Thermal conductivity of thermal mortars with EPS and silica aerogel

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Abstract

With the increase of indoor comfort requirements and consequently the building energy consumption for heating and cooling, the interest in materials with good thermal properties has been explored. Thermal mortars and nanomaterials could have an important role in energy efficient of buildings.

In the present work, the thermal conductivity of two thermal mortars was measured by different methods, two steady-state and tree transient methods, with the propose of comparing the results obtained with each method and it´s variability in the study of very low thermal conductivity materials. This study revealed that the different methods obtain results with high variations, values between 0,0495 and 0,0584 W/K.m were obtained for the same mortar. Furthermore, it was concluded that all the results obtained in the laboratory were higher than the value declared by the product and that were dependent on the moisture content and temperature of the samples.

1 INTRODUCTION

With the growing comforts needs and the consequent increase in energy consumption EU publish the 2010/31/UE Directive to promote the energy performance of buildings. One of the goals for 2020 is for the new buildings to have a zero energy needs (NZEB – Net zero energy buildings), this needs are calculated by the ratio between the energy consumption of the building by the provided energy from renewal sources [W1].

In general nanomaterials, have been developing an important role in sustainability, so is expected in the future that nanotechnology develop new techniques for production of materials with improved thermal performance [1].

Aerogels are becoming a promising material for building insulation, although the cost of this material is still very high. However, it is expected that with the growing interest, the new production methods and production in large scale this cost decrease [2].

Thermal mortars also have an important role in building insulation, for new construction and for rehabilitation of existing buildings. These are defined by EN 998-1 [3] for having a thermal conductivity lower than 0,2 W/K.m.

Thermal conductivity depends on several factors as moisture content and temperature gradient, so it's measurement is complex and some factors need to be taking in account according to ISO 10456 [4].

2 EXPERIMENTAL WORK

2.1 Materials and composition

Two thermal mortars were evaluated in this study: i) an industrial thermal mortar with EPS (A^{EPS}) and ii) a formulation with the incorporation of aerogel in the previous industrial mortar (A^{EPS+Ag}).

The mortar A^{EPS} is an industrial thermal mortar, composed with mineral binder and lightweight aggregates. It has a yellow color, uses cement and lime as a binder and EPS granules as aggregates. In additional it also has rheological agents, resins and air entrainers and hydrophobic agents.

Silica aerogel is extremely lightweight, density from 60 to 100 kg/m^3, and has a very low thermal conductivity, with thermal conductivity from 0.018 to 0.020 W/K.m; it is also amorphous, translucent, not reactive and has a good fire resistance [5].

For the curing process, after production the samples were storage in a chamber under laboratory control conditions, air temperature of 20°C ± 5°C and relative humidity of 50%. This process consisted in a wet curing in polyethylene bags for 7 days and dry curing for more 21 days, according to ISO 1015-11 [6].

2.2 Test methods

In this study two transient methods and three steady-state methods were carried out to measure the thermal conductivity.

i) Steady-state methods

The steady-state methods consist on establishing a steady temperature gradient over a known thickness of a sample and measuring the heat flow from one side to the other. These methods have some disadvantages as the long time it takes to reach a steady-state temperature gradient across the sample what leads to long times testing and the large gradients needed for the testing [7]. Some of them also need a calibration sample, it means longer time testing and a significant amount of resources to perform the tests.

In this study two heat flow meter methods were applied, (European EN ISO 8301 [8], Portuguese NP EN 12667 [9] and American ASTM C518-98 [10] standers). For this tests two equipment were used, Rapid K from Holometrix (HFM1) and anequipment developed by Materials and Ceramics Engineering Department from Universidade de Aveiro (HFM2). In heat flow meter method, the sample is in the middle of two isothermal heated plates, a hot plate and a cold plate, and the thermal conductivity is determined once the steady-state is achieved by applying the Fourier's Law for one dimension, Equation 1. Figure 1 is a schematic representation of this method and Figure 2 represents the apparatus of this test.

For HFM1 the temperatures chosen for the plates were 30°C and 50°C and the samples dimensions were 300x300x27 mm^3. This device measures thermal conductivity values between 0.015 – 0.43 W/K.m with an associate error of 5% according to the Rapid K operation and maintenance manual [11]. These tests were performed for the samples at 28 days age in equilibrium with air at 23°C and 50% relative humidity and for the dry state. In Figure 2 this equipment apparatus is represented.

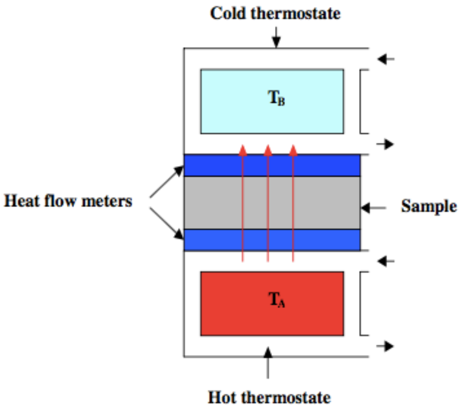

Figure 1: Schematic of a heat flow meter method (HFM)[7].

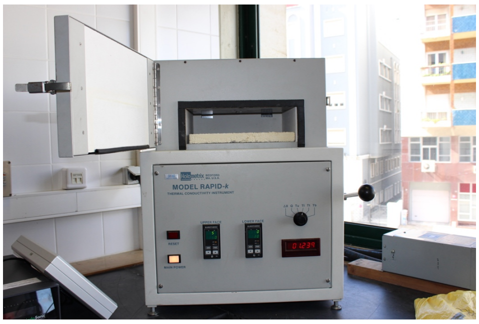

Figure 2: Rapid K apparatus (HFM1).

For HFM2 the temperatures chosen for the plates were 40°C and 55°C and the samples dimensions were 40x40x40 mm^3. This device measures thermal conductivity values between 0.02 – 0.8 W/K.m.

$$\frac{Q}{A} = \lambda \times \frac{\Delta T}{\Delta x} \qquad (1)$$

Where:
Q/A – heat flow by unit area [W/m^2];
λ - sample thermal conductivity [W/m.K];
Δx – sample thickness [m];
ΔT – temperature gradient sample's surfaces [K];

Additionally, the third steady-state method used was Lee's Disc. This method has two stages, the first one consists in having the sample in the middle of two metals discs, turn on the heater and wait for the system reach the steady-state, admitting the flow from the sample to disc 1 is equal to the flow form disk 1 to the air. In the second one disc 1 is heat 10 to 15°C above his steady-state temperature, and the sample is put above it immediately after this temperature is achieve and the heater turned off, then the temperature is registered, with fixed time intervals of 5 seconds, while the system is cooling down. The test finish when the system is in equilibrium with air and the thermal conductivity is calculated by equaling the equations for heat flux in the two stages for the steady-state temperature measured [12, W2]. In Figure 3 a schematic representation of Lee's disc method are presented and in Figure 4 the apparatus is presented.

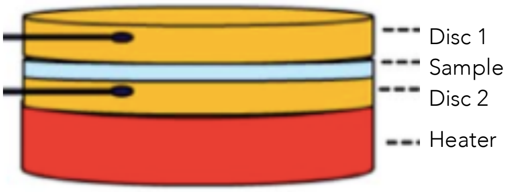

Figure 3: Schematic of a Lee's disc method[12].

Figure 4: Lee's disc apparatus.

For the first stage the heat flux for the steady-state condition is calculated by Equation 2:

$$Q = \lambda_{sample} A_{sample} \frac{T_2 - T_1}{x} \qquad (2)$$

Where:
Q – heat flux;
λ_{sample} – Sample thermal conductivity;
A_{sample} – sample area perpendicular to flux direction;
T_2 – disc 2 temperature;
T_1 – disc 1 temperature;
x – sample's thickness;

In the second stage the heat flux is calculated by the Equation 3:

$$Q = m_{disco2} Cp_{disco2} \frac{\partial T}{\partial t} \qquad (3)$$

Where:
Q – heat flux;
m_{disc1} – disc 2 mass;
Cp_{disc1} – disc 2 calorific capacity;
$\frac{\partial T}{\partial t}$ - tangent slope of the cooling graphic in T_2;

Assuming the heat flux is the same in bough stages, the sample thermal conductivity is calculated by Equation 4:

$$\lambda_{amostra} = \frac{m_{disco2} Cp_{disco2} \frac{\partial T}{\partial t}}{A_{amosra} \frac{T_2 - T_1}{x}} \qquad (4)$$

The samples used in this method have a very small thickness of 7 mm with a diameter of 45 mm.

ii) Transient methods

The transient methods are dynamic methods that measure the response to an electrical heat impulse sent by a source. The thermal conductivity is calculated by mathematics models with the temperature measure in defined time intervals. These methods have some advantages like the sort time tests and the dispense of a calibration sample but they are only able to perform if the sample is in thermal equilibrium with the air of the surround atmosphere [7].

In this study a modified transient plane source (MTPS) and a transient line source (TLS) were used, both from the same device ISOMET 2114 from Applied Precision. The plane source measures thermal conductivities between 0.04 to 0.3 W/K.m and the line source between 0.015 to 0.05 W/K.m bought with associate error of 3% + 0.001 W/K.m [13].

In Figures 5 and 6 a schematic representation is illustrated while in Figures 7 and 8 the apparatus of these two methods is shown.

It must be pointed out that for the measurements with the MTPS a plate of another thermal insulator material was used under the samples in order to prevent heat conduction between the sample and the stand.

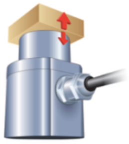

Figure 5: Schematic of a modified transient plane source method (MTPS)[W3]

Figure 6: Schematic of a transient line source method (TLS)[W3]

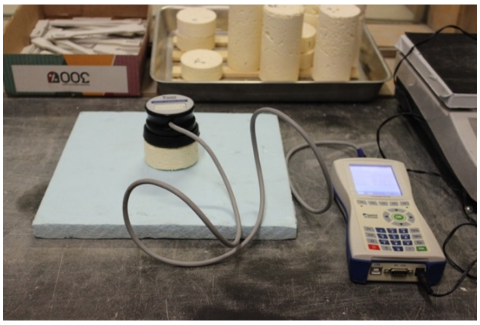

Figure 7: ISOMET – Plane source apparatus.

Figure 8: ISOMET - Line source apparatus.

The samples dimensions for the application of the MTPS method are D=72 mm and h=30 mm and for the TLS method D=67 mm and h=130 mm.

2.3 Analitical work

The thermal conductivity was measured first for the moisture content in equilibrium with air (the samples were in a chamber at 20°C and relative humidity of 50%), then for the dry state and then for some of the samples the thermal conductivity was also measured for different moisture contents. The different moisture content is usually achieved by saturating the samples and then let them dry to dry state with an oven or similar, but in this case, due to the fragility of the samples it was not possible to do it this way. Alternatively, the different moisture content was reach by putting the samples in a humidity chamber and the thermal conductivity was measured with time intervals of two days.

The moisture content for the five different points was calculated by volume as stablish by EN ISO 10456 [4], using the equation 5:

$$\Psi = \frac{(m_i - m_{seco})}{\rho_{água}} \Big/ V \qquad (5)$$

Where:

m_i – mass at each moisture state i [kg];
m_{dry} – mass at the dry state [kg];
ρ_{water} – water density, which is 1000 [kg/m^3];
V – total volume of the sample [m^3];

According to ISO 10456 [4], the values for thermal conductivity should be for one of the following conditions: Ia) reference temperature of 10°C and dry state; Ib) reference temperature of 10°C and moisture content when in equilibrium with air at 23°C and relative humidity of 50%; IIa) reference temperature of 23°C and dry state and IIb) reference temperature of 23°C and moisture content when in equilibrium with air at 23°C and relative humidity of 50%. In this study the testing conditions were close to conditions IIa) for the hardened state and II)b for the hardened dry state. Conversion factors must be taken in consideration for temperature, moisture content and ageing. In this case mostly for temperature since de different methods used different testing temperature. The conversion factor for ageing hasn't been consider since the samples were not subjected to accelerated ageing tests. The thermal conductivity value from the set conditions to another condition are calculated using the equation 6:

$$\lambda_2 = \lambda_1 F_T F_\Psi F_\alpha \qquad (6)$$

Where:

λ_1 – thermal conductivity for the first set conditions;
λ_2 – thermal conductivity for the second conditions;
F_T – conversion factor for temperature;
F_Ψ - conversion factor for moisture content;
F_α - conversion factor for ageing;

The conversions factors can be calculated from equation 7:

$$F_i = e^{f_i(i_2 - i_1)} \qquad (7)$$

Where:

F_i – conversion factor for temperature (i = T), moisture content (i = Ψ), ageing (i = a);

f_i – conversion coefficient for temperature (i = T), moisture content volume by volume (i = Ψ), ageing (i = a) according to the tabulated values in ISO 10456 for different materials;

i_1 – temperature (i = T), moisture content volume by volume (i = Ψ), ageing (i = a) for the first set conditions;

i_2 – temperature (i = T), moisture content volume by volume (i = Ψ), ageing (i = a) for the second set conditions;

In this study the conversion factor for temperature (f_T) was 0,003 and for the moisture content (f_Ψ) of 4, according to ISO 10456 [4].

3 EXPERIMENTAL RESULTS

3.1 Fresh state

For the introduction of aerogel, mixing water content increased, the value obtained for the water/powder ratio was 1,85 for A^{EPS+Ag} while for the A^{EPS} is 1,10.

3.2 Hardened state

3.2.1 Density and moisture content

Density and moisture content was determinate for part of the samples. The samples chosen for these tests were the ones which was possible to test for both the hardened state (in chamber environment conditions and dried state). The results are presented in table 1.

Table 1: Samples characteristics.

Test	Samples	ρ (kg/m³)	Δ (%)	(Ψ) (m³/m³)
MTPS	A^{EPS}	216,16		0,0063
	A^{EPS+Ag}	140,27	35,11	0,0051
TLS	A^{EPS}	229,32		0,0081
	A^{EPS+Ag}	138,45	39,63	0,0051
HFM1	A^{EPS}	221,88		0,0073
	A^{EPS+Ag}	119,37	46,20	0,0050

Subtitle: λ- thermal conductivity; $\lambda_{23°}$ - thermal conductivity for 23°; Δ - variation of A^{EPS+Ag} for A^{EPS}; Ψ - moisture content

3.2.2 Thermal conductivity

Since the thermal conductivity is influenced by the temperature and the different methods were performed for different temperatures, all the results were converted for 23°C, in order to compare them. The results are presented in Table 2.

Table 2: Thermal conductivity obtained by different methods

Test	Samples	λ (W/K.m)	$\lambda_{23°}$	Δ (%)
MTPS	A^{EPS}	0,0537	0,0542	
	A^{EPS+Ag}	0,0410	0,0413	23,71
TLS	A^{EPS}	0,0578	0,0584	
	A^{EPS+Ag}	0,0350	0,0353	39,48
HFM1	A^{EPS}	0,0668	0,0635	
	A^{EPS+Ag}	0,0308	0,0293	53,92
HFM2	A^{EPS}	0,0533	0,0495	
	A^{EPS+Ag}	0,0288	0,0267	40,19
Lee's Disc	A^{EPS}	0,0563	0,0551	
	A^{EPS+Ag}	0,0372	0,0364	33,93

Subtitle: λ- thermal conductivity; $\lambda_{23°}$ - thermal conductivity for 23°; Δ - variation of A^{EPS+Ag} for A^{EPS}

For the industrial thermal mortar, A^{EPS}, all the results are higher than the value declared for the product 0,042 W/K.m, but when compared with another study [14] the values are very similar, for example for the method MTPS the value obtain is exactly the same 0,0542 W/K.m.

The results for HFM1 are the ones with the higher difference between the two mortars, while for A^{EPS+Ag} the results are similar to the other HFM2, for A^{EPS} are the highest being a beet out of the pattern.

The results obtained for Lee's Disc are similar to the results obtained for the transient methods, being closer to TLS.

In general, the results for HFM2 are the lowest, and for the mortar A^{EPS} were the closest to the declared value for this industrial mortar.

i) Modified transient plane source vs transient line source

The results with the plane source have a lower variability than the results with the line source. For the mortar A^{EPS+Ag} the variability with the plane source was 0,24% and for the line source 12,5%, but even dough the results with de plane source have such consistency in this case it doesn't mean they have more reliability. The reason why these results have this consistency is because A^{EPS+Ag} has a thermal conductivity lower than the source limit, 0,04 W/K.m.

ii) Steady-state methods vs transient methods

The results for the steady-state methods were in general lower than the results for the transient methods, especially when comparing the two heat flow meters methods with transient plane source and transient line source. This fact could be related to the longer times testing and higher temperatures of heat flow meter tests, what could produce an effect similar to a drying process and that way obtain lower values. The difference between HFM2 and the transient methods are double than the difference between HFM1 and the transient methods. In fact, the tests with HFM1 have an average temperature of 40°C and durations of 2 hours, while the tests with HFM2 have an average temperature of 47°C and durations above 12 hours. This gives reliability to the idea above. This revels the possibility of the results for the steady-state methods not being for the hardened state with moisture content in equilibrium with air but for an intermediate state between this and the hardened dry state.

In Figure 9 a graphic is presented with results for the five methods all converted for the temperature of 23°C, conditions IIb) of ISO 10456 [4].

Comparing the results for A^{EPS} to the declared value, 0,042 W/K.m for the hardened state ate 28 days old, all the experimental results were higher than this value, HFM1 presents the results with the most difference around 50% above, than ISOMET presents results 39 and 49% above, for the line source and the plane source respectively. HFM2 presents the closest results to the declared value with just 18% difference and Lee's Disc presents results 34% above.

3.3 Hardened dry state

For the drying process the samples were storage in an oven at constant temperature of 60°C for four days and the density tests were performed immediately after the samples get out of the oven.

3.3.1 Density

As expected the density of the mortars reduced, that's because the drying process takes all the liquid water out. The variation registered when comparing with the hardened state were between 2,9 and 4,22%. The results are presented in Table 3.

Table 3: Results for the density at dry state

Test	Samples	ρ (kg/m³)	Δ (%)	δ (%)
MTPS	A^{EPS}	209,89		2,9
	A^{EPS+Ag}	135,22	35,57	3,6
TLS	A^{EPS}	221,22		3,56
	A^{EPS+Ag}	133,33	39,72	3,7
HFM1	A^{EPS}	214,56		3,3
	A^{EPS+Ag}	114,33	46,71	4,22

Subtitle: ρ - density; Δ - variation of A^{EPS+Ag} for A^{EPS}; δ - variation of dry state from hardened state

The averaged density obtained for A^{EPS} was 215,2 kg/m³ and for A^{EPS+Ag} 127,63 kg/m³, with a decreased of 41% for the introduction of aerogel.

3.3.2 Thermal conductivity

Once the thermal conductivity depends on the moisture content the results for the hardened dry state are lower than the results for the hardened state at 28 days old as expected. This way these results are closer to the declared value, even though the value in the technical datasheet do not refer for which conditions of temperature and moisture content. The results are presented in Table 4.

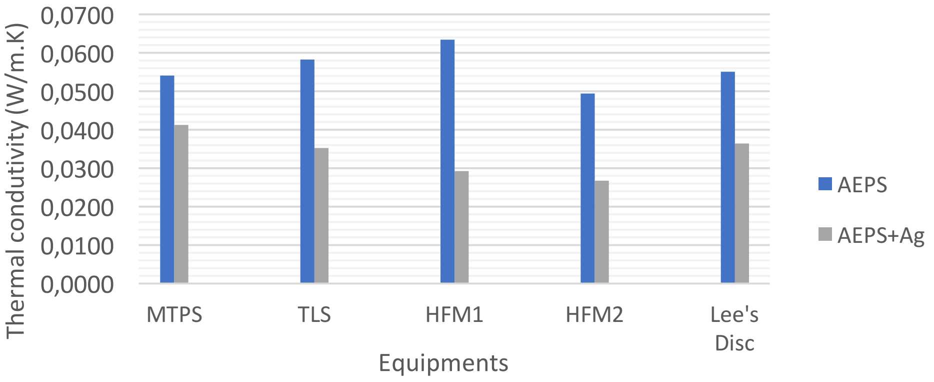

Figure 9: Graphic with the results for all the 5 methods

Table 4: Results for the thermal conductivity at dry state

Test	Samples	λ (W/K.m)	$\lambda_{23°}$	Δ (%)	δ (%)
MTPS	A^{EPS}	0,0513	0,0518		4,47
	A^{EPS+Ag}	0,0396	0,0399	22,87	3,42
TLS	A^{EPS}	0,0557	0,0562		3,63
	A^{EPS+Ag}	0,0321	0,0324	42,34	8,19
HFM1	A^{EPS}	0,0557	0,0529		16,71
	A^{EPS+Ag}	0,0291	0,0277	47,72	5,52

Subtitle: ρ - density; Δ - variation of A^{EPS+Ag} for A^{EPS}; δ - variation of dry state from hardened state

The variation δ and Δ for the transient plane source for A^{EPS+Ag} is the smallest but again the value is the limit of de source, 0,04W/K.m and doesn't correspond to real conductivity of this mortar.

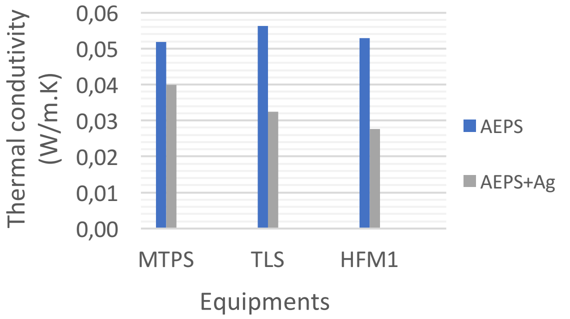

Figure 10: Results for thermal conductivity at dry state

The variation δ for A^{EPS} for the HFM1 is very high that is because the values for the hardened state are also very high and out of the pattern and maybe not corresponding to the reality. In Figure 10 these results are present in a graphic do it is easier to compare them.

3.3.3 Aerogel influence on dry bulk density and thermal conductivity

In Table 5 the influence of aerogel on dry bulk density and on thermal conductivity for the hardened state and for the hardened dry state is presented.

Table 5: Influence of aerogel in density and thermal conductivity

Δ (%)		Hardened state at 28 dias	Hardened dry state
ρ	MTPS	35,11%	35,57%
	TLS	39,63%	39,72%
	HFM1	46,20%	46,71%
λ	MTPS	23,71%	22,87%
	TLS	39,48%	42,72%
	HFM1	53,92%	47,72%

Subtitle: Δ - variation of A^{EPS+Ag} for A^{EPS}

The influence of aerogel is slightly higher for the hardened dry state than for the hardened state, this is due to the present of the liquid water in the hardened state that acts like a common constituent and masks this difference.

3.4 Correlations

Once ISOMET revels to be expeditious and smaller time consuming, thus this equipment also return the volumetric heat capacity, for that reasons this transient line source was the method chosen to study the influence of moisture content in thermal conductivity and volumetric heat capacity for these materials.

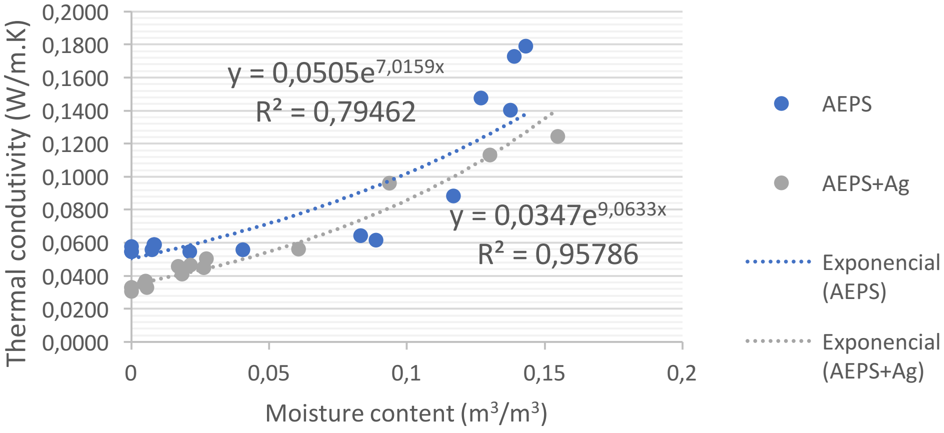

Figure 11: Influence of the moisture content in thermal conductivity

3.5 Influence of moisture content on thermal conductivity

The samples were storage in a humidity chamber, and the tests were performed each two days for different moisture contents. In the total five different points were study, the hardened dry state (with next to zero moisture content), the hardened state and three different moisture content achieved with the humidity chamber. In Figure 11 a graphic is presented with these results.

It's revel that the thermal conductivity increases as the moisture content increase, like in other studies [14, 15]. The two mortars, A^{EPS} and A^{EPS+Ag}, have the same sensibility to the moisture content once they have parallel curves. It means that the introduction of aerogel does not interfered in this characteristic.

The exponential factor was 7,02 and 9,06 for A^{EPS} and A^{EPS+Ag} which is double than the value indicated in ISO 10456 [4] and found in study [15].

It is pointed out that the introduction of aerogel increased a lot the frangibility of the mortars, so the samples lost mass while the tests were performed. It means that the moisture content calculated could be slightly under the real moisture content of the samples.

3.6 Influence of density on thermal conductivity

As expected the dry bulk density of the material influence the thermal conductivity, materials with lower thermal conductivity also have lower density. This is congruent with other studies.

In Figures 13 and 14 the graphics for the influence of dry bulk density in thermal conductivity are showed, Figure 13 for A^{EPS} and Figure 14 for A^{EPS+Ag}.

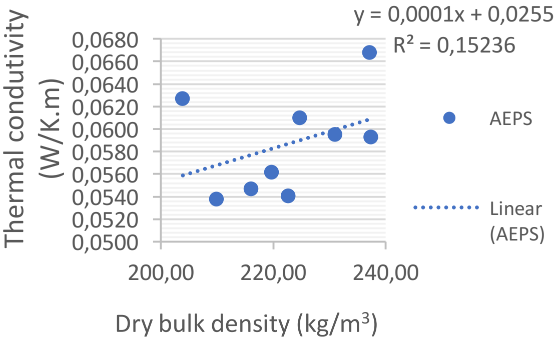

Figure 13: Influence of dry bulk density in thermal conductivity

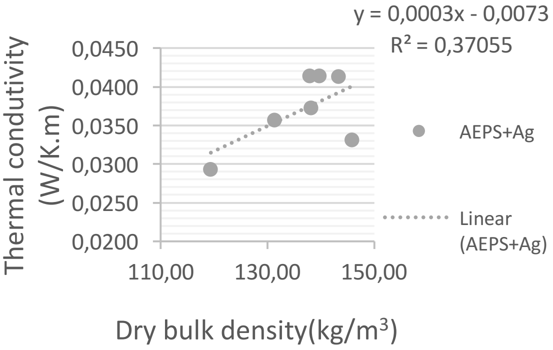

Figure 14: Influence of dry bulk density on thermal conductivity

3.7 Influence of moisture content on volumetric heat capacity

The moisture content influence the volumetric heat capacity, it was verified that samples with higher moisture content also revealed higher volumetric heat capacity. Thus, A^{EPS} revealed to be more susceptible to this characteristic, once it presents a tendency line with a greater slope. The introduction of aerogel lowered the susceptibility of volumetric heat capacity to moisture content. The results are represented in Figure 12.

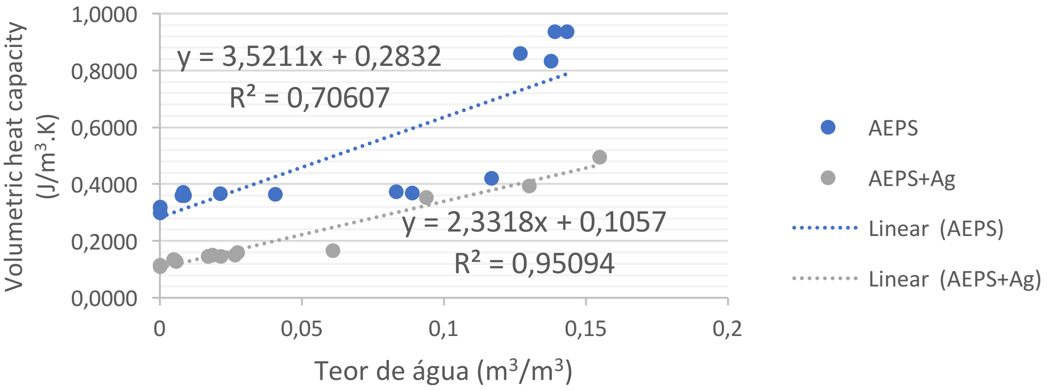

Figure 12: Influence of moisture content in volumetric heat capacity

4 CONCLUSIONS

This experimental work studied the thermal conductivity of thermal mortars using 5 different methods of measurement. It was possible to compare the results for two mortars using 5 different geometry of samples and study the influence of moisture content and temperature in the results. It was also possible to study the influence of aerogel in these characteristics.

This study revealed that the different methods obtain very different results, and characteristics as dry bulk density and moisture content influence the thermal conductivity of these materials.

Materials with lower dry bulk densities also have lower thermal conductivity. For moisture content the same conclusion was taken out, when exposed to different moisture contents the samples presented different thermal conductivity values.

The introduction of aerogel increased the amount of mixing water, so a water/powder ratio obtained for A^{EPS+Ag} was higher than for A^{EPS}. Aerogel also affected dry bulk density, the values obtains were 132,67 kg/m^3 for A^{EPS+Ag} and 222,45 kg/m^3 for A^{EPS}, what represents a decrease of 40%. For the thermal conductivity, the results for A^{EPS+Ag} were between 0,0267 and 0,0372 W/K.m, and for A^{EPS} 0,0495 and 0,0584 W/K.m, what resents a decrease of 42%. It means the aerogel had the same effect on these two characteristics.

This study brings up the idea that the results obtain for the state-state methods for the hardened state with the moisture content in equilibrium with air actually does not correspond to this state but to an intermediate state between the hardened state and the hardened dry state, as these tests produce some similar partial drying process on the samples during the tests.

It was revealed that all the results obtain in laboratory were higher than the declared value for the product studied.

This study also pointed out that there is a lack of information for declared values and study results for thermal conductivity, in the most cases information like temperature, moisture content or the methods used to obtain the values presented are not revealed, being this information extremely important to characterize and compare different results and materials.

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