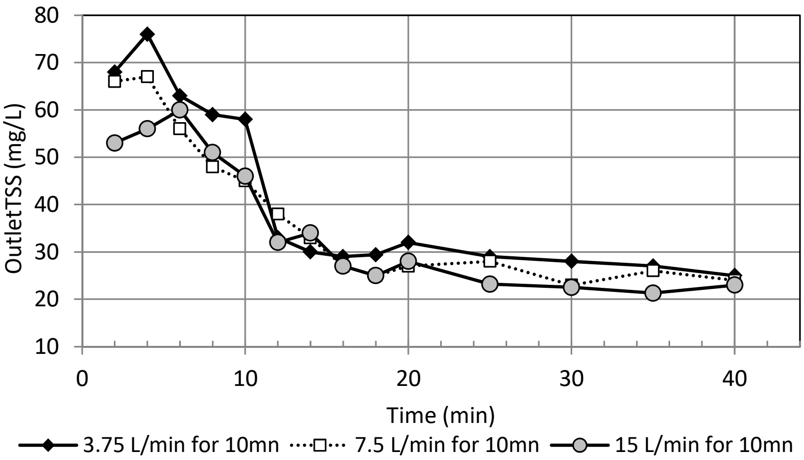


Fig. 4 Temporal variability of the concentration of TSS of the outlet water for 3.75 L/min, 7.5 L/min and 15 L/min flow rates for 10 min

In any case, all of tested configurations are found to exhibit high positive removal efficiency for suspended solids with an average value of 79.6%. The highest PREt that corresponds to a value of 80.8% is observed for 15 L/min for 10 min. These values of PREt are comparable with those reported in other studies [33], [34] for TTS.

2. Vertical Variability of Pollutant Removal Capability

Fig. 5 shows the variation of the mean concentration of TSS and the correspondent percentage of the cumulative total particles trapped by the different media layers along the height of the column. It can be seen that the concentration of TSS decreased and on the contrary the cumulative of PRE increased from the inlet to the drain outlet. It means that all media layers of the PPS (pervious concrete and several porous layers) were contributed to the pollutant removal.

Table VI summarizes all results for the assessment of the spatial variability of the PRE through the depth profile of the PPS. There was no water sampling for the bedding layer but based on its surface moisture and porosity values, and knowing the PRE for the subbase, we estimated that the percentage of trapped sediment by the bedding is approximately 4.1%. Thus, it can be said that the geotextile layer made the higher contribution in pollutant removal with a PRE of 32.8%, then the pervious concrete (27.4%), the subbase (15.3%), and finally the bedding (4.1%). By analyzing the size particle distribution of water samples, a decreasing of the amount of the size particle (D50) is noticed from the inlet flow (243 µm) to the outlet flow (42 µm). Most of the particles made up of 175 to 350 µm were trapped by the pervious concrete. Then, all particles greater than about 60 µm including some large particles infiltrated by the pervious concrete were retained by the geotextile. This can explain the fact that the geotextile has the higher capacity to trap pollutant than the other porous layer in the PPS. These findings agree with the results reported in reference [35] claiming that the clogging of the PPS is most likely to occur in the surface layer and in the geotextile layers, if these are used. Most of fine particles (less than 40 µm) were found at the outlet water. The results of the particle size distribution thus show that the accumulation of fine particles increases with depth.

TABLE V
RESULTS OF TEMPORAL VARIABILITY EXPERIMENTS

Parameter	3.75 L/min 10 mn Mean (±SD)	7.5 L/min 10 mn Mean (±SD)	15 L/min 10 mn Mean (±SD)	3.75 L/min 20 mn Mean (±SD)	7.5 L/min 20 mn Mean (±SD)	Mean
0-10 min	64.8 (±5.5)	56.4 (±7.3)	53.2 (±3.0)	54.6 (±7.5)	55.2 (±6.8)	56.8 (±6.0)
10-20 min	30.7 (±8.8)	30.0 (±6.3)	29.2 (±5.8)	36.4 (±3.8)	27.4 (±7.4)	30.7 (±6.4)
20-30 min	28.5 (±0.5)	25.5 (±2.5)	22.9 (±0.4)	27.9 (±0.4)	25.6 (±0.4)	26.1 (±0.8)
30min-tf	26.0 (±1.0)	25.0 (±1.0)	22.2 (±0.9)	26.4 (±0.1)	23.4 (±0.1)	24.6 (±0.6)
Total mean	41.9 (±16.4)	38.1 (±13.1)	35.9 (±12.4)	40.2 (±10.3)	36.5 (±13.4)	38.5 (±13.1)
PRE	77.7%	79.5%	80.8%	79.3%	80.5%	79.6%

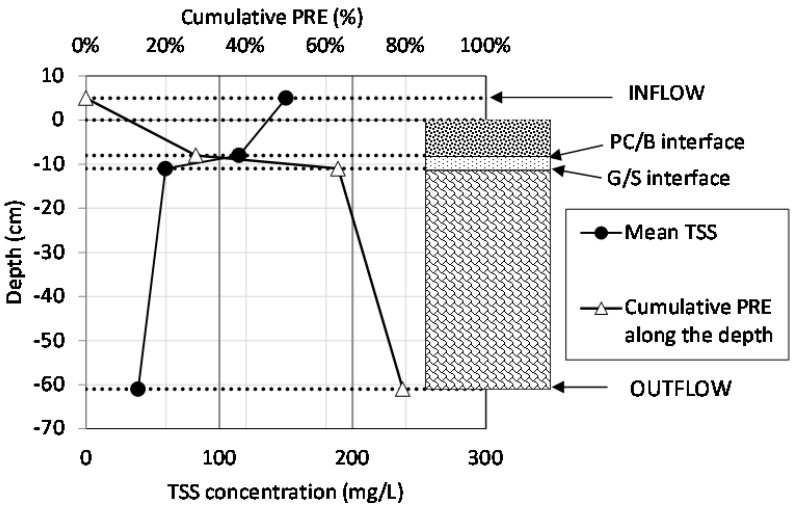


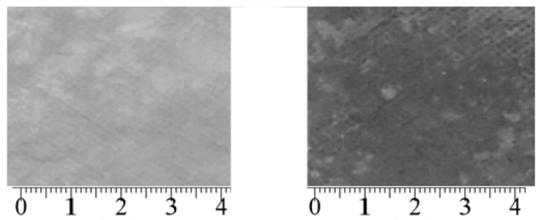
Fig. 5 Vertical distribution of the PRE

TABLE VI
RESULTS OF SPATIAL (VERTICAL) VARIABILITY EXPERIMENTS

Location	TSS (mg/L) Mean (±SD)	D50 (µm) Mean	Spatial variability of the PRE		
Inlet	150.0	356	Media	PRE	Cumulative PRE
PC-B interface	114.5 (±12.2)	172	PC	27.4%	27.4%
G-S interface	61.5 (±8.0)	58	B + G	36.9%	64.3%
Outlet	38.9 (±13.1)	42	S	15.3%	79.6%

SD: standard deviation, PC: pervious concrete, B: bedding, G: geotextile, S: subbasse.

At the end of the experiment, all the materials in the columns were autopsied. The majority of the particles of large sizes were found on the surface and within the first 2 cm from the pervious concrete. This observation is consistent with that indicated by other studies [36], [37]. A fine filter cake of suspended solids was clearly visible on the geotextile. This observation is illustrated in Fig. 6 which compares a virgin geotextile portion with a portion of the geotextile at the end of the experiment. A fine cake of suspended solids was also observed at the bottom of the column (below the drain outlet). This could correspond to the rest of the suspended solids that could not be retained by the system (about 20%). In the case of a design with a soil subgrade (infiltration design), this amount of pollutants could be attributed to pollutants that are infiltrated into the underlying soil.



(a) (b)

Fig. 6 Comparison of geotextile layers: (a) cutting picture, (b) under water infiltration demonstration

IV. CONCLUSION

The main objective of this study, conducted in the laboratory, was to evaluate both the hydraulic performance and the removal pollutant efficiency of PPS using pervious concrete based of SBP. The physical characteristics of all porous layers components of the PPS were determined before experiments. A number of key conclusions emerge from this research, and they are outlined below:

1) The proposed PPS using pervious concrete based of SBP have a great hydraulic performance through the high porosities of the porous media which form it. The initial vertical saturated hydraulic conductivity of the entire system is 0.25 cm/s (148 L/m^2/min).
2) The hydraulic functioning of the PPS was influenced by both the inlet flow rate value and the test duration. The total water losses range between 9% to 20% for all hydraulic experiments.
3) The proposed PPS has been shown to remove considerable amounts of TSS, with total removal pollutant efficiency about 80%.
4) The study of the vertical variability of pollutant removal rate showed that the geotextile layer made the higher contribution in pollutant removal with a PRE of 32.5%, then the pervious concrete (27.4%), the subbase (15.3%), and finally the bedding (4.1%).
5) Particle size distribution results for all experiments indicated that a part of larger particles were accumulate in the pervious concrete, most particles of any particle size (greater than its filtration opening size) were trapped by the geotextile layer, and smaller size fractions migrate to the bottom of the structure with some amount retained by the subbase. These findings are essential because they can allow estimating the degree and location of clogging of the structure along the depth.
6) The PPS can capture *first-flush*. The *first-flush* effect of TSS appears only at the beginning (about ten minutes approximately) of the experiments.

Synthetic pollution has the advantage of constituting simple cases with a single pollutant or a single family of pollutants present, in controlled concentrations that correspond to our choices based on the concentrations found in the runoff.

The very heavy rains were not simulated for this study. The maximum configuration studied was 15L/min, which corresponds to a rain intensity of 4 mm/h (moderate rain) for the prototype area. However, the use of a small scale laboratory test bench allowed overall understanding the hydraulic behavior of the PPS and obtaining an accurate characterization of TSS removal efficiency, especially the vertical variability which is difficult to quantify for field investigations. These laboratory results will serve as a basis for comparison and verification of actual site data. Then, they will allow long-term modeling of the hydraulic functioning, the dynamic pollutant fate and the PRE for PPS during natural rainfall.

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References

[1] P. D. Tennis, M. L. Leming and M. J. Akers. “Pervious concrete pavements”. *Skokie, IL: Portland Cement Association*, 2004.
[2] C. Dierkes, L. Kuhlmann, J. Kandasamy et al. “Pollution retention capability and maintenance of permeable pavements”, in *Global Solutions for Urban Drainage*. 2002. p. 1-13.
[3] M. E. Dietz, “Low impact development practices: A review of current research and recommendations for future directions”, *in Water, air, and soil pollution*, 2007, 186(1-4), 351-363.
[4] M. L. Leming, H. R. Malcom, and P. D. Tennis, “Hydrologic design of pervious concrete”. 2007.
[5] Union nationale des producteurs de granulats, http://www.unpg.fr/, 2017, Visited on April 26, 2017
[6] France Agri Mer, Les filières pêche et aquaculture en France, edition april 2016, 36 pages
[7] C. Engelaère-Robillard. “Etude de valorisation des coproduits marins coquilliers sous forme d'additions et de granulats dans les matériaux cimentaires”. *Doctoral thesis* – Caen. 2012.
[8] H-Y. Wang, W-T. Kuo, C-C. Lin, et al. “Study of the material properties of fly ash added to oyster cement mortar”, in *Construction and Building Materials*, 2013, vol. 41, p. 532-537.
[9] D. N. Nguyen, M. Boutouil, N. Sebaibi, et al. “Valorization of seashell by-products in pervious concrete pavers”, *in Construction and Building Materials*, 2013, vol. 49, p. 151-160.
[10] D. N. Nguyen, N. Sebaibi, M. Boutouil, et al. “A modified method for the design of pervious concrete mix”, *in Construction and Building Materials*, 2014, vol. 73, p. 271-282.
[11] D. N. Nguyen, M. Boutouil, N. Sebaibi, et al. “Durability of pervious concrete using crushed seashells”, in *Construction and Building Materials*, 2017, vol. 135, p. 137-150.
[12] M. C. Gromaire-Mertz, S. Garnaud, A. Gonzalez et al. “Characterisation of urban runoff pollution in Paris”, in *Water Science and Technology*, 1999, vol. 39, no 2, p. 1-8.
[13] E. Q. Segismundo, L-H. Kim, S-M. Jeong, et al. “A Laboratory Study on the Filtration and Clogging of the Sand-Bottom Ash Mixture for Stormwater Infiltration Filter Media”, in *Water*, 2017, vol. 9, no 1, p. 32.
[14] G. Langergraber, R. Haberl, J. Laber, et al. “Evaluation of substrate clogging processes in vertical flow constructed wetlands”, in *Water Science and Technology*, 2003, vol. 48, no 5, p. 25-34.
[15] B. E. Hatt, T. D. Fletcher, and A. Deletic. “Treatment performance of gravel filter media: Implications for design and application of stormwater infiltration systems”, in *Water research*, 2007, vol. 41, no 12, p. 2513-2524.
[16] P. Knowles, G. Dotro, J. Nivala, et al. “Clogging in subsurface-flow treatment wetlands: occurrence and contributing factors”, in *Ecological Engineering*, 2011, vol. 37, no 2, p. 99-112.
[17] S. P. Walsh. “The effect of sediment accumulation on the hydraulic conductivity of pervious concrete”. 2010. *Doctoral thesis*. Rutgers, The State University of New Jersey.
[18] C. J. Pratt. “Application of geosynthetics in sustainable drainage systems”, in *1st Int. Geosynthetics Society*, 2003, p. 121-135.
[19] M. Scholz. “Water quality improvement performance of geotextiles within permeable pavement systems: A critical review”, in *Wate*r, 2013, vol. 5, no 2, p. 462-479.
[20] S. J. Coupe, H. G. Smith, A. P. Newman, et al. “Biodegradation and microbial diversity within permeable pavements”, in *European Journal of Protistology*, 2003, vol. 39, no 4, p. 495-498.
[21] PTV 122 –PTV 122 “Permeable pavers and concrete slabs”. Edition 2 - 2005, Probeton ref. T 05/0063 N – C1:2005.02.15-Mod.2.
[22] FGSV 947: “Merkblatt für die wasserdurchlässige Befestigung von Verkehrsflächen”, in *Forschungsgesellschaft für Straßen - und Verkehrswesen;* Köln. 1998.
[23] NF EN 1338, “Concrete paving blocks - Requirements and test methods”, 2004, 68p.
[24] NF EN 1339, “Concrete paving flags - Requirements and test methods”, 2004, 70p.
[25] NF EN 1097-6, “Tests for mechanical and physical properties of aggregates - Part 6: determination of particle density and water

absorption", 2014, p58.

[26] ASTM, C. 29/C 29M, "Standard Test Method for Bulk Density ("Unit Weight") and Voids in Aggregate", *Annual Book of ASTM Standards*, 1997, vol. 4.

[27] ASTM C1688 / C1688M - 14a "Standard Test Method for Density and Void Content of Freshly Mixed Pervious Concrete". 2014.

[28] S. Rahman, V. Henderson, S. L. Tighe, S. L., et al. "Long Term Drainage Performance of Pervious Concrete Pavements in Canada", in *Transportation 2014: Past, Present, Future-2014 Conference and Exhibition of the Transportation Association of Canada//Transport*. 2014.

[29] L. V. Noto, V. Y. Ivanov, R. L. Bras, et al. "Effects of initialization on response of a fully-distributed hydrologic model", in *Journal of Hydrology*, 2008, vol. 352, no 1, p. 107-125.

[30] J.J. Randrianarimanana, "Etude expérimentale de la représentativité spatiale des vitesses et des polluants particulaires en réseau d'assainissement". *Doctoral thesis*. Université de Nantes. 2017.

[31] M. C. Gromaire, L. Veiga, M. Grimaldi, N. Aires. "Outils de bonne gestion des eaux de ruissellement en zones urbaines", *Agence de l'eau Seine-Normandie*; 63p. 2013.

[32] AFNOR, Norme, NF EN 872, "Water quality - Determination of suspended solids - Method by filtration through glass fibre filters", 2005. 10p.

[33] C. J. Pratt, J. D. G. Mantle, and P. A. Schofield. "Urban stormwater reduction and quality improvement through the use of permeable pavements", in *Water science and technology*, 1989, vol. 21, no 8-9, p. 769-778.

[34] R. A. Brown, D. E. Line and W. F. Hunt. "LID treatment train: Pervious concrete with subsurface storage in series with bioretention and care with seasonal high water tables", in *Journal of Environmental Engineering*, 2011, vol. 138, no 6, p. 689-697.

[35] M. Rommel, M. Rus, J. Argue et al. "Carpark with 1 to 1 (impervious/permeable) paving: performance of formpave blocks", in *Nouvelles technologies en assainissement pluvial". Conference international*. 2001. p. 807-814.

[36] E. Z. Bean, W. F. Hunt, D. A. Bidelspach. "Field survey of permeable pavement surface infiltration rates", in *Journal of Irrigation and Drainage Engineering*". 2007. 133(3), 249-255.

[37] W. James and H. Von Langsdorff. "The use of permeable concrete block pavement in controlling environmental stressors in urban areas", in *7th international conference on concrete block paving, Sun City, South Africa*. 2003.