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Hygrothermal and Mechanical Properties of Ceramic Bricks and Mortars

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Abstract

This work presents an extensive experimental characterisation of different building materials usually used in Portuguese building construction. First, an experimental characterization of the material properties (hygrothermal, thermal and mechanical properties) of three different ceramic brick blocks was done, with the main objective to determine the hygrothermal behaviour of the materials tested.

Secondly, an experimental laboratory characterization of material properties for mortars (cement mortar and lime mortar), commonly apply in Portuguese building construction, was done to determine their hygrothermal, mechanical and thermal properties. Finally, the results and conclusions reached in this work are exposed.

Keywords: Hygrothermal properties; Mechanical properties; Ceramic bricks; Mortars; Experimental campaign

Introduction

One of the major causes of building pathologies is originated by moisture, that can affect users' health and comfort and it is responsible for the degradation of building components. Most of these pathologies associated with moisture are due to the use of new building materials, with a poorly predicted performance, combined with innovative techniques. The solutions adopted to treating these pathologies are, in most cases, very complexes and with a very difficult implementation.

In accordance with this, the knowledge of material properties to predict a correct heat, air, and moisture (HAM) transport in buildings is essential to well characterize their behaviour and predict pathologies. The hygrothermal numerical simulation programs, frequently, used to predict the hygrothermal performance of building materials and components need, as inputs, correct (experimental) values of the material properties [1].

In literature, it is possible finding several numerical simulation programs used in different civil engineering fields, such as structural or building physics (hygrothermal) calculations [2,3]. These programs, namely the HAM models, usually used in the analyse of the absorption and drying processes of building elements and components to advance, but all these models require a very reliable set of inputs to yield relevant results. Among these inputs are included the hygrothermal properties of building materials.

Moreover, the study of moisture transport in building walls is a matter of great importance for a correct hygrothermal behaviour characterization, especially for the analyses associate to the following phenomena: durability, waterproofing, degradation appearance and thermal performance. It is well-known that a building wall, generally, consists of multiple layers (considering only a single layer is a rather simplistic approach that leads to many errors), and the moisture transfer study presumes the correct knowledge about the continuity between layers. For example, the hydraulic continuity is an interface configuration with interpenetration of both layers porous structure. The study of liquid transport across this interface configuration (ceramic brick and mortar, two materials described in detail) implies the correct knowledge of the hygrothermal mechanical and thermal properties of the build materials employed.

Materials and Methods

Ceramic bricks

In this work, three different ceramic blocks of red brick were tested with a sample similar size: ceramic brick "A" with a dimension of 4 × 4 × 10 cm^3 and ceramics bricks "B" and "C" with 5 × 5 × 10 cm^3 (Figure 1).

Physical properties: The bulk density (ρ) can be determined by several standards, for example, to measure the bulk density of ceramic tiles the standard ISO 10545-3 [4] is the most used; for concrete samples the researchers use the standard EN 12390-7 [5] and for masonry units the standard EN 772-13 [6] is more applied. For this experimental test, the samples volume was calculated based on the average of three measurements of each dimension. Such as for the measurement of bulk porosity, the samples tested must be, initially, dried until obtaining a constant mass.

Hydrothermal properties: One of the most important hygrothermal properties is the water absorption coefficient, Aw. The water absorption coefficient of the ceramic bricks tested was done in accordance with the partial immersion method described by ISO 15148 [7]. The ceramic brick samples analysed were placed in distilled water, with the base submerged only a few millimetres (~1-5 mm) in order to avoid build-up of hydrostatic pressure. The partial immersion method used is in accordance with the European Standard CEN/TC 89 [8]. All the experiments were conducted in laboratory conditions, i.e. with constant temperature (20 ± 0.5°C) and relative humidity (40 ± 0.5%), in order to avoid changes in water viscosity that might affect the absorption rate.

Finally, the moisture profiles, of each ceramic brick sample, were measured using gamma ray's method (Figure 2). In this work, the lateral sides of the samples were insulated by water- and vapour-proof epoxy resin. The front side of specimens was placed in contact with water. Then, the moisture profiles were measured in the climatic chamber under isothermal conditions (25°C) in order to eliminate secondary effects on moisture transport. After the experiment, the moisture profiles, of each sample, were measured using gamma ray's method.

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Figure 1: Samples tested.

Figure 2: Gamma ray's equipment.

Thermal properties: Thermal conductivity could be measured by different methods that are broadly classified as steady-state or transient methods. In this work, the measurements were performed using a transient method, the thermal shock probe method (CT-Mètre), in accordance with the standard protocol defined in ISO 8301 [9].

Mortars

Masonry mortar is used for wall lifting and it is well-known that the dosage used (rheological influence) is one of the most important factors for the workability. For the dosage used in this research, two references were consulted: NBR 7200 [10] and ASTM C270 [11]. The two standards have in common the same proportion of sand binder, i.e., 1:3 (in volume). Thus, the mortar experimental analyses was carried out with samples of 10 mm thickness, and two types of mortar were selected: lime mortar with a proportion of 1:3 (lime, sand) and cement mortar with a ratio of 1:1:6 (cement, lime, and sand).

As an attempt to reproduce mortars used in masonry walls and for supposed reproducibility in other researches, it is presented below, the experimental characterization of mortars tested (cement and lime mortar) and the mixture aggregates.

Fine aggregate analyse: The sand fine aggregates used to prepare the mortars were characterized in accordance with the following Brazilian standards: (a) NBR NM 248 [12] to determine the fine aggregate granulometry, fineness modulus, and maximum diameter; (b) NBR 52 [13] to measure the specific gravity of dry aggregate, the aggregate specific gravity in (SSS)[3] conditions and the bulk density; (c) NBR NM 46 [14] to determine the fine materials content; (d) NBR NM 45 [15] to measure the unit mass and (e) NBR NM 30 [16] to measure the water absorption.

A detailed explanation of the experimental procedures used, namely to determine the granulometric composition, specific mass, fine materials content and unit mass, could be found in Azevedo et al.

Finally, the water absorption test was done in accordance with the Brazilian standard NBR NM 30 [16]. This standard suggests the use of aggregate samples with 0.25 kg, which should be, previously, washed and placed at a constant temperature, of approximately 105°C for 6 hours, in a heater.

It's extremely relevant to specifically get from the aggregate its degree of absorption which will be used in a concrete trace, for instance. In this case, when aggregate already shows some moisture percentage the amount of water usually added to the paste should be decreased. Therefore, an eventual segregation will be prevented, where larger particles will separate from smaller ones, thus causing the emergence of layers in the concrete and consequently reducing seriously its resistance.

Cement portland: The cement mortar used in making samples was of the type CPII F 32, which, provided in 50 kg sacks, were purchased in a warehouse in the Metropolitan Region of Recife, Brazil. In Table 1 this product is featured by reference values, which are provided by the cement factory CIMPOR.

Hydrated lime: The lime used to make the mortar (laying and coating) was the one of type CHII of Dolomil, supplied in 20 kg sacks. Its features can be observed in Table 2 and were given be the quality control department of Dolomil industry.

Mortar properties

Mixture: The mortars used were submitted to an analysis process in which their properties were evaluated both in the fresh state and in the hardened state by diversifying traces with and without the cement addition. Table 3 shows the types of mortars studied.

Physical, hygrothermal and thermal properties: The fresh-state mortar was featured through tests related to consistency, density and air content incorporated. The mortar consistency can be evaluated through the procedures described in standard NBR 13276 [17], which allows verifying the degree of plasticity being supported by a consistency table ("Flow Table") as illustrated in Figure 3.

The mortar water absorption coefficient was determined in accordance with the standards described above for ceramic blocks

Test	Method	Result	Specification
Fineness #75µm (%)	NBR 11579 (2012)	2.1	≤12
Specific surface (cm²/g)	NBR 16372 (2015)	4955	≥2600
Start of curing time (min)	NBR NM 65 (2003)	182	≥60
End of curing time (min)	NBR NM 65 (2003)	254	≤600
Soundness (mm)	NBR 11582 (2016)	0	≤5
Compressive strength (MPa)	NBR 7215 (1996)	21.1 (3d)	≥10.0
		26.3 (7d)	≥20.0
		34.7 (28d)	≥32.0
Magnesium oxide - MgO (%)	FRXPA	5.7	≤6.5
Sulphuric anhydride - SO_3 - (%)	FRXPA	2.84	≤4.0
Calcium oxide - CaO (free) – (%)	FRXPA	1.40	X

Table 1: Cement Portland characterization.

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Test		Result	Specification
Relative Humidity (110°C) - %		0.75	X
Loss on ignition (1000°C) - %		27.35	X
Carbon dioxide - %		3.60	≤7.0
Sulphuric anhydride - %		0.03	X
Total calcium oxide - %		42.38	X
Magnesium oxide - %		27.23	X
CaO + MgO not hydrated - %		2.71	≤15.0
Total oxides on non-volatile - %		95.82	≥88.0
Water retention - %		97.64	≥75.0
Particle size - %	(+) 0.600 mm	0.0	≤0.5
	(+) 0.075 mm	11.85	<15.0

Table 2: Hydrated lime characterization.

Type	Proportion	Mixture				
		Cement	Lime	Fine sand	Coarse sand	Water
Cement mortar	Volume	1	1	3	3	
	Mass (g)	228	198	1058	1133	460
Lime mortar	Volume	0	1	1.5	1.5	
	Mass (g)	0	396	1058	1133	415

Table 3: Mortars mixtures analysed.

Figure 3: Consistency evaluation.

samples. The experimental campaign used to determine the water absorption coefficient was done in accordance with the partial immersion method described by ISO 15148 [7]. The samples were placed in distilled water, with the base submerged only a few millimetres (~1-3 mm) in order to avoid build-up of hydrostatic pressure. The environmental laboratory conditions were 20°C and 40% RH and the samples were placed in a constant-temperature water bath controlled within ±0.5°C to avoid changes in water viscosity that might affect the absorption rate. At regular time intervals, the samples were weighed to determine the moisture uptake. The moisture profiles, of each mortar sample, were measured using gamma ray's method, as described in above section.

Finally, the thermal conductivity was measured using a thermal shock probe method (CT-Mètre), in accordance with the standard protocol ISO 8301 [9].

Mechanical properties

The mortars in the hardened state were characterized by the following tests:

- Axial compressive strength (rupture test), NBR 13279 [18];
- Tensile strength in flexion, NBR 13279 [18].

In order to measure the axial compressive strength, six cylindrical specimens were prepared for each mortar type, with dimensions of 4 × 4 × 16 cm³ (Figure 4). Figure 5 sketches the resistance tests applied to the samples, previously cured for a period of 28 days, in order to determine tensile strength.

Results and Discussion

Ceramic bricks

The density of the tested materials was measured carefully and repeatedly in order to obtain a reproductively lesser than 10%. The experimental results showed that ceramic bricks type "A" presents a density value of approximately 1800 kg/m³, the ceramic bricks type "B" presents a density value of approximately 1600 kg/m³, and the higher value was given by ceramic bricks type "C" with a value 2100 kg/m³.

The water absorption coefficients of the ceramic brick samples tested were measured by independently repeating measurements (at least 4 identical samples, with the same configuration and material) in order to obtain an experimental reproducibility that did not differ by more than 10%.

The experimental values of the capillary absorption process, for the samples of monolithic red brick type "A", "B" and "C", were presented in Figure 6. The results of the average mass variation per contact area show a direct proportionally with the square root of time just as described by Bomberg [19]. This result is particularly evident in the absorption first step (short-time faster) of the water absorbed curve.

The slope of the linear variation, the water absorption coefficient (A_w), can be described by the following mathematical expression:

$$A_w = \frac{M_w}{A\sqrt{t}} = \frac{m_t - m_0}{A\sqrt{t}} \quad (1)$$

where A_w is the water absorption coefficient (kg/m²s$^{0.5}$), M_w is the total amount in time t (kg/m²), m_t is the weight of the specimen after time (kg), m_0 is the initial mass of the specimen (kg), A is the contact area (m²) and t is the time (s).

The absorption coefficients obtained were 0.10 kg/m²s$^{0.5}$, 0.19 kg/m²s$^{0.5}$ and 0.07 kg/m²s$^{0.5}$ for red brick type "A", "B" and "C", respectively. It is possible to observe that the water absorption coefficient of ceramic brick samples type "B" is approximately twice greater than the value obtained for ceramic "A" and 3 times greater than ceramic "C". This is an expectable result as the density of ceramic

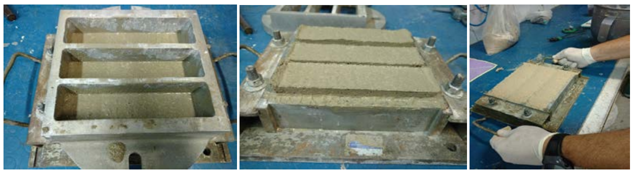

Figure 4: Granulometry of coarse sand aggregate - NBR NM 248 (2003).

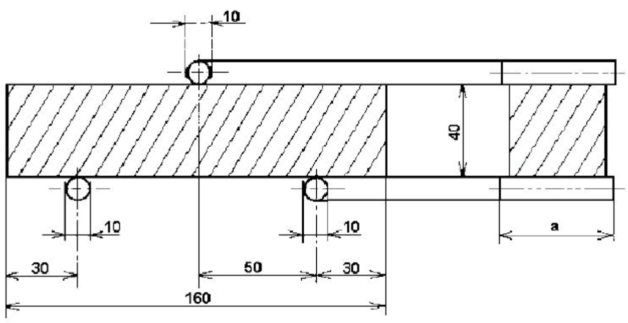

Figure 5: Loading device for determination of tensile strength in bending.

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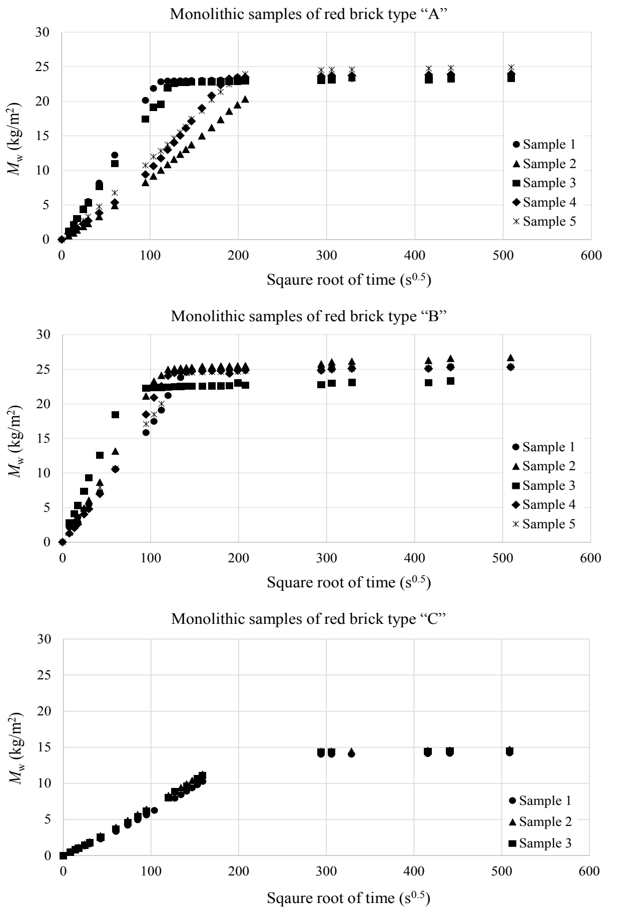

Figure 6: Capillary absorption curve of the ceramic brick samples tested as a function of the square root of time.

bricks "A" and "C" are greater than the density of the ceramic brick type "B". The experimental results obtained are in accordance with other experimental values found in literature, i.e., several authors presented a range of experimental values between 0.05 and 0.29 kg/m^{2}s$^{0.5}$, for these building materials [20-23].

Figure 7 shows the moisture profile results obtained for three different monolithic samples of ceramic red brick, using the moisture measurement device, based on the non-destructive method of gamma radiation attenuation. It is possible to observe that the damp front velocity presents a relation with water absorption coefficient (A_w). Comparing the two ceramic brick samples ("B" and "C") with the same dimensions (5 × 5 × 10 cm³), the damp front obtained with ceramic brick type "B", who presents the higher value of water absorption coefficient, reaches the face in contact with the environment (at 5 cm), in a shorter time period. On the other hand, ceramic brick "A", who presents an A_w greater than ceramic brick "C", reaches the damp front at 0.5 cm two hours after the beginning of the experimental test, i.e. a time period twice than observed with ceramic brick type "C". This result could be explained by the thickness wall sample effect of the test pieces, i.e., the damp front increases with the wall thickness and this increase is approximately a function of the square-root of the wall thickness [24,25].

Finally, Figure 8 shows the thermal conductivity values obtained, in function of moisture content, for the samples tested, ceramic blocks A and B. The values obtained, for the 2 ceramic blocks tested, are very similar and in accordance with the values reported by Taoukil et al. [26] who presents values of ceramic blocks in the range between 0.40 and 0.70 W/mK, for different values of moisture content.

Mortars

Fine aggregate analyse: Tables 4 and 5 present the experimental results of the granulometric composition obtained, and the experimental results of the aggregate characterization are described in Table 6. The results showed that the powder materials present lesser values than 5% for fine and coarse sand aggregates. The granulometric distribution of the two types of the sand analysed is a guarantee of a good sand compaction.

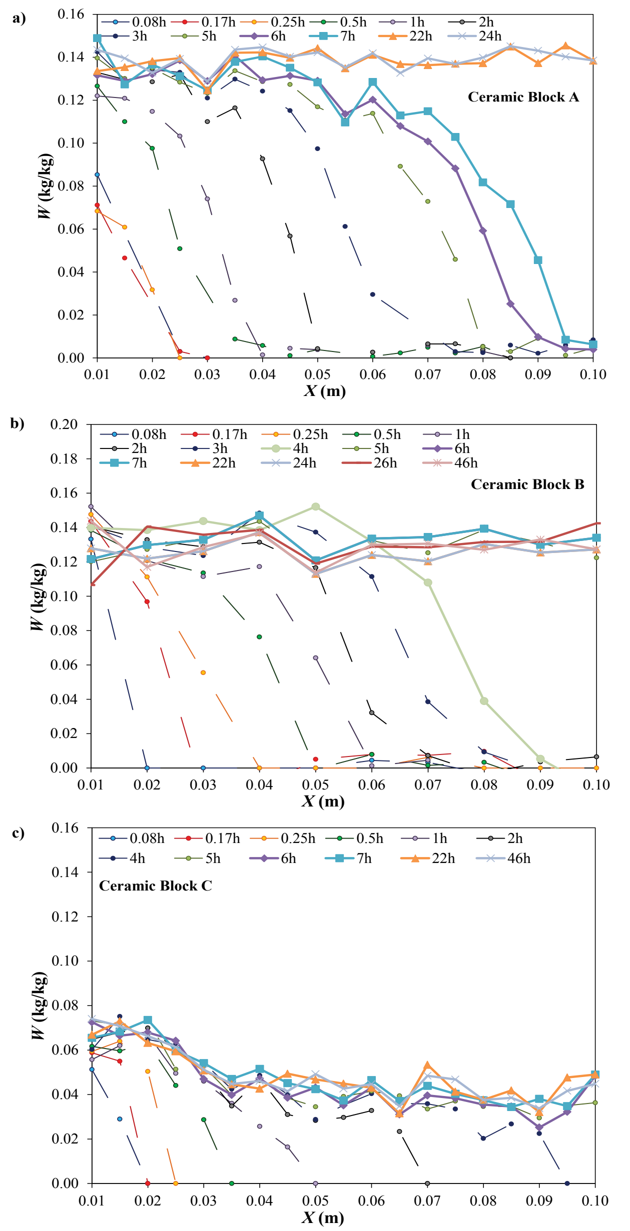

Figure 7: Moisture content profiles for monolithic ceramic red brick type samples tested.

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Mortar properties

Physical, hygrothermal and thermal properties: Samples are exposed to successive falls of pre-established height determining thus that the more plastic the mortar is, the bigger is its final diameter.

Mortar can be considered dry when the consistency index (flow table) is below 250 mm (e.g., mortar for sub-floor). When the consistency index of mortar is between 260 mm and 300 mm (e.g., plaster mortar) this is considered to be plastic. Finally, the mortar consistency index is above 360 mm (for example, roughcast mortar). The achieved results were summarized in Table 7.

The mortar density in the fresh state and the indoor air content incorporated obtained, in accordance with the procedures described in NBR 13278 [27], are presented in Table 8.

The water absorption coefficient reproducibility was tested by independently repeating measurements of at least 6 identical samples (i.e. the same configuration and material), under identical operating conditions, and repeated measurements of water absorption coefficient did not differ by more than 10%.

Figure 9 shows the results of the average mass variation per contact area in the capillary absorption process for the mortar samples tested. Such as for ceramic brick samples, the water absorbed curve present a direct proportionality with the square root of time, just as described by Eqn. (1). The experimental assessment of the water absorption coefficients showed a clear difference (twice) of values between the two mortars tested. The averages values obtained are 0.145 ± 0.09 kg/(m^2.s$^{0.5}$) and 0.124 ± 0.01 kg/(m^2.s$^{0.5}$), for cement mortar and lime mortar, respectively. The coefficient of variation found for each set of identical samples was approximately 15%.

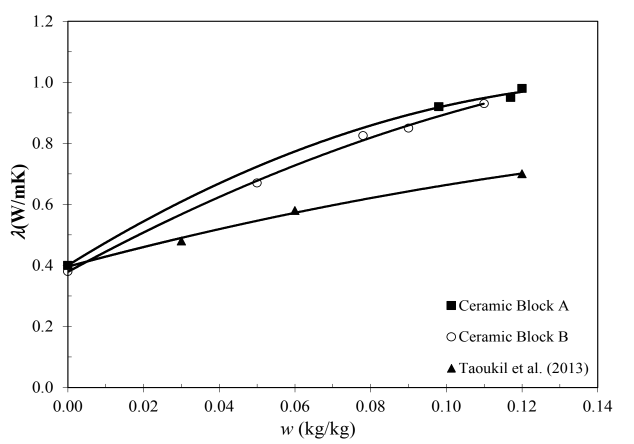

Figure 8: Thermal conductivity in function of moisture content.

Opening of the sieves (mm)	Mass retained (g)		Average of retained mass (g)	Average of retained mass (%)	Cumulated of retained mass (%)
	Test no. 1	Test no 2			
9.5	6	6.15	6.08	0.8	1
6.3	11.1	11.06	11.08	1.5	2
4.75	13.3	13.34	13.32	1.8	4
2.36	74	74.11	74.06	10.1	14
1.18	196.2	196.14	19.17	26.7	41
0.6	284.4	284.43	284.42	38.7	80
0.3	123.3	123.26	123.28	16.8	96
0.15	19.6	19.64	19.62	2.7	99
Bottom	7.5	7.43	7.47		
Total	735.4	735.6	735.5		

Table 4: Granulometry of coarse sand aggregate - NBR NM 248 (2003).

Opening of the sieves (mm)	Mass retained (g)		Average of retained mass (g)	Average of retained mass (%)	Cumulated of retained mass (%)
	Test no. 1	Test no 2			
9.5	6	6.15	6.08	0.8	1
6.3	11.1	11.06	11.08	1.5	2
4.75	13.3	13.34	13.32	1.8	4
2.36	74	74.11	74.06	10.1	14
1.18	196.2	196.14	19.17	26.7	41
0.6	284.4	284.43	284.42	38.7	80
0.3	123.3	123.26	123.28	16.8	96
0.15	19.6	19.64	19.62	2.7	99
Bottom	7.5	7.43	7.47		
Total	735.4	735.6	735.5		

Table 5: Granulometry of fine sand aggregate - NBR NM 248 (2003).

Figure 10 shows the moisture profile results obtained for cement and lime mortar samples, using the moisture measurement method of gamma radiation attenuation. It is possible to observe that cement mortar presents a slower damp front velocity than lime mortar.

Finally, the thermal conductivity values obtained for cement mortar was 0.786 W/mK and 0.799 W/mK for lime mortar. These values are practically identical and in accordance with the literature results, i.e, experimental data points in the range of 0.37 to 1.19 W/mK [28-31].

Mechanical properties: Tables 9 and 10 show the experimental results obtained for axial compression strength and tensile strength of two different mortar mixture, 1:1:6 and 0:1:3, respectively. The results showed that the mortars analysed are type "N" (Table 9), in accordance with the mixture and resistance (ASTM C270) [11]. Related to the mortar without cement Portland (Table 10) [32-36].

Conclusions

The knowledge of building materials properties is essential to predict heat, air and moisture transport in building elements and components, and for a correct characterization of the hygrothermal behaviour to predict pathologies. In this work, it was done two important studies: (a) a laboratory characterization of material properties for three different ceramic brick blocks was carried out to determine their hygrothermal behaviour; (b) moreover, the material properties of mortars (cement mortar and lime mortar) were done to determine their hygrothermal, mechanical and thermal properties.

Based on the experimental tests of this investigation, the following topics can be drawn for each study:

Ceramic brick blocks

The physical (bulk density), hygrothermal (water absorption coefficient and moisture profiles) and thermal (thermal conductivity) properties were measured. The results show the physical relation between the water absorption coefficient and the material density (inversely proportional), such as the moisture profile damp front and the material thickness.

Mortars

The properties measured were, not only the hygrothermal properties but also physical, thermal and mechanical properties, including a fine

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	Dry aggregate specific gravity (g/cm³)	Aggregate specific gravity in (SSS)³ conditions (g/cm³)	Bulk density (g/cm³)	Powder material (%)	Fineness modulus	Maximum diameter (mm)	Water absorption (%)
Fine aggregate	2.53	2.55	2.60	0.5	3.35	4.75	1.2
Coarse aggregate	2.42	2.44	2.48	2.7	2.02	2.02	1.0
	NBR NM 52 (2009)	NBR NM 52 (2009)	NBR NM 52 (2009)	NBR NM 46 (2003)	NBR NM 248 (2003)	NBR NM 248 (2003)	NBR NM 30 (2001)

Table 6: Experimental results of the aggregate characterization.

Mortar	Mixture	Test 1	Test 2	Average (mm)
Cement mortar	1:1:6	270.2	271.3	270.75
Lime mortar	0:1:3	178.8	178.3	178.55

Table 7: Values of the consistency index.

Mortar	Mixture	Fresh mortar density (g/cm³)	Air content incorporated (%)
Cement mortar	1:1:6	1.95	35
Lime mortar	0:1:3	2.07	29

Table 8: Experimental values of density of the fresh mortar and air content incorporated.

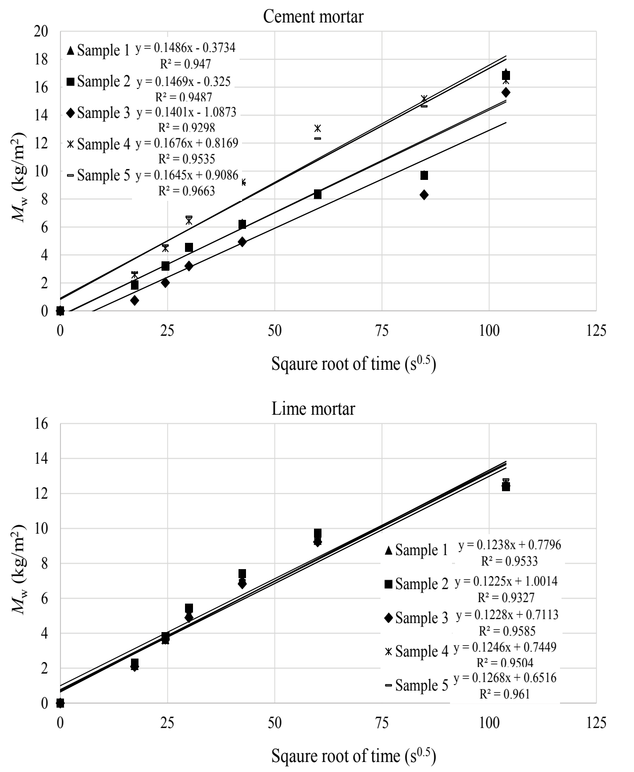

Figure 9: Capillary absorption curve of cement mortar and lime mortar in function of the square root of time.

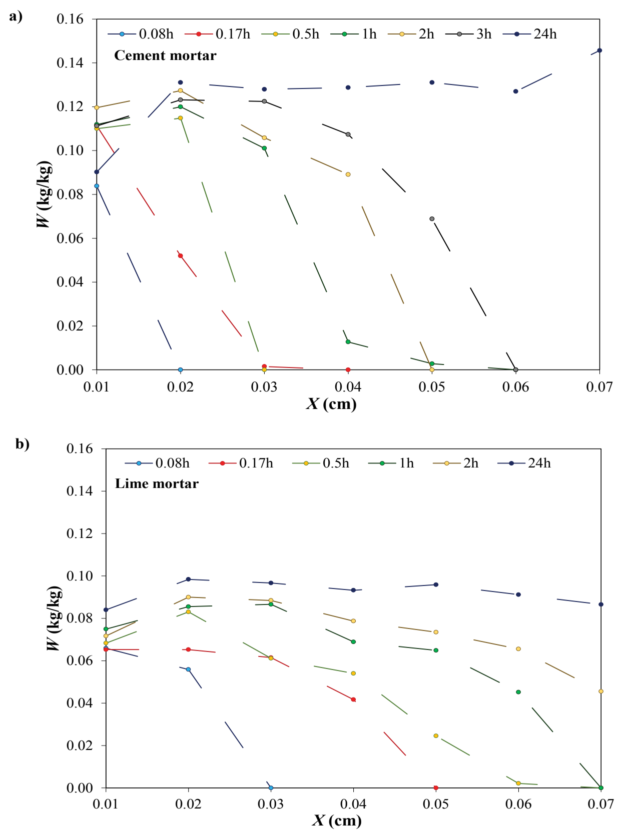

Figure 10: Moisture content profiles for mortar samples tested.

aggregate, analyse. The results show that cement mortar presents a slower damp front velocity than lime mortar.

- Those properties are commonly necessary as inputs for the hygrothermal simulation programs to predict building materials and components hygrothermal performance;
- With those results it is now possible to do several numerical studies to predict, for example, durability, waterproofing, degradation appearance and thermal performance of buildings or building components;
- If other authors want to study the hygrothermal behaviour of buildings or building components made by another material it is also useful to understand the way they can calculate/ determinate the required hygrothermal properties or even physical properties and mechanical properties here explained.

Mortar	Sample	Axial compressive strength (kN)	Tensile strength (MPa)
Mixture 1:1:6	1	164.8	10.3
	2	160.0	10.0
	3	153.6	9.6
	Axial compressive strength (average)		10.0
	Standard deviation		0.4
	Variation coefficient (%)		4

Table 9: Axial compression strength and tensile strength, for a mortar mixture of 1:1:6.

Mortar	Sample	Axial compressive strength (kN)	Tensile strength (MPa)
Mixture 0:1:3	1	20.8	1.3
	2	20.8	1.3
	3	20.8	1.3
	Axial compressive strength (average)		1.3
	Standard deviation		0
	Variation coefficient (%)		0

Table 10: Axial compression strength and tensile strength, for a mortar mixture 0:1:3.

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