Development and characterization of thermal insulation materials based on rice straw and natural binder

Yaping Zhou [a], *Abdelkrim* Trabelsi[b], *Mohamed* El Mankibi [c].

[a] Univ Lyon, LTDS, ENTPE, UMR5513, 69120 Vaulx-en-Velin, France, yaping.zhou@entpe.fr.

[b] Univ Lyon, UCBL, INSA Lyon, CNRS, CETHIL, UMR5008, 69622 Villeurbanne, France, abdelkrim.trabelsi@univ-lyon1.fr.

[c] Univ Lyon, LTDS, ENTPE, UMR5513, 69120 Vaulx-en-Velin, France, mohamed.elmankibi@entpe.fr.

Abstract. Thermal insulation is an essential factor to reduce energy demand during the stage of building operation. Nowadays, thermal insulation materials are however commonly produced from petrochemicals, causing high energy consumption and detrimental environment impact during production and arising the reuse and recycle issues. Insulation materials derived from local agricultural straws are becoming more attractive due to their availability, cost effectiveness, sustainability and low carbon footprint. Rice straw has the advantage of low density and low thermal conductivity due to its hollow internal structure. Also, the utilization of rice straw in buildings prevents the negative environmental impact of burning straw or mixing them with soil. The aim of this study is to develop an innovative composite insulation material from rice straw. A biobased binder, i.e., sodium alginate, derived from brown algae is used as binder. A modified method is developed to solve the water solubility issue of the composite material. The final product is rigid, lightweight and fully eco-friendly. The effect of fiber size and binder ratio (i.e., 8%, 16% and 24%) on the density, thermal conductivity and water vapor permeability are studied. The composite materials are insulating with thermal conductivity values in the range of 0.039-0.045 W/(m·K) for an average density in the range of 100 to 200 kg/m^3.

Keywords. Rice straw, sodium alginate, insulation material, water solubility, thermal conductivity.
DOI: https://doi.org/10.34641/clima.2022.332

1. Introduction

Nowadays, green buildings are increasing in demand to meet higher and more complex standards on energy efficiency, sustainability and comfort. To achieve this objective, an effective strategy is enhancing the insulation properties of the building envelop as well as using environment friendly materials in their lifetime. In this context, there is an increasing interest in production of thermal insulators from agricultural straw wastes. Agricultural straws (e.g., wheat, rice, barley, oats and rape straws) are available locally in any country in huge amounts [1]. They also exhibit the advantage of low density and low thermal conductivity due to its hollow internal structure [2].

A large quantity of 3.9 million tons rice straw is produced each year in Europe [3] . Burning straw in the field is one of the oldest practices in Europe and worldwide. It has negative effects, such as the greenhouse gases emission, pollution and toxicity to human health, which is banned in EU countries according EC regulation 1259/1999. Mixing rice straw with soil is another management option. This approach generates methane during the straw's anaerobic decomposition, leading to a higher global warming potential compared to burning straw [4]. Application of rice straw waste in building insulation material is a cost-effective alternative to solve these issues. Zhao et al [5] reported that agricultural straw waste insulation material has a life cycle cost of 150 RMB/m^2 for 25 years span, which is lower than the municipal solid waste, industrial solid waste and traditional insulation materials (e.g., XPS, EPS, rock wool and glass wool).

Nowadays, straw composites are produced by bonding straw fibers with inorganic cementing materials [6, 7] and organic resins [8]. These binders, however, can increase the embodied energy and prevent the degradability of the final insulation products. The use of natural binders, e.g., starch, alginate and chitosan, can be an alternative to solve this issue. Mati-Baouche et al. [9] have developed biobased insulating composites from sunflower's stalk particles and chitosan with thermal conductivity values of 0.056-0.058 W/(m·K) for density of 150-200 kg/m^3. Lacostea et al. [10] have developed wood fibers/recycled cotton fibers composites using sodium alginate as binder. The thermal conductivity values were ranging from 0.078 W/(m·K) to 0.089 W/(m·K) for density of 308-333 kg/m^3. Palumbo et al. [11] have developed insulation panels from three crop wastes, i.e., barley straw, corn pith and rice husk and three binders, i.e., corn starch, sodium alginate and casein. The results showed that the alginate-based composites had lower densities and thus presented lower thermal conductivity values. The lowest thermal conductivity of 0.052 W/(m·K) was obtained for the composite from corn pith and alginate with the density of 80 kg/m^3.

Sodium alginate is a natural polysaccharide which is derived mainly from brown seaweeds. It can dissolve in water and then form a gel at room temperature without a heating and cooling cycle. The properties of sodium alginate such as being nontoxic, adhesive, biocompatible, biodegradable with low cost make it appealing as a binder for biobased materials. But it should be noted that composites with sodium alginate as binder can have poor water resistance, and even be destroyed when they are contacted with water due to the solubility of sodium alginate in water. Water-insoluble property can be developed by adding multivalent cation [12].

The aim of this study is to develop a lightweight insulating composite from rice straw and sodium alginate. A modified procedure is developed to prepare insoluble alginate-based composite through inducing cross-link with ionic calcium. The effect of fiber size and binder ratio on the physical, thermal conductivity and water vapor permeability of the composites are also investigated.

2. Materials and methods

2.1 Raw Material

Two types of rice straw fibers i.e., RS1 and RS2 were provided by FBT isolation (Dagneux, France). The fiber size distribution of RS1 and RS2 was investigated by mechanical sieving [13]. First, a sample of 60 g rice straw fibers was manually homogenized and divided into four similar parts by a non-cutting blade. Then the three samples (approximately 15 g) were separated by applying a series of sieves (i.e., 0.5, 1, 2, 4, 8, 16, 32 mm). The mechanical sieving was done by a mechanical sieve shaker for 30 minutes. The mass fraction retained on each sieve was obtained by weighing each sieve with and without fibers.

Fig. 1 compares the fiber size distribution of the RS1 and RS2. Both the RS1 and RS2 contains the fibers between 0 and 32 mm. It could be clearly seen that the RS1 contained more fibers below 2 mm.

A commercial sodium alginate, purchased from Algaia™ under the trademark Algogel® 6021, was used to bind straw fibers in this study. It is composed of a fine water-soluble powder (<200 μm). It has a viscosity of 150-300 cps and a pH of 6-8.5 in a 1% aqueous solution. Calcium sulphate ($CaSO_4$), calcium chloride ($CaCl_2$) and sodium citrate were purchased from Glentham Life Sciences (UK).

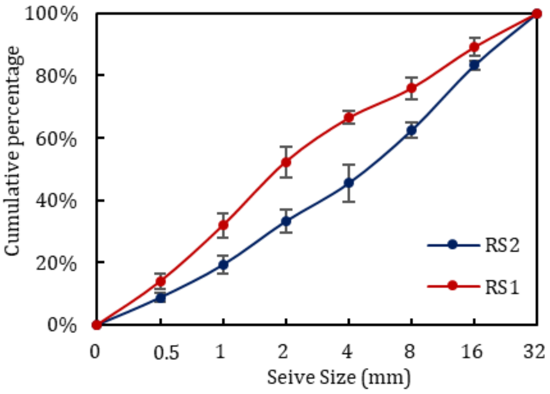

Fig. 1 – Fiber size distribution of RS1 and RS2

2.2 Sample preparation

The sodium alginate solution was firstly prepared by slowly adding sodium alginate power to distilled water under continuous stirring at 250 rpm for 30 min. The fibers were then mixed with the sodium alginate solution by using a force-action rotary paddle at 20 rpm for 2 min. The mixture was put into a polystyrene mold of dimensions 30×30×4 cm^3 and compacted using a weight of 10kg for 4 hours. Note that the aforementioned steps were done at ambient condition. The whole was then placed in an oven at 50 °C for 48 hours to accelerate the drying process. This method is referred as M0 to distinguish with other two modified procedures.

Modified procedures were prepared based on two different methods of calcium ion cross-linking [10, 14]. In the first modified method (M1), a content of 83 wt.% sodium alginate, 15 wt.% CaSO4 and 2 wt.% sodium citrates instead of pure sodium alginate for M0 was dissolved in distilled water to prepared the binder solution. In the second modified method (M2), the composite samples obtained from M0 was immersed in $CaCl_2$ solution at concentration of 4% (m/v) for 5 min. The process for obtaining bio-based composites from rice straw fibers and sodium alginate is shown in Fig. 2. After the immersion, the samples were drained for 10 min and then further oven-dried. In addition, different binder ratio (e.g., 0.08, 0.16 and 0.24) was investigated. Table 1 shows the different formulations.

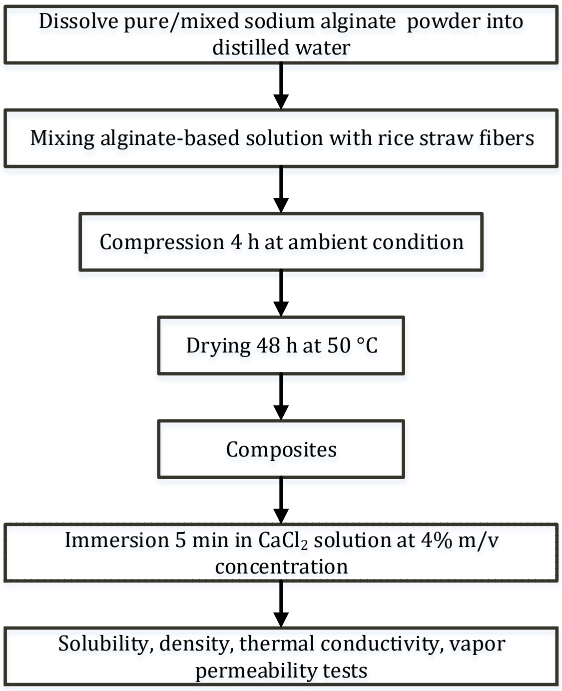

Fig. 2 – Manufacture process of composite samples from rice straw fibers and sodium alginate

Tab. 1 – Board formulation

Sample	Modification method	Straw type	Binder/straw ratio
1	M0	RS2	0.16
2	M1	RS2	0.16
3	M2	RS1	0.08
4	M2	RS1	0.16
5	M2	RS1	0.24
6	M2	RS2	0.08
7	M2	RS2	0.16
8	M2	RS2	0.24

3. Methods for materials characterization

3.1 Density

Three composite samples for each formulation with dimensions of 10×10×d cm^3 were used for density measurements. First, the samples were dried in an oven at 50 °C until a constant weight and then the volume was calculated after measuring the size by a vernier caliper. Density was determined by the gravimetric method that relates the mass and the volume of the composite samples.

3.2 Thermal conductivity

Thermal conductivity was measured by a hot wire apparatus. This technique allows for a quick measurement on small samples. First, the samples were dried in an oven at 50 ºC until a constant weight and then the samples were placed in desiccator to decrease their temperature to ambient temperature. Three pairs of samples (i.e., 1&2, 1&3, 2&3) with dimensions of 10×10×4 cm^3 were measured for each formulation.

3.3 Water vapor permeability

Water vapor permeability was measured by wet cup according to EN12572:2001 [15]. Prior to measurement, the composite samples were stored at 23±5ºC and 50±5% RH for a period long enough for their weight to stabilize (the difference in mass between the two measurements within 24 h is less than 5%). A thin layer of silicone was then applied to seal the samples on Plexiglas cups containing a saturated aqueous solution of potassium sulphate (97% RH). A vapor-tight aluminum tape was used to seal the sides of the sample with the side of the cup. The air layer, i.e., the space between the salt solution and the bottom of the composite sample was set to 20 mm. The whole cup was then put in a box containing a saturated aqueous solution of magnesium nitrate (53% RH). The box was placed in a room with temperature controlled at 20 ºC. The whole cup was weighed periodically until the change of the mass was constant (five successive determinations of change in mass within 24 h intervals is less than 5%).

Due to the partial water vapor pressure between the interior space of the cup and the box, a water vapor flow through the sample partial water vapor is generated, leading to the mass variation of the cup. The water vapor flow is calculated as follows:

$$G = \frac{\Delta m}{\Delta t}$$

$$\delta_p = \frac{G \cdot d}{A \cdot p_s (RH_1 - RH_2)}$$

$$\mu = \frac{\delta_a}{\delta_p}$$

Where m is the mass of sample and cup assembly, t is time, G is the water vapor flow rate through sample, A is the exposed area (m^2), p_s is saturated vapor pressure (Pa), RH_1 is the relative humidity inside the cup (%RH), RH_2 is the relative humidity in the box (%RH), d is the thickness of sample (m), δ_a is the water vapor permeability of air (kg/(s·m^2·Pa)), δ_p is the water vapor permeability of sample (kg/(s·m^2·Pa)), μ is the water vapor resistance factor of sample.

4. Results and discussion

4.1 Water solubility

Fig. 3 shows the revolution of the composite samples after immersed in water. The composite samples are sample 1, 2 and 7 from the left to right. It can be observed from Fig. 3 (b) that the thickness of the sample 1 and 2 were increased while that of the sample 7 remained unchanged after immersion in water for 1 hour. It can be seen from Fig. 3 (c) that the water color was red for the sample 1 and 2, while the color was light yellow for sample 7. This result indicated that the alginate was partly dissolved in water for the samples manufactured by M0 and M1. It can also be seen from Fig. 3 (d) that the sample 1 and 2 were destroyed, while the sample 7 kept complete after immersion in water for 24 hours.

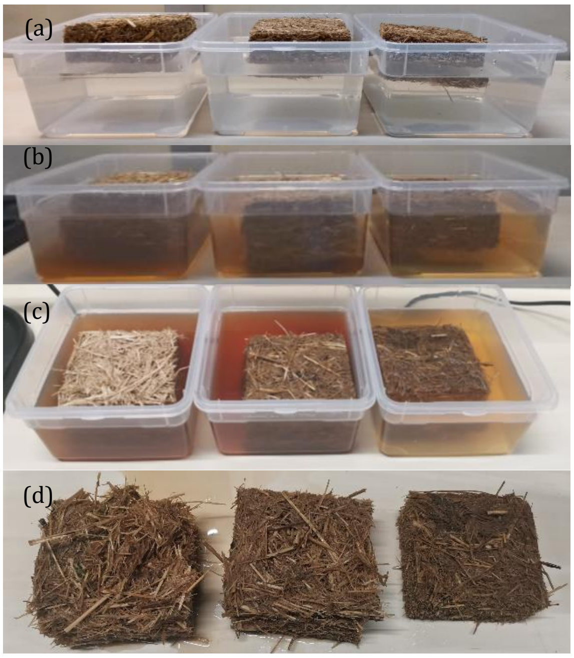

Fig. 3 - From left to right: sample 1, 2 and 7 immersed in water for (a) 1 min; (b) 1 h; (c) 24 h and (d) after 24h.

4.2 Density

Fig. 4 shows the average density with standard deviation of the composite samples by M2 with different types of rice straw fibers and binder ratio. All the composite samples have densities ranging from 100 to 200 kg/m³. It can be seen that the composite samples with RS1 have the larger density than the composite samples with RS1. Also, the density increases as the binder ratio increases.

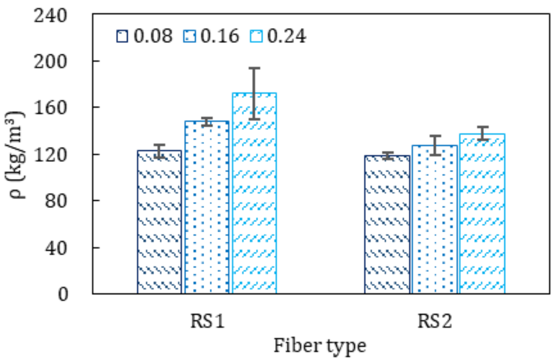

Fig. 4 - Density of the composite samples by M2 with different types of fibers and binder ratio.

4.3 Thermal conductivity

Fig. 5 shows the thermal conductivity of the composite samples by M2 with different types of rice straw fibers and binder ratio. All the composite samples are insulating with their thermal conductivity values from 0.039 to 0.045 W/(m·K). It can be seen that the composite samples with RS2 have the lower thermal conductivity than the composite samples with RS1. For example, the average thermal conductivity of the sample 3 was 0.044 W/(m·K), whereas that of the sample 6 was 0.039 W/(m·K). This can be attributed to the fact that the porosity of the composite samples increases by using the larger fibers, leading to the decrease of their thermal conductivity as air has a lower thermal conductivity. The binder ratio seems to have a minor effect on the thermal conductivity. This might because the binder content is low for all the composite samples.

Thermal conductivity values of straw insulating materials in the present study and literature are plotted versus their density, as shown in Fig. 6. Straw bale [16] and straw composites using starch [17, 18], liquid glass[19, 20], lime [21] and clay [22] as adhesive have been added for comparison. It can be seen from Fig. 6 that for density of around 150 kg/m³, the thermal conductivity values were 0.044 W/(m·K) in present study and 0.058 W/(m·K). The thermal conductivity of the composite samples is generally increased with their density. However, a weak correlation was observed in the present study, which can be attributed to the small variation in composites' densities.

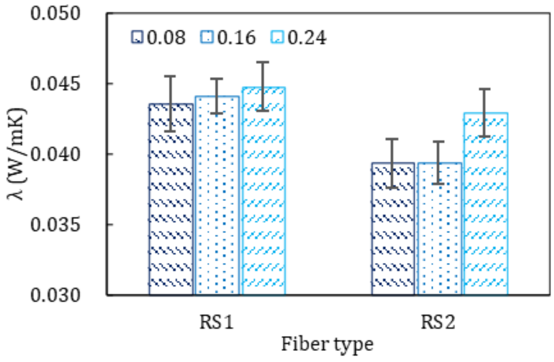

Fig. 5 – Thermal conductivity of the composite samples by M2 with different types of fibers and binder ratio.

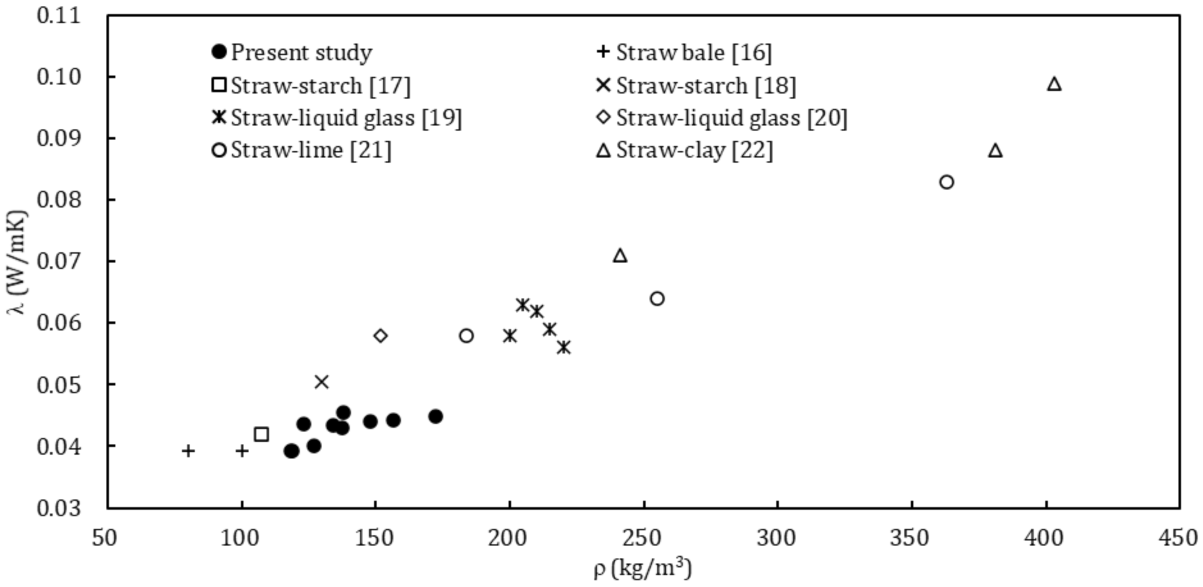

Fig. 6 - Density versus thermal conductivity in present study and in literature

4.4 Water vapor permeability

Fig. 7 shows the water vapor resistance factor of the composite samples by M2. It is clear that the fiber size and binder ratio have an effect on water vapor resistance factor of the composite samples by M2. Decreasing binder ratio from 0.24 to 0.08 decreased the μ-value by approximately 38% and 22% for RS1 and RS2, respectively. Compared to the composites from RS1, the composites from RS2 decreased the μ-value by 6%, 9% and 21% for binder ratios of 0.08, 0.16 and 0.24, respectively.

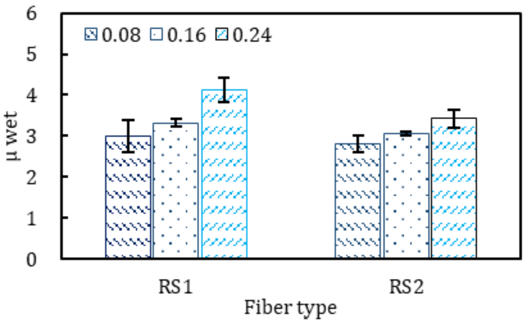

Fig. 7 – Water vapor resistance factor of the composite samples by M2 with different types of fibers and binder ratio.

5. Conclusions

Rice straw fibers with a biobased binder, sodium alginate, was developed for composite insulation materials in buildings. In order to solve the solubility issue, a modified procedure was developed to prepare insoluble alginate-based composite through inducing cross-link with ionic calcium. The water solubility of the composite samples with and without cross-link were investigated. The effect of fiber size and binder ratio on the density, thermal conductivity and water vapor resistance factor of the resulting composites were also studied.

Immersion the composite sample in $CaCl_2$ solution for a short time can solve the water solubility issue. All the composite samples can be considered as insulators for building applications. The larger fiber size leads to a lower density, thermal conductivity and water vapor resistance factor. The binder ratio seems to have a minor effect on the thermal conductivity.

6. Acknowledgement

The authors would like to thank the Région Auvergne-Rhône-Alpes for its financial contributions. In addition, the authors would like to thank the CSC (China Scholarship Council) to provide financial support for the study in France.

7. References

[1] A. Korjenic, V. Petránek, J. Zach, J. Hroudová, Development and performance evaluation of natural thermal-insulation materials composed of renewable resources, Energy and Buildings 43(9) (2011) 2518-2523.

[2] K. Strømdahl, Water sorption in wood and plant fibres, Technical University of Denmark. Danmarks Tekniske Universitet, Department of Structural Engineering and Materials Institut for Bærende Konstruktioner og Materialer (2000).

[3] M. Kapoor, D. Panwar, G. Kaira, Bioprocesses for enzyme production using agro-industrial wastes: technical challenges and commercialization potential, Agro-Industrial Wastes as Feedstock for Enzyme Production, Elsevier2016, pp. 61-93.

[4] A. Quintana-Gallardo, J.R. Clausell, I. Guillén-Guillamón, F.A. Mendiguchia, Waste valorization of rice straw as a building material in Valencia and its implications for local and global ecosystems, Journal of Cleaner Production 318

(2021) 128507.
[5] J. Zhao, S. Li, Life cycle cost assessment and multi-criteria decision analysis of environment-friendly building insulation materials-A review, Energy and Buildings (2021) 111582.
[6] Y. Zuo, J. Xiao, J. Wang, W. Liu, X. Li, Y. Wu, Preparation and characterization of fire retardant straw/magnesium cement composites with an organic-inorganic network structure, Construction and Building Materials 171 (2018) 404-413.
[7] M.R. Ahmad, B. Chen, M.A. Haque, S.F.A. Shah, Development of a sustainable and innovant hygrothermal bio-composite featuring the enhanced mechanical properties, Journal of Cleaner Production 229 (2019) 128-143.
[8] K. Wei, C. Lv, M. Chen, X. Zhou, Z. Dai, D. Shen, Development and performance evaluation of a new thermal insulation material from rice straw using high frequency hot-pressing, Energy and Buildings 87 (2015) 116-122.
[9] N. Mati-Baouche, H. De Baynast, A. Lebert, S. Sun, C.J.S. Lopez-Mingo, P. Leclaire, P. Michaud, Mechanical, thermal and acoustical characterizations of an insulating bio-based composite made from sunflower stalks particles and chitosan, Industrial Crops and Products 58 (2014) 244-250.
[10] C. Lacoste, R. El Hage, A. Bergeret, S. Corn, P. Lacroix, Sodium alginate adhesives as binders in wood fibers/textile waste fibers biocomposites for building insulation, Carbohydrate polymers 184 (2018) 1-8.
[11] P. Mariana, N. Antonia, A. Jaume, A.M. Lacasta, Characterization of thermal insulation materials developed with crop wastes and natural binders, WSB 14 Barcelona Sustainable Building, 2014, pp. 188-1-188-10.
[12] M.S. Hasnain, E. Jameel, B. Mohanta, A.K. Dhara, S. Alkahtani, A.K. Nayak, Alginates: sources, structure, and properties, Alginates in Drug Delivery, Elsevier2020, pp. 1-17.
[13] M. Viel, F. Collet, C. Lanos, Chemical and multi-physical characterization of agro-resources' by-product as a possible raw building material, Industrial Crops and Products 120 (2018) 214-237.
[14] J.-W. Rhim, Physical and mechanical properties of water resistant sodium alginate films, LWT-Food science and technology 37(3) (2004) 323-330.
[15] E.I. 12572, Hygrothermal performance of building materials and products-Determination of water vapour transmission properties-Cup method, British Standard, 2016.
[16] B. Marques, A. Tadeu, J. Almeida, J. António, J. de Brito, Characterization of sustainable building walls made from rice straw bales, Journal of Building Engineering (2019) 101041.
[17] M. Palumbo, A.M. Lacasta, N. Holcroft, A. Shea, P. Walker, Determination of hygrothermal parameters of experimental and commercial bio-based insulation materials, Construction and Building Materials 124 (2016) 269-275.
[18] M. Ali, A. Alabdulkarem, A. Nuhait, K. Al-Salem, G. Iannace, R. Almuzaiqer, A. Al-turki, F. Al-Ajlan, Y. Al-Mosabi, A. Al-Sulaimi, Thermal and acoustic characteristics of novel thermal insulating materials made of Eucalyptus Globulus leaves and wheat straw fibers, Journal of Building Engineering 32 (2020) 101452.
[19] A. Bakatovich, N. Davydenko, F. Gaspar, Thermal insulating plates produced on the basis of vegetable agricultural waste, Energy and Buildings 180 (2018) 72-82.
[20] S. Liuzzi, C. Rubino, F. Martellotta, P. Stefanizzi, C. Casavola, G. Pappalettera, Characterization of biomass-based materials for building applications: The case of straw and olive tree waste, Industrial Crops and Products 147 (2020) 112229.
[21] N. Belayachi, D. Hoxha, M. Slaimia, Impact of accelerated climatic aging on the behavior of gypsum plaster-straw material for building thermal insulation, Construction and Building Materials 125 (2016) 912-918.
[22] M. Labat, C. Magniont, N. Oudhof, J.-E. Aubert, From the experimental characterization of the hygrothermal properties of straw-clay mixtures to the numerical assessment of their buffering potential, Building and Environment 97 (2016) 69-81.

Data Statement

c. The datasets generated during and/or analysed during the current study are not available because they are proprietary and confidential in nature but the authors will make every reasonable effort to publish them in near future.