

Biopolymers impact on hygrothermal properties of rammed earth: from material to building scale

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1 Abstract

Three biopolymers were tested as rammed earth (RE) stabilizers, evaluating their impact on the hygrothermal behavior from material to building scale. Hygrothermal characterization included the determination of sorption isotherm, water vapor permeability, thermal conductivity at different moisture content, and specific heat capacity. The hygrothermal data were used as input for the simulation at whole-building scale considering combined heat and moisture transfer. The results were evaluated by comparing heating demand, thermal comfort during summer, and the contribution of walls for passively controlling indoor humidity. The results show that hygric properties were only slightly affected by the use of stabilizers, while the thermal conductivity was 33% higher for RE stabilized with lignin, consequently increasing the heating demand at whole-building scale. All RE walls were effective in reducing temperature oscillations in summer. In the particular case of a canicular event, the indoor temperature was reduced by up to 10° compared with the outdoor value. The indoor humidity also benefited from the passive regulation by RE walls, regardless of whether a stabilizer was used.

1 **Keywords:** rammed earth (RE); biopolymers; hygrothermal properties; heat and moisture transfer
2 simulation; building energy performances; HAMT EnergyPlus;

3 **Abbreviations:** RE (rammed earth), MIX (unstabilized RE specimens), LIG (MIX + lignin sulfonate),
4 TAN (MIX + tannins), WOOL (MIX + sheep wool fibers), EP (EnergyPlus)

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6 **Highlights:**

- 7 • Stabilization of RE with lignin sulfonate increases thermal conductivity by up to 30%.
- 8 • RE can reduce indoor temperature by up to 10° during canicular events.
- 9 • The use of paint on RE walls decreases their contribution to controlling indoor humidity.
- 10 • Uninsulated RE walls represent approximately 50% of the total sensible heat losses.

11 2 Introduction

12 2.1 Context and background

13 The buildings sector accounted for 30% of total global final energy consumption and for 30% of CO₂
14 emissions of total emissions at world scale in 2021, including the indirect emissions from electricity and heat
15 production [1]. Despite the increased activity levels in this sector, the related environmental impacts should
16 be reduced by 45% by 2050 in the scenario for Net Zero Emissions, to limitate climate change [1]. As an
17 example, the new French environmental regulation RE2020 [2] indicates three main objectives for the
18 building and construction sector aimed at reducing anthropic pressure on the environment: a reduction in
19 energy demand and in the carbon footprint of the whole lifecycle of a building while finding new strategies
20 to manage thermal comfort during summer. In this context, the use of earth as a construction material has
21 several advantages, and many researchers aspire to find innovative technologies to exploit its potential. It
22 should be mentioned that about one-third of world population still lives in earthen houses, distributed on all
23 five continents [3,4]. Moreover, earthen sites represent 10% of the World Heritage List of UNESCO [5]. These
24 vernacular techniques of construction are nowadays studied all over the world, producing an exponential
25 rate of publications and research on the subject [5,6].

1 Raw earth has low embodied energy thanks to local availability, low processing energy during the
2 construction phase, and recyclability [7,8]. Moreover, rammed earth construction offers the potential of re-
3 using non-hazardous waste from excavations, which represents around 7–10 million tons per year in France
4 [7]. In addition to their low environmental impact, some properties of raw earth materials are of interest for
5 the operational phase of a building's life, such as high thermal mass and the capacity to buffer moisture
6 variations. Thanks to their passive regulation of the indoor environment, these buildings are particularly
7 efficient in hot climates, where there is no need for additional insulating material during the mild winter
8 season [9,10]. The literature shows that rammed earth (RE) walls can provide passive regulation of indoor air
9 during summer when adequate sun protection is used in combination with efficient ventilation, in particular
10 during the night [11,12].

11 RE is one of the popular raw earth construction techniques, widespread in France from the 15th to
12 the 19th centuries, and it represents about 40% of the vernacular buildings in the Isere-Rhône-Alpes region
13 [13] (Figure 1). RE walls are built by compacting layers of soil of about 10-15 cm into formwork using a
14 pneumatic hammer. At the end of the process, the material is able to stand thanks to the combined action
15 of clay, the adequate quantity of water, and the compaction effort applied. A well-graded grain size
16 distribution for the soil is recommended in order to have an adequate percentage of clay, sand and gravel in
17 the mixture [15]. For unstabilized RE, clay is considered the only binder in the mixture and it is classified as
18 raw earth material due to the procedure of drying without a firing process. RE is a porous material, with a
19 high ability to adsorb and desorb water molecules in its porous network, in particular due to the presence of
20 clay particles. Thanks to this ability, earthen materials can simulate similar effects to phase change materials,
21 where the water is free to change phase to maintain the walls in equilibrium with the environmental
22 conditions. At the same time, the strong sensitivity to water represents a risk factor when the moisture
23 content in the material increases over a certain level [16].



Figure 1: Rammed earth house in the village of St. Chef, Iserre, south of France.

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Wider dissemination of raw earthen construction requires improvements in mechanical performance and durability, particularly with regard to leaching. To improve the mechanical strength of this material as well as its resistance to liquid water (rain, capillary rise, etc.), it is common practice to add stabilizers to the soil, notably cement or lime [8,17]. However, this leads to an increase in the environmental impact of the material of more than double with respect to unstabilized RE [8]. At the same time, the stabilization risks reducing the vapor permeability and the moisture buffer capacity [18,19]. In addition, it also involves problems of recyclability, due to the chemical reactions that transform earthen building elements into artificial stone.

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In a previous publication [20] the authors presented the first part of this research with the aim of investigating the effect of five biopolymers (citrus pomace, wool sheep fibers, lignin sulfonate, grapeseed flour and tannin) to improve the mechanical performance of raw earth materials while preserving their environmental sustainability. The use of lignin sulfonate, tannins, and wool as bio-stabilizers increased the unconfined compressive strength of the material by approximately 38%, 16%, and 6%, respectively, compared with control samples.

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The additives yielding promising results were selected to investigate the impact of stabilization on the hygrothermal properties both at material and at building scale. In the literature, there are some results presented on the modifications of the hygrothermal properties at the material scale when stabilizing the material, but there is a lack of knowledge about the impact at the building scale [18,21,22]. Beckett et al. [23] simulated the thermal behavior of an RE house with an accredited software used in Australia (BERS Pro, v4.3),

1 without combined heat and moisture transfer. Similar studies are available in the literature, all of which
2 consider only heat transfer through the walls with different commercial tools (TRANSYS, Design Builder)
3 [11,24–26]. The work by Medjelekh et al. [27] is worth mentioning for the combined heat and moisture
4 transfer simulations on unfired earthen bricks wall. Soudani et al. and Gao et al. also presented a study on
5 combined heat and moisture transfer for RE walls. More recently, Tan et al. and Jiang et al. [28,29]
6 investigated the influence of the use of a moisture barrier and non-constant hygrothermal parameters by
7 implementing a heat and moisture transfer model in Comsol to simulate the behavior of an RE wall in
8 northwest Sichuan, China. Finally, Allinson et al. [30] presented the first study with combined heat and
9 moisture transfer via WUFI PLUS at a whole-building scale for RE stabilized with cement; however, there is
10 no information in the literature on earth stabilized with biopolymers.

11 The present study aims to evaluate the impact of bio-stabilization on the hygrothermal properties of
12 RE from material to building scale. To study the different types of RE stabilized with additives and
13 biopolymers, we adopted an approach of finding experimentally the parameters that describe the physical
14 behavior of the materials to be used as input data in the numerical model that will consider combined heat
15 and moisture transfer.

16 2.2 Hygrothermal behavior of RE materials

17 The energy performance of RE materials strongly depends on vapor transfers, the description of this
18 phenomena is then explained before presenting the corresponding material properties and their
19 experimental measurements. Combined heat and moisture transfer in hygroscopic material can be described
20 by different models, which enables variations in the properties of the material as a function of moisture and
21 temperature conditions in the material itself. The mathematical model implemented here is based on the
22 theoretical moisture and heat balance equations for the building envelope in one dimension, as described by
23 Künzle, (equations ((1) and (2)) [31,32]. The three terms of equation (1) describe heat storage, heat transfer,
24 and heat generation, respectively, in the building envelope. The three terms of equation (2) refer to the
25 storage of moisture, liquid, and vapor moisture transport, respectively, in the building envelope.

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$$\frac{\partial H}{\partial T} \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(\lambda_w \frac{\partial T}{\partial x} \right) + h_v \frac{\partial}{\partial x} \left(\frac{\delta_a}{\mu} \frac{\partial(\varphi P_{\text{sat}})}{\partial x} \right) \quad (1)$$

$$\frac{\partial w}{\partial \varphi} \frac{\partial \varphi}{\partial t} = \frac{\partial}{\partial x} \left(D_w \frac{\partial w}{\partial \varphi} \frac{\partial \varphi}{\partial x} \right) + \frac{\partial}{\partial x} \left(\frac{\delta_a}{\mu} \frac{\partial(\varphi P_{\text{sat}})}{\partial x} \right) \quad (2)$$

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where T is the temperature (°C); w is the moisture content in the material (kg/kg); x is the length (m)

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considering the horizontal direction of the walls; t (s) is the time; h_v is the evaporation enthalpy of water

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(2 489 000 J/kg); φ is the relative humidity (RH); P_{sat} is the saturation vapor pressure; $\partial w/\partial \varphi$ is the moisture

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storage capacity, ξ ; and D_w (m^2/s) is the liquid transport coefficient. The ratio between the vapor permeability

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of the indoor air volume δ_a and the water vapor resistance factor μ describes the vapor permeability in the

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material ($\delta_{\text{wall_material}}$). The resistance factor is defined in formula (3).

$$\mu = \frac{\delta_a}{\delta_{\text{wall_material}}} \quad (3)$$

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where $\delta_{\text{wall_material}}$ is the vapor permeability of the wall and δ_a is the vapor permeability of the air. The

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thermal conductivity λ_w , the liquid transport coefficient D_w , the water vapor resistance factor μ , and the

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moisture storage capacity $\partial w/\partial \varphi$ are parameters that depend on the moisture level in the material [33].

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The heat storage capacity also depends on the moisture content of the material w (kg/kg), with the

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relationship described in the following equation by Kunzel [31]:

$$\frac{\partial H}{\partial T} = (C_p \rho + C_w w) \quad (4)$$

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where C_w is the specific heat capacity of water ($\text{J}/(\text{kg}\cdot\text{C})$); ρ is the density of the material (kg/m^3); and

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C_p is the specific heat capacity of the material ($\text{J}/(\text{kg}\cdot\text{C})$).

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The complete list of the material properties required for the HAMT model includes porosity (m^3/m^3),

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the moisture sorption isotherm curve (kg/m^3), thermal conductivity λ_w ($\text{W}/(\text{m}\cdot\text{K})$), specific heat capacity

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($\text{J}/(\text{kg}\cdot\text{K})$), vapor diffusion resistance factor μ_w (-), and liquid transport coefficient D_w (m^2/s). In the case of

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strong hygrothermal coupling, such as for the RE material, these parameters can vary with the adsorption

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and release of moisture. Consequently, it is important to define the measurement conditions (both

1 temperature and humidity) precisely in order to describe the behavior of the material at different RH%
2 conditions.

3 The article is organized into two parts. In the first part (section 4) the different RE materials were
4 tested in the laboratory at the material scale to obtain experimental data to be used as input for whole-scale
5 building simulation, which are described in the second part (section 5) of the article.

6 3 Material properties

7 3.1 Materials and methods

8 3.1.1 Samples preparation

9 The choice of the methodology for the sample preparation, the soil characterization, and the detailed
10 description of the additives are presented in detail in two previous articles by Losini et al. [20,34]. The
11 unstabilized control samples are abbreviated as MIX, while the samples stabilized with the additives are
12 abbreviated with the first letters of the additives: LIG (MIX + 1wt% of lignin sulfonate), TAN (MIX + 1wt% of
13 tannin), and WOOL (MIX + 0.25wt% of wool). Among the samples, MIX has the higher density (2.19 ± 0.03
14 g/cm^3), LIG and WOOL an intermediate value ($2.17\pm 0.03 \text{ g/cm}^3$), and TAN the lowest value ($2.13\pm 0.01 \text{ g/cm}^3$).

15 Small samples for sorption isotherms were prepared from a single layer of compacted soil, and larger
16 samples for water vapor permeability and thermal conductivity were prepared from a double layer of
17 compacted soil. The compaction process respects the standards of the Modified Proctor Test [35]. A detailed
18 description of the Proctor method is reported in the article by Losini et al. [20].

19 3.1.2 Criteria for reaching equilibrium in hygrothermal tests

20 The equilibrium criterion used in all the tests of the present article is satisfied when a mass variation
21 lower than 0.01% was reached for 3 consecutive days. Indeed, the criterion from the reference standard ISO
22 12571:2013 was increased from 0.1% to 0.01%, due to the high density of RE as compared to the common
23 hygroscopic materials with higher porosity [36]. The criterion was modified to 0.05% of mass variation only
24 in the case of 95% RH, due to the difficulty of maintaining stable conditions near 100% RH. Moreover, the

1 choice of 0.05% is a compromise between the requirement of greater stability in the equilibrium state and
2 maintaining a reasonable time to reach it without the risk of developing mold at a high RH level.

3 3.1.3 Sorption isotherm

4 The small cubic pieces of samples measured 2.5 cm on each side, with a mass of approximately 40 g
5 each. The dimensions of the specimens were designed to be the minimum acceptable by the standards so as
6 to accelerate the time necessary to reach equilibrium at each RH step.

7 Before starting the test, all the samples were dried in an oven at 50°C to avoid degrading until
8 equilibrium, using boxes of silica gel placed inside to maintain a dry environment. Once equilibrium was
9 reached, the samples were placed in desiccators to lower their temperature and to measure precisely their
10 dry mass (m_0) before starting the experiment. To avoid the risk of fragment loss during weighing, the samples
11 were wrapped in transpiring fabric that enables the transfer of water vapor while preserving the integrity of
12 the samples. Preliminary tests showed that the fabric was nonhygroscopic at the humidity levels used for the
13 test; therefore, the adsorption of water was only attributed to the RE specimen.

14 Air-locked containers with different saturated salt solutions were used to create different RH% levels.
15 Different salts were used to prepare the saturated solution (i.e., KOH, CH₃CO₂K, MgCl₂, NaBr, NaC, KCl, and
16 K₂SO₄) and the RH produced (9%, 22%, 33%, 58%, 75%, 84%, and 97%) [36,37]. The containers were designed
17 to store the salt solution on the bottom and the samples on a supporting grid. Hygrothermal sensors
18 (precision ±3% RH and ± 0.5°C) were placed inside the containers to monitor the humidity and temperature
19 conditions. A constant temperature of 25°C was maintained by a regulated oven (UNI 110 from Memert Ltd.).
20 A balance with a precision of ±1 mg was used for the test (Ohaus Corporation).

21 The samples were first placed in containers with the lowest level of RH until reaching equilibrium
22 before continuing at the next RH level. The mass of the samples was recorded every 24 h. The experiment
23 continued for 2 months to test seven RH levels for the sorption isotherm.

24 The moisture adsorption was calculated in reference to the initial dry conditions with the following
25 formula:

$$26 \quad u = \frac{m - m_0}{m_0} \quad (5)$$

1 where m_0 is the dry mass and m is the mass measured at equilibrium at different RH levels. At least
2 three samples were used to determine the moisture adsorption/desorption curve and the average of their
3 measurements was used to define the final curve. The standard deviation of the measurement of the three
4 samples was always verified to be lower than 3%.

5 3.1.4 Water vapor permeability

6 *Sample preparation and conditioning*

7 The samples for the water vapor permeability test were cut from a double layer of the Proctor. A
8 minimum of four specimens were prepared and tested for each mixture typology and level of RH. A standard
9 deviation lower than 2% in the density of the samples of the same type of mixture was considered sufficient
10 to ensure the reproducibility of the specimens [38].

11 The samples were left to dry in laboratory environmental conditions (25°C and about 40% RH). The
12 samples were then sealed with aluminum tape on the lateral side so as to maintain a single direction free for
13 the vapor exchange. All the samples were accurately measured to define the surface (about 3.5×3.5 cm) and
14 the thickness (2 ± 0.5 cm) with a micrometer comparator.

15 The samples were then connected with the open lids of the cup adapted for the test, using silicon
16 latex to seal the contact place and prevent the air leaking. To limit any possible hysteresis effect generated
17 during the drying procedure, all the samples were preconditioned at 8% RH inside airtight containers at 25°C
18 using a saturated KOH salt solution. Once equilibrium was reached, the samples were conditioned at 58% RH
19 and 25°C using a saturated salt solution of NaBr [39].

20 The samples fixed on the lids were connected to the cups with a saturated salt solution (KOH or
21 $MgCl_2$). An additional layer of aluminum tape was added to prevent air from leaking during the test (Figure

1) The layer of air between the surface of the samples and the saturated salt solution was verified to be constant at 2 cm, as reported in Figure 1.

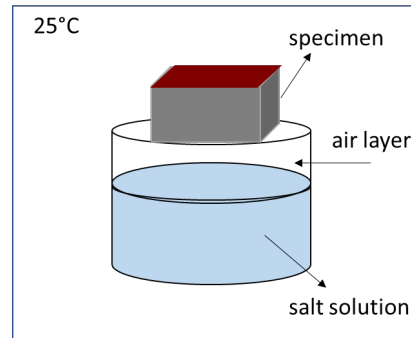


Figure 2: Diagram of the setup for the vapor permeability test in the RH-Box.

Test procedure

Water vapor permeability was determined with the wet-cup method based on the EN ISO 12572:2013 standard [40]. The samples prepared with the KOH solution in the cup were placed in the climatic chamber at 33% RH to expose the free surfaces of the specimens at different levels of RH (9–33% RH). The samples prepared with the $MgCl_2$ saturated solution in the cup were placed in the climatic chamber at 75% RH to test the vapor permeability with a different interval of vapor pressure on the two surfaces. The climatic chamber was maintained at a constant temperature of 25°C. Two electronic balances (accuracy ± 1 mg) were used to weigh the samples directly inside the chamber. The humidity and temperature levels in the two chambers were recorded and monitored with a hygrothermal sensor provided by Warnet Solutions (precision $\pm 3\%$ RH and $\pm 0.5^\circ C$).

The samples were measured four times per day with a minimum of 2 h between two measurements. Due to the difference in the partial vapor pressure outside and inside the cup, water vapor can flow through the specimen. The mass variation between two measurements is calculated with the following equation:

$$\Delta m = \frac{m_1 - m_2}{t_1 - t_2} \quad (6)$$

where m_1 is the mass at time t_1 and m_2 is the mass at time t_2 (kg), with t_1 and t_2 the measurement time (s). The regression line calculated between mass increment and time of measurement, excluding the first part of the nonlinear phase of the test, gives the slope G-line (kg/s). The test continued for about 2 weeks

1 until reaching a linear variation of mass for a sufficient time to obtain a good correlation in the regression
2 line ($R^2 > 0.999$).

3 Water vapor permeability δ (kg/(m·s·Pa)) could then be estimated using the following formula:

$$\delta = \frac{d}{\frac{A \cdot \Delta P_v}{G_{line}} - \frac{1}{\beta_{p_out}} - \frac{d_a}{\delta_a}} \quad (7)$$

4 where A is the sample area (m²), d (m) is the thickness of the sample, ΔP_v (Pa) is the water vapor
5 pressure difference across the specimen, and G (kg/s) is the slope of the line obtained by linear regression
6 on mass and time measurements of the samples. Two correction factors for boundary conditions are present
7 in the formula (d_a/δ_a , $1/\beta_{p_out}$), where δ_a (kg/m.s.Pa) is the water vapor permeability of air, d_a is the thickness
8 of the air gap (m), and β_{p_out} is the mass exchange coefficient. The correction is significant for highly
9 permeable materials. The first factor (d_a/δ_a) considers the resistance to the water vapor flow due to the air
10 layer between the sample's surface and the salt solution; the second factor ($1/\beta_{p_out}$) considers the resistance
11 to the water vapor flow due to the outer boundary layer. In our test facility, β_{p_out} was measured to be equal
12 to 9.8×10^{-9} kg/(Pa.s.m²), according to Nugyen et al. [41]

13 3.1.5 Thermal conductivity

14 The thermal conductivity of hygroscopic material depends on its porous structure and the state of
15 pore filling. The three-phase system is composed of soil grains, water, and air at equilibrium with the RH that
16 surrounds the system. The thermal conductivity of liquid water is about 30 times greater than that of air.
17 Consequently, when the pore space is filled by water, thermal conductivity increases. Because of this,
18 thermal conductivity was determined for samples in a dry state and conditioned at 58% and 84% RH.

19 In the present study, the Hot Disk technology was used, with the advantage of rapid dynamic
20 measurements. The time necessary for one measurement is within the range of 1 min, making it possible to
21 maintain the previously conditioned specimens in equilibrium at a specific temperature and RH.

22 The thermal measurements were taken with the Hot Disk apparatus (Transient Plane Source method)
23 from ThermConcept (TPS 2500S model). Thermal conductivity and diffusivity were directly measured. The
24 measurement technique is based on the placement of one sensor between two samples, the injection of
25 constant electrical power in the sensor, and the detection of the temperature variation in the samples (Figure

1 2). A sensor with a double spiral in nickel with Kapton insulation was used for the measurement – model
2 5501 F1 with a radius of 6.403 mm. The analysis of the temperature rise curves was carried out with the Hot
3 Disk 'Thermal Analyzer' software. The thermal conductivity measurements were carried out according to the
4 manufacturer's recommendations, i.e., (i) the total characteristic time in the range of 0.33 and 1, (ii) the total
5 temperature increase of the sample between 2 and 5°C, and (iii) the standard deviation on the temperature
6 maintained in the range of 10^{-4} and 10^{-5} K.

7 The tested samples had the following dimensions: $3 \times 6 \times 4$ cm³. The samples were dried in an oven at
8 50°C for 3 consecutive days until they reached equilibrium in weight. Then the samples were placed in boxes
9 with silica gel near the Hot Disk apparatus to have similar and stable conditions during the test (about 25°C).
10 The other two RH levels were tested, using a saturated salt solution of NaBr and KCl (58% and 84% RH,
11 respectively) to condition the samples.

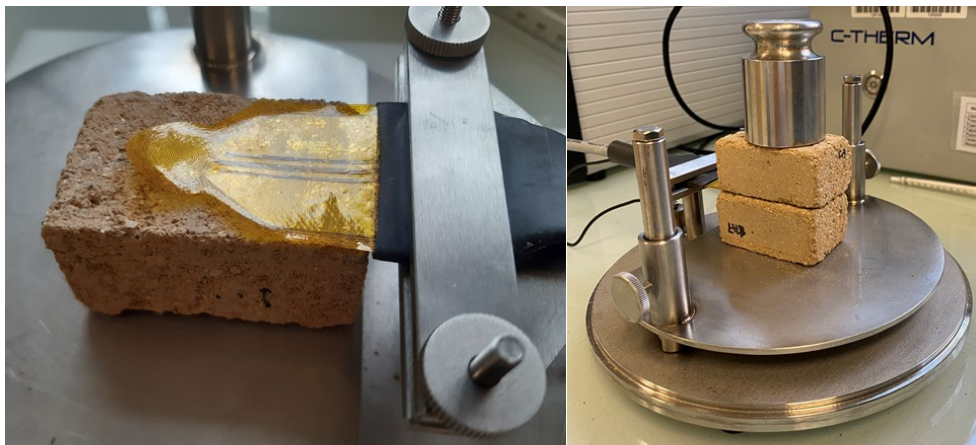


Figure 3: Hot Disk apparatus sensor and samples positioned during measurements.

12 3.1.6 Specific heat capacity

13 In order to measure the heat capacities of materials, we use a DSC-25 from TA Instrument®. The
14 method used is modulated (MDSC, Modulated Differential Scanning Calorimeter) standardized to ASTM
15 E1952 and E2716 with sapphire as the reference standard [42]. The measurements are obtained in a range
16 from 10°C to 50°C with a heating rate of 2 K/min, an oscillation period of 120 s, and an amplitude of 0.64°C.

1 3.2 Results

2 3.2.1 Sorption isotherm

3 Figure 3 reports the sorption isotherm for the control samples (MIX) and the stabilized mixtures. The
4 shape of the curve suggests a similarity with the type II isotherm described by IUPAC, typical of clayish
5 materials [43]. The use of the additives has a marginal impact on the sorption isotherm, which shows only a
6 very small variation. At a low level of RH% (0–20%), TAN has the highest adsorption, while MIX and WOOL
7 have intermediate values, with LIG having the lowest. In the intermediate levels of humidity (33–85% RH),
8 WOOL has slightly higher adsorption than MIX, and both are reached and surpassed by LIG (Figure 3). TAN
9 shows the highest adsorption at 60% and 80% RH, but it decreases at the higher values of the sorption
10 isotherm. For higher values of RH (84–98%), the values of WOOL, TAN, and MIX are more uniform and LIG
11 presents the highest levels of adsorption, despite showing the lowest adsorption level at low RH%. In general,
12 the samples show a maximum relative change in mass of about 1.8% for 98% RH, which is quite low compared
13 with values from the literature on earthen material with higher clay content that can reach values between
14 2.5% and 5% of mass variation [44–46]. This behavior may be due to the high content of sand in the mixture
15 (about 80%). Another factor to be taken into account is the drying temperature to determine m_0 , which was

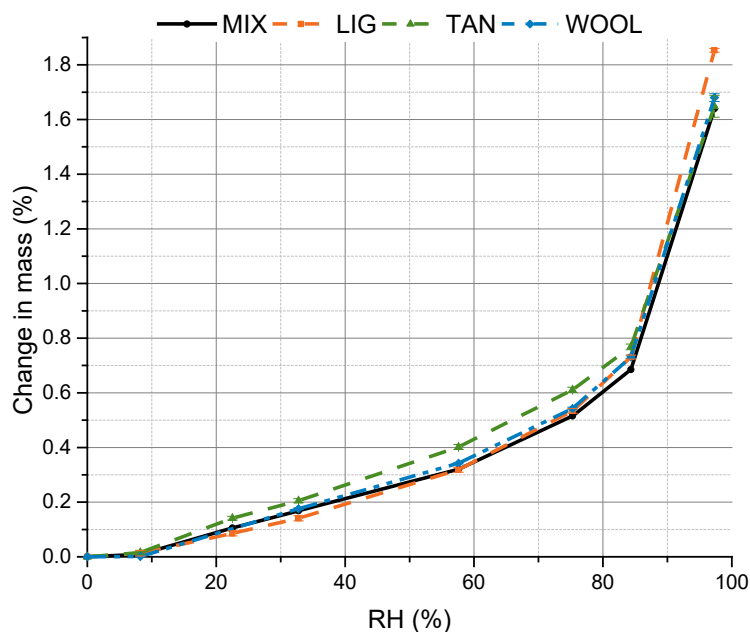


Figure 4: Sorption isotherm at 25°C.

16 chosen to avoid material degradation, in particular, due to the presence of fibers. Different temperatures are

1 proposed in the literature in a range from 55 to 105°C [46–48]. Of course, the use of a different reference for
 2 the dry mass can lead to an underestimation of adsorption properties compared to the drying process at
 3 105°C, as illustrated by Fabbri et al. [46].

4 3.2.2 Water vapor permeability

5 The diffusion of water vapor in a porous material describes the permeance of the material to water
 6 vapor transfer under the effect of vapor pressure. It can also be described as a resistance factor (μ), which is
 7 the ratio between the water vapor diffusion in the material (δ_v) and the water vapor diffusion in the air (δ_a).

8 The results are given as an average of a minimum of four samples for both intervals of RH, i.e., 9–
 9 33% and 33–75% RH (Figure 4). Considering the variability of the results, this test shows a high standard
 10 deviation, which does not enable a clear comparison with the results that have a small variation in values.
 11 Some minor tendencies can be seen: The water vapor permeability of LIG is slightly reduced compared to the
 12 control samples, while for TAN it is slightly increased. For WOOL specimens the value is slightly decreased for
 13 9–33% RH and equal to that of MIX for 33–75% RH%
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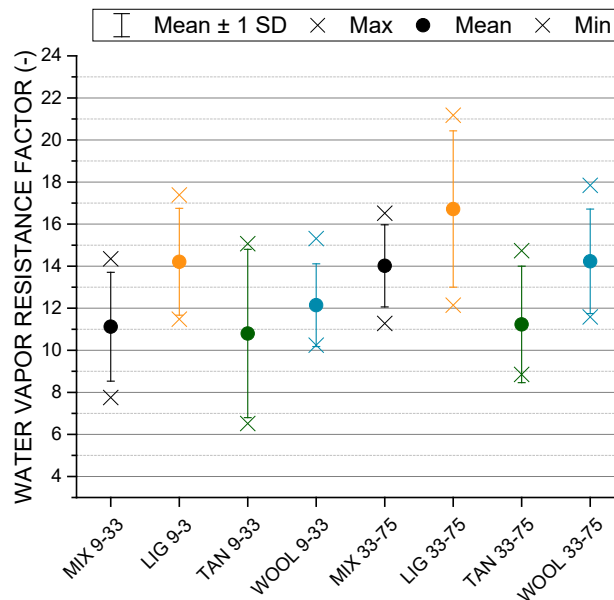


Figure 5: Water vapor resistance factor measured in two different intervals of RH% (9–33% and 33–75%).

15 Generally, for a higher RH, the moisture vapor transfer becomes a mixed-mode liquid–vapor transfer.
 16 These phenomena improve the moisture transfer that is higher at higher RH [49]. Conversely, the results of

1 our study suggest the opposite behavior. However, the increase in the vapor resistance factor is lower than
2 the standard deviation.

3 Common values of vapor resistance factor for unstabilized RE material in the literature are around
4 4–10 [48,50], and measurements of stabilized RE with 7% of Portland Concrete showed a value of 14.34 [30],
5 considering the wet-cup method comparison. These values are comparable to fired bricks and cellular
6 concrete but are competitive in relation to standard concrete (B25), which has a value 10 times higher.

7 3.2.3 Thermal conductivity

8 A couple of samples for each mixture were tested and two couples of samples in the case of WOOL
9 were used to obtain more information about the influence of the non-homogeneous distribution of the wool
10 fibers in the samples. By using four samples (two couples), we can evaluate the variation in thermal
11 conductivity due to different fiber arrangements. The standard deviation between the three measurements
12 is smaller (about 1%) than the average error of the measuring instrument, that is, 5% of the measured values.
13 Thus, the larger value of the measuring instrument (5% of the measured values) was considered.

14 Thermal conductivity shows a linear evolution with water content, as claimed by many authors for
15 other raw earth materials [13,22,28,48,51]. At the same time, no linear relationship was found between the
16 density and the dry thermal conductivity, in accordance with the findings of Chabriac [48]. The results show
17 a major increase in thermal conductivity for LIG specimens, with values around 1.87 W/(m·K), probably due
18 to the higher density of the samples, while the values for MIX, WOOL, and TAN are around 1.45 W/(m·K). The
19 values of thermal conductivity measured are slightly higher than those in the literature, where they are
20 reported to be between 0.6 and 1.1 W/(m·K)[52]. For the WOOL sample, the value of thermal conductivity
21 decreases compared to the value of the control samples. This is an unexpected phenomenon because the
22 addition of fibers usually decreases the density and thermal conductivity, but similar behavior was found in
23 the literature by Randazzo et al. [53].

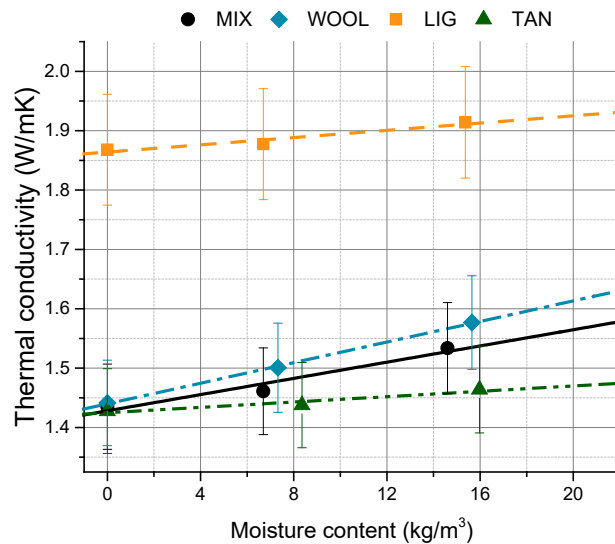


Figure 6: Thermal conductivity as a function of moisture content.

1 Figure 5 displays the thermal conductivity measured in samples conditioned at different RH%. WOOL
 2 and MIX show the highest increment of thermal conductivity, estimated by the slope of the linear
 3 interpolation, while TAN and LIG show a smaller increase.

4 3.2.4 Specific heat capacity

5 The results of MDSC (modulated differential scanning calorimetry) on MIX are calculated as an
 6 average of the measures in three different samples. The measured value at 25°C was 737 J/(kg·K), in
 7 accordance with results from the literature, which reports values between 0.684 and 939 J/(kg·K) for RE
 8 materials [48,52].

9 4 Impact at building scale

10 RE material stabilized with biopolymers has not been exploited in building construction to date, and
 11 thus a direct collection of data to obtain experimental measurements at the building scale was not
 12 considered a possibility. Moreover, the comparison of different stabilized RE materials involves the use of
 13 simulation tools, which enable the comparison of building performance in different case studies and
 14 locations, modeling precisely the occupancy scenarios.

15 The experimental data were used as input for the modeling of coupled heat and moisture transfer
 16 using EnergyPlus software. For many years, different tools have been available for simulating coupled heat

1 and moisture transfer, as presented in the international collaborative project IEA ECBCS Annex 41, Subtask 1
2 (Whole building heat, air and moisture response). Trnsys, EnergyPlus, and Wufi Plus are some of the software
3 used to evaluate building energy performance, which also enable simulations of coupled heat and moisture
4 transfers. Among the tools, the combined heat and mass transfer model (HAMT) of EnergyPlus was selected
5 for the present work for its widespread use, the possibility to implement detailed scenarios, and the
6 advantage of using free software licenses [32]. EnergyPlus (EP) collects different program modules that work
7 together to simulate energy behavior at a whole-building scale, calculating the energy required to heat and
8 cool a building following operating conditions and external conditions set as input in the simulation [54].
9 Equations (1) and (2) presented in section 3 describe the model used in EP for the envelope.

10 Simulations at the whole-building scale were carried out to evaluate the influence of the different RE
11 formulations on hygrothermal transfers. Five configurations were simulated, using different materials for the
12 vertical walls (MIX, TAN, LIG, WOOL) and in one case the use of painting on MIX walls (P-MIX). Details of the
13 building description, envelope materials, occupancy scenarios, and weather file will be illustrated.

14 4.1 Case study and configuration

15 4.1.1 Building description

16 *Geometry and location*

17 The test room used in the simulation is based on the well-known BESTEST building, which is used for
18 numerical model validation [55]. It has a total volume of 129.6 m³, the side is 8 m long on the east–west axis
19 and 6 m in north–south direction, for a total floor area of 48 m², as represented in Figure 6. The wall height
20 is 2.7 m. The building is simulated as one thermal zone.

21 The windows opening in the building were modified to follow the recommendation for the structural
22 stability of RE construction and to reduce the heating demand using solar gains. In France, the surface area
23 of windows should be at least one-sixth of the living area (*Réglementation thermique 2012*) and the south
24 face of the building is recommended to be heavily glazed, equivalent to 15–20% of the floor area so as to
25 allow for higher solar gains during wintertime. On the other hand, due to the structural requirements for RE
26 construction, the total horizontal length of the opening should not exceed one-third of the total wall length,

1 with a minimum distance of 0.6–1 m between the opening, 0.75 m from the corners and 0.45 m from above
2 the crown [56]. Moreover, according to Australian standards, the total opening area should not exceed 20%
3 of the total wall area [56]. Finally, four double glazed windows of 1.5 × 1.5 m² each were placed on three
4 sides – two windows on the south wall, one for the east and one for the west walls – resulting in a window-
5 to-wall ratio of 20.8% and 13.9%, respectively, for the façades.

6 A blind roll of bright aluminum was placed as a screen, located on the exterior side of the window
7 construction. It has a diffuse and visible solar reflectance of 0.6. The blind roll is activated when the indoor
8 temperature exceeds 23°C during summer from June to the end of August.

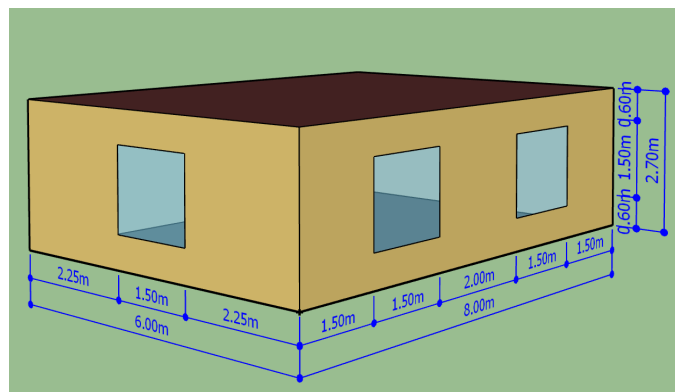


Figure 7: Test building.

9 The location for the building was chosen in Casablanca (Morocco), a city in a region where RE
10 constructions were traditionally built [57]. The annual rainfall precipitation is estimated at around 400 mL
11 and the city is a hot-summer Mediterranean climate zone (Csa) in the Koppen–Geiger Climate Classification
12 [58].

13 Due to mild winters, no additional insulation is required, enabling a better evaluation of the
14 contribution of RE to thermal comfort and fully exploring its behavior during summer.

15 4.1.2 Walls and construction materials

16 All four vertical walls of the building are composed of RE materials and their thickness of 50 cm was
17 defined according to international guidelines for RE construction and the current thickness of RE construction
18 in France and Europe [56,59]. Both the roof and the floor are made of a 15-cm-thick concrete slab, with 20
19 cm of glass fiber insulation on the exterior side of the roof and the interior side for the floor, as presented
20 in Figure 1. The internal layer of the roof is also covered with 1.2 cm of plasterboard ceiling. Table 2 presents
21 the thickness and the principal properties of each material used in the wall assemblies.

1 Material properties for concrete, plasterboard and glass fiber insulation were taken from the EP
 2 library. The properties of the RE materials (MIX, LIG, TAN, and WOOL) required for HAMT simulation were
 3 obtained by hygrothermal measurements described in the previous chapter.

4

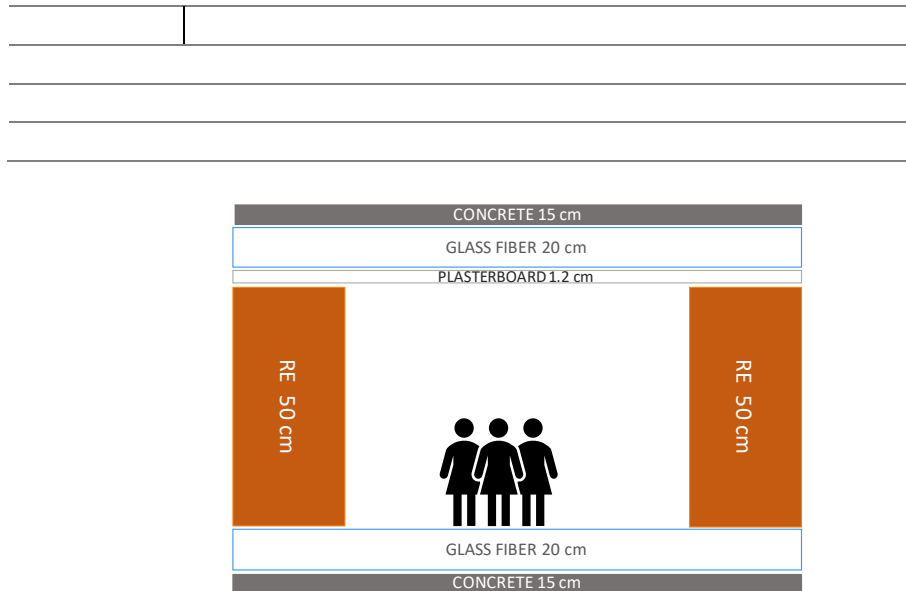


Figure 8 : Schematic representation of wall assemblies.

5

6 The thermal absorbance and solar (visible) absorbance of wall materials taken from the EP library
 7 are, respectively, 0.9 and 0.7. The same values were used for RE materials, because they are in line with
 8 reports from the literature and they enable easier comparisons between different configurations [10].

9

Table 1: Summary description of material properties used as input for HAMT simulations.

Material		RE MIX	Glass fiber ins.	Plasterboard
Density	kg/m ³	2190	80	250
Thickness	cm	50	20	1.2
Thermal conductivity	W/(m·K)	1.4-1.8	0.04	0.2
Specific heat	J/(kg·K)	737	850	840
μ1	-	11.1 (0.20 RH)	1.25 (0 RH)	8.3 (0 RH)
μ2	-	14.0 (0.54 RH)	-	-
Sorption isotherm	kg/m ³	36.07 (0.97 RH)	2.27 (0.97 RH)	23.4 (0.97 RH)
Porosity	m ³ /m ³	0.2-0.23	0.95	0.65

14

1 In one configuration, a vapor-tight layer of painting was added on the RE walls of MIX to show and
2 isolate the contribution of RE walls to vapor exchange. This combination was called “painted MIX” (P-MIX).
3 A layer of paint with an equivalent thickness (S_d) of approximately 10 m of air was considered on the internal
4 side of the vertical walls.

5 4.1.3 Occupancy scenario

6 The occupancy scenario is based on a residential building. The summer vacation is not considered
7 and the occupancy is maintained unaltered for all the weeks of the year. An ideal heating system is activated
8 throughout the year at a setpoint of 20°C, and only ventilation systems are used for natural cooling during
9 summer to investigate the efficiency of RE materials in mitigating overheating. No humidification or
10 dehumidification systems are used in order to better assess the effect of the RE walls on regulating the indoor
11 climate.

12 *Human occupancy and activities*

13 The residential building hosts three people, who are supposed to work away from home during
14 weekdays. The occupancy schedule reported in Figure 7 is inspired by a literature review performed by Labat
15 et al. [60] and Poirier et al. [61]. The time spent outside the home due to transportation and work amounts
16 to 11 h per day, Monday to Friday from 07:00 to 18:00, while during the weekend the occupants spend 8 h
17 per day away from home mainly during the afternoon (14:00–22:00).

18 *Sensible and latent load from occupants*

19 Human presence and human activities are responsible for the emissions of latent and sensible heat,
20 which were defined based on data from the literature [61]. Each person emits 55 g of vapor per hour when
21 awake, and 40 g of vapor per hour during the sleeping period, as shown in Table 3. The sensible heat
22 emissions due to the presence of people are set at 65 W, based on the ASHRAE Handbook indications [62].

23 Moisture emissions in residential buildings vary depending on activities, as shown, for example, in
24 Table 3 based on Poirier et al. [61]. In our case, the emissions of moisture due to cooking activities and
25 showers have a daily cycle, while laundry and laundry drying are concentrated during the weekend.

1 Preparation of lunch takes place only during the weekend since the occupants are absent during working
 2 hours.

3 Table 3 also presents the daily average moisture production, calculated as grams of moisture per
 4 person and as total production in the whole building. The sensible loads are generated by the heat released
 5 by human bodies, to which are added the emissions from electrical equipment. The residential building has
 6 seven pieces of electrical equipment related to daily life needs: fridge, oven, stovetop, microwave, TV, laptop,
 7 and lamp. Table 4 lists the average power of this equipment and the hours of use per day. The use of light in
 8 the dwelling is considered at approximately 5 h per day, with a lighting power equal to 1.4 W/ m² [63].

9 Moisture sources are vapor sources and are modeled as “steam production” in EP. It should be noted
 10 that the drying process for laundry is different, as it is a liquid source, and latent heat of evaporation must
 11 be considered. It is therefore represented in EP as a double source: a positive steam source and a sensible
 12 heat source that is set as a negative power of 139.85 W required during the process. In this way, the model
 13 considers an amount of sensible heat equal to the negative latent heat necessary to dry the wet clothes and
 14 is able to represent a source of liquid water.

15 *Table 2: Moisture emissions due to different activities in the residential building;* liquid water release. The last two rows*
 16 *report the results of the daily moisture emissions during the weekday and weekend.*

Activity	Vapor production (g/(h·person))	Duration /person
Sleep	40	8 h/weekday–9 h/weekend
Awake	55	5 h/weekday–7 h/weekend
Shower	240	10 min/day
Breakfast	378	15 min/day
Lunch	1134	30 min/day (only weekend)
Dinner	1896	40 min/week
Laundry	252	2 h/week
Laundry drying	136.8*	11 h/week
Daily moisture production	Weekday	Weekend
Residential (kg/(person·day))	3.12	6.65
Total residential (kg/day)	9.33	19.96

17

18 *Table 3: Use of electrical equipment for the residential scenario, based on Stefanoiu et al. [63].*

Electrical equipment	Average power (W)	Use (h/day)
Fridge	36	24
Oven	1040	0.43
Stovetop	778	1

Microwave	213	0.25
TV	64	2
Laptop/computer	90	2

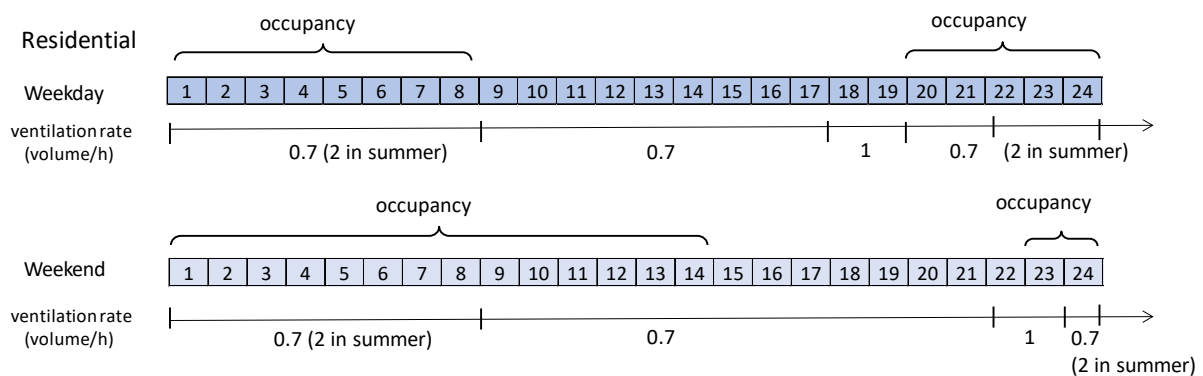
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2 *Ventilation*

3 Ventilation systems, adequate for occupancy scenarios, are designed to guarantee acceptable
 4 parameters of indoor air quality. In this study, the ventilation aims to remove a significant part of moisture
 5 production due to occupancy and to ensure a high air change rate during summer nights to cool down the
 6 building that collects heat during the hot summer days. Infiltrations are assumed to be included in the
 7 ventilation rate.

8 The residential building hosts different activities during the day, and, consequently, different
 9 moisture production rates. The ventilation is adapted not only to the needs of people but also to the need of
 10 evacuating the peak moisture due to specific activities such as cooking. The highest level of ventilation
 11 suggested by Standard EN15251 guidelines considers 10 L/s/person, which when adapted for three residents
 12 is approximately equal to 0.8 volume/h (108m³/h) [64]. The proposed ventilation rate is set to 1 volume/h
 13 during cooking (the activity that produces the highest rate of moisture), and 0.7 volume/h during other
 14 activities.

15 A higher ventilation rate is necessary during summer nights to remove the heat stored in the building
 16 due to the high temperature reached during the day. From 22:00 to 08:00 the ventilation rate is set at 2
 17 volume/h (277.2 m³/h) from June to August. The complete ventilation schedules are presented in Figure 7.



1 4.1.4 Initial conditions and run period

2 The initial moisture content of materials w (kg/kg) must be specified in order to start the simulation.
3 An additional study was carried out to set the initial moisture content at full operative state. Simulations
4 were performed over several years in order to assess the impact of initial conditions. Since the difference
5 between the second and third year was negligible (less than 5%), the run period was set up to 2 years. The
6 results were analyzed in the second year of simulation only, in order to avoid any possible influence related

Figure 9: Occupancy and ventilation rate schedule, for weekdays and weekends.

7 to the initial conditions.

8 4.2 Results and discussion

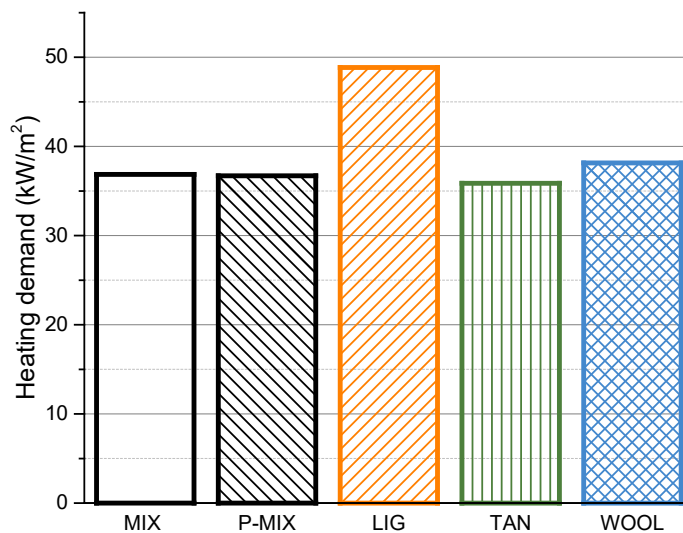
9 The results of the simulation are analyzed from different points of view: the heating demand, the thermal
10 comfort reached with natural ventilation during summer, and the contribution of walls to the passive
11 regulation of indoor air quality. The analysis of the global annual sensible and latent heat balances
12 complements the study and allows for the quantification of the contribution of RE walls to global heat and
13 moisture gains and losses in the different configurations. These global balances are based on averaged yearly
14 values of different energy flows. The balance of sensible heat includes the energy required to increase or
15 decrease the indoor temperature, while the balance of latent heat considers the gain or loss that increases
16 or decreases the moisture content of the indoor air. The sensible and latent contribution from occupancy
17 considers both the heat produced by people and the heat from electrical equipment. The heating system has
18 no impact on humidification or dehumidification and, consequently, it is considered only in the analysis of
19 sensible heat balance.

20 In the following, the energy fluxes in the balance are described considering as gain (or loss) the
21 increased (or decreased) latent or sensible heat of the indoor air. Of course, instantaneous heat gain in the
22 transient state is generally different from heat loss, since the difference represents the evolution of the
23 system energy (storage). However, by averaging the different fluxes over a significant period (here, for 1
24 year), energy storage can be neglected.

1 4.2.1 Heating demand and sensible heat

2 Figure 8 reports the annual heating demand for the reference RE (MIX), the bio-stabilized RE
3 materials (LIG, TAN, and WOOL), and the painted RE (P-MIX). All values are in the range of 36–38 kW/m²,
4 except for RE stabilized with lignin sulfonate (LIG), which reaches 49 kW/m². LIG shows an increase in heating
5 demand of 32.5% compared with the control samples, while for TAN and WOOL there is a decrease of –3.5%
6 and –3, respectively. The higher heating demand of LIG is probably due to the thermal conductivity that is
7 higher by about 30% than that of MIX, TAN, and WOOL. P-MIX does not present a significant variation in
8 heating demand compared to MIX.

9 Considering sensible heat balance, the results for the P-MIX materials TAN and WOOL are very similar



10 to those found for MIX. The heating system and occupancy are the main sources of sensible heat gain for the
11 indoor air volume in all the configurations, representing 30% and 40%, respectively, of the sensible heat gain.
12 The heating system is activated mainly during winter with 20°C setpoint, and therefore the daily occupancy
13 has a major contribution to the heating gain due to its continuity all year long. The remaining significant
14 contributions are made by the floor and the roof, representing 17% and 7%, respectively, of the sensible heat
15 gain. The floor gives off sensible heat to the air due to the solar radiation that is transmitted through the
16 windows and heats the floor surface. The remaining contributions to the heat gain are attributable to the
17 walls and windows.

Figure 10 Annual heating demand.

1 Ventilation and transfer through the walls are the main causes of sensible heat loss. The heat loss
2 through RE walls represents approximately 51% of the total sensible heat losses; the remaining contribution
3 is due to the ventilation that is associated with about 32% of heating losses. The remaining contributions to
4 the sensible losses are due to the other walls (including the roof, floor, and windows).

5 Heat loss due to ventilation mainly occurs during summer nights, in order to efficiently cool down
6 the room without heating the air during the day. The north wall has the highest heat loss (20%) because of
7 its larger surface and its orientation that limits solar gains, while the other walls have heat losses of about
8 10% each. The reduced losses are due to position of the sun but also to the reduction of the available wall
9 surface area due to the presence of windows, which are two on the south wall, one in the east and one on
10 the west side.

11 LIG exhibits a higher sensible loss through the walls, about 55% versus 50% for the other
12 configurations, while the losses due to ventilation are slightly reduced (28%). This is a consequence of higher
13 heating demand for LIG: the lower thermal resistance generates higher heat losses through the walls and, as
14 a result, the relative contribution due to ventilation is slightly reduced.

15 4.2.2 Summer thermal comfort

16 This section presents the thermal comfort analysis, starting with a comparison of the number of
17 hours where the room temperature is over 28°C (considering the whole year, 24 h/day, including the period

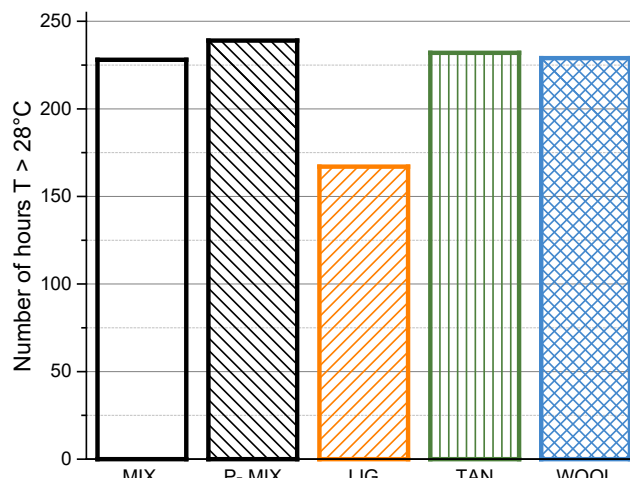


Figure 11: Number of hours where the room temperature is over 28°C (annual values).

1 of unoccupancy). These data provide the first information on how often the room is in a condition of elevated
2 temperature (Figure 9).

3 Although the risk of overheating is mitigated by the ventilation system that controls the airflow rate
4 from the outdoor environment, the building has around 230 h/year with a temperature over 28°C. The
5 different materials for the vertical walls -- MIX, P-MIX, TAN, and WOOL -- yield similar values. The highest
6 number of hours is shown by P-MIX, with an increase of about 5% compared to MIX. This result suggests that
7 limiting the moisture buffering of the RE walls may reduce thermal comfort during summer. On the other
8 hand, no evidence of this behavior is given by the data of temperature at a daily scale (Figure 12). Conversely,
9 LIG has the lowest number of hours that exceed 28°C: 167 h versus 228 h for MIX, a reduction of about 27%.
10 The different behavior of LIG may be due to the different thermal conductivity, higher thermal diffusivity,
11 and lower thermal resistance. An additional investigation was conducted to check the possible influence of
12 the threshold effect. This was verified and excluded by repeating the calculation with two different threshold
13 values (29°C and 27°C in addition to 28°C). In all cases, the difference between the number of hours with a
14 temperature higher than the threshold for the different materials was maintained.

15 The boxplot in Figure 10 shows the indoor temperatures for the configurations with different wall
16 materials during summer (June 22 to September 22). In all the configurations, the median and average
17 temperatures in summer are around 26°C and the indoor temperature ranges between 23°C and 33°C. LIG

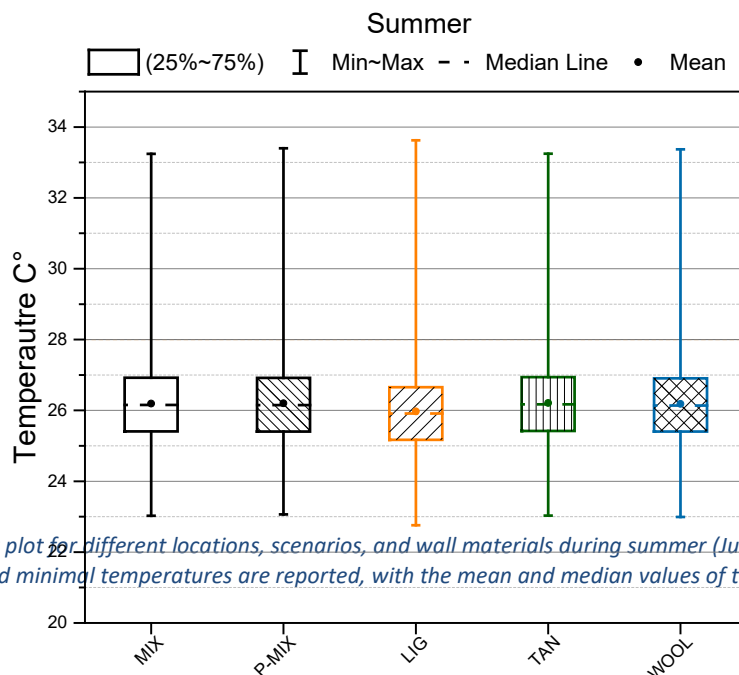


Figure 12: Temperature box plot for different locations, scenarios, and wall materials during summer (June 22 to September 22). The maximal and minimal temperatures are reported, with the mean and median values of temperature.

1 has a slightly higher range of temperature variability, while the median temperature is marginally lower than
2 for the other configurations. This behavior confirms the previous results on the number of hours with a
3 temperature higher than 28°C, showing that LIG has slightly reduced thermal resistance. Consequently, the
4 indoor temperature can follow the outdoor temperature faster, reaching higher values during the day but
5 also cooling down the walls quickly during the night.

6 To better illustrate the physical behavior, Figure 11 presents the indoor and outdoor temperatures
7 of the configurations with MIX walls. Only MIX is reported because the differences between the different
8 materials are not appreciable at this scale. The outdoor temperature shows large daily variations, with an
9 amplitude in the range of 10°C. In all the configurations, the indoor temperatures have a similar daily
10 variation, within a range of 4°C. The inertia of RE maintains a stable temperature in the indoor environment
11 during the day. The night ventilation increased from 22:00 to 08:00 (2 volume/h), from June to August,
12 favoring cooling during the night (when the outdoor temperature is lower) to release the heat stored during
13 the day. Considering the graph in Figure 11, some canicular events can be identified, where the temperature
14 remains exceptionally high for 2–3 days consecutively. In this case, the inertia of the building is particularly
15 useful for avoiding extremely high temperatures, maintaining a difference of 10°C between the indoor and
16 outdoor environments during the highest peak of temperature in the day. A similar behavior was observed
17 by Becket et al. [23] during summer canicular events in an RE house built in the hot-arid climate of Western
18 Australia. Fernandes et al. [65] also presented the results of a measurement campaign in southern Portugal
19 on a vernacular RE building. They found more variability in the temperature buffering, with recurrent values
20 of around 8°C difference between outdoor and indoor conditions, and exceptionally a difference of 11°C.
21 Soudani [13] observed a maximal buffering in temperature equal to 9°C for an RE house located in Isère,
22 south-eastern France. The highest daily difference of 15°C was observed by Bassoud et al. [66] in mud bricks
23 in adobe building in Adrar (southern Algeria), classified as arid desert areas. These examples illustrate the
24 good performance of earthen houses, thereby guaranteeing thermal comfort in summer. This behavior may
25 be particularly beneficial in a scenario of climate change, where canicular episodes are expected to be
26 recurrent. Moreover, the ventilation schedule may be adapted and augmented to allow for faster cooling of
27 the material on the days following the canicular episode. Figure 12 reports the daily variation of temperature

1 of the outdoor and indoor environments, compared to the variation of the average water content in the
 2 south wall. The graph compares 3 days and only the results of MIX, P-MIX, and LIG are reported because at
 3 a daily scale the differences between other materials are not appreciable. Therefore, the results achieved
 4 with MIX are considered representative of TAN, WOOL, and P-MIX results. The P-MIX temperatures almost
 5 overlap the results of MIX. LIG shows slightly lower temperatures in the indoor environment, in particular
 6 during the day, while the night temperatures are probably more uniform due to the higher ventilation rate.
 7 These differences are still minimal, but their impact is evident in Figure 9 and Figure 10 that present statistics
 8 at a seasonal scale, in particular for the number of hours at temperatures higher than 28°C. The oscillation
 9 of temperature in the external environment is $\pm 5^\circ\text{C}$, while for both cases the indoor environment is
 10 maintained in a range of $\pm 1.5^\circ\text{C}$.

11 Considering the wall moisture content, all the materials show similar values, between 0.385% and
 12 0.398%. PMIX shows a slightly lower moisture content than MIX and LIG, with a daily cycle of moisture and
 13 adsorption release of slightly lower amplitude. Since the indoor environment is the main source of moisture,
 14 the presence of the painting reduces the adsorption of water vapor by the wall, both as storage and buffering.
 15 Observing the case of P-MIX, at daily scale the impact of using a layer of painting on the indoor temperature
 16 is not remarkable, while at the scale of 1 year some differences are evident (Figure 9). The daily fluctuation
 17 of moisture content in the walls is low, reaching its maximal value in the morning around 09:00–10:00; then,
 18 due to temperature rise, the evaporation of moisture occurs until 18:00–19:00, when the minimum value is
 19 reached.

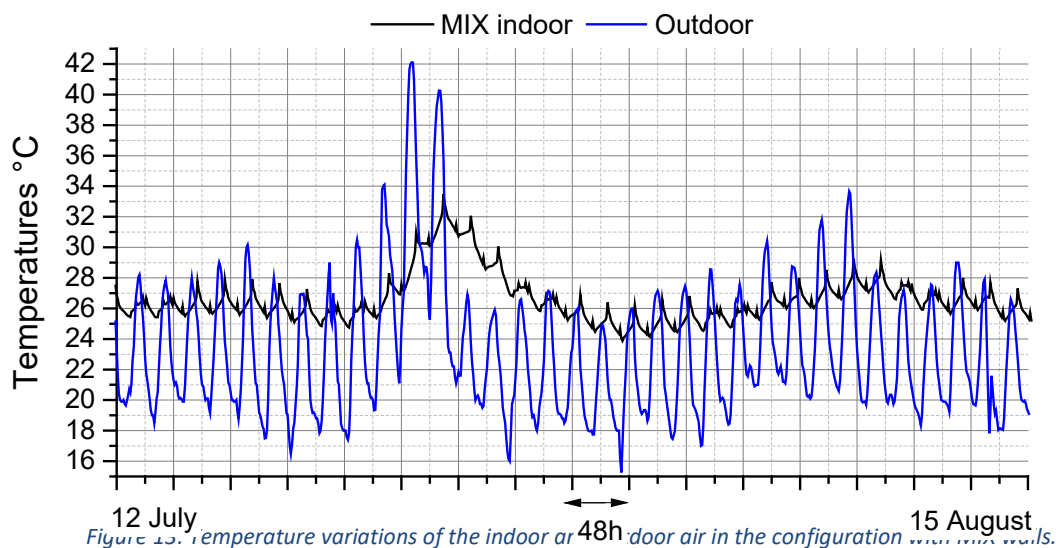


Figure 13. Temperature variations of the indoor air in the configuration with MIX walls.

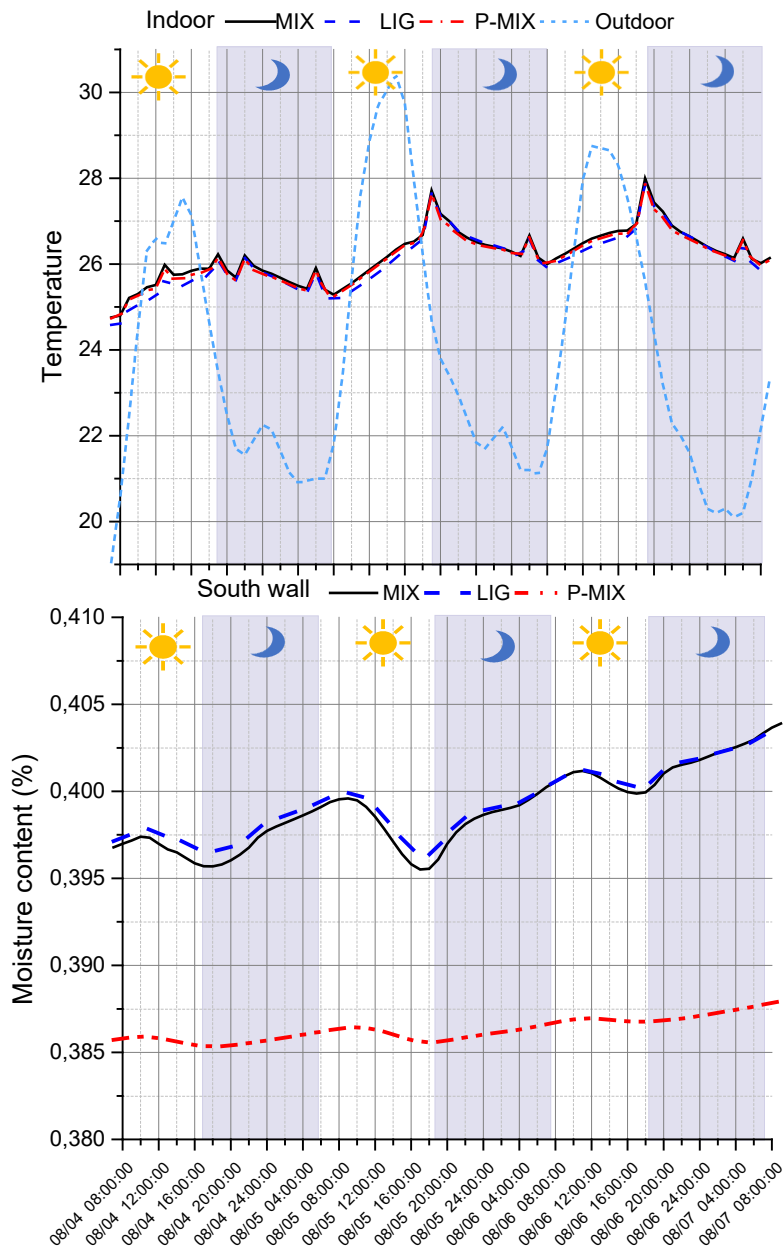


Figure 14: Daily variation of temperature in indoor and outdoor environment, with the indoor surface temperature variation, compared with the moisture variations in the south wall.

1 Observing the daily temperature variation during summer, it is possible to identify a daily thermal lag
 2 that makes the indoor environment reach the maximal temperature when the outdoor temperature is
 3 already descending, with a delay of about 5 h. As shown in Figure 12, the maximal outdoor temperature is
 4 reached around 14:00–15:00, while the maximal indoor temperature is reached at 17:00. A similar thermal
 5 lag (6 h) for RE walls was previously measured by Soudani et al. [10,13], for an RE house with a wall thickness
 6 of 50 cm. Bassoud et al. [66] also measured a phase difference of 4 h between the indoor and outdoor
 7 temperature for an adobe house in Algeria, in the region of Adrar. For a broader case study consideration,

1 Beckett et al. [67] present a range of RE thermal lag values, which can vary from 1 to 10 h, depending on the
 2 density and thickness of the walls but also on the geometry of the dwelling and the occupancy scenarios.

3 4.2.3 Indoor air humidity and latent balance

4 The European standard EN15251 for indoor air quality simulation [64] indicates different ranges of
 5 RH comfort zones for different categories. Category II (from 25% to 60% RH) was chosen to evaluate the
 6 comfort range of RH in the results of the simulation. The standard considers a heating set point at 20°C and
 7 a cooling setpoint at a temperature of 26°C; the latter is absent in the present study and only substituted by
 8 a ventilation system [64]. Owing to the absence of a cooling system, the maximal temperature and humidity
 9 reached are higher in the present study.

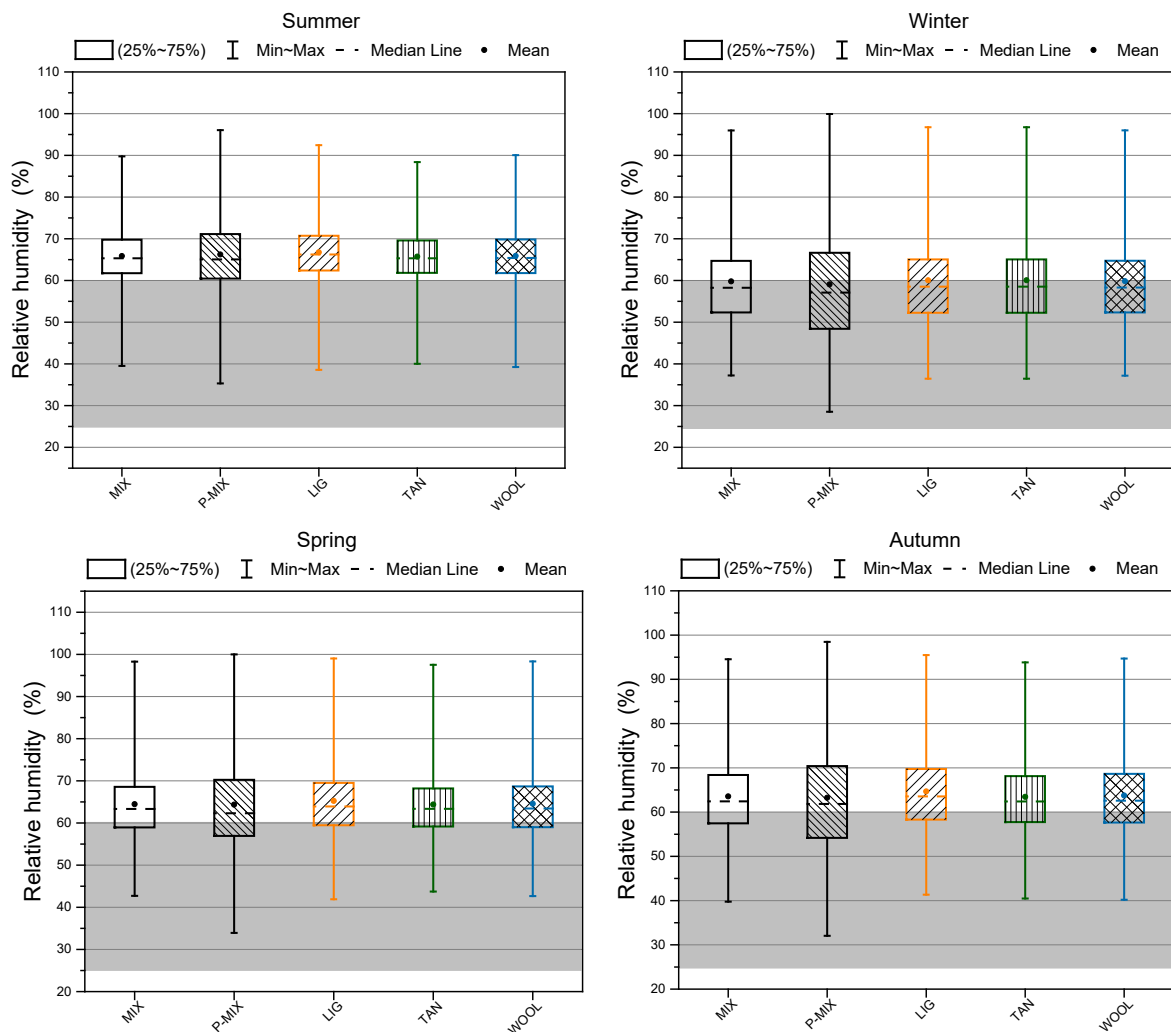
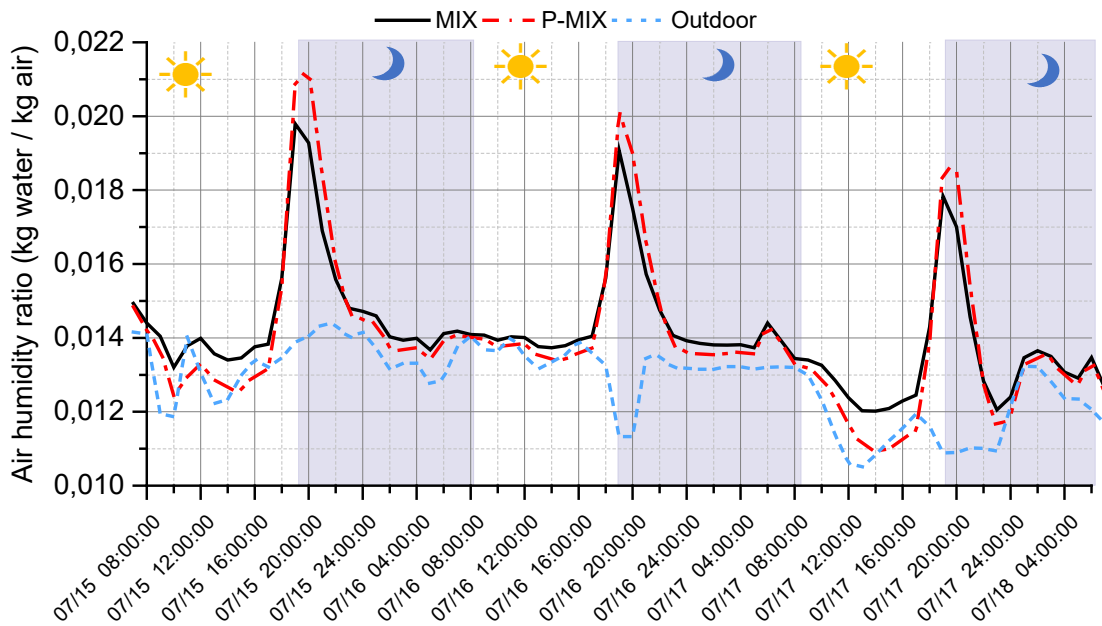


Figure 15: Box-plot of the seasonal relative humidity values for the different configurations. Winter (December 22 to March 21), summer (June 22 to September 22), spring (21 March to June 22), and autumn (September 22 to December 22).

1 Figure 13 presents the annual indoor humidity, during spring (March 22 to June 21), autumn (June
 2 23 to September 21), winter (December 22 to March 21), and summer (June 22 to September 22), with a
 3 gray band to show the range of the comfort zone in accordance with the European standard EN15251. The
 4 different materials of the vertical walls – WOOL, LIG, and MIX – yield similar values. By contrast, P-MIX
 5 presents higher extreme values out of the comfort zone, as a consequence of the reduced buffering capacity.
 6 For TAN, the highest values for RH are slightly reduced in comparison with the other materials, in particular
 7 during summer and spring.



8
 9 *Figure 16: Weekly variation of air humidity ratio in the outdoor climate of Casablanca and the indoor environment with*
 10 *MIX (representative of LIG, TAN, and WOOL configurations) and P-MIX*

11
 12 To provide more detailed insight into the physical behavior,
 13 Figure 14 reports the daily variations of the outdoor and indoor humidity ratios for P-MIX and MIX
 14 configurations. The daily peaks of moisture are related to cooking activities during dinner. P-MIX shows the
 15 widest daily variation in humidity ratio, while MIX shows a slightly better ability to reduce these peaks in
 16 moisture. The impact of the other RE materials (not shown in the graphs for the sake of clarity) is very similar.
 17 WOOL and LIG present the same cycles as MIX, while TAN reduces minimally the variation of indoor humidity.
 18

1 At a yearly scale, occupancy is the principal contribution to the latent gain, due to the anthropic
2 presence and activities that produce moisture. It accounts for about 67% of the latent gain for MIX, TAN, LIG,
3 and WOOL, while the desorption of RE walls represents 31% of the latent gain contribution. For the P-MIX
4 configuration, by contrast, almost all of the latent gain is due to occupancy activities (98%). Similarly, the
5 latent loss is principally attributed to ventilation (93%) while RE walls for MIX, TAN, LIG, and WOOL contribute
6 about 6% to latent loss. Again, P-MIX walls have an almost negligible contribution to moisture buffering and
7 they do not contribute to latent losses. These results show clearly that RE walls without paint adsorb and
8 release water vapor, contributing to buffer moisture variations in the indoor environment.

9 5 Conclusions and outlook

10 Three biopolymers (lignin sulfonate, tannins, and wool) were tested as RE stabilizers. The
11 modifications in the hygrothermal properties at the material scale were found to be significant only in the
12 case of thermal conductivity of RE stabilized with lignin sulfonate, which was increased by about 30%
13 compared with the control samples. The hygrothermal characterization was used to describe the material
14 properties necessary as input data for a whole-building simulation using a combined heat and moisture
15 transfer model in EnergyPlus. Various configurations were tested with vertical walls made of the different RE
16 stabilized materials, considering a warm climate with a residential scenario for the occupancy.

17 The use of RE walls stabilized with lignin sulfonate results in an increment of the heating demand by
18 about 32%, probably due to the higher thermal conductivity, while the thermal comfort is slightly improved.
19 At a yearly scale, the uninsulated RE walls represent approximately 50% of the total sensible heat losses. All
20 RE walls are effective in reducing temperature oscillations, particularly in the case of canicular events, where
21 the indoor temperature can be reduced by up to 10° compared with the outdoor temperature. The
22 ventilation during summer nights was particularly effective in evacuating the heat stored in the walls during
23 the day.

24 The indoor humidity benefits from the passive regulation by RE walls, whereas applying paint on the
25 indoor surface (painted MIX) reduces this effect significantly with a higher number of hours out of the
26 comfort zone. On a yearly scale, RE walls (except painted MIX) represent 31% of the latent gain (desorption)

1 for indoor air, while the contribution of RE to the latent losses (adsorption) is only about 6%; indoor moisture
2 is removed mainly by ventilation. The contribution of the walls to vapor exchange is remarkable when
3 compared with the configuration with paint, which should be avoided in the case of RE walls.

4 Concluding, the strategy used to characterize the material properties and simulate their impact on
5 the whole-building scale offers a new interesting possibility of analysis and investigation of RE materials, in
6 particular using HAMT simulation to compare materials under realistic climate conditions and occupancy
7 scenarios. The use of HAMT simulations combined with characterization at the material scale provides a more
8 extensive investigation approach, which opens the possibility of research in different directions, promoting
9 the study of the impact of hygrothermal properties and the use of RE materials for different climates and
10 occupancy scenarios.

11

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