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# Reuse of River Sediments in Pervious Concrete: Towards an Adaptation of Concrete to the Circular Economy and Climate Change Challenges

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## Abstract

The construction industry is one of the main sectors responsible for today's climate change as well as the extraction of large volumes of raw materials for concrete manufacturing. At the same time, significant volumes of sediments are being dredged each year (in France, nearly 60 M m<sup>3</sup>), and given their waste status these materials are barely or not at all being reused. This industry is the primary target chosen by sediment managers to ensure a viable and sustainable reuse stream. More specifically, pervious concrete is considered as a green infrastructure solution for urban areas. In this work, sediments dredged from the Seine Basin in Paris (France) were used to produce a cleaner pervious concrete. Two sets of pervious concretes were prepared, the first based on sandy sediments by fully substituting the conventional sand, while the second set of concretes was based on fine sediments by partially substituting the cement. Slump, fresh density, hydration, porosity, permeability, compressive strength, tensile splitting strength and thermal conductivity were all evaluated through testing. Results show that the incorporation of sediments delayed, albeit marginally, the cement hydration (by less than 3 hours) due to the presence of organic matter. The properties of pervious concrete are affected by the grain size of the incorporated sediment. The finer the sediment, the more compact the concrete structure, hence generating less porosity in the mixture, lower permeability and higher compressive strength. The thermal conductivity and volumetric heat of these pervious sediment-based concretes were also comparable to measures of the control concrete yet lower than those of ordinary concrete.

*Keywords:* Pervious concrete, Sediments, Porosity, Permeability, Thermal and mechanical properties.

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## 28 **Highlights :**

- 29 • Pervious concretes with both sandy and fine river sediments were studied.
- 30 • Incorporating sandy sediments yielded nearly similar properties.
- 31 • The incorporation of fine sediments reduced porosity and permeability.
- 32 • The incorporation of fine sediments improved mechanical properties.
- 33 • The thermal conductivity of pervious concrete is lower than that of ordinary concrete.

## 34 **1. Introduction**

35 Today's major ecological challenges are forcing public authorities and construction professionals  
36 to rethink their policies on urbanization and the sustainable management of natural resources.  
37 Indeed, concrete is one of the most widely consumed materials in the world, which in turn has  
38 an effect on the deposits of aggregates and minerals that are directly or indirectly involved in  
39 the manufacturing of concrete. In order to slow down the depletion of these resources, sector  
40 professionals are required to introduce alternative materials into construction processes. The circular  
41 economy approach appears to offer the solution, in allowing the material to be reinjected into the  
42 economic cycle while ensuring a global supply/demand balance. At both European and national  
43 levels, waste recycling is increasingly regulated. In March 2020, the European Commission adopted  
44 a new Circular Economy Action Plan (CEAP), whose aim is to ensure that resources used are kept  
45 within the European economy for as long as possible through making the economy fully circular.  
46 One of the keys to the EU's environmental policy is the Polluter Pays Principle (PPP). When  
47 applied, this principle requires polluters to bear the costs of the pollution they create, thereby  
48 encouraging polluters to avoid environmental damage by holding them responsible. At the French  
49 national level, laws and decrees have been adopted, including the law promoting Anti-Waste for a  
50 Circular Economy (AGEC) and the 31 December 2021 Decree on Extended Producer Responsibility  
51 for Construction Products and Materials in the Construction Sector (REP). These regulations seek  
52 to enact measures to promote cleaner production through reducing waste and improving recycling.

53 Nowadays, the use of various types of wastes as alternative sources of aggregates or cement  
54 in concrete production are being studied, in evaluating the properties of the materials derived.  
55 Dredged sediments are among the wastes offering considerable advantages when used in different  
56 civil engineering applications. Sediment reuse includes infrastructure and public works applications  
57 (sub-base materials for road construction and replacement fill for quay construction) [1, 2], the  
58 replacement of raw material in clinker production [3, 4], the substitution of natural clay for brick  
59 industries [5, 6], and mineral additions, filler, sand and coarse aggregates for mortar and concrete  
60 manufacturing [7-11]. The choice of these reuse options depends on both sediment characteristics  
61 and local needs.

62 Pervious concrete serves as another reuse pathway for waste [12-15]. However, to the best of the  
63 authors' knowledge, sediment reuse in pervious concrete has yet to be investigated. Pervious con-  
64 crete is considered an environmentally friendly material for permeable pavements; it is increasingly  
65 used as a replacement of conventional concrete, mainly on roads with low traffic volumes or mainly  
66 passenger vehicle flows, as well as for parking lots. Pervious concrete can reduce surface runoff and  
67 increase the natural recharge of aquifers through its water infiltration capacity [16, 17], thus pro-  
68 viding a real solution to soil sealing problems, notably in urbanized areas, and therefore to flooding  
69 risks. Pervious concrete pavements are suggested to help mitigate urban heat islands [18-21]. This  
70 type of concrete tends to store less heat and may have lower surface temperatures compared with  
71 conventional concretes under wet conditions. It has also been shown that this material can reduce  
72 tire-pavement noise and remove pollutants through water infiltration [22, 23].

73 The worldwide demand for permeable pavements has been on the rise. At the European scale  
74 however, no standard is in place to specify either the initial/final properties or a particular manufac-  
75 turing process. Overall, water permeability is the most critical characteristic of pervious concrete,  
76 and mechanical strength proves to be an essential parameter of its ability to withstand traffic loads.  
77 Pervious concrete is an open material with near-zero slump, consisting of Portland cement, coarse  
78 aggregate, just a few or no fine aggregates (less than 10%, [24, 25]), admixtures and water. The  
79 small amount of cement paste and low sand content provide for high porosity, while a system of  
80 interconnected voids allows water to flow through the material. Thus, pervious concrete should  
81 have a pore size of 2 mm to 8 mm, a porosity lying between 15% and 35%, and a high permeability  
82 ranging from 0.02 cm/s to 1.2 cm/s. Its compressive strength varies from 2.8 MPa to 28 MPa  
83 [26-28]. For pervious concrete to achieve specific characteristics, an appropriate mix design, along  
84 with compaction method and energy are required to meet certain structural and hydrological per-  
85 formance requirements (e.g. balancing porosity/permeability with mechanical properties). Several  
86 studies have reported the effects of water/cement ratio, aggregate size, aggregate/cement ratio, sand  
87 addition and compaction energy on pervious concrete properties [15, 24, 27-32]. The water/cement  
88 ratio (w/c) is an important factor in achieving the targeted permeability and strength in pervious  
89 concrete. A high w/c reduces the quality of the paste-aggregate bond and allows the paste to flow  
90 and fill voids. A low w/c will prevent the effective mixing and uniform distribution of the cement  
91 paste, which in turn will reduce the concrete strength [24, 27, 29]. The porosity of pervious con-  
92 crete can be affected by the shape, angularity, texture and other properties of coarse aggregates.  
93 Unlike standard concrete, the effect of coarse aggregate size on the compressive strength of pervious  
94 concrete is not clear from the literature due to its impact on porosity, which exhibits an inverse  
95 correlation with strength [15, 30, 31]. Fine aggregates may be added into pervious concrete in order  
96 to improve strength and durability properties. Many studies have shown that incorporating sand  
97 in a proportion of 5-10% of the coarse aggregate mass yields good pervious concrete performance  
98 [24, 28, 32].

99 The novelty of this research lies in adapting concrete to the circular economy and climate change  
100 challenges by promoting the use of dredged sediments in pervious concrete. This study investigates

101 the effect of incorporating river sediments on the physical, transport and mechanical performance of  
102 pervious concrete. A total of 12 mixtures have been prepared: one control concrete, seven concretes  
103 based on sandy sediments (0.08 - 4 mm), three based on fine sediments ( $< 0.08$  mm), and one  
104 incorporating both a sandy and fine sediment. The mix design of these concretes was established  
105 according to the method proposed by *Nguyen et al.* [24], which is based on a calculation of the  
106 cement paste volume needed to cover the aggregates and ensure achieving the targeted strength  
107 and permeability. An assessment of various water-to-cement ratios and compaction energies was  
108 carried out in order to choose the adequate parameters for this study. Next, the pervious concrete  
109 mixtures were tested for: fresh properties, hydration, porosity, permeability, compressive strength,  
110 splitting tensile strength, thermal conductivity, and volumetric heat.

## 111 2. Materials and methods

### 112 2.1. Material characterization

113 A Portland cement CEM I 52.5 R CE CP2 NF from the Calcia plant (in France) was used for  
114 this study. Its characteristics are presented in Table 1. This cement was chosen to both obtain  
115 high early strength and meet the minimum characteristic requirements. For the control concrete, a  
116 silico-calcareous fine aggregates (FA: 0-4 mm) from Ormes Quarries (France) were used. The origin  
117 of these fine aggregates is alluvial, which is similar to fluvial sediments in terms of mineralogical  
118 characteristics. Calcareous coarse aggregate (CA: 4-8 mm) from the Boulonnais Quarry (France)  
119 were introduced. The aggregate properties, density and absorption coefficient, are listed in Table 2.  
120 The pycnometer method is applied to measure the density and the water absorption of aggregate  
121 in accordance with European Standard EN 1097-6 [33].

122 For the sediment-based concretes included in this study, ten sediments were extracted from  
123 distinct locations across the Seine Basin: seven of them were mainly sandy (S1...S7: 0.08-4 mm), and  
124 the other three were fines ( $< 80\mu\text{m}$ ). These fine sediments were collected in the form of sludge, dried  
125 at  $105^\circ\text{C}$  and crushed into particles passing through an  $80\mu\text{m}$  sieve (F1, F2 and F3). The sediment  
126 properties are presented in Table 2, while the particle size distribution of the sandy sediments  
127 as well as that of conventional aggregates is provided in Fig. 1. The particle size distribution is  
128 determined by dry sieving, according to the European standard EN 933-1 [34]. The properties of the  
129 sediments are influenced by the geological, topographical and hydrometeorological characteristics  
130 that are related to the extraction site, hence the difference in the results presented in Table 2 and  
131 Fig. 1 from one sediment to another.

132 An environmental characterization was carried out for the different sediments; the results ob-  
133 tained were then compared with the S1 and ISDI threshold values defining the respective limits  
134 beyond which the sediment is considered to be dangerous and non-inert [35, 36]. According to  
135 Table 3, the contents of heavy metals and pollutants in these sediments comply with both the ISDI  
136 and S1 thresholds.

Table 1: Cement characteristics.

Chemical characteristics (%)		Physical characteristics	
SiO <sub>2</sub>	20.2	density	3.14
Al <sub>2</sub> O <sub>3</sub>	4.3	Specific surface (Blaine) (cm <sup>2</sup> /g)	4885
Fe <sub>2</sub> O <sub>3</sub>	2.2	<b>Compressive Strength (MPa)</b>	
TiO <sub>2</sub>	0.2	1 Jour	33
CaO	64	2 Jours	45
MgO	4	7 Jours	56
SO <sub>3</sub>	2	28 Jours	63
K <sub>2</sub> O	0.65	<b>setting time</b>	
Na <sub>2</sub> O	0.17	1H58'	
P <sub>2</sub> O <sub>5</sub>	0.2		
phases distribution (%)			
C <sub>3</sub> S	C <sub>2</sub> S	C <sub>3</sub> A	C <sub>4</sub> AF
68	10	9	7

Table 2: Physical properties of conventional aggregates and sediments.

	CA	FA	S1	S2	S3	S4	S5	S6	S7	F1	F2	F3
Density	2.65	2.41	2.41	2.22	2.21	2.16	2.22	2.05	2.03	2.26	2.24	2.41
Absorption coefficient (%)	0.7	4.3	3.7	8.5	11.7	8.2	8.1	17.2	16.3	—	—	—

## 137 2.2. Mixture design and specimen preparation

### 138 2.2.1. Concrete design method

139 In this paper, the method proposed by *Nguyen et al.* [24] was used for the pervious concrete  
 140 mixture design. This method consists of calculating the amount of cement paste  $V_p$  needed to cover  
 141 the aggregates while ensuring both sufficient strength for the concrete and sufficient free space  
 142 between aggregates to allow water to pass through.

143 A scaling factor "k" ( $k = (D_i + 2e_i)/D_i$ ) was defined to provide for a layer of cement paste  
 144 (thickness:  $e_i$ ) around the aggregates proportional to the size of the aggregate (diameter  $D_i$ ). The  
 145 pervious concrete mixture design is thus initially determined by calculating the sufficient volume  
 146 of aggregates  $V_{agg}$  (including sand) and then that of the cement paste  $V_p$  using Equations (1)  
 147 and (2) respectively [24]. Next, with a determined volume of cement paste, it becomes necessary to  
 148 determine the corresponding  $w/c$  ratio that allows the aggregates to be coated and yields a somewhat  
 149 illiquid paste in order to avoid being drawn down by draining under the effect of vibration.

$$V_{agg} = \frac{1-V_v}{a(k^3-1)+1+b} \quad (1)$$

$$V_p = \frac{3(1-V_v)(k-1)(k+1)^2}{4(a(k^3-1)+1+b)} \quad (2)$$

150 Where,  $a(\%)$ : percentage of aggregates larger than 80  $\mu\text{m}$ .  $b(\%)$ : absorption of aggregate (sand  
 151 included)  $V_v$  (%): Volume of void in concrete

152 As regards the amount of sand, many studies have investigated the effect of using sand in  
 153 pervious concrete [28, 37, 38]. These studies have shown that replacing 7% by weight of the coarse  
 154 aggregate by sand produces the best pervious concrete performance.

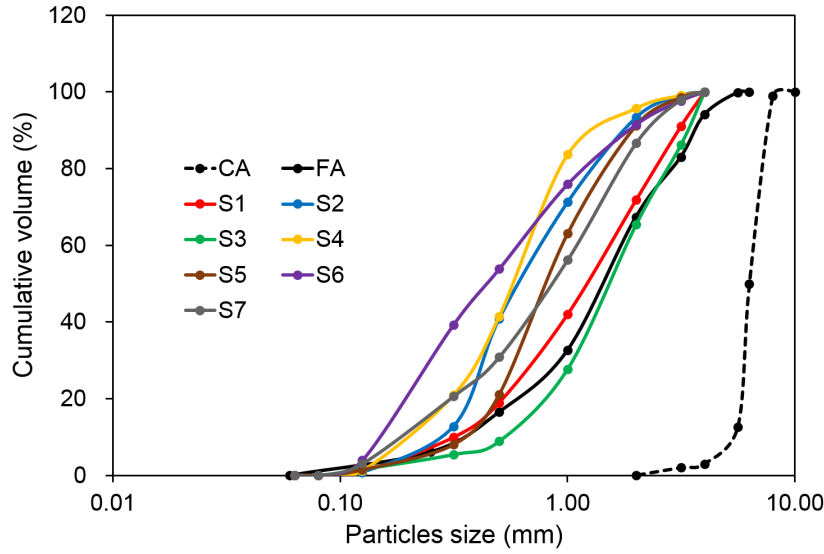


Fig. 1: Particles size distributions.

Table 3: Environmental characterization of sediment.

Parameter	unit	S1	S2	S3	S4	S5	S6	S7	F1	F2	F3	S1 threshold	ISDI threshold
Pb	mg/kg	4.54	6.37	2.36	4.68	8.31	1.50	2.48	6.41	1.63	1.05	100	-
Zn	mg/kg	20.47	30.96	22.56	26.94	38.80	12.24	144.06	124.53	121.62	9.16	300	-
Sb (leached)	mg/kg	<0.01	<0.01	<0.01	< 0.01	< 0.01	<0.01	<0.01	<0.01	0.014	0.017	-	0.06
PCBs	mg/kg	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.68	-
Sulphates	mg/kg	37.31	32.73	4.22	70.62	41.82	358.60	5.41	18.60	9.55	58.43	-	1000
Organic matter	%	1.52	1.58	1.22	2.49	3.03	3.61	12.89	6.53	9.93	5.39	-	-
pH	-	8.4	8.0	8.2	7.9	8.2	8.1	8.2	7.9	8.2	7.9	-	-

### 2.2.2. Mixture characteristics

- $V_v$  : For sufficient concrete permeability, a connected porosity of 20% has been chosen for this study.
- $k$  : According to several studies, the scale factor  $k$  varies from 1.064 to 1.233 [24, 31, 39, 40]. The amount of cement in the mixture depends on the value of  $k$ , hence the focus on reducing the value of  $k$  as much as possible, resulting in a lower amount of cement in the mixture. In some studies, it has been noted that a low value of  $k = 1.116$  is indeed sufficient to provide a high level of pervious concrete strength [24, 31]. Thus, this value has been adopted for our study.
- $w/c$  and compacting energy: In order to determine the appropriate  $w/c$  ratio and compaction energy, three  $w/c$  ratios (0.31, 0.33 and 0.35) and two compaction energies (E1 and E2 corresponding respectively to 2 seconds and 5 seconds of vibration at 50 Hz under 10 KPa pressure) were assessed. Table 4 displays the composition of the resulting concretes.

The density in the fresh state and 7-day compressive strength of these various mixtures were then studied so as to ensure that the chosen design provided the desired properties. Fig. 2 shows that only mixtures 0.33-E2 and 0.35-E2 achieve the targeted compaction, as evidenced

Table 4: Mixture design for the optimisation of pervious concrete ( $kg/m^3$ ).

Name	Cement	Fine aggregates	Coarse aggregates	w/c	Effective water	Total water
0.31-E1/0.31-E2	332.0	98.5	1406.6	0.31	102.9	117.0
0.33-E1/0.33-E2	321.7	98.5	1406.6	0.33	106.1	120.2
0.35-E1/0.35-E2	312.1	98.5	1406.6	0.35	109.2	123.3

171 by experimental density values similar to the theoretical ones. Regarding 7-day compressive  
 172 strength, the 0.35-E2 mixture exhibits the highest value. By virtue of this optimization study,  
 173 the 0.35-E2 mixture has been chosen as the control concrete herein. Moreover, this mixture  
 174 features an additional advantage, namely less cement consumption.

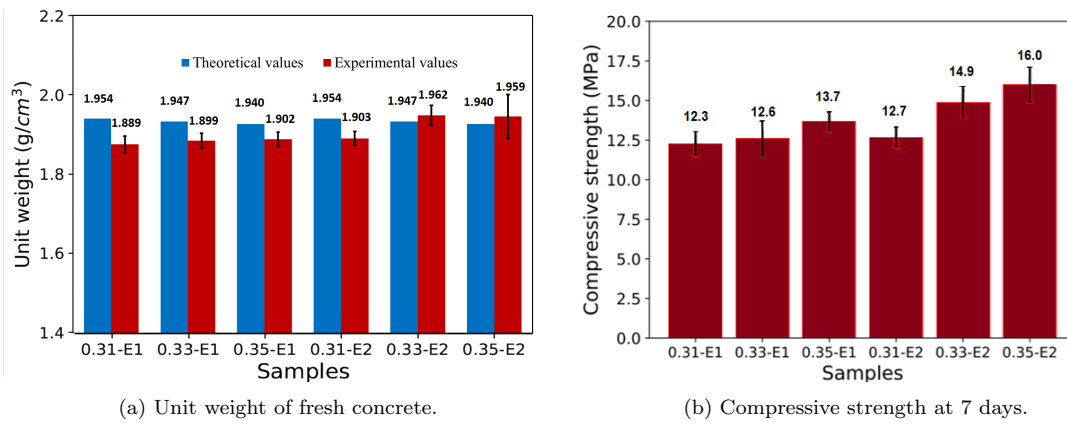


Fig. 2: Properties of pervious concrete for mixture design optimisation.

175 An overview of the proposed design method is presented in Fig. 3

### 176 2.2.3. Pervious concrete mixtures

177 This study has been conducted on twelve pervious concrete mixtures (Table 5): a control con-  
 178 crete, seven sandy sediment-based concretes, three fine sediment-based concretes, and one pervious  
 179 concrete produced by incorporating both sandy and fine sediments. The sandy sediments were  
 180 incorporated by substituting the total volume of fine aggregates. As regards the incorporation of  
 181 fine sediments, the quantity of cement was reduced by 10%. To offset the effect of a reduced ce-  
 182 ment amount on concrete strength, fine sediments were incorporated by tolerating a 2% increase in  
 183 paste volume (i.e. a 2% decrease in the total connected porosity). All concretes have the same wa-  
 184 ter/binder ratio. However, the total amount of water varies according to the absorption coefficient  
 185 of the sediments. The amount of water absorbed by the aggregates and sediments is added so as to  
 186 maintain the same effective water-to-binder ratio.

## 187 2.3. Methodology

### 188 2.3.1. Hydration

189 Hydration tests were carried out using a semi-adiabatic calorimetric device (i.e. the Langavant  
 190 method) in accordance with European Standard [41]. The temperature changes induced by the heat

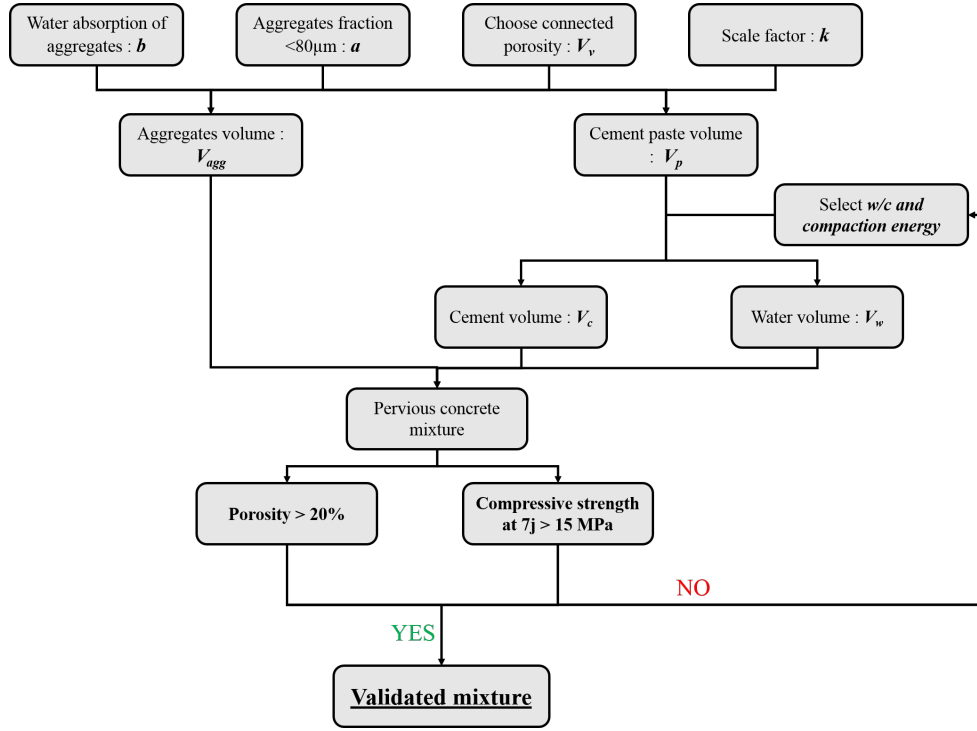


Fig. 3: Algorithm of the formulation method adapted from [24]

191 released through hydration were measured and recorded every 10 min for 5 days.

### 192 2.3.2. Water accessible porosity

193 Water accessible porosity was measured on cylindrical samples 11 cm in diameter and 5 cm  
 194 thick. To accurately measure this porosity, the sample was wrapped in aluminum foil (except for  
 195 its upper surface, see Fig. 4). First, the sample was saturated with water for 24 hours by filling the  
 196 sample pores with water. Then, the water-filled sample was weighed ( $m_{air}$ ). Next, a hydrostatic  
 197 weighing ( $m_{water}$ ) was performed. And lastly, the sample was placed in an oven at 80°C (without  
 198 aluminum foil) until reaching a constant mass ( $m_{dry}$ ). These three values allow us to calculate the  
 199 sample porosity as follows:

$$p(\%) = \frac{m_{air} - m_{alu} - m_{dry}}{m_{air} - m_{water}} \quad (3)$$

200 Where  $m_{alu}$  is the mass of the aluminium foil.

### 201 2.3.3. Water permeability

202 Cylindrical specimens 110 mm in diameter and 50 mm high were used to measure the water  
 203 permeability of pervious concrete. The permeability measurement device employed is shown in Fig.  
 204 5. The test was initially conducted at a constant water height H throughout the test. Water was  
 205 allowed to be present until a steady state flow could be achieved, after which the time required  
 206 ( $t$ ) for a volume of water ( $V$ ) to flow through the sample was measured. Water permeability is

Table 5: Mixture design for the different pervious concretes ( $kg/m^3$ ).

Name	Cement	Fillers	Sediments	Fine aggregates	Coarse aggregates	w/b	Total water
PC-C	312.1			98.5	1406.6	0.35	123.3
<b>Pervious concrete based on sandy sediments</b>							
PC-S1	312.1		98.5		1406.6	0.35	122.7
PC-S2	312.1		90.8		1406.6	0.35	126.8
PC-S3	312.1		90.5		1406.6	0.35	129.7
PC-S4	312.1		88.7		1406.6	0.35	126.3
PC-S5	312.1		90.9		1406.6	0.35	126.4
PC-S6	312.1		83.7		1406.6	0.35	133.5
PC-S7	312.1		83.2		1406.6	0.35	132.6
<b>Pervious concrete based on fillers</b>							
PC-F	280.9	53.9		98.5	1406.6	0.35	131.3
<b>Pervious concrete based on fine sediments</b>							
PC-F2	280.9		52.9	98.5	1406.6	0.35	130.9
PC-F3	280.9		52.9	98.5	1406.6	0.35	130.9
PC-F4	280.9		52.3	98.5	1406.6	0.35	130.7
PC-F7	280.9		52.9	98.5	1406.6	0.35	130.9
<b>Pervious concrete based on sandy and fine sediments</b>							
PC-S5+F2	280.9		52.9	90.9	1406.6	0.35	134.6



Fig. 4: Porosity measurement.

207 calculated according to the equation:

$$P_w = \frac{V.L}{A.H.t} \quad (4)$$

208 where  $P_w$  is the water permeability, mm/s; V is the volume of the flowing water, ml; L is the  
 209 thickness of the sample, cm; A is the cross-sectional area of specimens,  $cm^2$ ; H is the constant water  
 210 height, cm;  $t$  is the flowing time, s.

#### 211 2.3.4. Compressive strength

212 The compressive strength tests were performed on three cylindrical specimen per mixture, each  
 213 measuring  $\phi 11cm \times 22cm$ , in accordance with European Standard [42]. The specimens had been  
 214 previously surfaced; each side of the cylinder was coated with a sulfur mortar, according to the  
 215 same standard, in order to obtain plane and parallel surfaces. These tests were performed at 7 and  
 216 28 days.

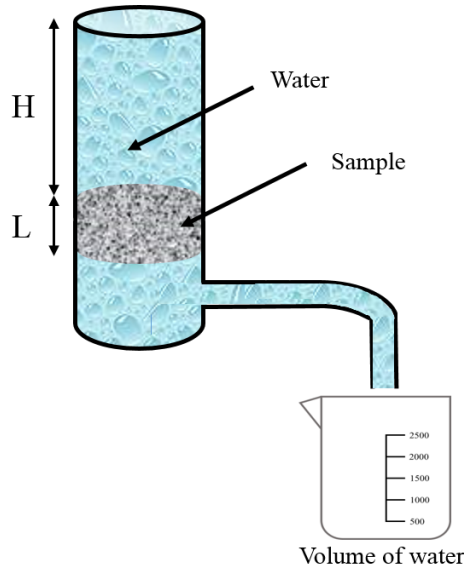


Fig. 5: Device for measuring water permeability.

### 2.3.5. Splitting tensile strength

Since the bonds between aggregates are considerably reduced, our attention was clearly focused on splitting tensile strength. It is not recommended to use the standard correlation with compressive strength given that aggregate rearrangement during compression is responsible for the high compressive strength values. The splitting tensile strength test was performed on three cubic specimens per mixture, measuring  $15 \times 15 \times 15 \text{ cm}^3$ , according to European Standard [43].

### 2.3.6. Thermal conductivity and specific heat capacity

In order to assess the potential of using sediment-based pervious concretes to reduce urban heat islands, it is necessary to characterize their thermal properties, especially thermal conductivity  $\lambda$  and volumetric heat  $C_v$ .  $\lambda$  characterizes the heat insulation capacity of a material, while  $C_v$  reflects its capacity to store heat in a unit volume. The hot disc method has been used in this study to measure the thermal properties ( $\lambda$  and  $C_v$ ) of the designed pervious concretes; it relies on a hot thin film (heater) sandwiched between two similar pervious concrete specimens. Each sample had been sawed to obtain approximately 5 cm thick samples from a standard 16 cm x 32 cm compacted cylindrical specimen, as displayed in Fig. 6. The specimens have the same diameter as the plane heater (i.e. 16 mm). Thermal sensors were placed on both the top and bottom surfaces of the heater as well as on the cold surfaces of each sample, thus making it possible to record temperature kinetics during the test. The lateral, top and bottom surfaces of the tested specimens had all been insulated to limit heat loss. A loading force was applied on the upper surface of the top insulator to ensure better contact between the specimens and the thin heater, thereby reducing the thermal contact resistance. The heater was connected to an electric power system to allow imposing a constant heat flux  $\phi$  of  $480 \text{ W.m}^{-2}$  throughout the test.

Fig. 7 shows an example of the temperature profile recorded during the test. Note that the

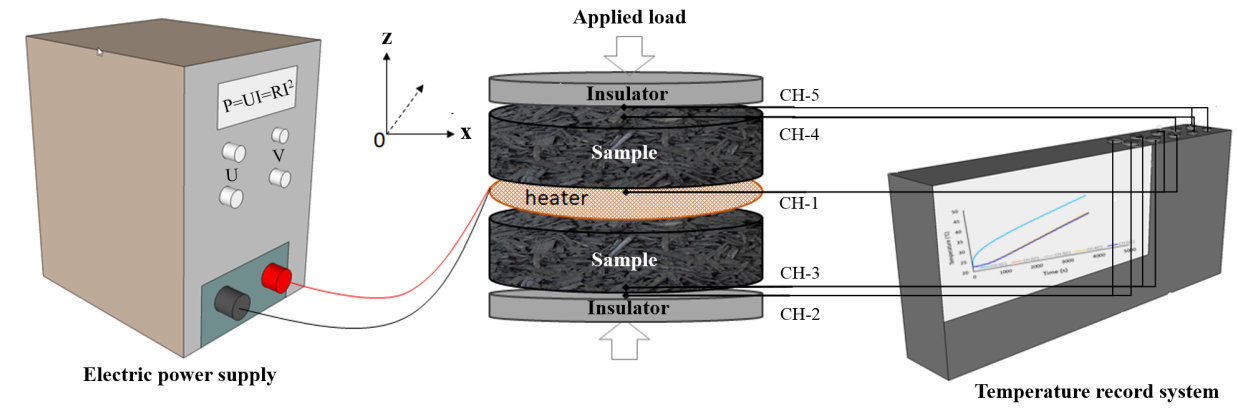


Fig. 6: Schematic view of the experimental device

240 temperature recorded from sensor CH-1[C] represents the temperature on the heated surface of the  
 241 specimens, while sensors CH-2[C] to CH-5[C] output the temperature on the cold surface of each  
 242 specimen.

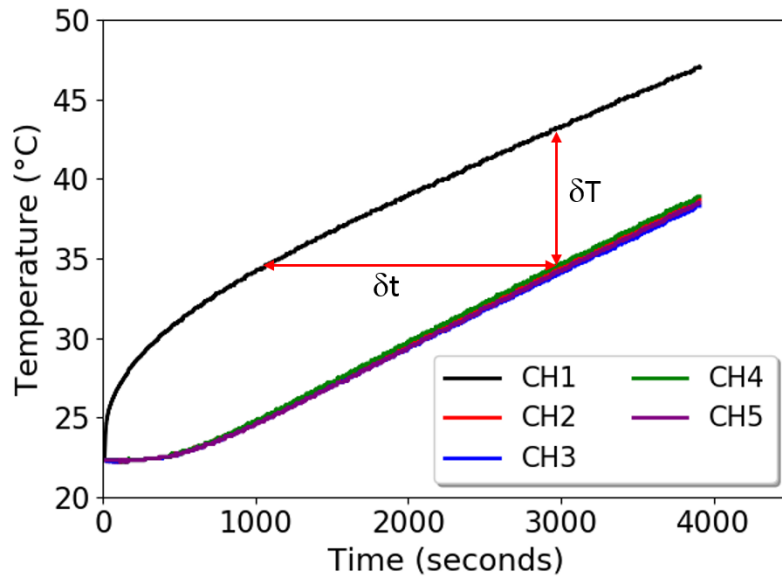


Fig. 7: Measured temperatures.

243 It has been demonstrated that the thermal properties  $\lambda$  and the  $C_v (= \rho \times C_p)$  can be evaluated  
 244 from the temperature profiles in Fig. 7, as based on the following relations [44, 45]:

$$\lambda \approx \frac{\phi \cdot l}{2 \cdot \delta T} \quad (5)$$

$$C_v = \rho C_p \approx \frac{\phi \cdot \delta t}{l \cdot \delta T} \quad (6)$$

245 This evaluation becomes possible when the long-term temperature profiles are parallel.  
246  $\phi$  represents the imposed heat flux,  $l$  the thickness of the specimen,  $\delta T$  the temperature gap between  
247 the hot and cold surfaces, and  $\delta t$  the time required for the temperature at the cold surface to reach  
248 a value previously found on the heated surface (Fig. 7).  $\rho$  and  $C_p$  respectively denote the density  
249 and specific heat of each specimen.

### 250 3. Results

#### 251 3.1. Fresh concrete properties

252 A zero slump has been obtained for all concretes (Fig. 8). Fresh pervious concretes remain very  
253 stiff as less cement paste and a low w/c ratio are introduced.



Fig. 8: Consistency of fresh concrete.

254 The unit weight values of fresh concrete, as reported in Fig. 9, are computed by weighing the 11  
255 cm  $\times$  22 cm cylindrical samples cast for the compressive strength tests. Values ranged from 1.91 to  
256 1.99  $g/cm^3$  for pervious concrete based on sandy sediments and from 1.96 to 2.05  $g/cm^3$  for those  
257 based on fine sediments, while the control concrete had a value of 1.96  $g/cm^3$ . These values, which  
258 are less than those of traditional impervious concrete, are indeed typical of pervious concrete [28].

259 The effect of substituting conventional sand with sandy sediment does not reveal any clear trend  
260 on the fresh concrete density, which increases slightly with the incorporation of sediment S6 and  
261 decreases with the incorporation of sediment S1. According to Table 2 these results do not reflect  
262 the density of the incorporated sediments; for example, S1 with the highest density results in a  
263 concrete with the lowest density, while S6 with a low density yields a concrete with the highest  
264 density. Instead, these results can be explained by the sediment particle size (Fig. 1). The more

265 fine elements the sediment contains, the more compact the concrete and therefore the higher the  
 266 density. Fig. 9 shows that the incorporation of fine sediments increases the density of fresh concrete;  
 267 this finding is logical since the design of these concretes allows for increased paste volume, which  
 268 makes the concrete less porous compared to both the control concrete and concretes based on sandy  
 269 sediments.

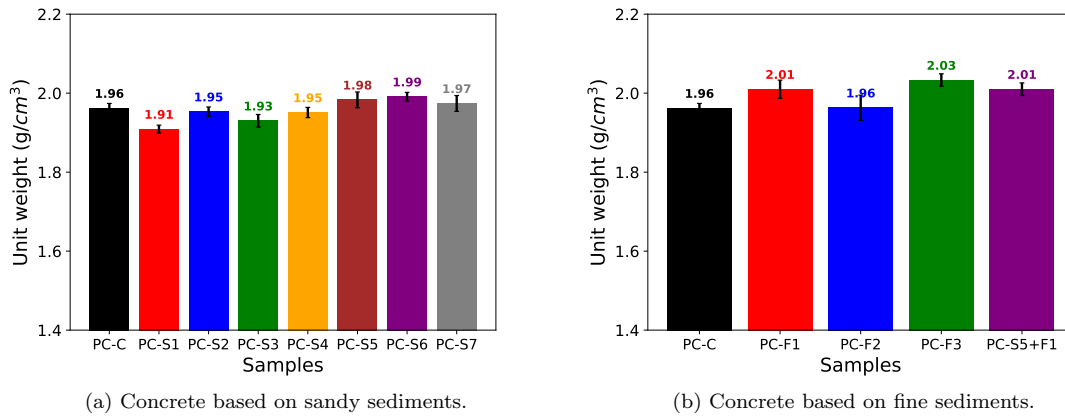


Fig. 9: Unit weight of fresh pervious concretes.

### 270 3.2. Hydration tests

271 Figs 10a and 11a illustrate the hydration kinetics of sandy sediment-based concrete and fine  
 272 sediment-based concrete, respectively. Except for sediments S5 and S6, which produce a slight  
 273 delay (less than 2 hours), the incorporation of sandy sediments does not delay cement hydration.  
 274 On the other hand, all fine sediments induce a delay in the cement hydration process, while the  
 275 amount of fine sediments introduced into the mixtures is much lower than that of sandy sediments  
 276 ( $50\text{kg}/\text{m}^3$  vs  $90\text{kg}/\text{m}^3$ ). PC-S5+F1 shows the greatest delay in hydration by virtue of incorporating  
 277 both sandy and fine sediments, which means that a high organic matter content is introduced into  
 278 this concrete. According to Tables 3 and 6, the delay of the main hydration peak of PC-S is not  
 279 proportional to the organic matter content of the sediments. For example, S7 has a high organic  
 280 matter content, i.e. nearly four times higher than that of sediment S5, yet no delay is observed for  
 281 PC-S7; however, PC-S5 shows a delay of nearly two hours. In fact, only a portion of the organic  
 282 matter measured, i.e. the soluble part of the humic substances, is responsible for the delay in  
 283 hydration kinetics, whereas wood pieces, found for example in the sediments, do not contribute to  
 284 the hydration delay [46]. River sediments may contain humic substances [46, 47]; they are capable  
 285 of adsorbing onto the cement particles and delaying its hydration from a few hours to several days  
 286 [48, 49]. The delay produced does depend on the amount of soluble humic substances per weight of  
 287 cement [49]. The soluble organic matter is therefore more heavily concentrated in the fine fraction  
 288 of the sediment, which explains why a fine sediment with a low organic matter content induces a  
 289 longer delay than a sandy sediment rich in organic matter. pH measurements are also provided in  
 290 Table 3 to confirm the presence of humic acids and therefore their effect on hydration. The results

291 show that the pH values vary slightly from one sediment to another. Furthermore, the values do not  
 292 show that sediments that produce more hydration delay have a lower pH. In fact, the pH value can  
 293 also vary due to the presence of other impurities and humic substances are not the only parameter  
 294 that influences it. A study has been carried out, by Beddaa et al [50], on the same sediments to  
 295 evaluate their content of humic substances according to the colorimetric method described in the  
 296 European standard EN 1744-1+A1 [51]. This research has shown that there is a positive correlation  
 297 between the hydration delay produced and the content of humic substances in the sediments. Other  
 298 impurities, such as sulphates, can have an impact on the hydration heat of cement [52]. However,  
 299 the sediments used in this study contain low sulfates contents (Table 3) which are less than 0.01%  
 300 of the cement mass (taking into account the composition of the concrete mixtures). These values  
 301 are well below the sulphates content of the used cement, which is 2% (Table 1). Thus, the effect of  
 302 sulphates on the hydration of cement can be considered as negligible.

303 The heat released during hydration was monitored over 120 hours. The total heat release after  
 304 5 days of hydration of the control concrete was equal to 312 J/g of cement, while that of PC-S  
 305 and PC-F concretes varied respectively between 315 and 352 J/g of binder and between 288 and  
 306 301 J/g of binder (Table 6). It can be noted that the incorporation of sandy sediments increases  
 307 the total heat release; conversely, the incorporation of fine sediments decreases it. For PC-S,  
 308 the water added to the mixture for sediment saturation can be consumed in the cement hydration, thus  
 309 increasing both the hydration rate and heat release. Alternatively, concretes based on fine sediments  
 310 are deprived of 10% of the cement, thereby reducing the heat released by such concretes. These  
 311 results highlight the fact that the incorporated fine sediments do not contain reagents consumed by  
 312 hydration reactions and moreover the effect of sediments on hydration is limited to a filler effect.  
 313 Similar results had been found when using fine sediments in ordinary concrete [53].

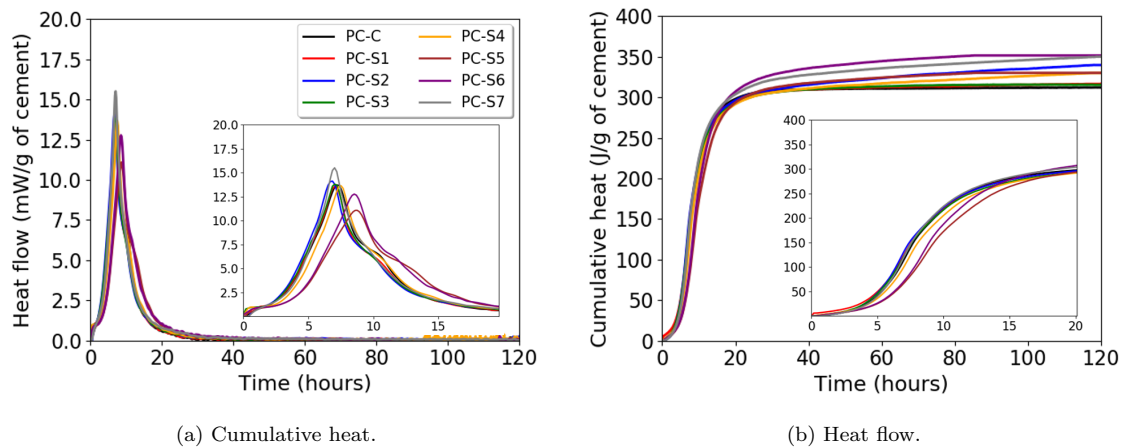


Fig. 10: Hydration kinetics of concretes based on sandy sediments.

314 *3.3. Porosity and permeability*

315 Fig.s 12 and 13 respectively show the porosity accessible to water and the water permeability of  
 316 hardened pervious concretes. The porosity of the various concrete specimens varies between 19%

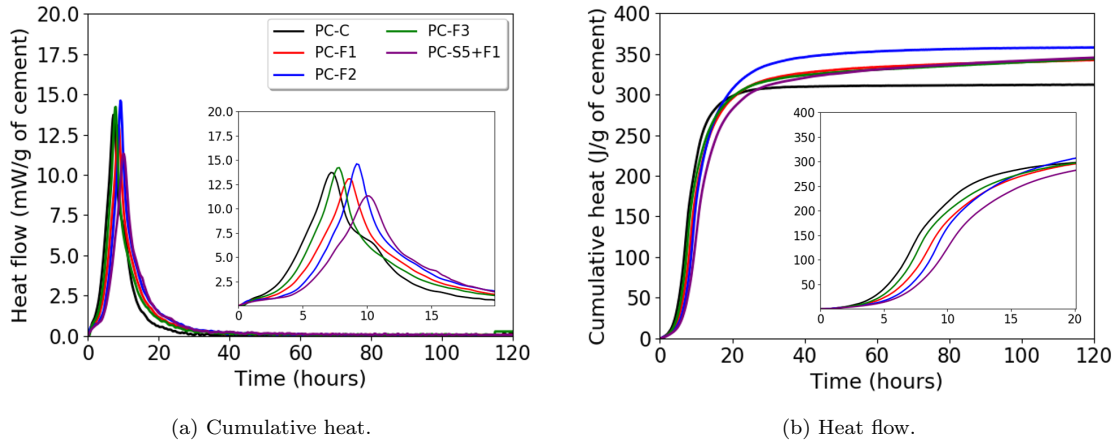


Fig. 11: Hydration kinetics of concretes based on fine sediments.

Table 6: Overview of hydration test results: total heat release, maximum flow and time of its occurrence

Mixtures	Cumulative heat after 5 days (J/g of cement)	Maximum flow (mW/g of cement)	Time of appearance (hours)
PC-C	312	13.7	7.2
PC-S1	317	13.6	7.0
PC-S2	340	14.1	6.9
PC-S3	315	13.8	7.0
PC-S4	330	13.6	7.5
PC-S5	330	11.1	8.8
PC-S6	352	12.8	8.5
PC-S7	350	15.5	7.0
PC-F1	343	14.6	8.7
PC-F2	358	14.2	9.2
PC-F3	344	15.7	7.8
PC-S5+F1	346	11.3	10.0

317 and 27%, which are typical values of pervious concretes [28, 29, 54-56]. As an example, the porosity  
 318 of an ordinary concrete is around 15% at 28 days, while that of a high performance concrete equals  
 319 10% to 12% and that of a very high performance concrete can vary between 7% and 9% [57].

320 The total substitution of sand by sandy sediments can both increase and decrease the porosity  
 321 of the resulting pervious concrete. With the incorporation of sediments S1, S3 and S4, porosity  
 322 increases slightly whereas it decreases with the incorporation of sediments S5, S6 and S7. This  
 323 outcome is correlated with the different grain sizes of these sediments. For instance, S3 has the  
 324 lowest fineness coefficient, thus making the concrete less compact. In contrast, sediment S6 possesses  
 325 the highest fineness coefficient (Fig. 1). These fine particles can fill the voids in the concrete, hence  
 326 producing a less porous concrete structure. Regarding the incorporation of fine sediments, an  
 327 increase in the volume of the paste was allowed, which served to increase the compactness of the  
 328 concrete and decrease its porosity. The results presented in Fig. 13 point to a decrease in concrete  
 329 porosity. These results are in complete accordance with the density of concrete in the fresh state;  
 330 the more porous concretes display a lower density while the less porous ones prove to be denser.

331 Pervious concretes, due to their high connected porosity, have a typical water permeability

332 ranging from 2 to 12 mm/s [28, 58]. The results of this study fall well within this range (Figs.  
 333 12-b and 13-b). The water permeability results follow a trend similar to that of the water accessible  
 334 porosity; however, a small decrease in porosity value produces a large decrease in water permeability.  
 335 Several studies have shown analogous results, in finding therefore that the two parameters can be  
 336 related by an exponential regression model [55, 56, 58, 59].

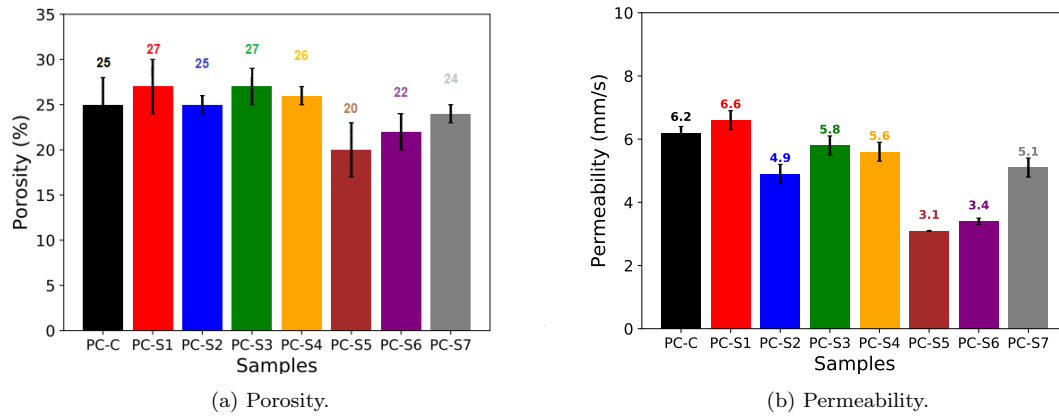


Fig. 12: Porosity and permeability of pervious concretes based on sandy sediments.

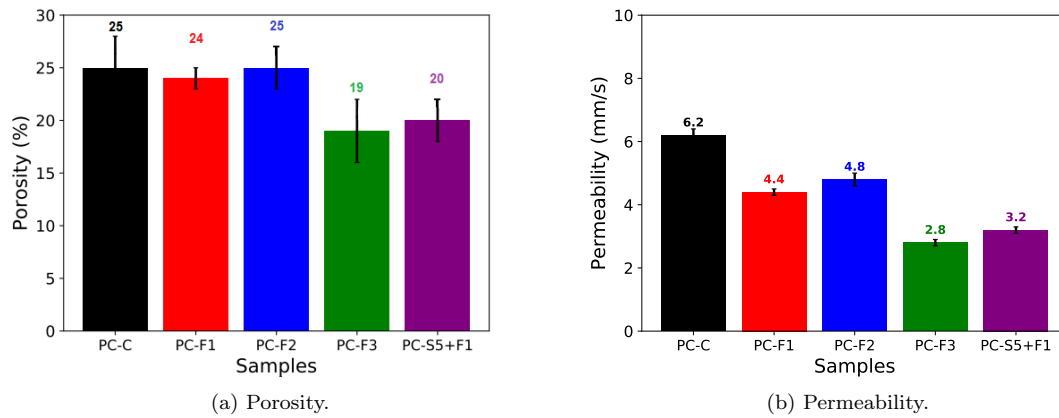


Fig. 13: Porosity and permeability of pervious concretes based on fine sediments.

### 337 3.4. Compressive and splitting tensile strength

338 The results of the compressive strength of various pervious concretes at the ages of 7 and 28  
 339 days are provided in Figs. 14 and 15. The development of compressive strength between 7 and 28  
 340 days is very slight, hence the highest strength gain occurs during the first 7 days. Except for PC-S1  
 341 and PC-S3, the concretes based on sandy sediments do reach the required compressive strength  
 342 value (15 MPa). S1 and S3 are the sandy sediments containing the least amount of fines (Fig.  
 343 1). The presence of more fine elements in the other sediments yields a more compact and less

344 porous concrete, thus resulting in a more resistant concrete. Fig. 16 confirms this hypothesis by  
 345 showing a strong positive correlation ( $R^2 = 0.75$ ) between the concrete compressive strength and  
 346 its porosity. The incorporation of fine sediments served to improve the compressive strength of  
 347 pervious concrete (by up to 32%), indicating that the effect of increasing the volume of paste in the  
 348 mixture outweighs that of decreasing the amount of cement. A larger volume of paste both ensures  
 349 a strong bond between aggregates and reduces voids in the concrete, which has a more significant  
 350 impact on the strength of pervious concrete.

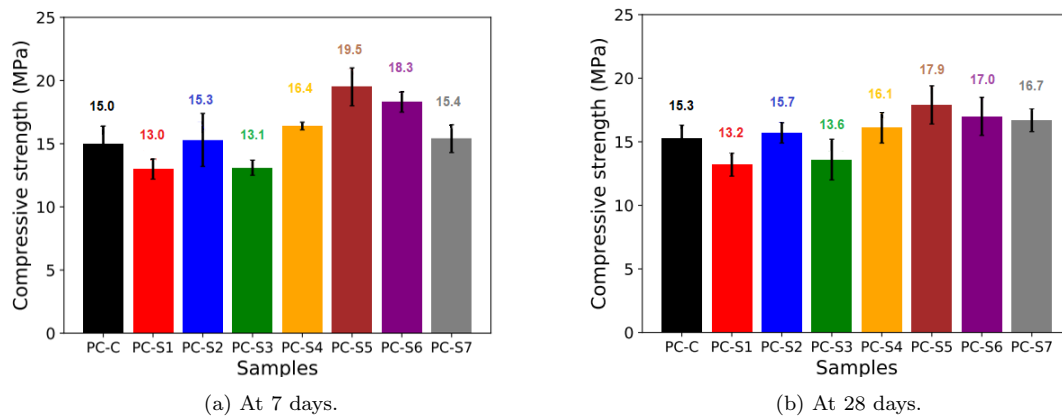


Fig. 14: Compressive strength of previous concretes based on sandy sediments.

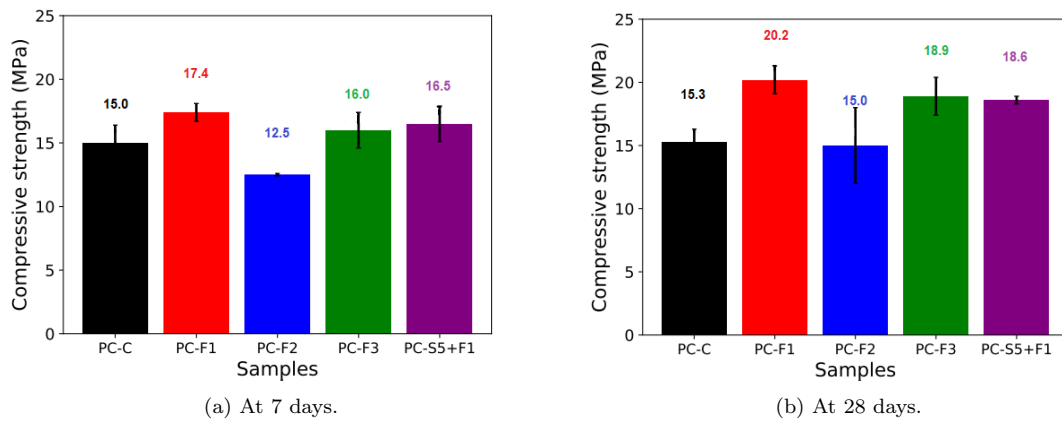


Fig. 15: Compressive strength of previous concretes based on fine sediments.

351 The tensile splitting strength of pervious concrete samples is presented in Fig. 17. Values range  
 352 from 1.02 to 1.49 MPa, displaying a trend similar to that of compressive strength: the concretes  
 353 with high compressive strength are also those with good splitting tensile strength and vice versa.  
 354 These values lie within the same range as those in the previous studies [55, 58, 59].

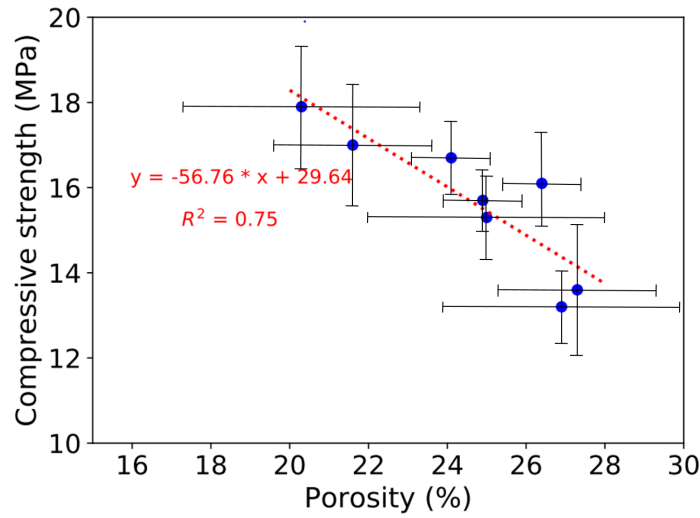
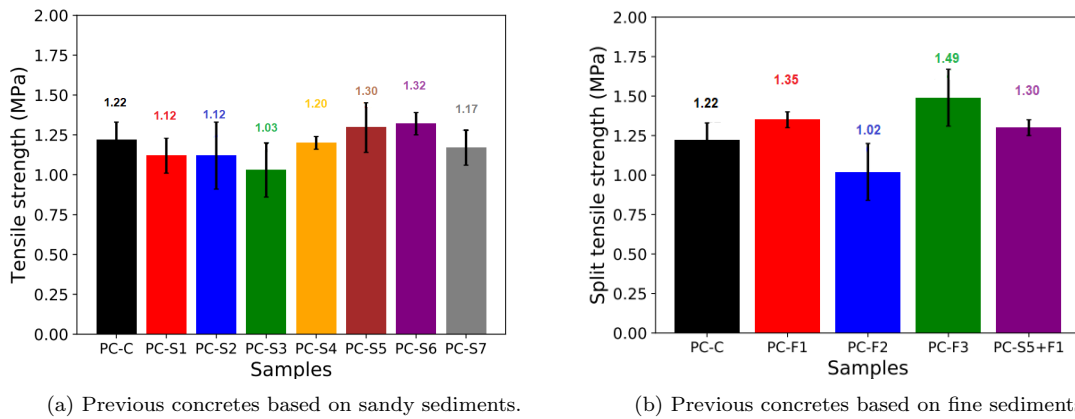


Fig. 16: Compressive strength at 28 days vs. porosity of pervious concrete based on sandy sediments.



(a) Previous concretes based on sandy sediments.

(b) Previous concretes based on fine sediments.

Fig. 17: Tensile strength at 28 days of previous concretes based on sediments.

### 355 3.5. Thermal conductivity

356 The results of thermal conductivity and volumetric heat of the pervious concretes studies are  
 357 depicted in Figs. [18] and [19], respectively. These results show that the thermal conductivities of the  
 358 pervious concretes produced with sediments vary from  $0.9$  to  $1.6 W.m^{-1}K^{-1}$ , while the corresponding  
 359 volumetric heat varies from  $1.3$  to  $2.3 MJ.m^{-3}K^{-1}$ . Let's note that the thermal conductivity of  
 360 pervious concrete is significantly lower than that of ordinary concrete, whose thermal conductivity  
 361 equals roughly  $1.75$  to  $2.25 W.m^{-1}K^{-1}$  [60, 61], with a volumetric heat of about  $2.2 MJ.m^{-3}K^{-1}$   
 362 [61]. Due to their high porosity therefore, pervious concretes have a low thermal conductivity  $\lambda$   
 363 and volumetric heat  $C_v$ , compared to ordinary concretes. In the case of pervious concretes made  
 364 with sandy sediments, the highest thermal conductivity and volumetric heat values are obtained  
 365 for pervious concrete PC-S3, which contains the lowest amount of fines and a higher porosity,  
 366 supposedly inducing lower conductivity. This outcome may be due to a higher thermal conductivity

367 of the sandy particles in the S3 sediment, as compared to other sediments, in compensating for  
 368 the effect of its high porosity. In addition, for those concretes made with sandy sediments, the  
 369 lower thermal conductivity is produced by PC-S5, which displays the lower porosity, meaning that  
 370 the heat conduction properties are not directly correlated with porosity but more likely with the  
 371 thermal property of the sandy sediment particles. A similar conclusion can be drawn for pervious  
 372 concrete made with fine sediment F3, which shows higher thermal conductivity at lower porosity.  
 373 Nevertheless, compared to ordinary concretes, the thermal properties of pervious concrete made  
 374 with sandy and fine sediments feature a lower heat storage capacity and lower thermal conductivity.  
 375 These materials can therefore be suitable in reducing urban heat islands provided they are placed on  
 376 top of a stone layer acting as a reservoir, as shown in [18, 62]. In retrospect, it would be appropriate  
 377 to measure the thermal emissivity  $\epsilon$  and albedo of the pervious concretes, which constitute essential  
 378 thermal properties indicating a material's ability to radiate stored heat. [62] showed that the albedo  
 379 has a greater impact on surface temperature than thermal conductivity.

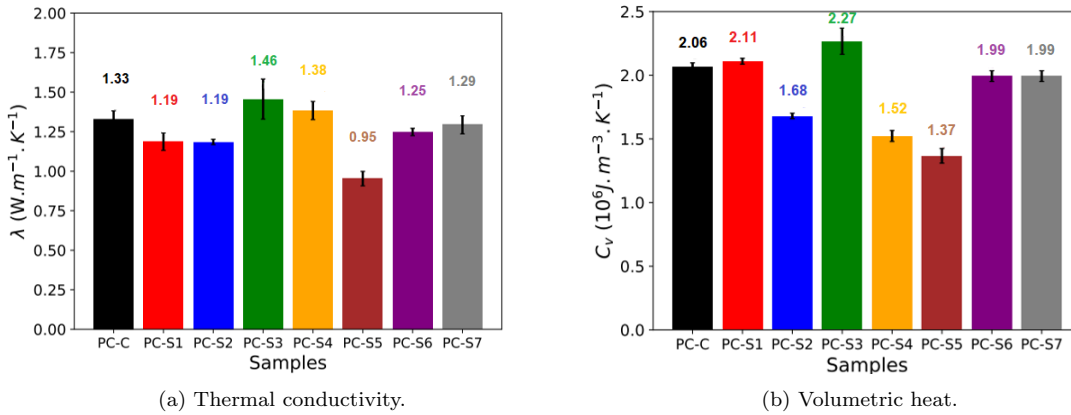


Fig. 18: Thermal conductivity and volumetric heat of the pervious concretes based on sandy sediments.

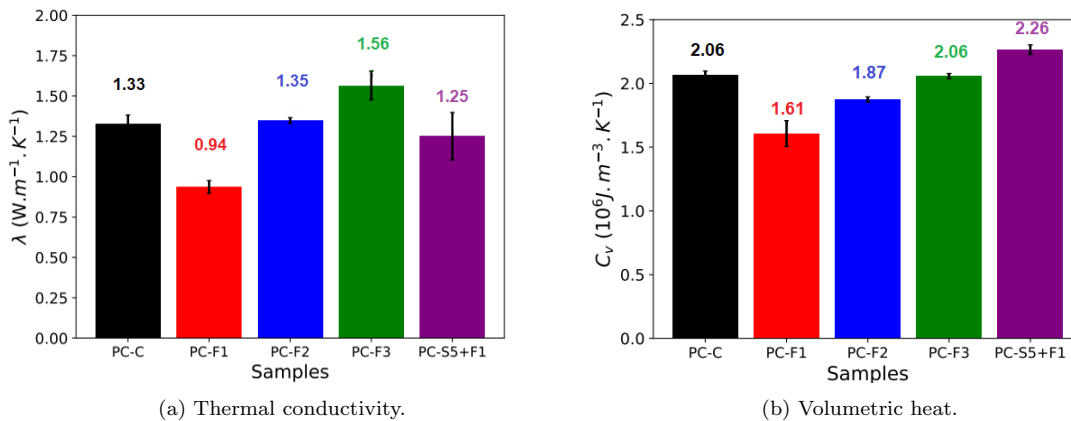


Fig. 19: Thermal conductivity and volumetric heat of the pervious concretes based on fine sediments.

#### 4. Discussion

This work has sought to develop a green and sustainable pervious concrete by means of incorporating dredged sediments. The results of the experimental investigations concluded that the technical feasibility of using sediments in pavement concrete has indeed been confirmed. These results also revealed a strong correlation among the various properties. As both the porosity and permeability of the concrete increase, its compressive and tensile strengths decrease. Sediment fineness is another important factor in the production of pervious concrete. The presence of more fines in a sediment clogs the connected pores and therefore reduces its drainage capacity. However, this fineness improves the material strength and increases its thermal conductivity. The sediments can therefore be classified according to their properties and consequently their effects on the produced concrete properties. For example, sediments S1 and S3 have a grain size that is almost similar to that of conventional sand, which has subsequently produced concretes with good porosity and permeability. Sediments S2, S4 and S7 have a finer grain size than conventional sand. As a result, concretes with lower porosity and permeability than the first group of sediments were made. By means of the fineness of these sediments the strength of these concretes was improved. The remaining sediments S5 and S6 produce concretes with the lowest porosity and permeability but with the best strengths. These sediments were able to clog more the connected pores which provided the observed results. For fine sediments, a decrease in porosity and permeability and good compressive strengths were observed. These results can be explained by the increase in the paste fraction in this type of concrete.

The manufacturing of pervious concretes based on sediments fully complies with the circular economy approach. The substitution of conventional sand or cement by sandy or fine sediments, respectively, allows for: the reuse of waste (sediments), the preservation of natural resources, and the reduction of  $CO_2$  emissions generated by their production. Pervious concrete itself offers major environmental benefits; it is among the solutions capable of contributing to climate change adaptation by mitigating the increase in urban temperatures [63]. The use of pervious concrete reduces the impervious surfaces that cause a significant increase in surface temperatures. Pervious concrete cools the pavement surface by evaporating the water stored from precipitation due to its high permeability. This cooling technique is controlled by the presence of water near the surface, a condition that highlights the importance of capillary rise in maintaining hydraulic continuity over a long distance, which effectively prolongs evaporation [18, 19]. The presence of cement paste in pervious concrete not only conveys high strength to the material but also ensures that water stored in the large pores can rise due to its strong capillary force. Porosity and permeability are therefore not the sole properties that need to be taken into account when designing pervious concrete, as the capillary power of the material is key as well. Based on the above water permeability results, it is impossible to consider concretes based on fine sediments as less effective in reducing surface temperature, especially as they contain more paste, which increases the overall capillary force of the mixture. However, the presence of a strong capillary force alone is not enough to cool the surface if the material is insufficiently porous and permeable to allow for the storage of water, which in turn

419 will serve to cool the surface by means of capillarity.

## 420 **5. Conclusion**

421 The effect of incorporating sediments, by totally substituting sand with sandy sediments or  
422 partially substituting cement with fine sediments, on the properties of pervious concrete has been  
423 studied herein. The salient conclusions are summarized below:

- 424 • The use of sediments results in a delay in cement hydration kinetics due to their organic  
425 content. This delay is more significant when incorporating fine sediments.
- 426 • The porosities of pervious concretes are inversely proportional to fresh concrete density. The  
427 grain size of the sandy sediments has an effect on the porous structure of the concrete; since  
428 the sediments contain finer elements, the concrete structure is more heavily compacted, thus  
429 creating less porosity in the mixture. The incorporation of fine sediments decreases the porosity  
430 of pervious concrete; this decrease is due to the mixture design, for which a tolerance of  
431 2% decrease in porosity has been acknowledged.
- 432 • The results of permeability follow the same trend as those of porosity. Permeability values  
433 range from 2.8 to 6.6 mm/s, which enables all prepared concretes to be used as a pervious  
434 concrete pavement.
- 435 • The compressive and tensile splitting strengths are inversely proportional to porosity: the in-  
436 corporation of sandy sediments has no clear effect, while incorporating fine sediments increases  
437 the mechanical performance of pervious concretes. Overall, all prepared pervious concretes  
438 displayed acceptable mechanical properties, regardless of the particle size of the incorporated  
439 sediment.
- 440 • The thermal conductivities and volumetric heat of pervious concrete are lower than those of  
441 ordinary concrete, offering a low capacity to conduct and store heat. Pervious concretes can  
442 therefore be used to reduce urban heat islands.

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- Pervious concretes with both sandy and fine river sediments were studied.
- Incorporating sandy sediments yielded nearly similar properties.
- The incorporation of fine sediments reduced porosity and permeability.
- The incorporation of fine sediments improved mechanical properties.
- The thermal conductivity of pervious concrete is lower than that of ordinary concrete.

**Hamza Beddaa:** Investigation, Methodology, Visualization, Writing - original draft, Writing - review & editing. **Junior Tchiotsop:** Investigation, Conceptualization, Methodology, Visualization, Writing - original draft. **Amor Ben Fraj:** Conceptualization, Methodology, Writing - review & editing, Supervision, Project administration. **Ciryle Somé :** Investigation, Writing - review & editing.

## **Declaration of interests**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: