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

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HIGHLIGHTS

- Hygrothermal and mechanical properties of a recycled expanded polystyrene-based material have been assessed;
- Sorption isotherm curves of expanded polystyrene mortar exhibit hysteresis phenomenon and show a low water vapor adsorption;
- Thermal conductivity and specific heat capacity are highly dependent of temperature and water content;
- Water vapor permeability coefficient increases with polystyrene incorporation because of air 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.

KEY WORDS

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

1. INTRODUCTION

The world is facing major energy and environment problems, especially as buildings are the main energy consumers. Reducing the building related energy consumption and promoting the use of low environmental impact materials are measures to be taken in order to avoid overexploitation of natural resources and available energy sources. The construction and operation of buildings is responsible for the consumption of 33% of the world's total energy use [1], and it is actually the most important confront in the construction sector. Moreover, buildings-related CO₂ emissions reached an all-time high of 10 Gt CO₂ in 2019 [2,3], which accounts for nearly 57% in the total carbon dioxide emissions [4].

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

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

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

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

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

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

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

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

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

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

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

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

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

2. MATERIALS AND METHODS

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

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



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

Table 1. Composition of the polystyrene mortar

Materials	Volume ratio
Cement	30%
Polystyrene beads	53%
Water	17%

After the manufacturing, the samples are put into molds of the following dimensions: 15x15x5 cm, 4x4x16 cm and $\phi 11 \times 22$ cm. They are de-moulded after 24 hours then stored in a climatic chamber with controlled temperature and relative humidity ($T = 20^{\circ}\text{C}$ and $\text{HR} = 50\%$). The experimental campaign begins 3 months later, and included the determination of the water vapor sorption isotherms, moisture storage capacity, sorption hysteresis loops, moisture buffer value, water vapor permeability, thermal conductivity and specific heat capacity. Compressive

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

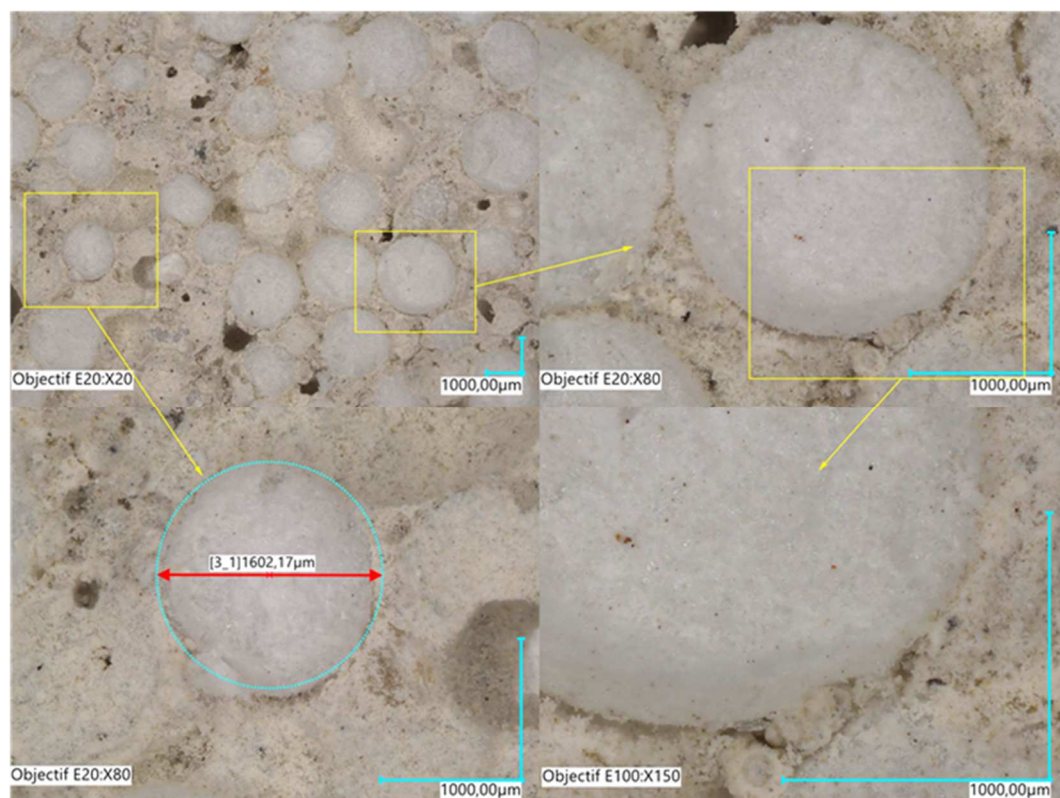


Fig.2. Digital microscope observations of the surface of polystyrene mortar

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

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

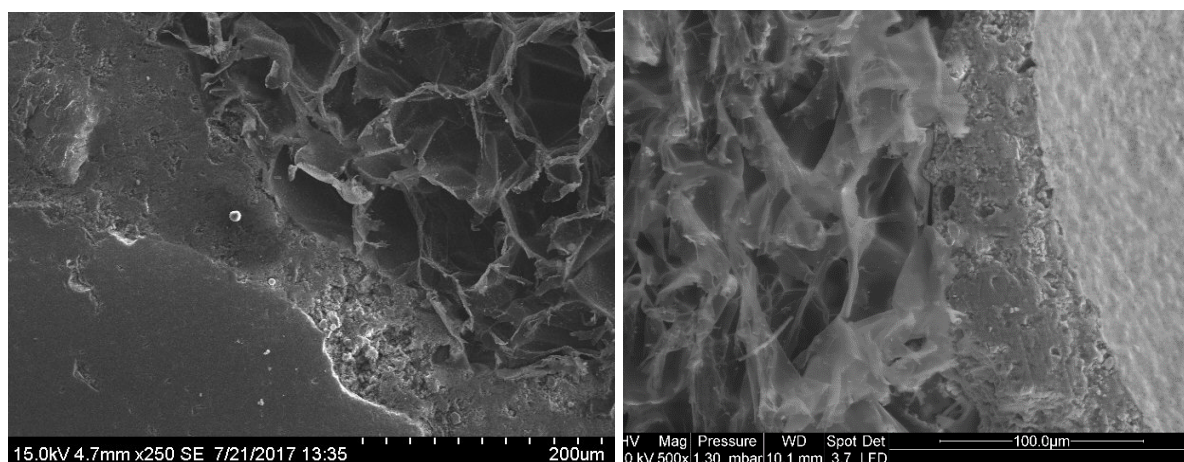


Fig.3. SEM images of the cement/polystyrene interface

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

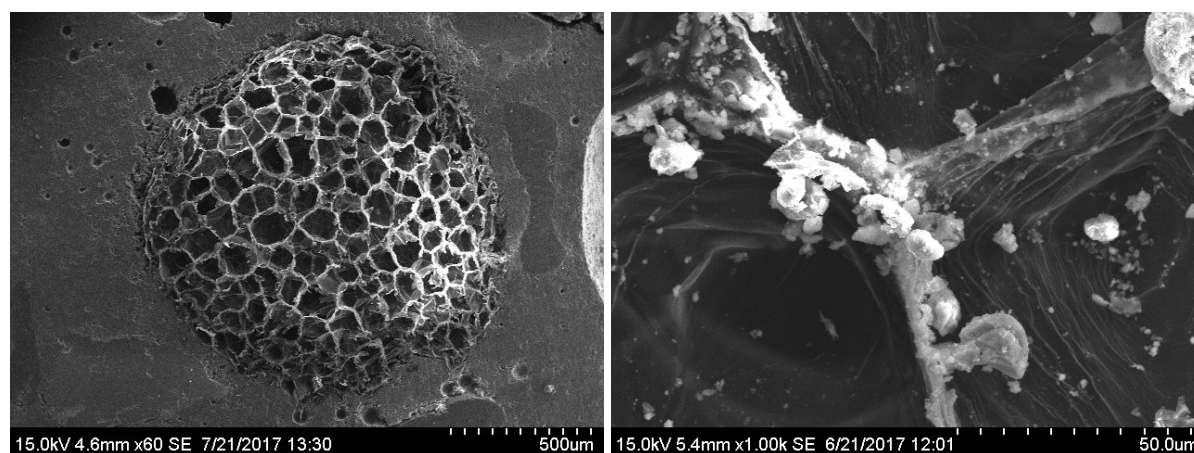


Fig.4. SEM images of a polystyrene bead

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

2.1. Main adsorption and desorption curves

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

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

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

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

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

2.2. Intermediate sorption isotherms

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

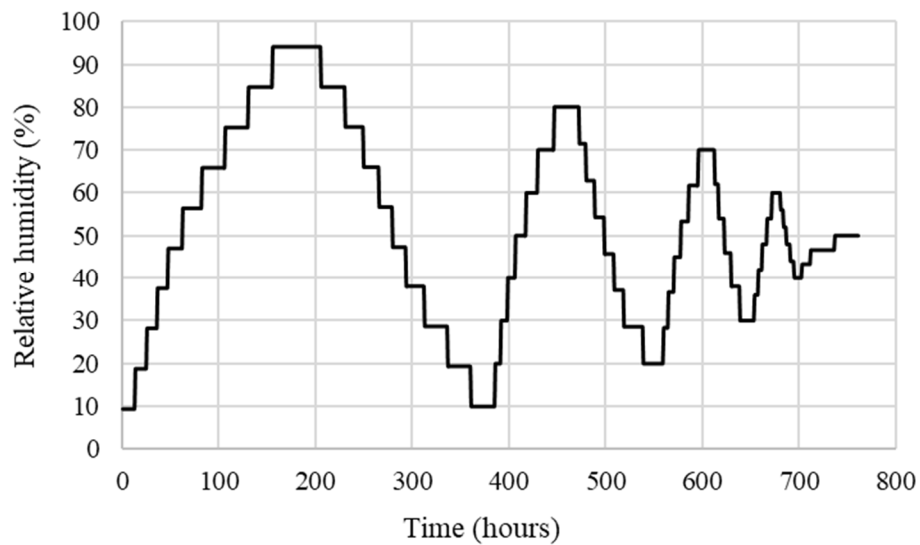


Fig.5. Relative humidity levels for intermediate sorption curves measurements

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

2.3. Moisture Buffer Value (MBV)

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

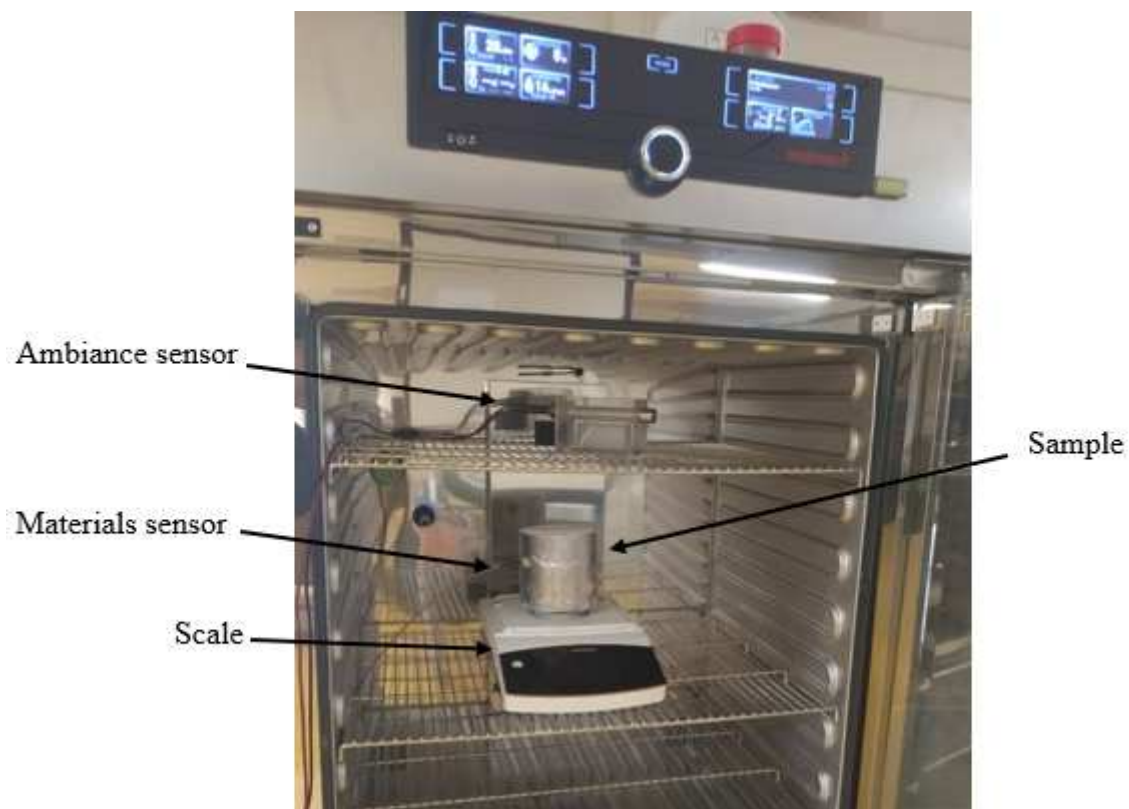


Fig.6. Experimental setup for the MBV measurements

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

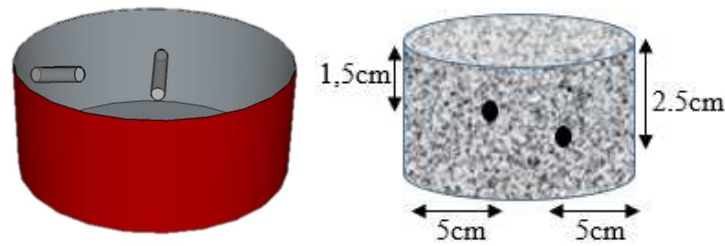


Fig.7. Hygrothermal sensors setup inside samples

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

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

2.4. Water vapor permeability

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

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

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

2.5. Thermal conductivity

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

2.6. Specific heat capacity

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

2.7. Compressive strength

Compressive strength of expanded polystyrene mortar helps define its application in buildings. In this work, compressive strength was determined following the standards NF EN 13892-2. Samples used were the 4x4x16cm³ after 28 days on fabrication, and test were carried out on three samples at a loading rate of 2,4kN/s.

3. RESULTS AND DISCUSSION

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

3.1. Main adsorption/desorption curves

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

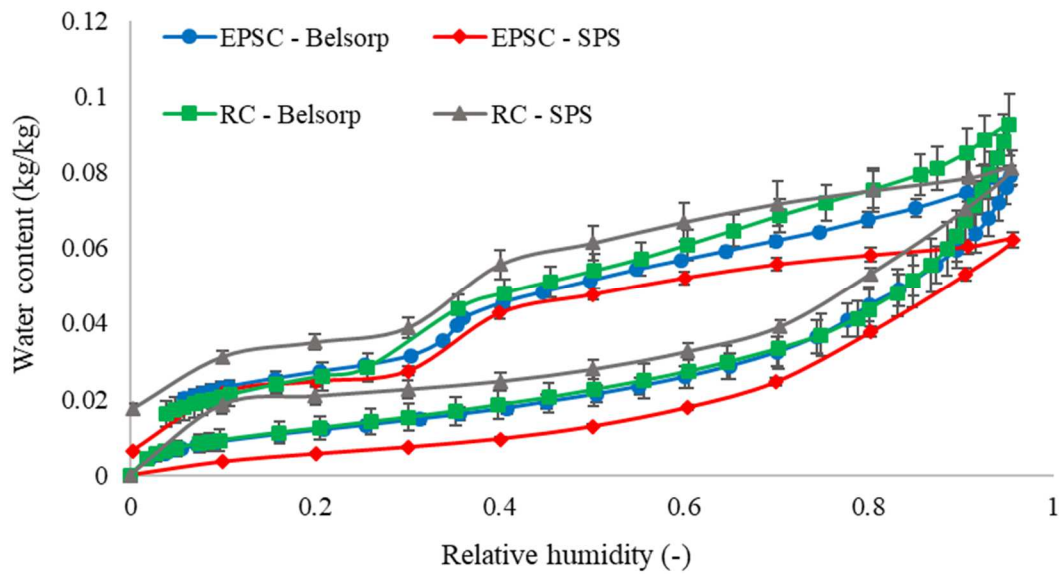


Fig.8. Water vapor sorption isotherms for EPSC and RC

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.

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

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

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

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

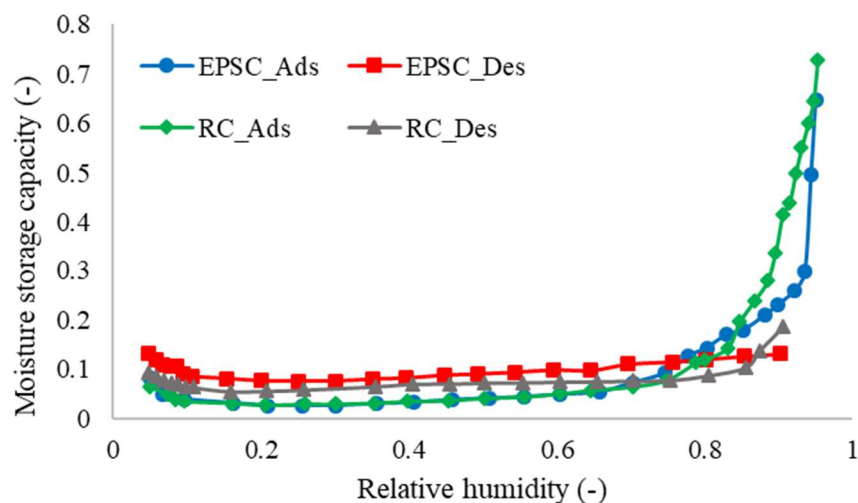


Fig.9. Moisture storage capacity for expanded EPSC and RC

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

3.2. Intermediate adsorption/desorption curves

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

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

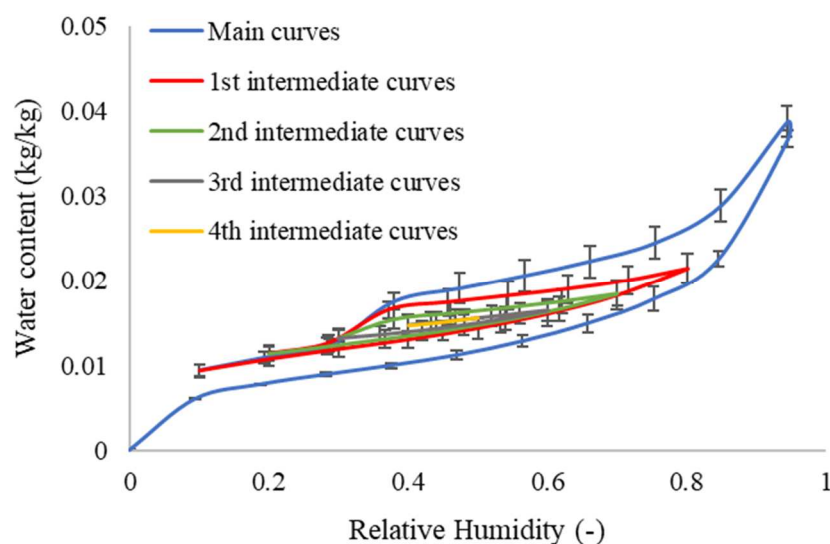


Fig.10. Main and intermediate adsorption/desorption isotherm curves of EPSC

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

3.3. Moisture Buffer Value

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

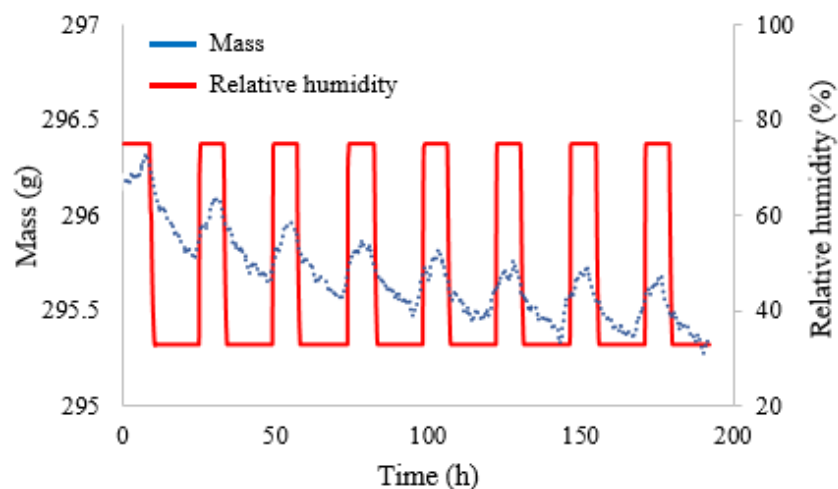


Fig.11. Mass evolution of expanded polystyrene mortar during MBV test

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

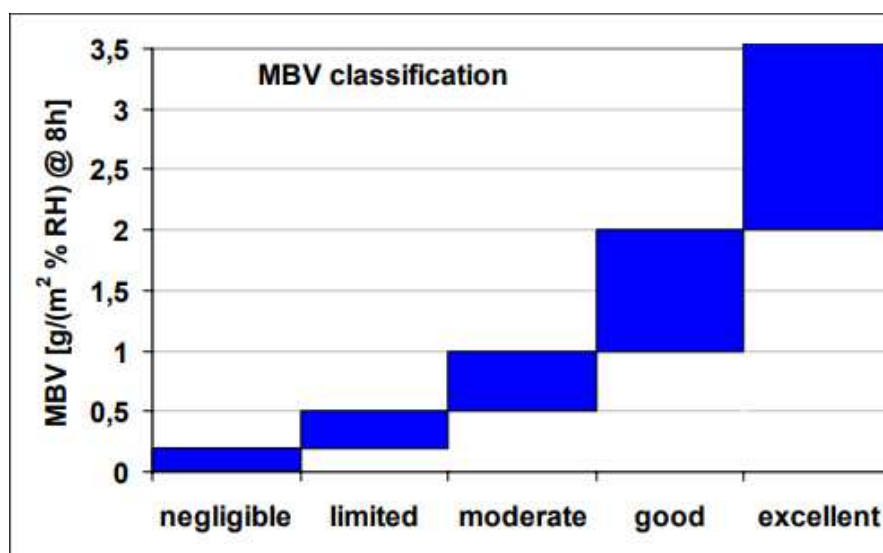


Fig.12. Moisture buffer value classification [36]

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

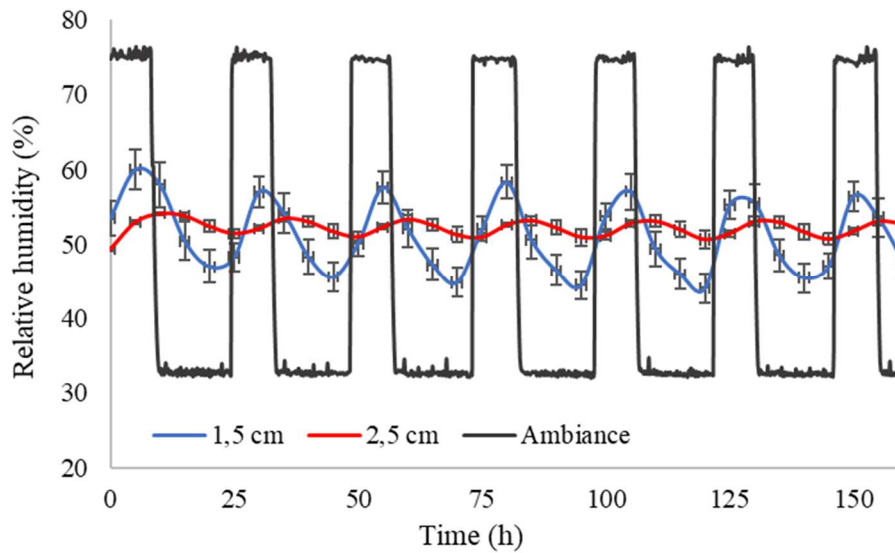


Fig.13. Relative humidity evolution inside samples

During the test, relative humidity variation at two depths in the samples and in the ambiance were also recorded, and are shown in Fig.13. Relative humidity inside the samples follows the same variations of the ambient air, with a little phase shift over the last three cycles. At the position of 2.5 cm inside the sample, relative humidity is only slightly affected by external variations. In the case of unidirectional transfer, the mass transfer kinetics are inversely proportional to the depth of the material, which explains why the relative humidity variations at 1.5 cm position are higher than those at 2.5 cm.

3.4. Water vapor permeability

Water vapor permeability was measured for both expanded polystyrene mortar and the reference cement paste, in order to evaluate the polystyrene influence. Results shows that the reference cement paste has the lowest value. As presented in Fig.14, water vapor permeability 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 concrete. This results from the expanded polystyrene beads incorporation, which causes air inclusion appearance in the cement matrix.

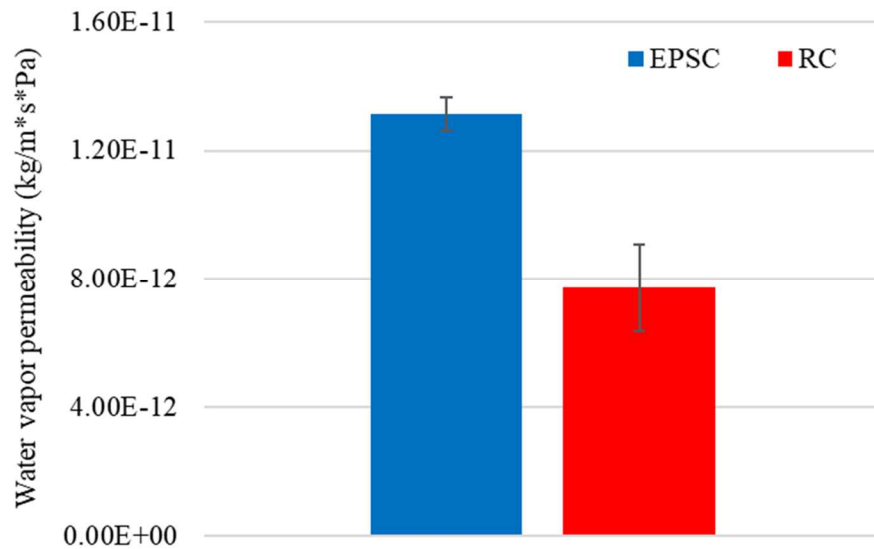


Fig.14. Water vapor permeability of EPSC and RC with wet cup method

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.

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.

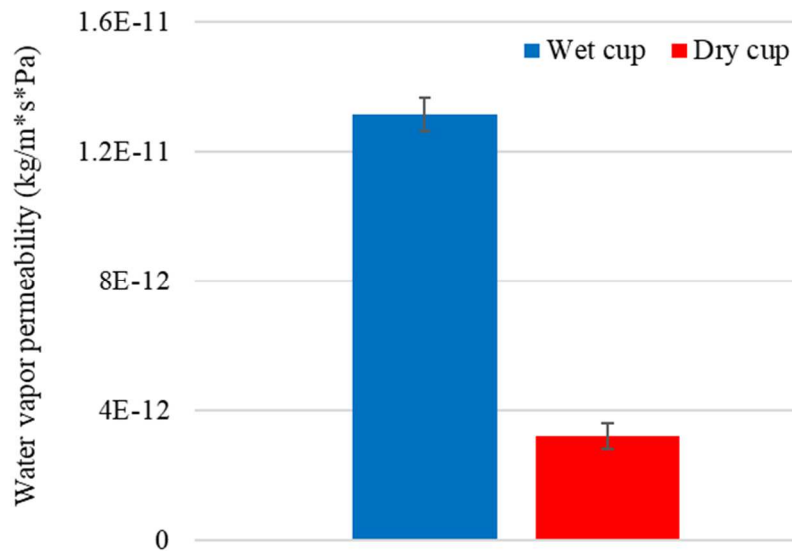


Fig.15. Water vapor permeability of expanded polystyrene mortar

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%.

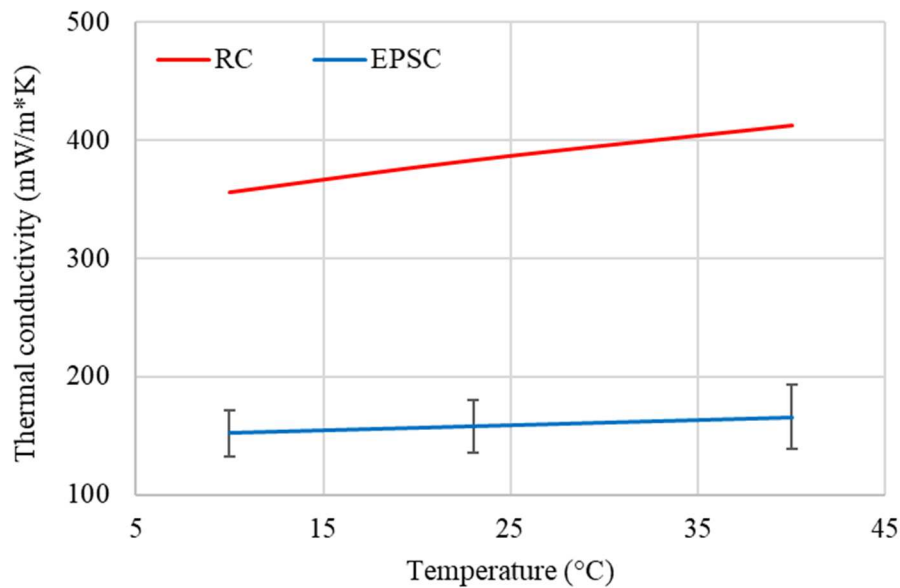


Fig.16. Thermal conductivity of expanded polystyrene mortar and reference cement paste

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

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

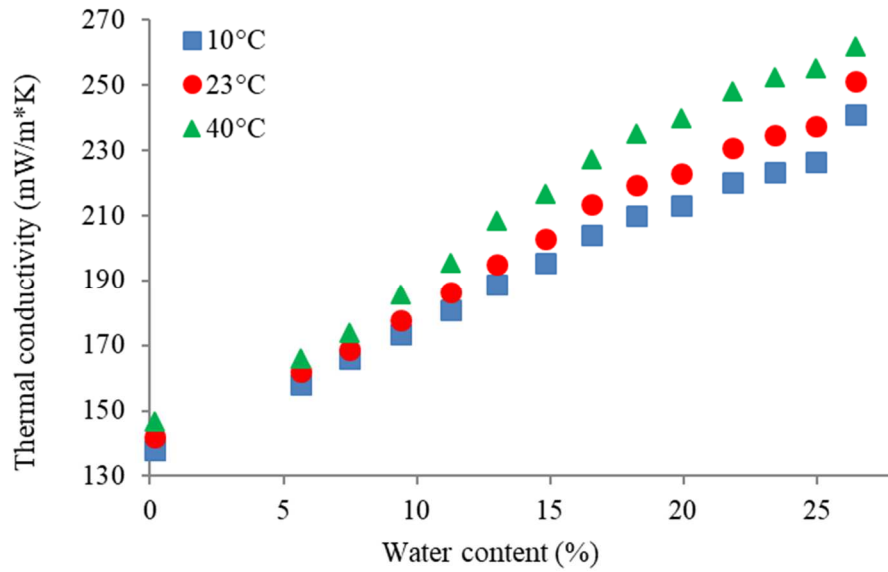


Fig.17. Thermal conductivity function of water content of polystyrene mortar

Thermal conductivity is also determined as a function of the water content of the polystyrene mortar for the three temperatures, and the results are shown in Fig.17. For all three temperatures, thermal conductivity raises with increasing water content. At 23°C, it goes from 142 mW/m.K for a dry sample to 251 mW/m.K at saturation. In all, thermal conductivity presents an increase between the dry and saturated state around 74 – 78 %. These values are lower than the ones usually obtained for lightweight materials, such as hemp concrete whose thermal conductivity increases by 120% [27] or a palm fibers mortar that shows an increase of 200% [55]. This results mostly from the saturation water content value, which is lower for polystyrene mortar due to its low-hygroscopic nature.

In general, the air content in a porous material decreases with increasing water content. Thermal 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 25°C), consequently thermal conductivity would increase with water content.

3.6. Specific heat capacity

Specific heat capacity evolution of polystyrene mortar and reference cement paste is presented in Fig.18, as a function of temperature. For expanded polystyrene mortar, specific heat varies

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. This proves a reasonable heat storage capacity of the material, but still lower than that of plant-based materials [27] and very lightweight materials [53].

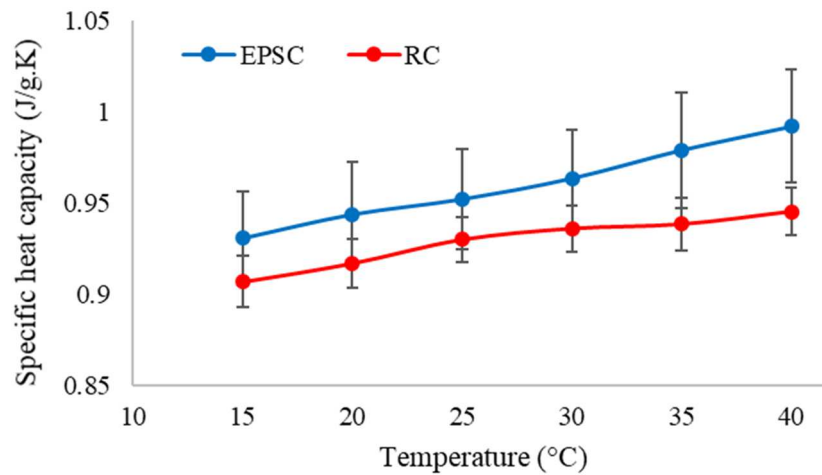


Fig.18. Specific heat of polystyrene mortar and cement paste

Specific heat capacity of the reference cement paste also increases with temperature, and varies 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 than that displayed by polystyrene mortar. The addition of expanded polystyrene beads therefore gives the cement-based material a better heat storage capacity, since the specific heat capacity increases by 5% over the temperature variations. Indeed, specific heat capacity of expanded polystyrene varies from 1.2 J/g.K to 1.45 J/g.K [56], and its addition improves heat storage capacity following up on the general rule of mixtures.

3.7. Compressive strength

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

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

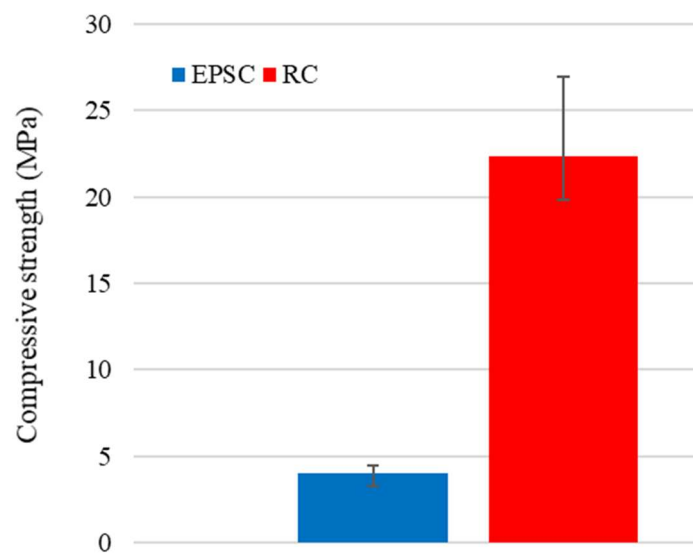


Fig.19. Compressive strength of polystyrene mortar and cement paste

4. CONCLUSION

In this work, we presented a full hygrothermal characterization of a recycled expanded polystyrene mortar, as well as a reference cement paste to assess the influence of the addition of expanded polystyrene beads. Polystyrene mortar is a relatively new material including the use of recycled expanded polystyrene waste. Its hygrothermal and physical properties are not widely dealt with in the literature. This work therefore provides results that will extend the databases and complete knowledge of the intrinsic properties of this kind of lightweight materials. The experimental campaign began with the determination of main and intermediate 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.

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

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

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