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1 Full characterization of hygrothermal, mechanical and  
2 morphological properties of a recycled expanded polystyrene-  
3 based mortar

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11

12 **HIGHLIGHTS**

13 • Hygrothermal and mechanical properties of a recycled expanded polystyrene-based material  
14 have been assessed;

15 • Sorption isotherm curves of expanded polystyrene mortar exhibit hysteresis phenomenon and  
16 show a low water vapor adsorption;

17 • Thermal conductivity and specific heat capacity are highly dependent of temperature and  
18 water content;

19 • Water vapor permeability coefficient increases with polystyrene incorporation because of air  
20 bubbles appearance;

21 **ABSTRACT**

22 The construction sector is the most energy consuming one in the world, and it has a significant  
23 ecological impact. Indeed, concrete manufacturing overuses natural resources such as sand or  
24 gravel, and the need to use alternative building materials is urgent. Choosing adequate building  
25 materials takes an important part in the success of a high environmental quality project. This  
26 suggests using new alternative solutions, based on recycled materials or waste. However, their  
27 use being relatively recent, these materials properties are not widely known and there is lack of  
28 information concerning their hygrothermal and mechanical behavior.

29 In this context, the present work aims then to highlight the experimental characterization of  
30 hygric, thermal, physical and mechanical properties of a recycled expanded polystyrene mortar,  
31 which is a relatively new building material, generally used for its thermal performances. Indeed,  
32 a complete characterization campaign was elaborated in this work, allowing a precise  
33 determination of the main properties of the material. The experimental characterization also  
34 included a usual cement paste made of the same cement as a reference material, in order to  
35 evaluate the polystyrene adding impact on the measured hygrothermal properties.

36 Different methods of sorption isotherms determination were presented, and a better attention  
37 was devoted to the sorption hysteresis phenomenon characterization. The macroscopic  
38 hygrothermal properties, such as water vapor permeability, thermal conductivity and thermal  
39 capacity were also investigated function of the temperature and water content evolution.  
40 Mechanical strength was also determined, and SEM observations were performed to study the  
41 morphology of the material. Experimental results show that expanded polystyrene mortar  
42 exhibits a good thermal conductivity and thermal capacity, and a higher water vapor  
43 permeability. These results provide data for better forecast on the prediction of the hygrothermal  
44 and mechanical behavior of such material.

45 **KEY WORDS**

46 Experimental characterization; Sorption isotherms; Moisture storage capacity; Moisture buffer  
47 value; Water vapor permeability; Thermal conductivity; Specific heat capacity; Compressive  
48 strength

49 **1. INTRODUCTION**

50 The world is facing major energy and environment problems, especially as buildings are the  
51 main energy consumers. Reducing the building related energy consumption and promoting the  
52 use of low environmental impact materials are measures to be taken in order to avoid  
53 overexploitation of natural resources and available energy sources. The construction and  
54 operation of buildings is responsible for the consumption of 33% of the world's total energy  
55 use [1], and it is actually the most important confront in the construction sector. Moreover,  
56 buildings-related CO<sub>2</sub> emissions reached an all-time high of 10 Gt CO<sub>2</sub> in 2019 [2,3], which  
57 accounts for nearly 57% in the total carbon dioxide emissions [4].

58 On the other hand, waste management is a problematic issue given the consequent increase in  
59 the world's urbanization, causing a considerable amount of wastes. Recycling and reusing this  
60 waste is important for various reasons, and the most important of all are the conservation of  
61 natural resources and the reduction of the environment pollution.

62 In this context, waste based materials appear as an interesting alternative for usual building  
63 materials in modern construction applications. Most of recycled waste are lightweight  
64 aggregates, such as rubber tires, glass and wood chippings [5], expanded polystyrene [6,7],  
65 plastic wastes [8, 9], etc. Incorporating them in building materials results in generation of  
66 lightweight concrete, that significantly reduces the structures weight and presents many  
67 advantages. Besides the load reduction of buildings, lightweight concrete has a lower density,  
68 enhanced thermal properties, better fire resistance and higher acoustic insulation [10 – 13].

69 Given its low density, this type of concrete often has poor mechanical performances [14], and  
70 are generally destined to be non-load bearing elements.

71 Recycled expanded polystyrene (EPS) is an interesting choice in the lightweight concrete  
72 production. It is generally used in packaging and often released into nature after its use in  
73 various industrial fields. Being non-biodegradable, it remains present for many years and  
74 contributes to the pollution of the environment, and recycling it benefits to both the environment  
75 and the economy. Moreover, using EPS as aggregates substitute reduces the overexploitation  
76 of natural resources usually involved in building materials [6]. Recycled EPS is not toxic and  
77 does not develop bacteria and molds.

78 In recent years, interest in polystyrene-based materials has increased, in view of all the benefits  
79 it offers. It is generally used for many non-structural applications, such as in blocks and wall  
80 panels [15]. In the previous works, most studies were centered on mechanical and thermal  
81 properties of polystyrene concrete. Mechanical performance linked to polystyrene content was  
82 widely discussed, as it is a crucial property for building materials. Wang et al. [16]  
83 experimentally investigated the physical and mechanical properties of lightweight concrete  
84 incorporating EPS beads and soft marine clay, and concluded that reducing the EPS content  
85 will increase the mass density and compressive strength as expected. Cadere et al. [17], Nikbin  
86 et al. [18] and Ali et al. [19] came to the same conclusion while studying mechanical properties  
87 of building materials with polystyrene particles.

88 Other studies focused on both mechanical and thermal properties given the enhanced thermal  
89 insulation of expanded polystyrene and lightweight concrete. Increasing the volume of EPS  
90 significantly reduces the thermal conductivity of the material along with its compressive  
91 strength, because of the decrease of its density. These results can be seen in multiple studies  
92 such as the works of Sayadi et al. [20] on polystyrene foamed concrete, Koksall et al. [14] on  
93 expanded polystyrene powder-based mortars, Ali et al. [21] on expanded polystyrene mortars,

94 Tasdemir et al. [22] on expanded polystyrene concrete and Ferrandiz-Mas et al. [23] on ground  
95 and powdered polystyrene-based concrete. They all highlighted the excellent thermal  
96 performances of polystyrene-based building materials and the interest in using them as non-  
97 structural insulating items.

98 Few studies investigated the microstructural aspects of polystyrene-based materials, especially  
99 the adherence between the expanded polystyrene and the cement. Fathi et al. [24] argued that  
100 there was a wide transition zone between two components while Laukaitis et al. [25] and  
101 Lanzon et al. [26] all showed that there was a good adherence and no interfacial zone but rather  
102 polystyrene overlapping cement. In a previous work, we used recent techniques such as X-rays  
103 micro-tomography to characterize the expanded polystyrene concrete morphology at a  
104 microscopic level [6], and highlighted its complex heterogeneity.

105 Regarding the hygric properties, only few researchers were interested in such studies, despite  
106 the importance of understanding the hygric behavior of such materials before including them  
107 into buildings. Moreover, water content greatly affects thermal properties [27], and given the  
108 insulating purposes of polystyrene concrete, knowing the hygric state influencing the thermal  
109 performance seems highly relevant. In the previous works, the interest in hygric properties was  
110 mainly about capillary absorption, which is an indicator of the materials durability. The results  
111 showed that the incorporation of recycled expanded polystyrene decreased the capillary  
112 absorption coefficient, thus improving the durability [24,28,29]. Ferrandiz-Mas [30] used two  
113 types of recycled expanded polystyrene aggregates, and proved that ground EPS mortars had  
114 lower capillary absorption than powdered EPS mortars, thus better durability.

115 Some studies also highlighted the moisture content influence on polystyrene insulation  
116 materials generally used in building envelopes, thus its impact on building energy performance  
117 [31]. The results revealed that the combined impact of the temperature and humidity on the  
118 thermal conductivity change is significant, especially at a high operating temperature and

119 moisture content. Chikhi et al. [32] led an experimental investigation of a composite concrete  
120 loaded by polystyrene chips. The water vapor sorption curves allowed the materials to be  
121 classified as capillaro-porous hygroscopic materials, and the findings showed that the  
122 hygrothermal behavior of the materials is highly influenced by the air humidity variations,  
123 especially near the surface.

124 Lack of interest about hygric characterization of polystyrene-based building materials drives  
125 this work. Indeed, it is important to determine the hygric properties of polystyrene mortar in  
126 order to fully apprehend its hygrothermal behavior when introduced in buildings. Also, the  
127 evolution of the hygrothermal properties function of the relative humidity and the temperature  
128 was not considered before, which leads this work to pay a special attention to it.

129 In this context, we propose to lead a complete experimental campaign to determine the  
130 hygrothermal and mechanical properties of a recycled expanded polystyrene concrete. The full  
131 characterization of the material is carried on using recent and multiple techniques, to accurately  
132 measure the properties. The sorption isotherms are first determined, using two different  
133 methods (volumetric and gravimetric) and confronting the two results. Sorption hysteresis  
134 phenomenon is highlighted through multiple sorption loops, representing the real behavior of  
135 the material under successive wetting and drying cycles. Also, the moisture storage capacity is  
136 presented, along with the moisture buffer value and the water vapor permeability of the  
137 polystyrene mortar. Thermal properties are finally determined using recent and accurate  
138 equipment, through the measurements of thermal conductivity and specific heat capacity.

## 139 **2. MATERIALS AND METHODS**

140 The lightweight material of interest in this article is displayed in Fig.1. It is a recycled expanded  
141 polystyrene mortar whose composition is presented in table 1. We will also study a usual cement  
142 paste made of the same cement as a reference material, in order to evaluate the polystyrene

143 adding impact on the measured hygrothermal properties. The cement is of type CEMII and the  
144 aggregates are recycled expanded polystyrene beads. The used water/cement mass ratio is 0.32.  
145 The expanded polystyrene beads have a spherical shape and their diameters vary between 1 to  
146 3 mm.



147

148 Fig.1. a) Expanded polystyrene mortar; b) Cement paste

148

149

Table 1. Composition of the polystyrene mortar

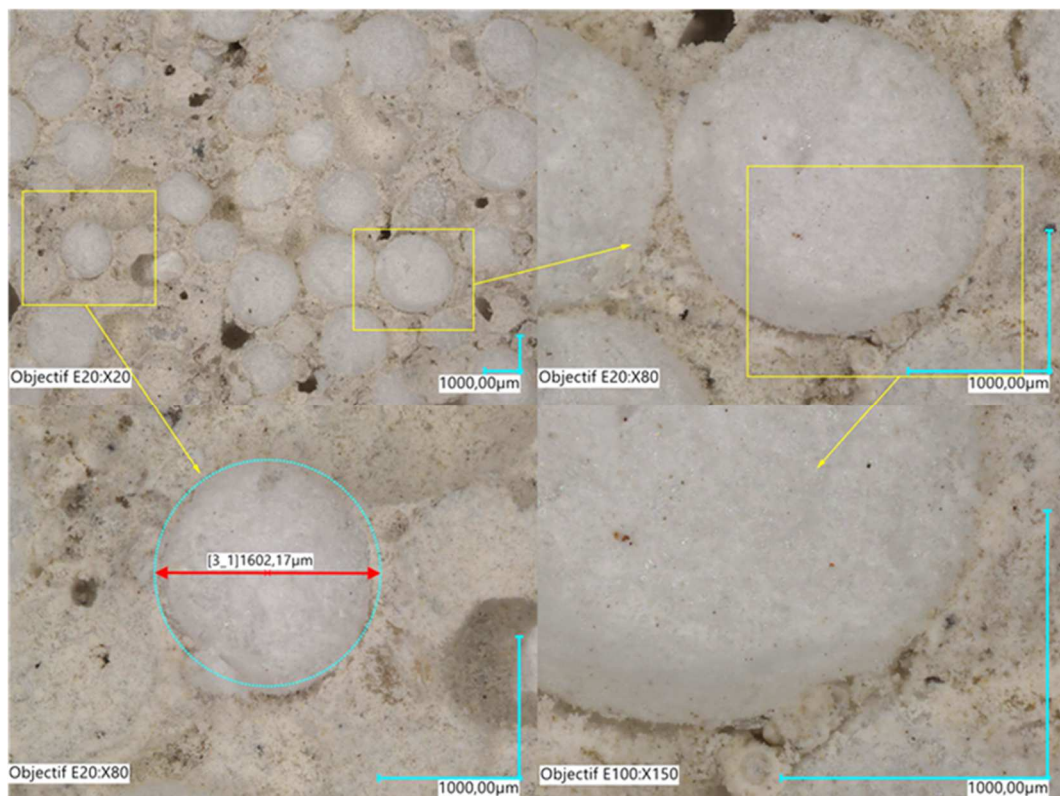
<b>Materials</b>	<b>Volume ratio</b>
Cement	30%
Polystyrene beads	53%
Water	17%

150

151 After the manufacturing, the samples are put into molds of the following dimensions: 15x15x5  
152 cm, 4x4x16 cm and  $\phi$ 11x22 cm. They are de-moulded after 24 hours then stored in a climatic  
153 chamber with controlled temperature and relative humidity ( $T = 20^{\circ}\text{C}$  and  $\text{HR} = 50\%$ ). The  
154 experimental campaign begins 3 months later, and included the determination of the water  
155 vapor sorption isotherms, moisture storage capacity, sorption hysteresis loops, moisture buffer  
156 value, water vapor permeability, thermal conductivity and specific heat capacity. Compressive



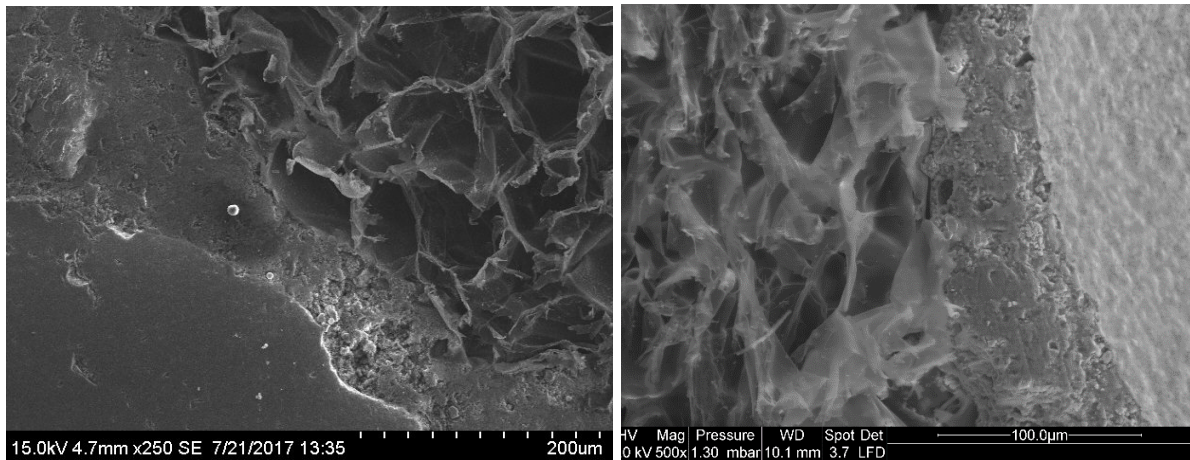
157 strength was also determined but only 28 days after fabrication. The measured density of the  
158 material is  $540 \text{ kg/m}^3$  and its open porosity is 8.7% [6]. The total porosity is 64%, but it is  
159 mainly a closed porosity since the expanded polystyrene beads have a closed structure [6].  
160 Observations performed by the digital microscope "Keyence" show that the polystyrene beads  
161 adhere perfectly to the cement paste (Fig.2). The expanded polystyrene beads distribution is  
162 almost homogeneous. Some imperfections as cracks can be noticed on the polystyrene/paste  
163 interface. However, these cracks are very superficial and do not affect the adhesion of the two  
164 phases in depth as confirmed by SEM observations (see Fig.3). These observations show good  
165 adherence between the polystyrene beads and the cement paste with no interfacial transition  
166 zone.



168 Fig.2. Digital microscope observations of the surface of polystyrene mortar

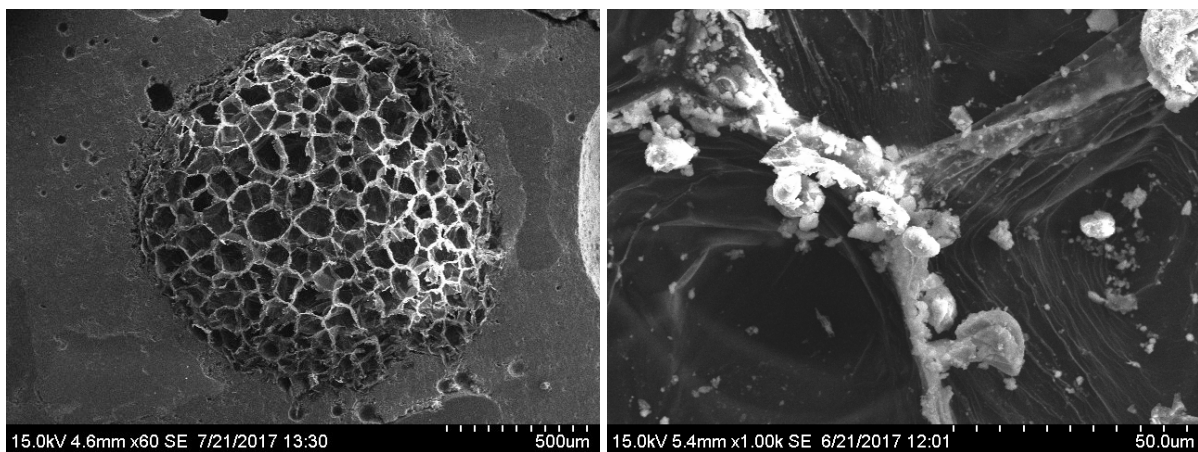
169 Fig.3 shows scanning electron microscopy images of the polystyrene mortar. Once again, the  
170 adhesion between the polystyrene and the cement appears to be of good quality. The image of

171 the interface with a 500x magnification shows an overlapping of the two phases and no  
172 interfacial transition zone.



174 Fig.3. SEM images of the cement/polystyrene interface

175 The microstructure of the expanded polystyrene beads was also investigated through SEM.  
176 Fig.4 shows microscopic images of the internal structure of the beads, at a resolution reaching  
177 50 µm. The bead is characterized by a cellular structure like a beehive, and it is constituted of  
178 a multitude of small sized cells whose inside is empty. The walls of these cells seem to be  
179 extremely fine, with some polystyrene particles hanging on either sides.



181 Fig.4. SEM images of a polystyrene bead

182 This structure results from the expansion process that allows obtaining the expanded  
183 polystyrene beads, and explains their very low density. Indeed, the air occupies almost the entire  
184 volume of the bead, apart from the cell walls where hangs some polystyrene and which are very  
185 thin [6].

## 186 **2.1. Main adsorption and desorption curves**

187 The water vapor sorption isotherms curves represent the water content evolution in equilibrium  
188 with the air relative humidity at a given temperature. They can be determined using several  
189 methods, either gravimetric or volumetric. The gravimetric method is based on a continuous  
190 mass monitoring, until reaching equilibrium. The water content corresponding to each relative  
191 humidity value is obtained from the mass variation, and after sweeping all the relative humidity  
192 levels in both wetting and drying, the adsorption and desorption curve results [33]. On the other  
193 hand, the volumetric method relies on measuring the water vapor volume using the number of  
194 moles adsorbed or desorbed by the sample.

195 In this work, sorption isotherm curves are determined using two different equipment: The  
196 ProUmid® SPS device, based on the gravimetric method and the Belsorp aqua 3 device, based  
197 on the volumetric one. Samples were dried at 60 °C until mass stabilization, which was  
198 determined by a mass variation less than 0.01% during 60 minutes. They were then placed in  
199 the device chamber and exposed to different levels of relative humidity at a temperature of 23  
200 °C. Water content was determined whether by mass variation or by water vapor pressure change  
201 at equilibrium. The test was carried out on three cylindrical samples of 40 mm diameter and 5  
202 mm thickness, and the mass monitoring was performed by a precision scale (accurate to  $10^{-4}$ g).

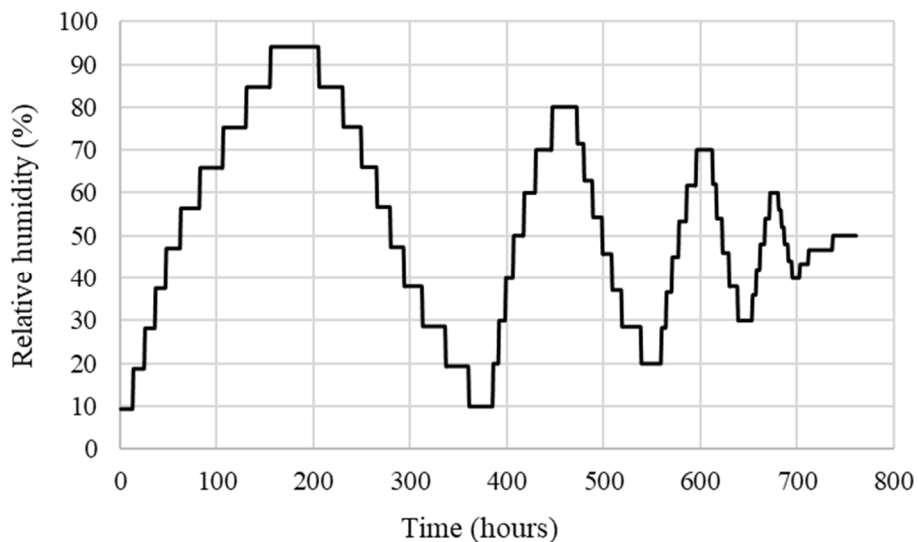
203 Water vapor sorption isotherms allow determining the moisture storage capacity of the material  
204 that represents water accumulation in the porosity. It is defined as the slope of the sorption  
205 isotherm curves and it differs whether the material is subject to wetting or drying. Moisture

206 storage capacity  $C_m$  is expressed by equation (1),  $\omega$  being the material water content in (kg/kg)  
207 and HR(%) the air relative humidity.

208 
$$C_m = \frac{\partial \omega}{\partial HR} \quad (1)$$

209 **2.2. Intermediate sorption isotherms**

210 Sorption hysteresis phenomenon characterizes the behavior of a porous material that tends to  
211 have different water content at equilibrium whether it is in adsorption or desorption phase [34].  
212 Building materials undergo several cycles of wetting and drying, and if it does not dry  
213 completely in the desorption phase, the water content will not follow the main adsorption curve  
214 at the next wetting, but rather an adsorption curve located between the two main curves, called  
215 the intermediate adsorption curve. Intermediate sorption isotherms of polystyrene mortar are  
216 determined using the ProUmid SPS device, following the relative humidity levels presented in  
217 Fig.5, each level lasting until reaching equilibrium. The latter was determined by a mass  
218 variation less than 0.01% during 60 minutes.



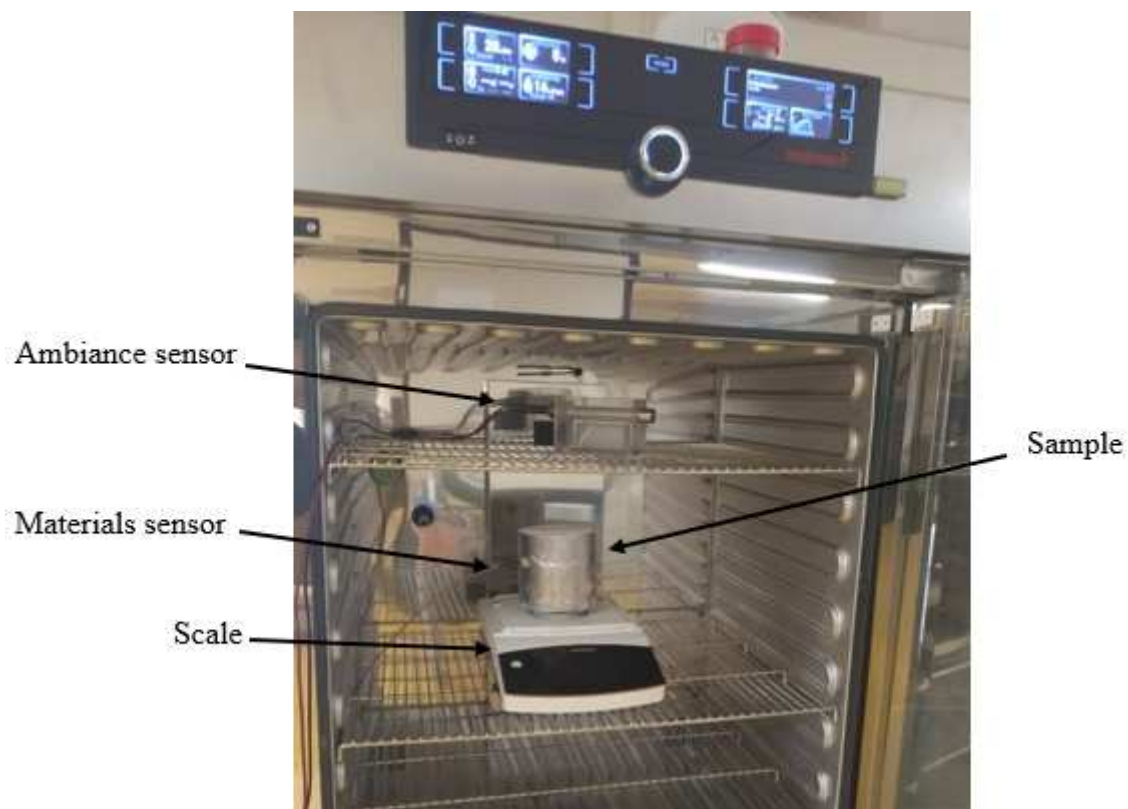
219

220 Fig.5. Relative humidity levels for intermediate sorption curves measurements

221 The tested samples were cylindrical with a diameter of 50 mm and a thickness of 10 mm, and  
222 three samples were tested. This test could not be carried out with the Belsorp because the latter  
223 requires that the samples be completely dried and degassed before carrying out the  
224 measurements.

### 225 **2.3. Moisture Buffer Value (MBV)**

226 Moisture buffer capacity is an indicator for a materials ability to moderate indoor relative  
227 humidity variations (seasonal or diurnal). It represents its capacity to adsorb moisture from the  
228 ambient air when relative humidity is high, and release moisture when relative humidity gets  
229 lower [35]. It is determined following the NORDTEST protocol [36] suggesting a specific  
230 experimental set up. The sample is initially conditioned at 23°C and 50% of relative humidity,  
231 then exposed to cyclic relative humidity variations between high and low values to simulate the  
232 diurnal variations.



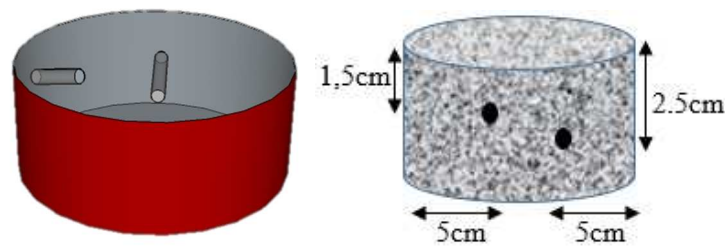
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234

Fig.6. Experimental setup for the MBV measurements



235 In this work, three samples are tested, and they were of cylindrical shape and insulated on all  
236 sides except the superior one. Their dimensions are 110 mm of diameter and 40 mm of  
237 thickness. They are exposed to 8 h at 75% RH and 16 h at 33% at a temperature of 23°C.  
238 Samples are weighted continuously using a 0.1g precision scale, and the test stops when the  
239 mass change between the three last cycles is less than 5%. High precision sensors are put in the  
240 climatic chamber and inside the samples in order to record temperature and relative humidity  
241 evolution through time. The experimental setup is presented in Fig.6. Inside the samples, the  
242 temperature and relative humidity sensors were positioned at two different heights, at 1.5 cm  
243 and 2.5 cm from the upper surface exposed to the varying hygrometry. The samples setup is  
244 presented in Fig.7.



245

246 Fig.7. Hygrothermal sensors setup inside samples

247 The moisture buffer value is then obtained using the equation (2),  $\Delta m$  being the mass change  
248 during one cycle,  $S$  the exposed area, and  $HR_w$  and  $HR_d$  respectively the wetting and drying  
249 relative humidity value.

250

$$MBV = \frac{\Delta m}{S (HR_w - HR_d)} \quad (2)$$

251 **2.4. Water vapor permeability**

252 Water vapor permeability of a material reflects its ability to transmit water vapor from one side  
253 to another. It is strongly influenced by density, and can thus change from single to double when  
254 density decreases. It is a great indicator of material's durability as it is used to assess the risk of

255 condensation in the walls of buildings. In this study, water vapor permeability is measured using  
256 the cup test method based on the standards NF EN ISO 12572 [37]. Two approaches can be  
257 done to measure the water vapor transmission, a dry cup and a wet cup method. The two  
258 methods have the same experimental setups but with different climatic conditions. The wet cup  
259 method is used when the material is expected to be exposed at a high relative humidity, while  
260 the dry cup method is advocated whenever relative humidity levels are lower.

261 In our study, the test is performed using the GINTRONIC Gravitest device, which contains a  
262 climatic chamber and a high precision scale. The climatic conditions are set up to  $T = 23^{\circ}\text{C}$  and  
263  $\text{HR} = 50\%$ , and the relative humidity inside the cup varies whether it is a wet cup test ( $\text{HR} =$   
264  $93\%$ ) and dry cup test ( $\text{HR} = 3\%$ ). The tested samples were cylinders with a diameter of 80 mm  
265 and 10 mm thickness, and each test was performed on three different samples to ensure  
266 repeatability of the results.

## 267 **2.5. Thermal conductivity**

268 Thermal conductivity of building materials can be determined through multiple techniques,  
269 depending on the thermal conductivity range and the materials density. In this work, thermal  
270 conductivity is measured using the  $\lambda$ -Meter Ep500e device, whose principle is based on the  
271 guarded hot plate method. The test is carried on under stationary conditions according to the  
272 standards EN 12667 and EN 12664 [38], and it lasts for 3 to 4 days for each sample. During the  
273 test, a unidirectional heat transfer goes through a sample of 15x15x5 cm. Thermal conductivity  
274 is measured in terms of temperature and water content, as it depends on both parameters. The  
275 measurements were conducted on three samples of expanded polystyrene mortar and one  
276 sample of reference cement paste. In the measurement in terms of water content, samples are  
277 initially saturated in water, then wrapped in a plastic film to ensure that the total water content  
278 is controlled.

## 279        **2.6. Specific heat capacity**

280        Specific heat capacity is one of the most important thermal properties of building materials, in  
281        addition to thermal conductivity. It reflects the materials ability to store some heat quantity. It  
282        is measured using the calorimeter Calvet BT 2.15 based on a static measurement method. This  
283        device possess 3D sensors that completely enclose the sample, so all of the emitted heat is  
284        measured. The three tested samples are cylindrical of 6 cm in height and 1 cm in diameter, and  
285        are dried at 60°C until mass equilibrium before testing.

## 286        **2.7. Compressive strength**

287        Compressive strength of expanded polystyrene mortar helps define its application in buildings.  
288        In this work, compressive strength was determined following the standards NF EN 13892-2.  
289        Samples used were the 4x4x16cm<sup>3</sup> after 28 days on fabrication, and test were carried out on  
290        three samples at a loading rate of 2,4kN/s.

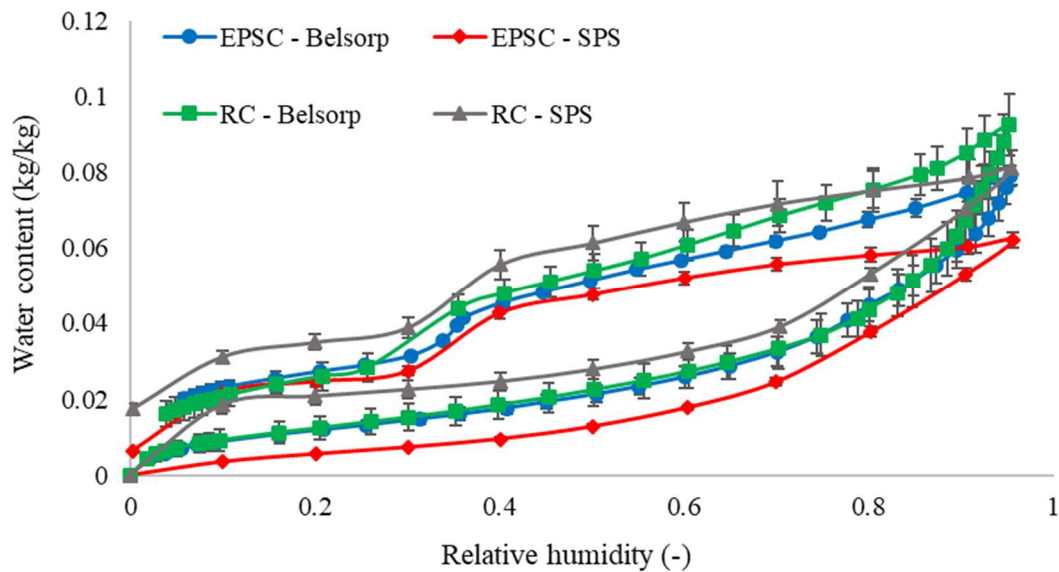
## 291        **3. RESULTS AND DISCUSSION**

292        The experimental program being summarized before, we are now presenting the results of the  
293        full hygrothermal characterization of the recycled expanded polystyrene mortar. In the  
294        following, acronyms will be used for the materials of interest. Recycled expanded polystyrene  
295        mortar will be referred to as ESPC, and the reference cement paste as RC.

### 296        **3.1. Main adsorption/desorption curves**

297        The main adsorption and desorption isotherm curves are presented in Fig.8. For both  
298        polystyrene concrete and cement paste, the water content gradually increases with the relative  
299        humidity and it quickly rises when humidity values are high (in the super-hygroscopic zone).  
300        This is due to capillary mechanisms, which are triggered at high relative humidity.





301

302

Fig.8. Water vapor sorption isotherms for EPSC and RC

303

The curves present sorption hysteresis phenomenon since the adsorption and desorption curves do not follow the same path. They also show that polystyrene mortar does not have a high moisture absorption, mainly because of its low porosity discussed in a previous work [6]. The obtained curves are type III according to the IUPAC classification [39], which is consistent with the structure of polystyrene mortar and its low water adsorption [26, 29, 40]. The reference cement paste is characterized by isotherm curves of similar pace but with a higher water content at saturation. This is due to the hydrophobic nature of expanded polystyrene that tends to lower the water adsorption.

311

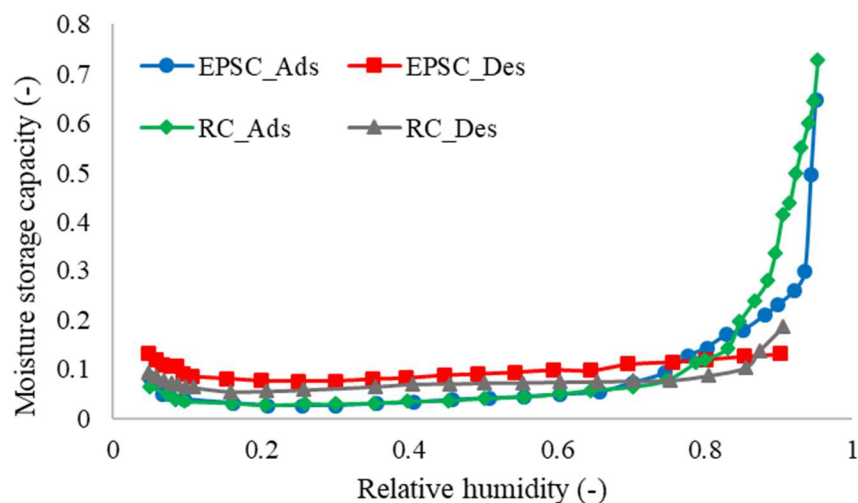
In view of the results, there seems to be a slight difference in the sorption isotherms, depending on the chosen method. Indeed, using the volumetric method results in higher water content values, especially at a high relative humidity. However, both curves have the same allure, which proves a good agreement of the results. The volumetric method presents higher water content values because it allows the access to all water vapor molecules that are present in the porosity. The gravimetric method are influenced by measurement errors (depending on the scales precision for example), especially in the case of small samples of lightweight and low

317

318 hygroscopic materials. As it is the case for expanded polystyrene concrete, the adsorption is  
319 low and the samples mass does not vary much. It is then not always precisely recorded,  
320 depending on the scale resolution, and it explains the difference in the water content values  
321 obtained using the two methods.

322 For both materials, the sorption isotherms present a sudden and significant decrease in water  
323 content in desorption phase. This often appears in multiscale materials at a relative humidity  
324 close to 40% and a temperature of 25°C. It is due to cavitation or nucleation that is the formation  
325 of gas cavities in the liquid [41]. It is characteristic of cement-based materials and usually  
326 appears in desorption isotherm curves of cement pastes with and without any additions.

327 Moisture storage capacity of expanded polystyrene concrete can be determined using the main  
328 water vapor sorption isotherms. It is presented in Fig.9 depending of relative humidity for both  
329 the expanded polystyrene mortar and the cement paste. Given that the adsorption and desorption  
330 curves present hysteresis phenomenon, the moisture storage capacity curves will be different  
331 whether it is the adsorption or desorption phase. We only present moisture storage capacity  
332 obtained using the volumetric method, as it is more precise for lightweight materials.



333

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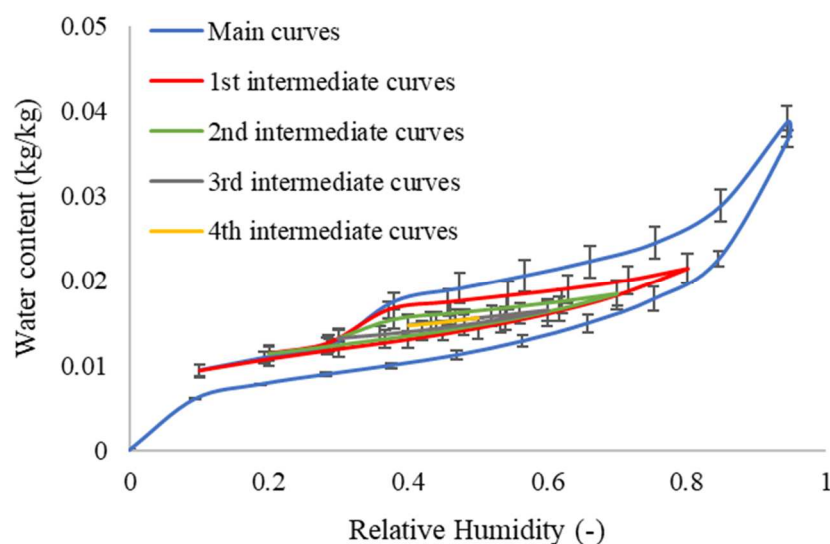
Fig.9. Moisture storage capacity for expanded EPSC and RC

335 For both materials, the evolution of moisture storage capacity has the same shape and relatively  
336 similar values. Since the adsorption and desorption isotherms of the two materials do not show  
337 much difference, moisture storage curves are almost similar. There is a considerable increase  
338 of this property at high relative humidity values (above 80%), where the moisture storage  
339 capacity of cement paste is slightly higher than this of the expanded polystyrene mortar.

### 340 3.2. Intermediate adsorption/desorption curves

341 In reality, buildings materials undergo several cycles of wetting and drying, and they are not  
342 completely dry or wet. The intermediate sorption curves allow describing their hydric state,  
343 whatever the ambient relative humidity.

344 The main and intermediate adsorption and desorption curves are presented in Fig.10. It shows  
345 a maximal water content of 0.04 kg/kg at a relative humidity of 95%, which is a lower value  
346 than that obtained previously with the SPS device (0.06 kg/kg in Fig.8). This is due to the fact  
347 that the used samples in the two experiments did not come from the same batch and were not  
348 tested at the same age.



349

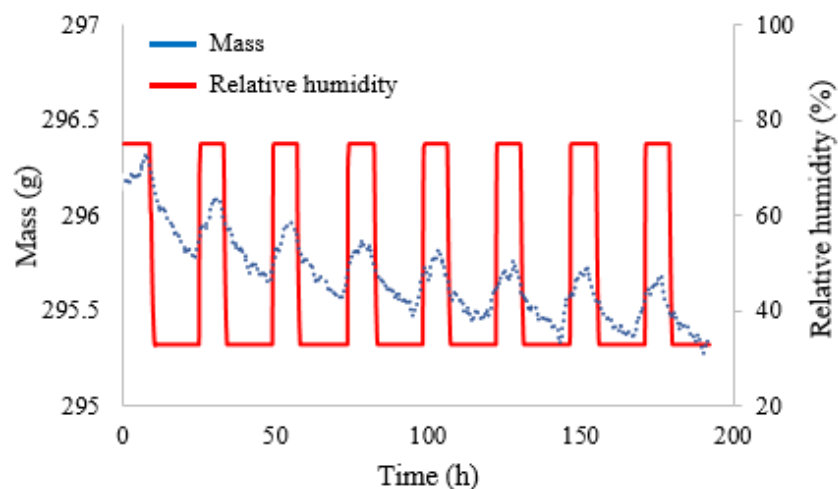
350

Fig.10. Main and intermediate adsorption/desorption isotherm curves of EPSC

351 The intermediate adsorption and desorption curves are included within the main curves, which  
352 constitute an envelope. The intermediate curves have the same shape as the main curves (in  
353 blue in Fig.10), and the intermediate desorption curves also have the decrease in water content  
354 between 30% and 40% relative humidity. After four cycles of wetting and drying, the  
355 intermediate curves begin to overlay, and we can clearly observe that the fourth adsorption  
356 curve overlaps with the third desorption curve. This is due to the water accumulation in the  
357 materials pores and the relative humidity levels that are narrowed at each cycle. Indeed, relative  
358 humidity is initially changing between 0 and 94%, and vary between 40 and 50% in the last  
359 cycle.

### 360 3.3. Moisture Buffer Value

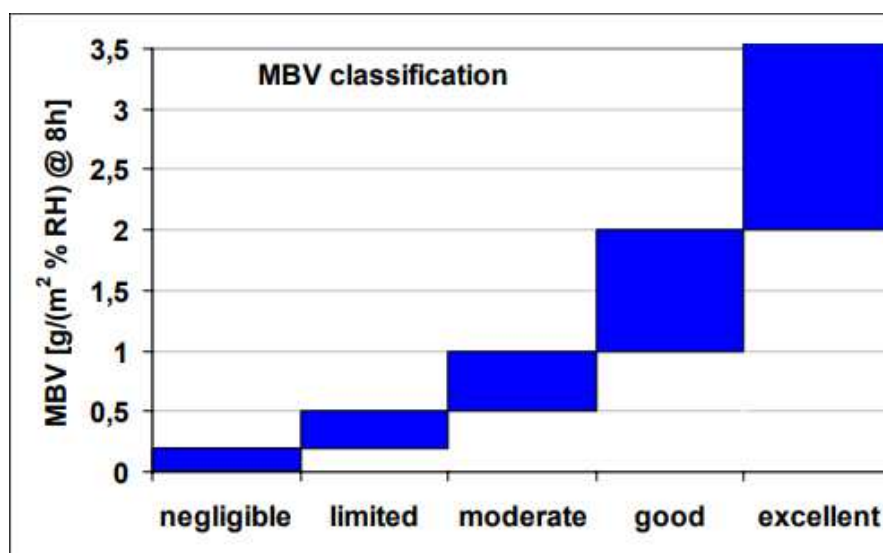
361 The moisture buffer capacity of the expanded polystyrene mortar is determined through mass  
362 evolution recording, and the result is displayed in Fig.11. Graph shows a decreasing mass  
363 variation over time, with a stabilization in the three last cycles. Expanded polystyrene mortar is  
364 not a very hygroscopic material, and the drying kinetics in this test are more important than this  
365 of the wetting. Therefore, the samples lose more moisture than they can adsorb. This kind of  
366 behavior is not unusual, since it can also happen in the case of hygroscopic materials [42].



367

368 Fig.11. Mass evolution of expanded polystyrene mortar during MBV test

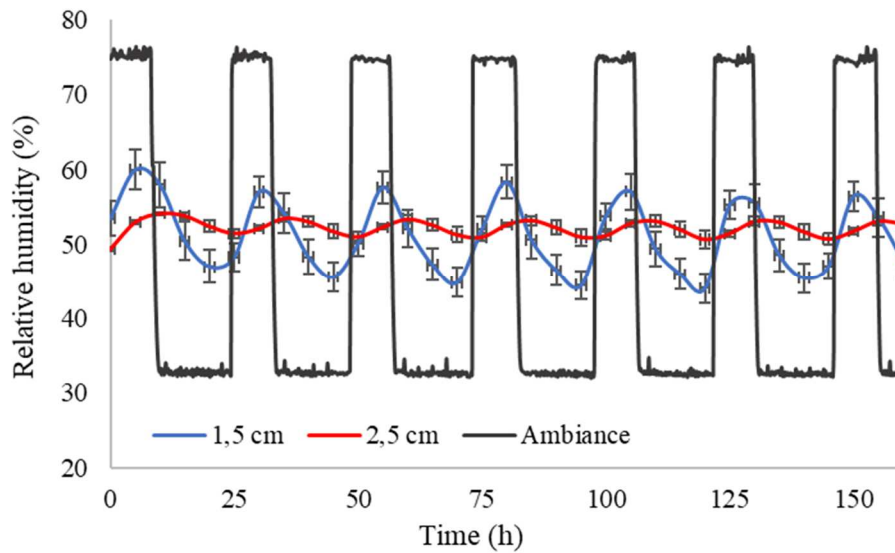
369 In the case of the expanded polystyrene mortar, the mass gain and loss are not very high because  
 370 of its low open porosity (around 9% [6]). In addition, expanded polystyrene is hydrophobic and  
 371 does not adsorb any moisture. The measured moisture buffer value of the expanded polystyrene  
 372 mortar is  $0.55 \text{ g/m}^2 \cdot \% \text{RH}$ . NORDTEST protocol [36] also proposed a classification for materials  
 373 according to their moisture buffer capacity values. It is displayed in Fig.12 and offers a  
 374 repartition of the moisture regulation. The obtained results classify the polystyrene mortar in  
 375 the category of materials with moderate moisture buffer capacity, such as gypsum [36]. The  
 376 obtained moisture buffer value of the reference cement paste is  $0.8 \text{ g/m}^2 \cdot \% \text{RH}$ , which is a  
 377 slightly higher than this of the expanded polystyrene mortar, but still in the range of moderate  
 378 moisture buffer capacity.



379

380 Fig.12. Moisture buffer value classification [36]

381 Moisture buffer value of usual concrete is  $0.4 \text{ g/m}^2 \cdot \% \text{RH}$  [36] and expanded polystyrene is not  
 382 capillary active, thus it has no moisture absorption capacity, and it is characterized by an  
 383 absence of moisture buffering capacity [43]. The measured MBV of expanded polystyrene  
 384 mortar is then consistent with literature. The dynamic ability of expanded polystyrene mortar  
 385 to mitigate daily relative humidity variations in building envelopes therefore remains moderate.



386

387

Fig.13. Relative humidity evolution inside samples

388

During the test, relative humidity variation at two depths in the samples and in the ambiance

389

were also recorded, and are shown in Fig.13. Relative humidity inside the samples follows the

390

same variations of the ambient air, with a little phase shift over the last three cycles. At the

391

position of 2.5 cm inside the sample, relative humidity is only slightly affected by external

392

variations. In the case of unidirectional transfer, the mass transfer kinetics are inversely

393

proportional to the depth of the material, which explains why the relative humidity variations

394

at 1.5 cm position are higher than those at 2.5 cm.

395

### 3.4. Water vapor permeability

396

Water vapor permeability was measured for both expanded polystyrene mortar and the

397

reference cement paste, in order to evaluate the polystyrene influence. Results shows that the

398

reference cement paste has the lowest value. As presented in Fig.14, water vapor permeability

399

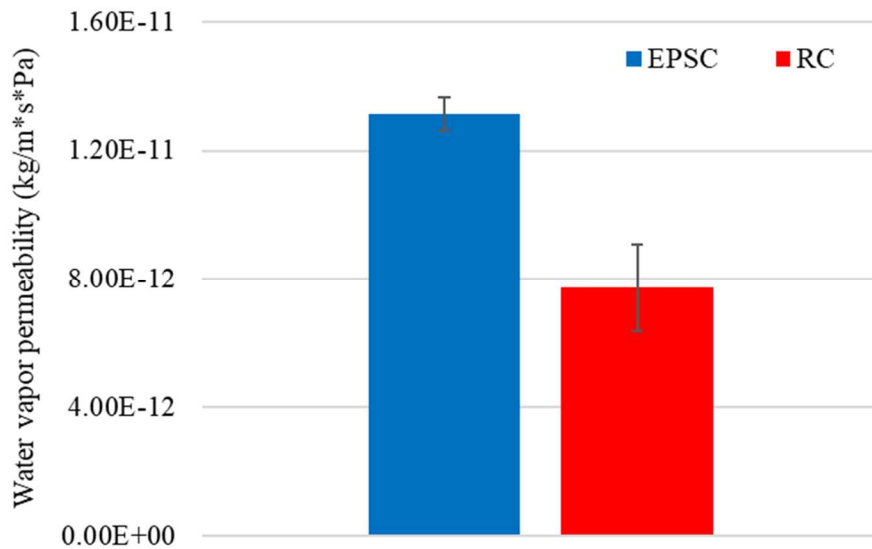
of cement paste is  $7.72 \cdot 10^{-12}$  kg/m.s.Pa while it reaches  $1.32 \cdot 10^{-11}$  kg/m.s.Pa for polystyrene

400

concrete. This results from the expanded polystyrene beads incorporation, which causes air

401

inclusion appearance in the cement matrix.



402

403

Fig.14. Water vapor permeability of EPSC and RC with wet cup method

404

The vapor permeability was also measured for the expanded polystyrene mortar in two different ambient conditions (wet and dry cup), as shown in Fig.15. Results show an increase in water vapor permeability with increasing humidity, as it was proven for other lightweight materials [44, 45]. This is due to moisture transfer kinetics that are driven mainly by diffusion at low relative humidity. However, at a higher hygrometry, evaporation and condensation phenomena also happen, leading to a higher water vapor transmission.

410

At low humidity, water vapor permeability of polystyrene mortar is  $3.22 \cdot 10^{-12}$  kg/m.s.Pa, and increase by nearly 300% since it reaches  $1.32 \cdot 10^{-11}$  kg/m.s.Pa in high hygrometry. The results show that polystyrene mortar does not transmit a significant water vapor flow. In fact, they present lower values in comparison with the measured values of other lightweight materials such as hemp concrete [27], plastic based concrete [46] and aerated concrete [47]. The moderate water vapor permeability value of expanded polystyrene mortar indicates a good durability over time. Indeed, increasing water vapor infiltration in building walls causes capillary condensation and liquid water flow. This would cause mold appearance and degradation of interior air quality, thus altering buildings durability.

418

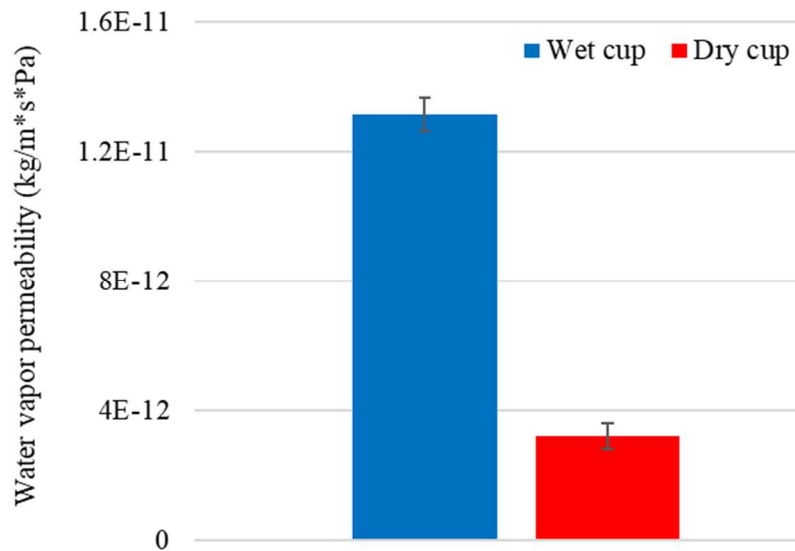


Fig.15. Water vapor permeability of expanded polystyrene mortar

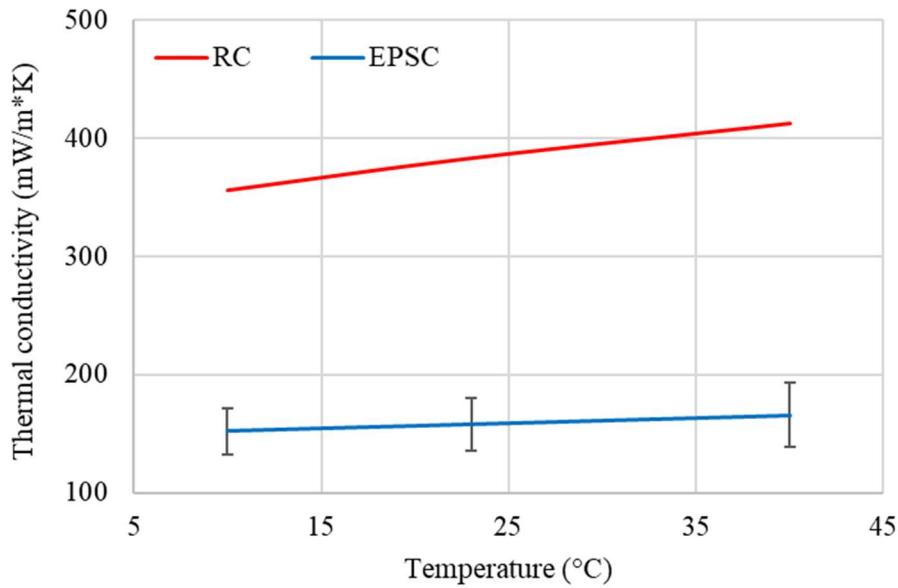
### 3.5. Thermal conductivity

Thermal conductivity of the polystyrene mortar and the reference cement paste is measured for three different temperatures: 10, 23 and 40°C. Its evolution depending on temperature variations is linear, and is described by an empirical equation explicated in (3).

$$\lambda = 0,2876.T + 135,19 \quad (3)$$

Results are presented in Fig.16. As expected, thermal conductivity increases linearly with temperature, agreeing with results in literature [48]. In the case of the expanded polystyrene mortar, the total increase in thermal conductivity from 10°C to 40°C is not significant since it is very low. This is due to the insulating nature of the expanded polystyrene beads whose thermal conductivity increases very little as the temperature increases [49]. On the other hand, cement paste presents a higher increase in function of the temperature, as it raises for 20%.



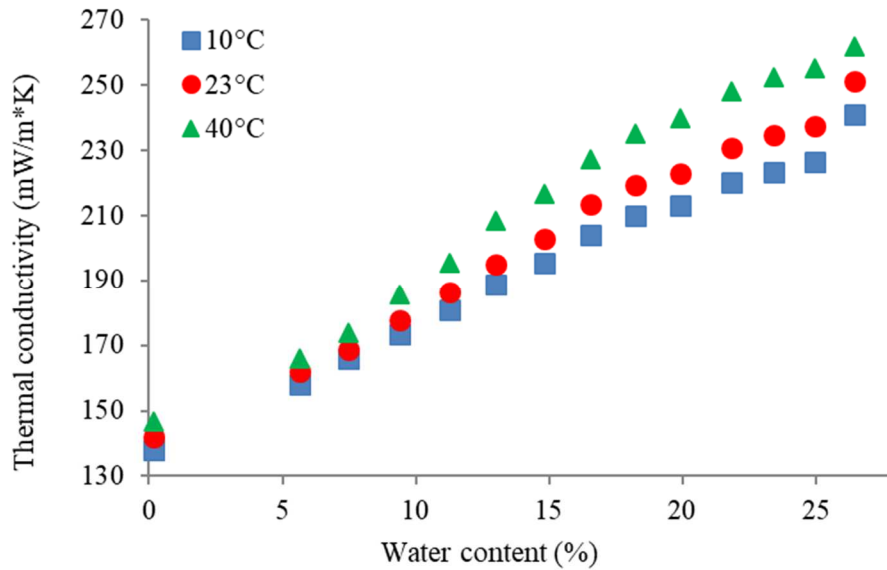


432

433 Fig.16. Thermal conductivity of expanded polystyrene mortar and reference cement paste

434 Measured thermal conductivity of the reference cement paste is much higher, since it reaches  
 435 383 mW/m.K at 23°C compared to only 157 mW/m.K for polystyrene mortar. This represents  
 436 an increase of 143% at 23°C, and can go up to 150% increase at 40°C. This important difference  
 437 is due to the expanded polystyrene beads that are characterized by a low thermal conductivity  
 438 around 30 – 40 mW/m.K [50]. Results are in good agreement with literature, when comparing  
 439 to polystyrene-based materials with rather same densities [22,51]. In some works, thermal  
 440 conductivity of almost similar materials than ours is higher with lower mechanical performance  
 441 [23].

442 The thermal conductivity of the expanded polystyrene mortar reflects good thermal insulation  
 443 properties. The obtained results are lower than those obtained for cork-based concretes [52],  
 444 but are still higher than that of other materials such as cork-gypsum composites, which are both  
 445 lightweight aggregates [53], and hemp concrete because of its double porosity [54].



446

447

Fig.17. Thermal conductivity function of water content of polystyrene mortar

448

Thermal conductivity is also determined as a function of the water content of the polystyrene

449

mortar for the three temperatures, and the results are shown in Fig.17. For all three temperatures,

450

thermal conductivity raises with increasing water content. At 23°C, it goes from 142 mW/m.K

451

for a dry sample to 251 mW/m.K at saturation. In all, thermal conductivity presents an increase

452

between the dry and saturated state around 74 – 78 %. These values are lower than the ones

453

usually obtained for lightweight materials, such as hemp concrete whose thermal conductivity

454

increases by 120% [27] or a palm fibers mortar that shows an increase of 200% [55]. This

455

results mostly from the saturation water content value, which is lower for polystyrene mortar

456

due to its low-hygroscopic nature.

457

In general, the air content in a porous material decreases with increasing water content. Thermal

458

conductivity of water is much higher than air ( $\lambda_{\text{water}} = 600 \text{ mW/m.K}$  and  $\lambda_{\text{air}} = 25 \text{ mW/m.K}$  at

459

25°C), consequently thermal conductivity would increase with water content.

460

### 3.6. Specific heat capacity

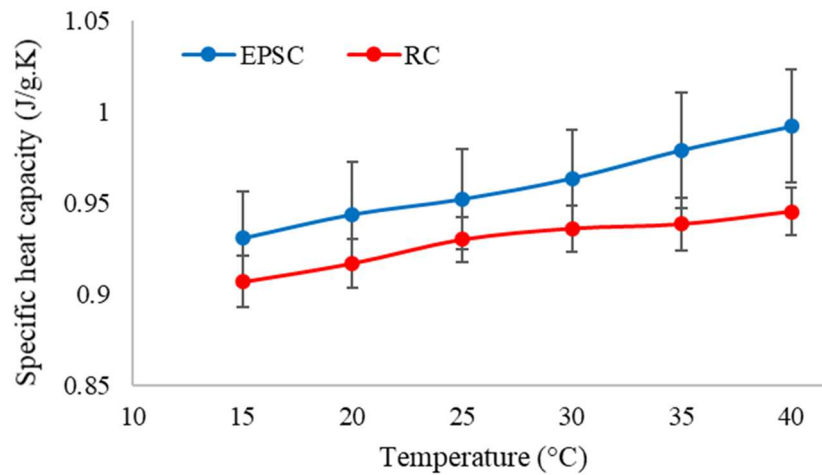
461

Specific heat capacity evolution of polystyrene mortar and reference cement paste is presented

462

in Fig.18, as a function of temperature. For expanded polystyrene mortar, specific heat varies

463 between 0.93 J/g.K and 1 J/g.K, and results show an increase of 6,5% between 15°C and 40°C.  
464 This proves a reasonable heat storage capacity of the material, but still lower than that of plant-  
465 based materials [27] and very lightweight materials [53].



466

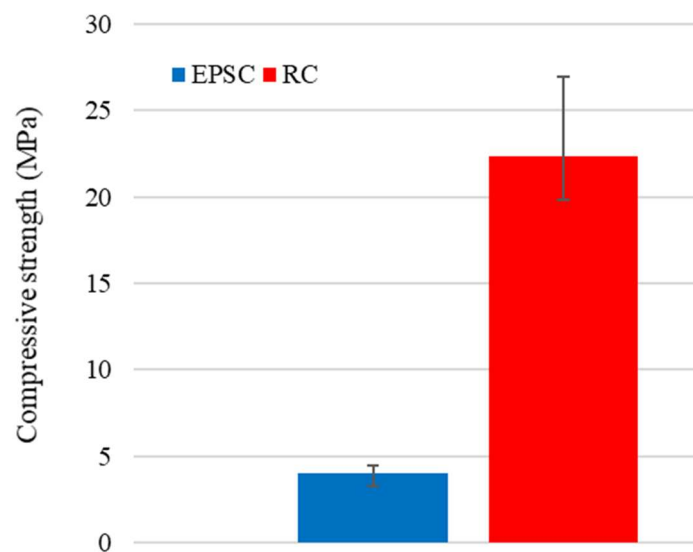
467 Fig.18. Specific heat of polystyrene mortar and cement paste

468 Specific heat capacity of the reference cement paste also increases with temperature, and varies  
469 between 0.89 J/g.K at 15°C, and 0.94 J/g.K at 40°C. The increase corresponds to 5%, thus less  
470 than that displayed by polystyrene mortar. The addition of expanded polystyrene beads  
471 therefore gives the cement-based material a better heat storage capacity, since the specific heat  
472 capacity increases by 5% over the temperature variations. Indeed, specific heat capacity of  
473 expanded polystyrene varies from 1.2 J/g.K to 1.45 J/g.K [56], and its addition improves heat  
474 storage capacity following up on the general rule of mixtures.

### 475 3.7. Compressive strength

476 Compressive strengths of expanded polystyrene mortar and cement paste are presented in  
477 Fig.19. As expected, expanded polystyrene incorporation highly alters mechanical  
478 performances of the cement paste. Indeed, compressive strength decreases from 22.5 MPa for  
479 the reference cement paste to only 4 MPa for the polystyrene mortar, which corresponds to 80%  
480 decrease. The values obtained for polystyrene mortar are in good agreement with literature, for

481 cement-based materials with approximately the same volume ratio of incorporated expanded  
482 polystyrene [18, 21, 23]. This can be explained mainly by the nature and low compressive  
483 strength of the polystyrene beads incorporated in the cementitious matrix, which weakens the  
484 mechanical behavior of the mixture. As a result, the compressive strength of the polystyrene  
485 mortar decreases despite the good adhesion of the polystyrene beads with the cementitious  
486 matrix.



487

488 Fig.19. Compressive strength of polystyrene mortar and cement paste

#### 489 4. CONCLUSION

490 In this work, we presented a full hygrothermal characterization of a recycled expanded  
491 polystyrene mortar, as well as a reference cement paste to assess the influence of the addition  
492 of expanded polystyrene beads. Polystyrene mortar is a relatively new material including the  
493 use of recycled expanded polystyrene waste. Its hygrothermal and physical properties are not  
494 widely dealt with in the literature. This work therefore provides results that will extend the  
495 databases and complete knowledge of the intrinsic properties of this kind of lightweight  
496 materials. The experimental campaign began with the determination of main and intermediate  
497 water vapor sorption isotherms, followed by moisture storage capacity and moisture buffer

498 value. Afterwards, water vapor permeability coefficient was determined, along with thermal  
499 conductivity and at last, specific heat capacity.

500 The main water vapor adsorption and desorption isotherm curves exhibit a hysteresis  
501 phenomenon, which is characteristic of cement-based materials. The curves show that the  
502 polystyrene mortar is a low-hygroscopic material, and the saturation water content only reaches  
503 0,8kg/kg because of its low porosity and hydrophobic nature of expanded polystyrene beads.  
504 These curves constitute an envelope to the intermediate curves, which correspond to the path  
505 followed by the water content when the material undergoes several wetting and drying cycles,  
506 as it is the case for buildings. As the cycles go, the gap between the intermediate curves narrows  
507 until the curves overlap.

508 The water vapor sorption isotherm curves allow determining the moisture storage capacity of  
509 the polystyrene concrete. It depends on the ambience hygrometry and is different whether it is  
510 an adsorption or desorption phase. Results show a significant increase above 80% of relative  
511 humidity, due to capillary condensation phenomena. The moisture buffer capacity of the  
512 polystyrene mortar was also determined, exhibiting the moderate ability of the material to  
513 regulate the relative humidity variations. This is due to the hydrophobic nature of expanded  
514 polystyrene and the low adsorption of the material, but it still has a higher moisture buffer  
515 capacity than regular concrete.

516 In continuity of hygric characterization, the water vapor permeability coefficient was measured.  
517 Results demonstrate a good resistance of polystyrene mortar to water vapor transmission, in  
518 comparison to other lightweight materials in the literature. This property is highly influenced  
519 by relative humidity conditions, and the water vapor permeability increases with increasing  
520 hygrometry. Despite the closed porosity of expanded polystyrene beads, their incorporation in  
521 cement-based materials causes a higher water vapor permeability, because of the air bubbles  
522 that result from their adding.

523 Regarding the thermal properties, thermal conductivity was measured for both materials at three  
524 different temperatures, and showed a linear evolution. As expected, expanded polystyrene  
525 adding improves thermal insulation of the material, and polystyrene mortar has an excellent  
526 thermal conductivity. Polystyrene has a very low thermal conductivity, therefore, polystyrene  
527 mortar is a great thermal insulation material. Thermal conductivity also depends on the relative  
528 humidity, and results demonstrate an increasing thermal conductivity proportionally to water  
529 content of the material.

530 At last, specific heat capacity was also determined for polystyrene mortar and the reference  
531 cement paste. Expanded polystyrene beads confer a higher specific heat capacity to the mortar,  
532 exhibiting then a better heat storage ability. Polystyrene mortar is characterized with a rather  
533 good specific heat capacity in comparison with usual concrete, but still lower than that of plant-  
534 based materials.

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539 2015-2020 » and Energy saving certificate program of the French Ministry of Ecological and  
540 Solidarity Transition "SmartReno Support" 2019-2021.

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