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Experimental research to evaluate the percentage change of thermal and mechanical performances of bricks in historical buildings due to moisture

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HIGHLIGHTS

- It's shown that the materials characteristics vary depending on their wet content.
- The presence of moisture inside the walls causes the loss of thermal insulation.
- Thermal conductivity of materials increases even if the water content is low.
- The production process of bricks influences their performances.
- The energetic material's performances are different from theory when they're wet.

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ABSTRACT

The presence of moisture inside building materials decreases their thermal and mechanical performances. Knowing the variability of these properties as a function of saturation is essential both to evaluate the aging of the material over time, and to characterize the durability of the new materials introduced in the restoration.

The study presents an experimental research, carried out on some bricks produced for the restoration of historical buildings in Madrid, aimed at evaluating the percentage change of thermal and mechanical strength of these materials due to the presence of water in different saturation levels.

1. Introduction

Traditional building materials consist mainly of a porous structure with small interconnected capillaries [1–4]. This feature makes them particularly vulnerable to the presence of water which enters in both liquid and vapour form due to various factors and forces acting on the water/masonry system [5]. The most evident sign of the presence of water inside masonry is provided by the formation of stains, molds, exfoliation of the pictorial layers and spraying of the finishes. The effects the phenomenon produces on the reduction of masonry's mechanical and thermal performances are less evident by visual inspection, but considerably more damaging.

Experimental studies carried out on both natural stones and bricks have shown that mechanical characteristics vary depending on wet content, with a 50% loss of uni axial compression strength from dry to saturated condition calculated on quartzitic sandstone [6] and even more, around 78%, calculated in Greensand [7].

The laboratory survey campaigns carried out by researchers of the University of Sannio and the University of Naples Federico II [8], on seven different types of tuff, have recorded that the medium compressive strength of these materials in saturated and semi-saturated conditions can experience a reduction of up to 40% compared to the values obtained on specimens tested in dry conditions.

Similar studies carried out by the researchers of the University of Bologna [9] on clay elements in dry and wet conditions and on

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walls made of both lime and cement mortar, have again observed a reduction in the compressive strength of the material in wet conditions.

Researchers at University of Turkey found that the reduction of mechanical properties of local clay-bearing rock, corresponding to a water content increase, was even higher than that found in previous studies [10].

In addition to affecting the mechanical strength, the filling of capillary pores with water alters the physical characteristics of masonry blocks: researchers of the Universidad Politécnica de Madrid, at the beginning of the 90s [11], set out to assess the capacity of expansion by moisture in ceramics; in their investigations, they showed that the presence of water produces an increase in weight and volume of the material which varies depending on its mineralogy and cooking. On completion of their tests, carried out on 18 ceramic samples, subjected to different vapour absorption conditions, a maximum value of the material expansion close to 0,6 mm/m was recorded; this was reached in variable times depending on the ceramics' manufacture process. The mathematical equation which describes expansion of material as a function of the clay cooking time is given by the *Power-Law of moisture expansion kinetics* developed by the researchers C. Hall and W.D. Hoff Eq. (1):

$$\varepsilon = b + a\,t^{1/4} \tag{1}$$

Here, ε represents the moisture expansion voltage; $b$is a constant describing the expansion that takes place immediately after cooking and that, depending on the environment hygrometric conditions, can be reversible; finally, the parameter $a\,t^{1/4}$ (where a is a constant, a material property which describes the magnitude of the progressive long-term moisture expansion, and t is time) describes the long-term expansion due to the chemical reaction between clay and moisture, defined as *moisture expansivity*, which can be reversed only by baking the material at 500 °C [12].

Furthermore, the presence of moisture inside the walls causes a vulnerability factor for the energy performance of the building envelope, in terms of loss of thermal insulation and increased conductivity when the material's saturation increases.

The energetic analysis of existing buildings carried out with different methodologies [13], focuses on the solution of equations simulating building thermal behaviour. Many of these studies, including those conducted by the University of Roma TRE [14], highlight a strong discrepancy between the energy performance of some technological elements, derived from accurate modeling of the building, and real behaviour detected in situ [15,16]. In some occasions, researchers found that software programs introduce corrective parameters which tend to underestimate or overestimate U-values of traditional building walls; there are many factors which affects thermal behaviour of this kind of masonry, which can be related to its inhomogeneity and thickness [17]. Many researchers believe that the in situ U-value is not straightforward to define, due to the long periods of measurements and to the substantial level of skills required for the analysis of the data; in addition, many boundary conditions must be taken in account to give a correct interpretation of the data recorded [18]. As a result of the difference estimated between calculated and measured U-values, some researchers recommend that an adjustment of theoretical data must be applied according to the "Delta-U" terms observed [19].

Researchers of the University of Salford in the United Kingdom found that in some cases the difference between design values and those directly measured on masonry, defined as *prediction gap*, exceeds 18%; this discrepancy is attributed to the extreme variability of the air permeability parameters of the building envelope, due also to the moisture inside the wall, and results in a substantial difference between the theoretical consumption of construction and the real ones [20,21].

In order to schematize the real behaviour of the masonry in environmental conditions, quantifying the variability of the performances of building materials due to the presence of moisture is essential. This explorative analysis must also be developed in order to characterize those new materials introduced in the context of repairs or replacement of damaged masonry elements.

Research carried out on wood-based materials has shown that thermal conductivity increases almost linearly with moisture content at a given temperature and with greater variability as temperature increases [22]. A similar study aimed at measuring thermal conductivity value of autoclaved aerated concrete in 0 °C–45 °C temperatures and 0%–41.5% moisture content has shown that, due to the porosity of the analysed material, its thermal conductivity changes significantly with moisture and temperature; this happens obviously because the thermal conductivity of moist air is higher than that of dry air [23].

However, no studies have been found which analyses thermal behaviour of bricks at different moisture levels. For this purpose, an experimental survey was conducted to assess the effect that moisture has on this material in terms of loss of thermal and mechanical resistance.

The experiment is part of a wider research developed in partnership between the University of Naples Federico II and the Polytechnic University of Madrid, which explores the issues of rising damp and investigates innovative and non-invasive methods of diagnosis and rehabilitation of wet masonries in historical buildings [24,25].

This paper focuses on the results of the experimental campaign conducted on the solid bricks produced by the factory "Ladrillos Artesanos" located in the municipality of Navas de Oro, part of the Spanish Autonomous Community of Castilla y León. The company is specialized in the production of handmade bricks "made the ancient way" which are used in the restoration of historical architectures to replace the damaged or degraded parts of buildings.

2. Material and methods

2.1. The use of bricks in Madrid's architectural tradition

The architecture style with exposed bricks, representative of many Spanish monuments that merge the Romanesque and Gothic tastes with Arabic art, is classified as *neo-mudéjar*. Thanks to the possibility of creating new different masonry textures with the arrangement of the bricks in the plan, named *aparejo en el ladrillo* was adopted throughout Europe over the centuries [26].

Nowadays, in order to respect this architectural style, bricks used to replace the damaged parts of ancient buildings are manufactured in shapes like the original ones, whose dimensions vary according to the historical era in which they were built [27]. Until the 19*th* century bricks were made using human proportions. The Madrid Ordinance of 1820 established measures of *"seventeen fingers in length, thirteen in width and three fingers of average thickness*", corresponding to elements of size 31.5 cm × 24 cm × 6.5 cm [28]. The subsequent Ordinance of 1857 provided a proportion between the sides of 3: 4, with size elements of 29,6 cm × 20,9 cm × 3,7 cm. The Construction Treaty drawn up in the first half of the 20*th* century defined the proportions between the sides of the element but did not specify the relationship with the height [29]. Only after the industrialization process of the 1920s the production of bricks started following standard shapes: in 1942, in accordance with the International Metric System, it was decided to align the size of the bricks to the measures of 25 cm × 12 cm × 5 cm.

2.2. Laboratory testing

For the tests two types of bricks have been used: both are made with the same composition of clay and water, they only differ in the way they are fired. In fact, some samples are dried in open air, with the traditional method, and for this reason are distinguished with the letter T; the others are fired in a biomass oven, following a modern method, denoted with the letter M Fig. 1.

The investigated parameters:

Two prismatic elements of size 4 cm x4 cm x16 cm have been obtained from each brick, with a total of 24 specimens which have been subjected, as a preliminary step, to a physical characterization carried out by microscopic observation. The comparison between the images with 225 × enlargement shows that the solid matrix of the bricks dried to air T Fig. 2 is less compact than the solid matrix of those fired in oven M Fig. 3.

This is confirmed by the measurement of the two specimens' physical characteristics: the ratio between the volume of solids and the volume of voids, obtained by calculating the volume occupied by water in complete saturation conditions, shows that the average porosity of T samples is greater than the average porosity of M samples. The calculation was based on an arithmetic mean of the values obtained on the twelve type-T samples, indicated by the abbreviation T_{1-12} and type-M samples, indicated by the abbreviation M_{1-12} (Table 1).

The difference between the two types of samples T and M has also been assessed by calculating the water absorption coefficient according to UNI EN 772-11 [30] applying Eq. (2):

$$\frac{m_d - m_w}{S_s\sqrt{t_{sat}}} \times 10^6 \left[\frac{g}{m^2\, s^{0,5}}\right] \tag{2}$$

where m_d represents the weight of the dry material, m_w represents the weight of the wet material, S_s is the side surfaces of the blocks dipped in water and t_{sat} the total time needed for the complete saturation. Consistently with the previous data, there is an absorption coefficient higher of 15% in the air-dried than in the oven-fired samples.

Moreover, a direct non-invasive measurement of thermal conductivity has been carried out for each batch of samples conditioned to a given saturation degree. The instrument used, C-therm TCi system, applies the Modified Transient Plane Source (MTPS) technology, standardized by ASTMD7984 [31]. The technique uses a heat reflectance sensor that is emitted through the spiral plate at its top, in contact with the material Fig. 4.

The temperature increase between the test piece and the sensor causes a change in voltage of the sensor inversely proportional to the material thermal conductivity: the voltage increase is faster for thermally insulating materials.

Fig. 1. Production phases of bricks and air drying.

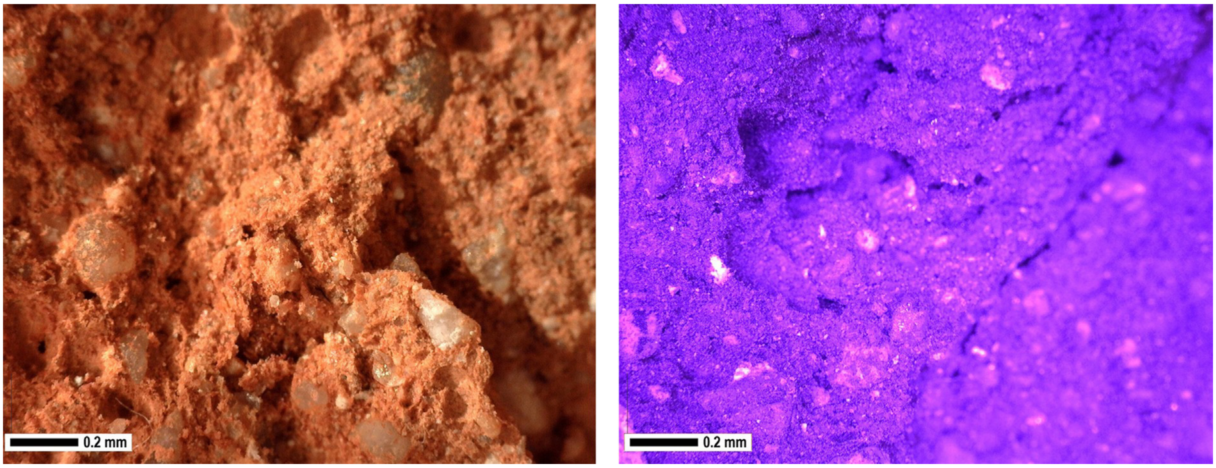

Fig. 2. Microscopic images of T-samples.

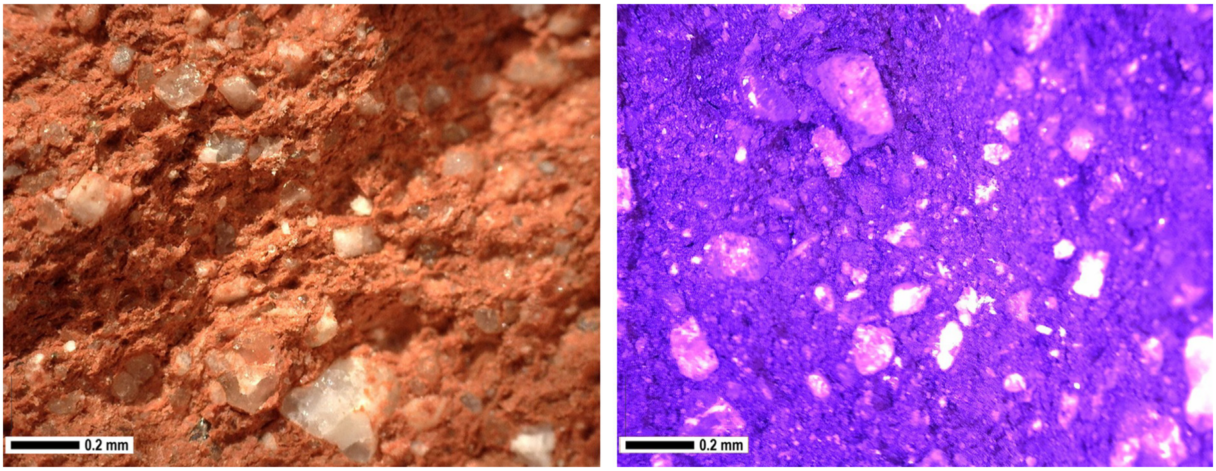

Fig. 3. Microscopic images of M-samples.

Table 1
Physical properties of the material.

	Volume V [cm^3]	Volume of voids V_v [cm^3]	Volume of solid $V_s = V - V_v$ V_s [cm^3]	Porosity $n = V_v / V$ n	Porosity index V_v / V_s e
T_{1-12}	256,00	60,42	195,58	0,24	0,31
M_{1-12}	256,00	51,02	204,95	0,20	0,25

Fig. 4. Equipment used for measuring thermo-physical properties.

In the specific case of measurement on solid material, in order to limit the contact resistance between the test piece and the sensor, a thin layer of Wakefield 120 paste has been applied: this is a known strength contact agent which applies a correction factor to the measurement made. The equipment, therefore, allows reading in real time, through the software interface, the thermo-physical properties of diffusivity, thermal conductivity (calculated from thermal effusivity), thermal capacity (or specific volumetric heat), isolation value and penetration depth of the sample under investigation.

Finally, the groups of samples were subjected to mechanical strength tests according to UNI EN 12372 [32] and then to uniaxial compression according to UNI EN 772–1 [33] Fig. 5.

Methodology for conditioning samples

The samples were divided into groups of 3, setting for each one a different saturation level: an average of the test values recorded for each group was considered.

The bibliographical references concerning similar studies suggested testing the specimens under dry (S = 0%), semi-saturated (S = 50%) and saturated (S = 100%) conditions [8,9]. The calculation was based on an arithmetic mean of the values obtained: on three type-T samples $T_{10} - T_{11} - T_{12}$ (indicated with T_{10-12}) and three type-M samples $M_{10} - M_{11} - M_{12}$ (indicated with M_{10-12}) carried in dry conditions (S = 0%); on three type-T samples $T_4 - T_5 - T_6$ (indicated with T_{4-6}) and three type-M samples $M_4 - M_5 - M_6$ (indicated with M_{4-6}) carried in semi saturated conditions (S = 50%); on three type-T samples $T_1 - T_2 - T_3$ (indicated with T_{1-3}) and three type-M samples $M_1 - M_2 - M_3$ (indicated with M_{1-3}) carried in saturated conditions (S = 100%).

Furthermore, considering that limited amounts of moisture inside the walls can have a significant impact on the alteration of thermal insulation, causing a sudden lowering of the thermo–hygrometric comfort inside the internal environments, it was decided to introduce a further class, conditioning the samples also

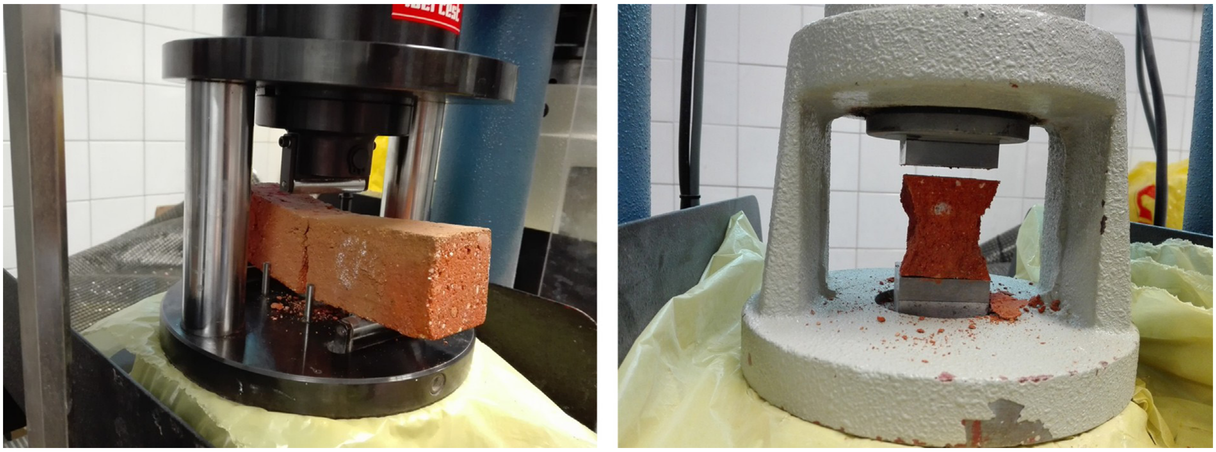

Fig. 5. Equipment used for bending and compression mechanical strength tests.

at a degree of saturation between 15% and 30%, which is a level similar to the conditions in which a masonry usually works.

The arithmetic average of the values has been obtained on three type-T samples $T_7 - T_8 - T_9$ (indicated with T_{7-9}) and three type-M samples $M_7 - M_8 - M_9$ (indicated with M_{7-9}) carried in saturation conditions of $S \approx 25\%$ Table 2.

The conditioning of samples was reached according to the weight method described by UNI 11085 [34], based on the principle of the mass loss of a sample after drying, and has been applied using the following equipment:

- Balance with accuracy of 0.01 g
- Electric laboratory oven capable of maintaining the drying temperature with a stability and uniformity of 2 °C
- Dryer containing silica gel with cobalt chloride indicator

After recording the weight of the 24 specimens under environmental conditions, they were all subjected to 4-h drying cycles into the oven and cooling in the dryer until the environmental temperature was reached. At the end of each step the samples were weighed. The test has been completed when the difference between two subsequent weighs was less than 0,1%, so finding the dry weight of the samples. The dry weight was reached up in 24 h after two cycles in oven at 105 °C and dryer leaved at the environmental temperature of 25 °C.

Subsequently, the samples were completely dipped in water until the constant weight was reached, thus determining the wet weight for each-one. The wet weight was reached up in 120 h dipped in the water at 22 °C. The percentage of water content absorbed$C_w$was obtained applying the Eq. (3):

$$C_w = \frac{(w_w - w_d)}{w_d} \times 100 \tag{3}$$

where w_w represents the weight of the wet material and w_d represents the weight of the dry material.

On T_{1-3} and M_{1-3} specimens thermal and mechanical properties were measured at S = 100%. The other samples were placed back in the oven until the intermediate values of moisture were reached: starting from the wet and dry weight calculated for each sample it has been possible to calculate the maximum amount of water that each sample could adsorb. Subsequently, hypothetical weights corresponding to different moisture levels were determined Table 3.

In order to ensure a uniform distribution of the wet content within the tested elements, before each test the samples were placed in thermo-hygrometric equilibrium for 2 h in the humid chamber (with a temperature in the range 20 °C–22 °C and relative humidity of 40%–60%). Although the measurements of thermal conductivity are relatively fast to carry out, the samples have been weighted before and after the test to ensure the maintenance of the same weight (the same quantity of water).

The moisture level S = 0.5 was reached up after 2 h in the oven while the level S = 25% was reached up after 3.5 h.

Finally, the test T_{10-12} and M_{10-12} specimens were restored to the condition S = 0% by drying in the oven until the initial dry weight was reached up (after 20 h) and evaluating the thermal and mechanical properties in dry condition.

3. Calculation

A measurement of thermal properties was carried out for each group of specimens, conditioned at the amount of water imposed by the test. In order to ensure homogeneity of the test, four data points were collected on the opposite sides of each sample. The averaged values of the measurements provided the material's thermal effusivity E and conductivity K.

The test was also performed on some T-samples in environmental thermo-hygrometric conditions, indicated with EC in Table 4, which represents the condition of bricks after their production,

Table 2
Grouping of test pieces.

Saturation degree	Air-dried bricks (T)	Oven- fired bricks (M)
S = 100%	T_{1-3}	M_{1-3}
$S \approx 50\%$	T_{4-6}	M_{4-6}
$S \approx 25\%$	T_{7-9}	M_{7-9}
S = 0%	T_{10-12}	M_{10-12}

Table 3
Hypothetical weights corresponding to different moisture levels.

After 24 h in the oven	After 120 h in the water		Hypothetical weights			
W_d [gr] Dry weight	W_w [gr] Wet weight	C_w [gr] Content of water	S = 1 W_w	S = 0,5 $W_d + 0.5\ C_w$	S = 0,25 $W_d + 0.25\ C_w$	S = 0 W_d

Table 4
Thermal measurements at different saturation degrees.

Sample	Saturation [%]	Effusivity E [$Ws^{\frac{1}{2}}/m^2K$]	Standard deviation [%]	Conductivity K [W/mK]	Standard deviation [%]
T_{1-3}	S = 100%	1921,25	2,3	1,90	4,5
T_{4-6}	S ≈ 50%	1562,63	4,1	1,30	6,4
T_{7-9}	S ≈ 25%	1203,05	14,8	0,87	21,2
T_{10-12}	S = 0%	1225,98	5,8	0,89	9,2
M_{1-3}	S = 100%	1981,96	0,6	2,02	1,1
M_{4-6}	S ≈ 50%	1695,39	6,1	1,47	13,1
M_{7-9}	S ≈ 25%	1263,72	2,2	0,93	3,5
M_{10-12}	S = 0%	1121,76	9,0	0,77	14,1
EC	S ≈ 4%	1156,25	–	0,81	–

when the amount of water they contain is related only to the equilibrium with thermo-hygrometric parameters of the surrounding environment. In order to find the value corresponding to EC, some samples have been weighted in this condition, then dried in the oven in dry condition. Applying Eq. (3), a physiological moisture value of approximately 4% has been calculated Fig. 6.

Subsequently, the samples were subjected to mechanical strength tests reaching the bending break.

Every half of the samples obtained from the bending break was tested to uniaxial compression with a load application speed of 0.05 (N/mm^2)/s.

Again, the average value of the tests performed for each saturation degree was compared to that obtained on samples in environmental thermo-hygrometric conditions, EC in Table 5 Fig. 7.

4. Results and discussion

The results obtained from the survey offer the opportunity to make different assessments: first of all an evaluation of the percentage variation of materials performances, especially thermal, depending on their saturation degree; secondly, the evidence that, even with the same moisture content, a different behaviour of the air-dried samples T compared to those fired in the oven M can be recorded. This is symptomatic of how the manufacture process affects the accomplishment of the thermal and mechanical properties of building materials.

The most significant information is the decay of the thermal performance even at a low water content.

For air-dried samples T, an increase in thermal conductivity of 46% from dry to semi-saturated condition (S = 50%) and 113% from dry to saturated condition (S = 100%) was found.

This performance decay is even more important in specimens fired in oven M for which there is an increase in thermal conductivity of 90% from dry to semi-saturated condition (S = 50%) and 160% from dry to saturated condition (S = 100%).

At the same saturation level there is a difference in the data recorded for the two types of samples: The increase in thermal effusivity and conductivity as the water content increases is greater in samples fired in the oven M.

Both indexes of variation, depending on the degree of saturation or on the way of bricks manufacture, are not considered in the common design practice that suggests the adoption of standard values. As an example, the value of the thermal conductivity of

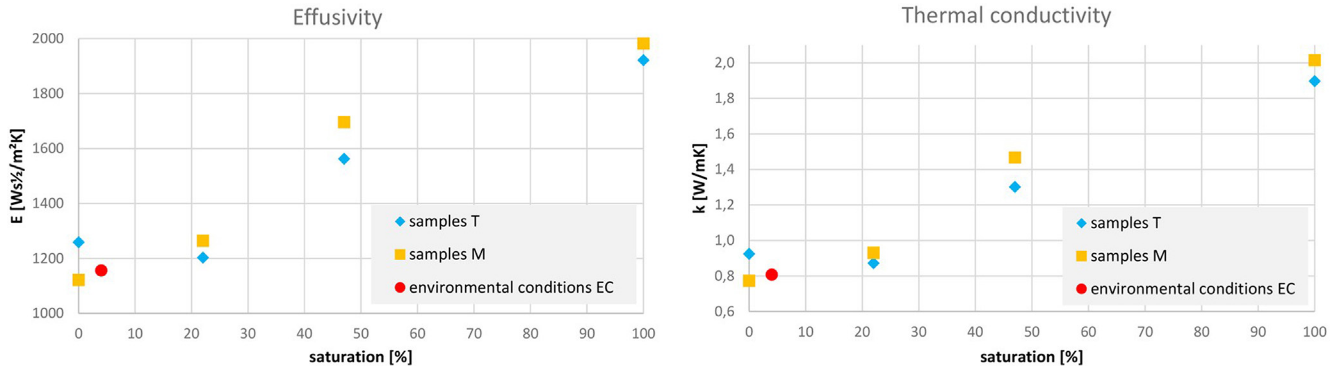

Fig. 6. Thermal effusivity and conductivity values at different saturation degrees.

Table 5
Mechanical measurements at different saturation degrees

Sample	Saturation [%]	f_{btm}[MPa]	Standard deviation [%]	f_{bm}[MPa]	Standard deviation [%]
T_{1-3}	S = 100%	2,30	51,1	8,80	21,4
T_{4-6}	S ≈ 50%	2,22	31,3	6,48	43,6
T_{7-9}	S ≈ 25%	2,90	16,1	8,68	11,7
T_{10-12}	S = 0%	2,62	10,0	9,15	13,4
M_{1-3}	S = 100%	4,67	16,7	13,75	13,9
M_{4-6}	S ≈ 50%	3,97	26,6	12,46	8,5
M_{7-9}	S ≈ 25%	4,51	20,2	12,94	2,9
M_{10-12}	S = 0%	4,79	22,8	14,41	23,2
EC	S ≈ 4%	2,36	–	11,33	–

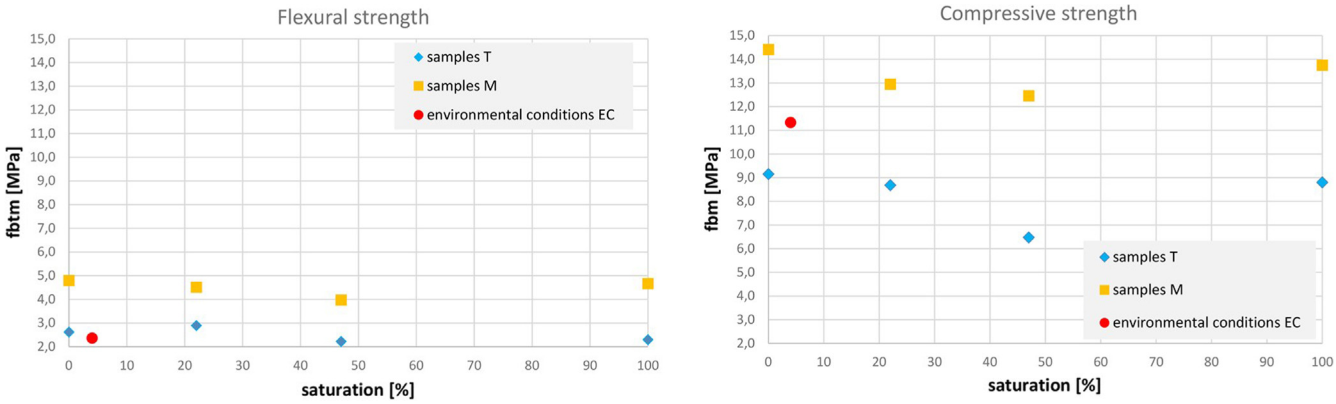

Fig. 7. Flexural and Compressive strength values at different saturation degrees.

solid masonry bricks extracted from the database of a software commonly used for numerical simulations of the masonry behaviour, equal to 0.6 W/m K, is lower than the calculated value of 0.87 W/m K (for T samples) and 0.93 W/m K (for M samples) at the lowest saturation range of 25%. According to EN ISO 10456 it is possible to pass from a thermal conductivity value related to a specific condition to another value considering different features including the moisture content. But it is also specified that "*data are not valid when there could be a continuous supply of moisture to the warm side of the insulation*", that is the actual case of a type of masonry which adsorbs water by capillarity from the soil. Moreover, in the Table 3 of EN ISO 10456 only one value of the thermal conductivity is given while, in Table 4, the moisture conversion coefficient to be applied to pass through different conditions is limited to the range from 0 to 0,25 m^3/m^3 moisture content. Nothing is shown for larger amounts of water.

Although with lower incidence, mechanical resistance tests have also shown a performance decay of wet material. For air-dried samples T, a 29% reduction in compressive strength from dry to semi-saturated condition (S = 50%) and 4% from dry to saturated condition (S = 100%) was found.

For fired in oven samples M this reduction is 14% from dry to semi-saturated (S = 50%) and 5% from dry to saturated condition (S = 100%).

It is interesting that the performance drop, for mechanical strength, is sthan in the completely saturated conditions. This evidence is probably linked to the way of conditioning: after an initial drying phase in the oven for the determination of the dry weight, in fact, all the samples were completely immersed in water until the saturated weight was reached. Then, some specimens were tested with maximum saturation while the others were brought to intermediate saturation levels by further drying cycles in the oven. Therefore, it is reasonable to hypothesize that this second cycle of forced drying has led to a further decay of material's mechanical performance.

In both cases, there is a decrease of uniaxial compression resistance of 75% in samples in semi-saturated condition (S = 50%) and 29% in completely wet samples (S = 100%) compared to the values of samples in the environmental thermo–hygrometric conditions (shown in red in the graphs).

5. Conclusions

The results of the tests have shown the extreme variability of the thermal and mechanical performances of building materials depending on their degree of saturation. In particular, the thermal performance of bricks experiences a significant decay at relatively low saturation levels.

This variation causes a great uncertainty about the real behaviour of masonry in operating conditions. This is even more evident if the experimental data is compared with the tabulated values of mechanical or thermal resistance generally introduced within the software simulations.

Therefore, this research shows innovative and original results related to the measurement of the percentage variation of mechanical and, even more significantly, thermal properties of wet materials, at different moisture levels, where the latter was never tested before. In addition, the investigation revealed an interesting aspect of performance variability in samples, with analogous moisture levels, manufactured with the same solid matrix but using two different drying processes. This reveals how crucial it is to consider the importance of a preliminary phase of material characterization.

The survey must be conducted both on existing materials in the building, in order to define a complete diagnosis, and on new materials to be introduced for the replacement or repair of small portions, in order to ensure a thermo–hygrometric equilibrium of the wall in favour of the building's health conditions maintenance and the prevention of localized degradation phenomena linked to physical and material inhomogeneity.

Declaration of Competing Interest

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

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