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Hygrothermal Behaviour of Non-traditional Mortars and Concretes

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Abstract. *In 2015, the European Commission adopted a Circular Economy Action Plan to stimulate the transition of European countries towards the circular economy. In the 2030 Agenda, which includes the 17 Sustainable Development Goals, the United Nations has also defined targets to be implemented by the construction sector based on circular economy concepts. In this context, the importance of directing the development of the construction sector towards sustainable solutions to address the challenges of energy consumption, climate change, resource reduction and waste production is undeniable. Waste incorporation in thermal mortars is already under study by several authors. Among the possibilities of producing sustainable mortars, the reduction of natural aggregates in their preparation, such as sand, or of binders, such as cement, stands out. The incorporation of residual materials in mortars is, therefore, a possible alternative to guarantee more sustainable solutions. The objective of this work was to evaluate the hygrothermal behaviour of non-traditional mortars and concretes, such as fibre-reinforced mortar (P1); sprayable thermal insulation mortar (P2); mortar with granulated cork (P3); concrete with expanded clay (P4); concrete with metallic fibres (P5); cement mortar with construction and demolition waste (P6). The thermal conductivity of these materials, with different moisture contents, from totally dry to saturated after 24 hours of total immersion was determined. The results showed that the thermal conductivity values of the dry materials were similar to those found in the literature. After the 24 hours of humidification, there was, as expected, an increase in mass, with a minimum of 2% for specimen P3 and a maximum of 51% for specimen P2. Regarding the thermal conductivity, there was also an increase in its value for higher moisture contents, being that increase more relevant in specimen P2, with a variation of 294%, and less relevant in specimen P5, with a variation of 18%.*

Keywords: *Thermal Conductivity, Moisture Content, Non-traditional Mortars, Non-traditional Concretes.*

1 Introduction

According to the European Commission (EU) (European Commission, 2020), buildings contribute to about 40% of the global energy consumption and are responsible for about 36% of the overall greenhouse gas emissions. To tackle this issue, the EU launched the European Green Deal, which, among others, has the goal of reducing net greenhouse gas emissions by at least 55% by 2030. One of the main building blocks of this Europe's new agenda for sustainable growth is the new Circular Economy Action Plan that intends to stimulate the transition of European countries towards the circular economy. In the 2030 Agenda, which includes the 17 Sustainable Development Goals, the United Nations has also defined targets to be implemented by the construction sector based on circular economy concepts (United Nations, 2015). In fact, it is crucial to develop new systems and constructive solutions that contribute to sustainable buildings and lower energy consumptions. Hafez et al, 2023, present a recent systematic review to identify the challenges, motivations, recommendations, and pathways for future work in the topic of energy efficiency in sustainable buildings.

In this context, the importance of directing the development of the construction sector towards sustainable solutions to address the challenges of energy consumption, climate change, resource reduction and waste production is undeniable (Farinha et al, 2019). The production of biomaterials such as thermal mortars with waste incorporation is under study by several authors (Khitab, 2016; Brás et al, 2020; Ramírez et al, 2020). Among the possibilities of producing sustainable mortars, the reduction of natural aggregates in their preparation, such as sand, or of binders, such as cement, stands out. The incorporation of residual materials in mortars is, therefore, a possible alternative to guarantee more sustainable solutions.

There are several works in the literature focused on the characterization of the mechanical performance of these new materials (Malešev et al, 2010; Silva et al, 2014), but their hygrothermal behaviour is less documented. From the energy performance point of view, thermal conductivity is the most relevant property. However, its value depends on the moisture content of the material, so the hygric behaviour of these materials must also be evaluated. Several studies presented by different researchers (Stahl et al, 2012; Maia et al, 2021) are focused on the hygrothermal characterisation of material properties. Therefore, the methods for the hygrothermal characterization of construction materials are well established and can be applied in these new materials.

The objective of this work was to evaluate the hygrothermal behaviour of non-traditional mortars and concretes. To that end, a large experimental campaign was designed to address the following points: (i) to characterize the drying process; and (ii) to measure the thermal conductivity of the materials with different moisture content.

2 Materials and Methods

The following equipment was used for the test campaign (Figure 1): (a) ventilated oven, to dry out the specimens; (b) temperature and relative humidity sensor, to characterize the environment in the laboratory; (c) pachymeter, to measure the dimensions of the specimens; (d) precision balance, to measure the mass of the specimens; and (e) ISOMET 2114 to assess thermal conductivity, including a measuring unit and surface probe.

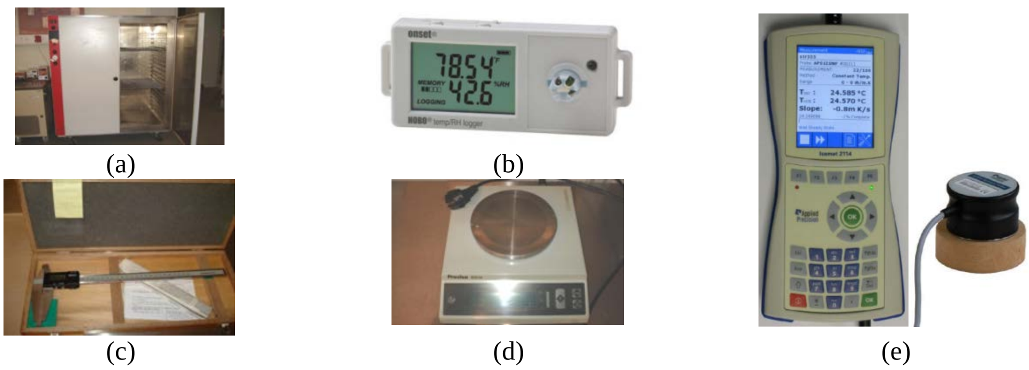


Figure 1. Equipment: (a) oven; (b) temperature and relative humidity sensor; (c) pachymeter; (d) precision balance; (e) ISOMET 2114 to assess thermal conductivity (measuring unit and surface probe).

The ISOMET 2114 equipment directly measures the thermal conductivity (λ) of several materials, using a dynamic measurement method and two types of probes (needle probes for soft materials and surface probes for hard materials). In this work, a surface probe was used. The measurement range accuracy for thermal conductivity is 5 % of reading + 0.001 W/(m.K), when λ varies between 0.015 and 0.70 W/(m.K), and 10 % of reading, when λ varies between 0.70 and 6.0 W/(m.K). The measurement reproducibility is 3 % of reading + 0.001 W/(m.K). More information about this device can be found in ISOMET 2114 (2011).

The materials under study were: fibre-reinforced mortar (P1), sprayable thermal insulation mortar (P2), mortar with granulated cork (P3), concrete with expanded clay (P4), concrete with metallic fibres (P5), and cement mortar with construction and demolition waste (P6). The characteristics of the specimens are shown in Table 1 and Figure 2. Specimens P1 and P2 are commercial mortars, and their reference thermal properties can be found in technical sheets provided by SECIL (2023). The thermal conductivity of the remaining specimens (P3 to P6) was collected from Santos and Matias (2006) and also corresponds to reference values.

Table 1. Characteristics of the specimens under study.

Specimen	**Material**	ρ_{dry} **[kg/m³]**	**λ [W/(m.K)]**
P1	Fibre-reinforced mortar	1348	0.47*$_1$
P2	Sprayable thermal insulation mortar	388	0.05*$_1$
P3	Mortar with granulated cork	1477	0.80*$_2$
P4	Concrete with expanded clay	1314	0.70*$_2$
P5	Concrete with metallic fibres	2239	2.0*$_2$
P6	Mortar with construction and demolition waste	2150	1.8*$_2$

*$_1$ Values from the technical sheet from SECIL (2023); *$_2$ Reference values from Santos and Matias (2006)

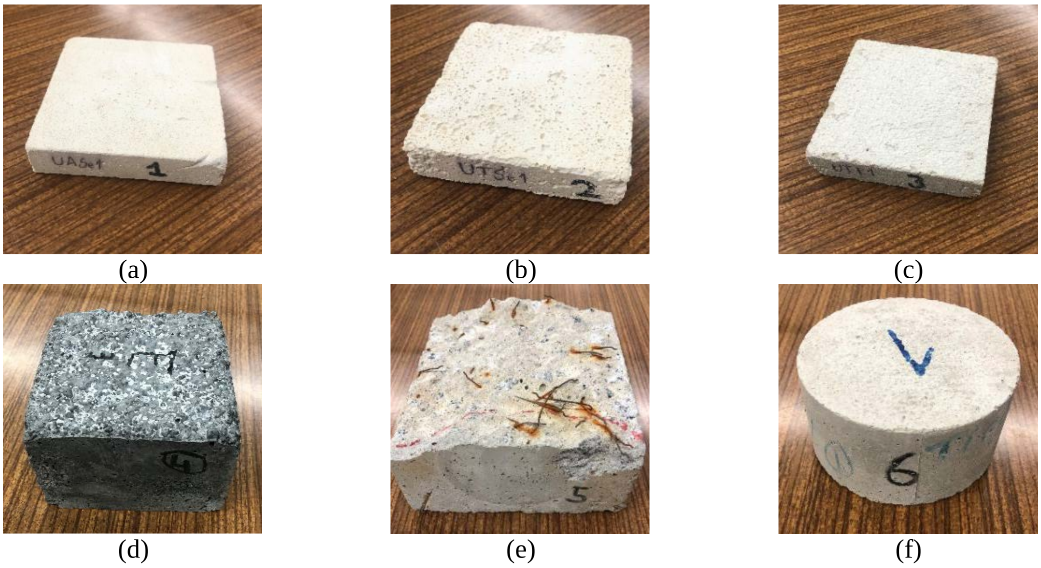
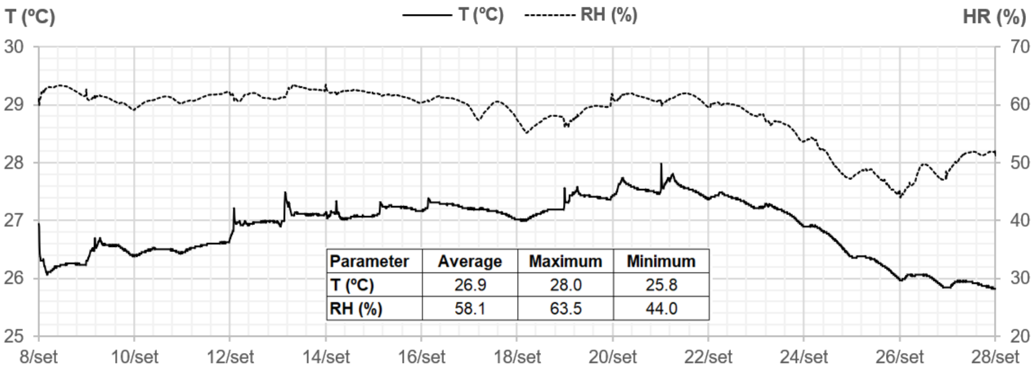


Figure 2. Materials under study: (a) fibre-reinforced mortar (P1); (b) sprayable thermal insulation mortar (P2); (c) mortar with granulated cork (P3); (d) concrete with expanded clay (P4); (e) concrete with metallic fibres (P5): (f) cement mortar with construction and demolition waste (P6).

To measure the thermal conductivity of the materials with different moisture contents, the specimens were first dried in a ventilated oven at 90 ºC. After mass stabilization, they were weighed and wrapped in a plastic film to cool down until they reached thermal equilibrium with the laboratory environment. The thermal conductivity of the dry material was measured with the specimens always wrapped in plastic film, except for the surface in contact with the probe, to ensure that the mass remained constant (Figure 3). Afterwards, the samples were saturated during 24 hours of total immersion in water. Then, the specimens were weighed, and their thermal conductivity was measured. Then the specimens were dried in the laboratory environment (Figure 4). The mass and the thermal conductivity of the material during the drying period were measured at 24-hour multiples intervals. The test ended after 20 days of drying.

Figure 3. Procedure to measure the thermal conductivity of the dry material.

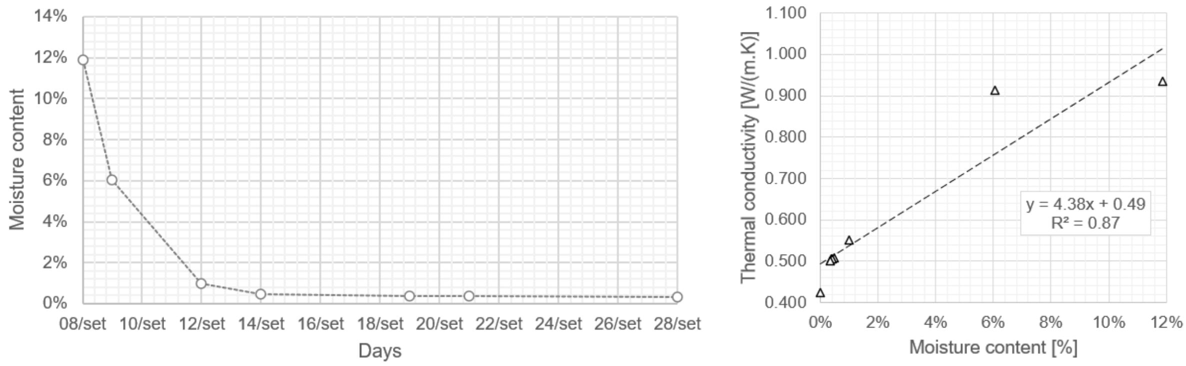


Parameter	Average	Maximum	Minimum
T (ºC)	26.9	28.0	25.8
RH (%)	58.1	63.5	44.0

Figure 4. Temperature (T) and Relative Humidity (RH) in the laboratory during the measurements.

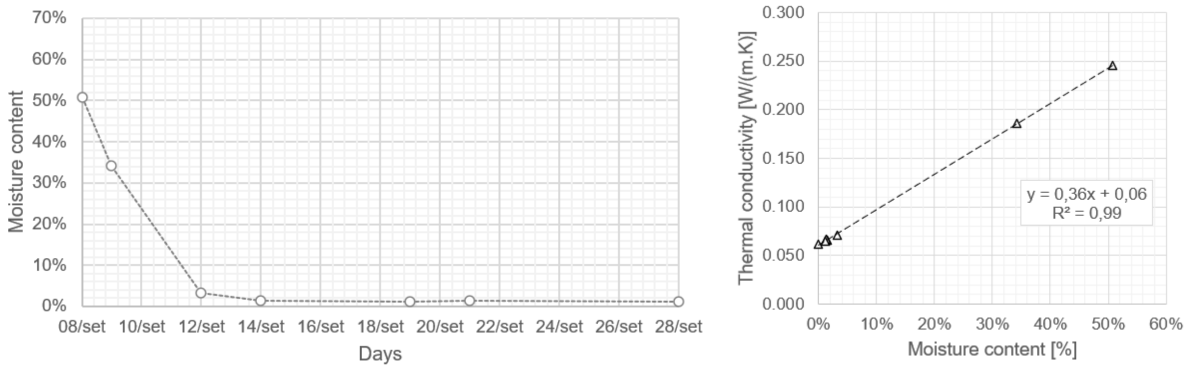
3 Results

The moisture content time variation and its relationship with the thermal conductivity are shown in Figure 5 to Figure 10. It is possible to state that, as expected, the maximum moisture content, obtained after 24 hours of total immersion, varied for different materials. The lowest value for the saturated moisture content was obtained for specimen P3 (mortar with granulated cork) and the highest for specimen P2 (sprayable thermal insulation mortar). The moisture content of P2 is 51%, which is very high and somehow unexpected. However, this value is in line with the ones found in the literature (Maia et al, 2018) and is related to the physical characteristics of this kind of material. During the drying process, the moisture content decreased over time, with the highest variation in mass occurring during the first 4 days, from 70% for P4 and P5 to 97% for P3. For specimens P1 to P3, moisture content had stabilized at the end of 20 days. However, for specimens P4 to P6, that had not occurred yet.



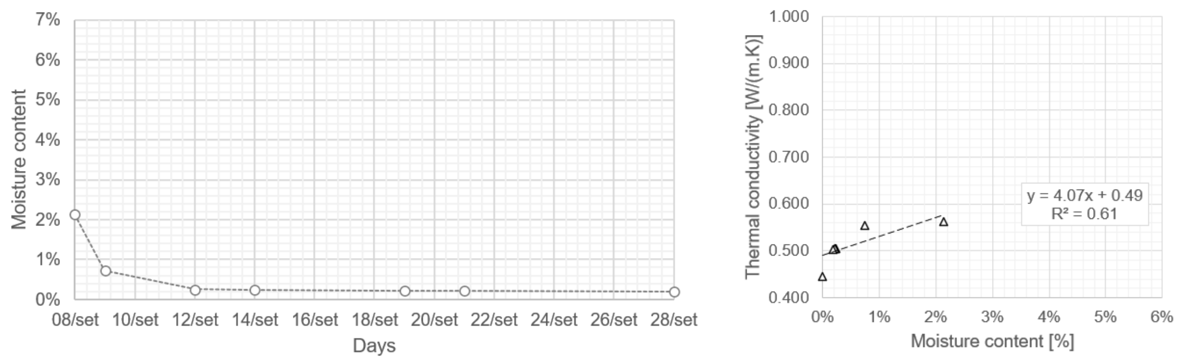
(a) (b)

Figure 5. Specimen P1: (a) Moisture content [%] vs Time;
(b) Thermal conductivity [W/(m.K)] vs Moisture content [%].



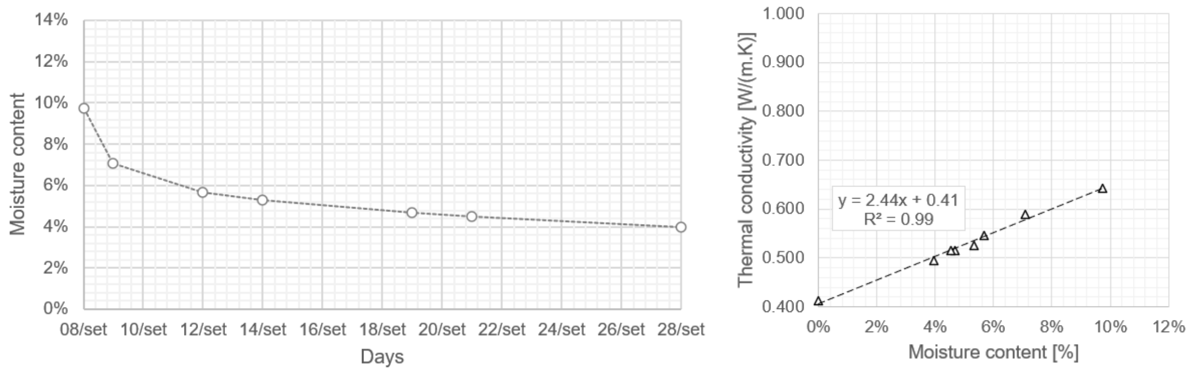
(a) (b)

Figure 6. Specimen P2: (a) Moisture content [%] vs Time;
(b) Thermal conductivity [W/(m.K)] vs Moisture content [%].



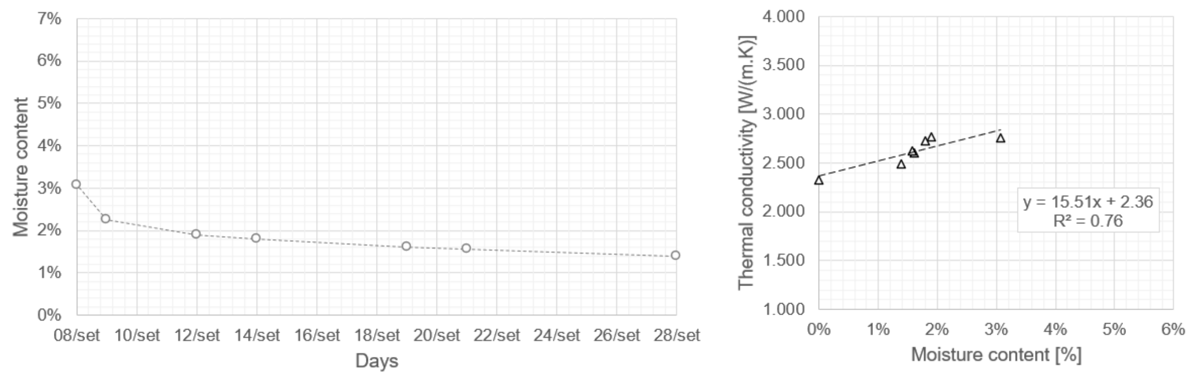
(a) (b)

Figure 7. Specimen P3: (a) Moisture content [%] vs Time;
(b) Thermal conductivity [W/(m.K)] vs Moisture content [%].



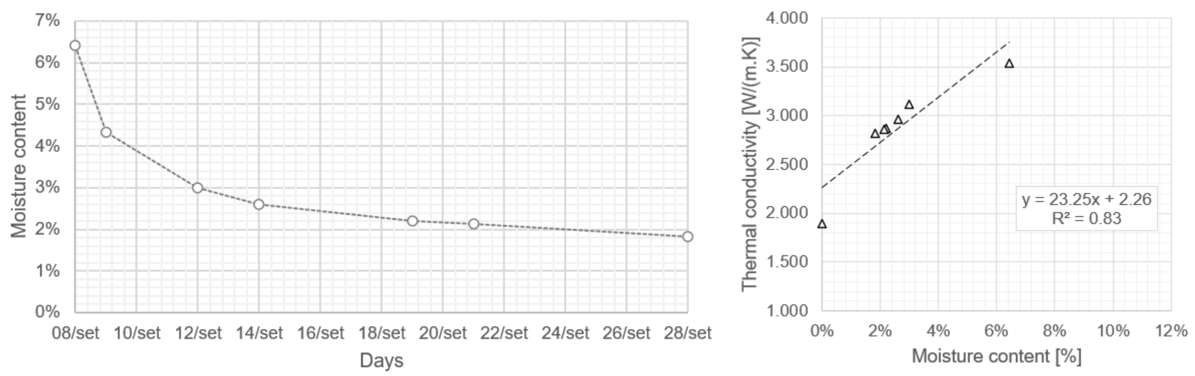
(a) (b)

Figure 8. Specimen P4: (a) Moisture content [%] vs Time;
(b) Thermal conductivity [W/(m.K)] vs Moisture content [%].



(a) (b)

Figure 9. Specimen P5: (a) Moisture content [%] vs Time;
(b) Thermal conductivity [W/(m.K)] vs Moisture content [%].



(a) (b)

Figure 10. Specimen P6: (a) Moisture content [%] vs Time;
(b) Thermal conductivity [W/(m.K)] vs Moisture content [%].

Regarding the variation of the thermal conductivity with the moisture content, it increases when the amount of water in the porous is higher. Linearity between the two properties can be found, although in specimens P3 and P5 the agreement between the measurements and the linear tendency line is weaker. That may be related to a less homogeneous mixture of the incorporated cork (specimen P3) and metallic fibres (specimen P5).

Comparing the thermal conductivity of the specimen dry and wet, it is possible to state that specimen P2 had the highest variation, with a value of 294%, and the less relevant variation occurred in specimen P5, with a value of 18%. Once again, the large variation in the thermal conductivity of P2 is probably related to its particular characteristics, as the λ values mainly increase when the specimen is highly saturated (8 and 9 of September).

The results also show that the thermal conductivity values of the dry materials were similar to those found in the literature, although specimens P3, P4 and P5 presented a higher deviation because no equivalent generic material was actually found in Santos and Matias (2006). Table 2 summarises the obtained results, namely, the thermal conductivity of the dry material, the thermal conductivity of the wet material and the generic value of thermal conductivity found in the literature.

Table 2. Thermal conductivity of the dry material (λ_{dry}), wet material (λ_{wet}) and from the literature (λ_{lit}).

Specimen	Material	λ_{dry} [W/(m.K)]	λ_{wet} [W/(m.K)]	λ_{lit} [W/(m.K)]
P1	Fibre-reinforced mortar	0,424	0,935	$0.47*_1$
P2	Sprayable thermal insulation mortar	0,062	0,245	$0.05*_1$
P3	Mortar with granulated cork	0,446	0,563	$0.80*_2$
P4	Concrete with expanded clay	0,412	0,643	$0.70*_2$
P5	Concrete with metallic fibres	2,329	2,755	$2.0*_2$
P6	Mortar with construction and demolition waste	1,894	3,536	$1.8*_2$

$*_1$ Values from the technical sheet from SECIL (2023); $*_2$ Generic values from Santos and Matias (2006)

4 Conclusions

The main conclusions of this work are:

- The thermal conductivity values of the dry materials are similar to those found in the literature, although specimens P3 (mortar with granulated cork), P4 (concrete with expanded clay) and P5 (concrete with metallic fibres) presented a higher deviation because no equivalent generic material was found.
- After the 24 hours of humidification, there was, as expected, an increase in mass, with a minimum of 2% for specimen P3 (mortar with granulated cork) and a maximum of 51% for specimen P2 (sprayable thermal insulation mortar).
- Regarding the thermal conductivity, there was also an increase in its value for higher moisture contents, being that increase more relevant in specimen P2 (sprayable thermal insulation mortar), with a variation of 294%, and less relevant in specimen P5 (concrete with metallic fibres), with a variation of 18%.
- This study confirmed that moisture has an enormous impact on thermal conductivity, which brings additional challenges when designing building components exposed to outdoor conditions, as normally only values for the dry materials are considered.

- Future work will include the measurement of additional properties of the studied materials, such as porosity, water vapour permeability and liquid water absorption.

Acknowledgements

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