AEROGEL INFLUENCE ON THE THERMAL MORTARS PHYSICAL PERFORMANCE

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1. Introduction

With the world's population growth, the upward trend of migration to urban areas, and the population's increasing awareness about their dwellings thermal comfort level, energy expenditure has grown at a problematic rate. According to *Enerdata* (2012), about 41% of the energy consumed throughout Europe in 2010 was used in the construction sector, 32% in transportation, 25% in industry and 2% in agriculture. Much of this energy expenditure within the housing sector is directly related to the need to keeping an inside ambient temperature, regardless of the outside temperature (figure 1).

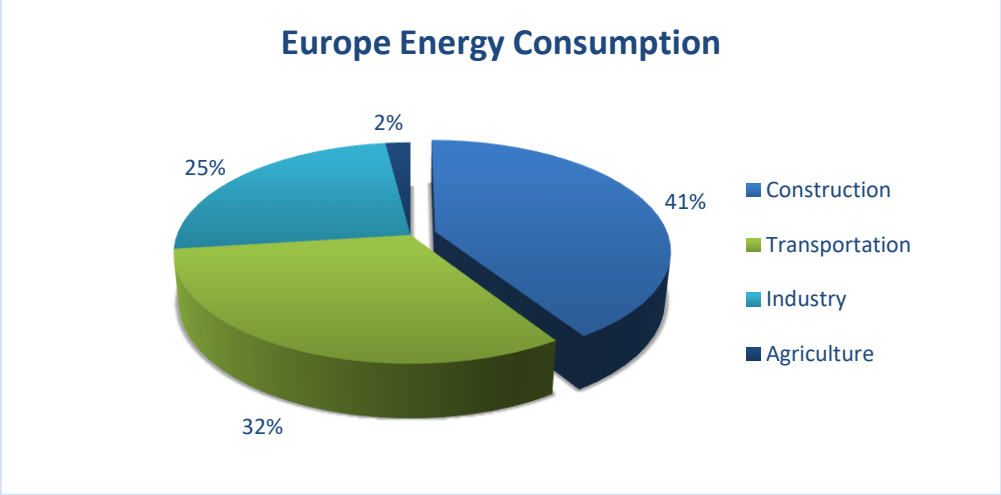

Figure 1 Europe energy consumption on the different sectors (Enerdata, 2012).

To reduce all of these energy losses, the existing legislation in Portugal, the RCCTE (Buildings Thermal Characteristics Behavior Regulation, 1990), was revised in 2013, and created new regulation, the Energy Performance of Housing Buildings Regulation (REH). This regulation requires all properties to have an Energy Certificate (Decree-Law no. 118/2013 of August 20), when advertised, or when any contract relating to the property is tendered. The Certificate may range from A+ to F, depending on the property energy performance, with A+ being the best possible classification and F the worst.

Currently, the energy problems mentioned above coupled with the concern of reducing the environmental impacts of constructions, led to new materials/systems development that improved thermal insulation performance of the building walls. Those improvements include lowering the thermal conductivity without affecting other constructive building elements.

One such system that intends to solve the thermal insulation problem within walls is the ETICS (or sometimes known as EIFS - Exterior insulation and finish system - in countries like USA and Canada). ETICS is an insulation composite system made of several layers, which is placed as an outer covering of the building and increases thermal behavior of the walls. With insulating materials, such as EPS (expanded polystyrene), XPS (extruded polystyrene), MW (mineral wool), ICB (expanded cork agglomerate), thermal conductivity can achieve values between 0.035-0.037 W/m.K (Veiga et al, 2012). Although the ETICS is a very reasonable solution, this system has some inherent disadvantages, such as the fact that it requires a high initial investment solution (even though it is compensated for after some time), it has a low mechanical resistance (regardless of the fact it can be reinforced with fiberglass or metal mesh), a low durability (frequent presence of abnormalities associated to hygrothermal phenomena and impact resistance) and it is difficult to apply on irregular zones or detailed areas (Corrêa, 2016).

Thermal mortars are also a coating solution that aims to improve the thermal performance of the wall, and they serve as an alternative to ETICS solutions. Thermal mortars are defined as mortars that have light aggregates in their constitution, instead of higher bulk density aggregates, such as sand aggregates, and are characterized for having a thermal conductivity class of T1 or T2 (T1 – $\lambda \leq 0.1$ W/m.K; T2 – $\lambda \leq 0.2$ W/m.K), regulated in the European Standard EN 998-1 (CEN, 2010).

A thermal mortar for wall cladding must also comply with the existing regulation regarding the building's thermal performance (RCCTE, 2006). In addition to the mentioned properties above, these mortars should also respect the classifications specified in table 1, which are the basis for a quality check with CE Marking.

Table 1 Required properties for a thermal mortar, adapted from the Standard EN 998-1 (CEN, 2010).

Properties	Classes	Requirements
Bulk density	-	Declared range of values
Compressive strength	CS I to CS IV	CS I to CS II
Adhesion	-	Declared value and fracture pattern
Capillary water absorption	W0, W1 and W2	W1 ($c \leq 0{,}40\ \mathrm{kg/m^2 min^{0,5}}$)
Thermal conductivity	T1 and T2	T1 ≤ 0,10 W/m.K or T2 ≤ 0,20 W/m.K
Reaction to fire	A to F	If organic material ≤ 1% - A1, if not it is required a test
Durability	-	Declare durability
Water vapor permeability coefficient	-	μ ≤ 15

Although thermal mortars present higher thermal conductivity values (minimum λ around 0,05 W/m.K), when compared to ETICS, they also have a higher potential to be applied in a greater variety of situations, such as the following: rehabilitation of older buildings or buildings with complex architecture or with curved surfaces; in order to increase the thermal performance of existing walls that already have some thermal insulation; and to held keep the appearance of the building's existing façade;

For this experimental work, light aggregates such as EPS, perlite and silica aerogel were tested. The first two have historically been included in industrial mortars, and the last (aerogel) was added to the industrial mortars mentioned for the purpose of this test.

The first industrial mortar named $\mathrm{A^{Eps}}$, is a product that provides high thermal performance to a surface and is usually used for insulation of new and rehabilitated walls. It is a continuous mineral insulation product with a yellowish color. It is composed of mineral binders (lime and cement), mineral fillers, special adjuvants (rheology, air introducers, resin and water repellents) and light loads, in particular EPS aggregates. The second industrial mortar used during this experimental campaign, named $A^{Perlite}$, is also a product used to improve the thermal performance of a surface, however it is made up of a different composition. This material is a coating mortar that is still being studied by industry professionals, and may be referred to as a super insulating plaster (SIP). Its composition is comprised of mineral binders, such as Portland cement, other reactive cements and light aggregates of expanded perlite.

Included in a large portion of this experimental study there is a lightweight aggregate called silica aerogel, which was added to the mortars to give them an even lower bulk density and thermal conductivity. The silica aerogel was used as a granular aggregate (figure 2). It is considered translucent, amorphous, hydrophobic and was produced by supercritical drying. It has a very substantial durability and resistance to humidity and heat. It is a non-toxic material when

ignited or exposed to high temperatures and is still capable of maintaining the thermal properties after being subjected to accelerated aging cycles at 200 °C in a saturated wet environment. The aerogel used has a bulk density that ranges 60-100 kg/m³ and a thermal conductivity of 0,018-0,020 W/m.K (figure 2).

Figure 2 Silica aerogel used on the experimental work.

2. Experimental work

The aim of this experimental work is to characterize the thermal and mechanical behavior of two industrial thermal mortars with different lightweight aggregates (A^{Eps} – EPS aggregate; $A^{Perlite}$ - perlite aggregate), and when silica aerogel is added to their composition. This characterization involves the analysis of the mortars in a fresh state, meaning right after their production, and in the hardened state. Bulk density was determined in the fresh state, while the following properties were evaluated in the hardened state: bulk density, thermal conductivity, compressive strength, dynamic modulus of elasticity, and modulus of torsion.

In the hardened state, the mortars were assessed after two lengths of time, 28 days and 31 days. After the first length of time had passed, (28 days) the samples were tested after being exposed to dry cure chamber conditions (temperature at 20 °C ± 5 °C and relative humidity of 65% ± 5%). This condition is named wet hardened state. After the sample had cured for 28 days, the samples were placed in the electric oven at 60 °C for three additional days (totaling 31 days from its production). After the samples were removed from the electric oven and samples had return to ambient temperature, the bulk density and the thermal conductivity were determined. This state is called dry hardened state.

This experimental procedure consists of 3 distinct phases, with the purpose of analyzing and comparing the thermal and mechanical properties of the thermal mortars with different constitutions. During the first stage, 12 thermal mortars were produced. Six (6) of them were produced with an industrial mortar composed of lightweight EPS aggregates (A^{EPS}) as the base of the mixture, and the remaining 6 consisted of another industrial mortar composed of lightweight perlite aggregates ($A^{Perlite}$). Silica aerogel was added to these industrial mortars in different quantities, allowing the study of the aerogel influence on a thermal and mechanical performance (figure 3).

For each of the industrial mortars a control sample was produced, meaning no aerogel was added. Five more samples were also produced with different percentages of aerogel. The samples contained the following percentages of aerogel when compared to the industrial mortar mass: 25%, 56%, 119%, 133% and 181%. The amount of water used in each mixture was determined during the production, according to the workability and cohesion capacity of the mortar components.

As shown in figure 3, cylindrical samples were produced with the purpose of using a contact probe in order to characterize the thermal performance of the mortars. However, as the contact prone was unable to determine the precise performance value for some thermal mortars, samples that could be used with a needle probe were produced. These samples were produced to evaluate ranges of values lower in number than the contact probe could measure (0.04-0.3 W/m.K), more precisely, between 0.01-0.05 W/m.K (figure 3). In this second stage, were used cylindrical molds of plasticized cardboard, with a diameter of 80 mm and a height of approximately 130 mm. Six samples were produced. Three (3) of them are based on the industrial mortar A^{EPS} (A^{119}, A^{133}, A^{181}), while and the remaining 3 are $A^{Perlite}$ based (S^{119}, S^{133}, S^{181}).

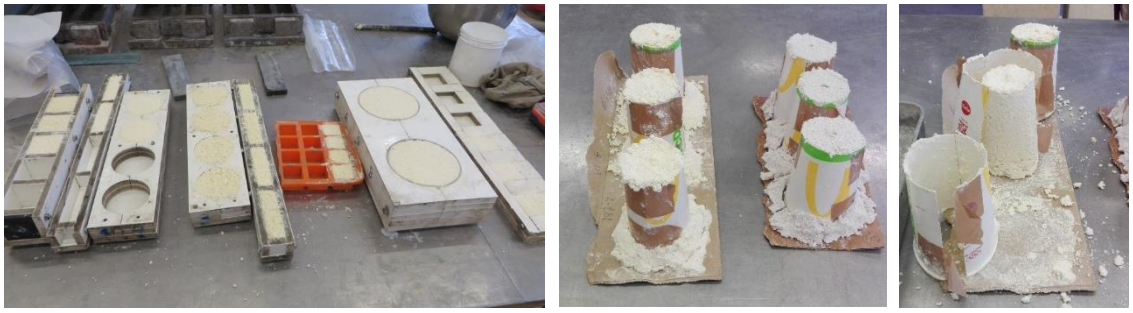

Figure 3 First and second stage of the experimental campaign.

Figure 4 Third stage of the experimental campaign.

To validate the thermal conductivity results previously obtained by the needle probe, two different methods of measurement and two separate molds were used for the same mortar, in order to compare values during the third and final stage. Eight samples were produced, four of which were cylindrical specimens of 50mm diameter and 130mm height, which were to be used with the needle probe application. The remaining four, prismatic specimens of 330x330x30mm³ which were to be evaluating using the Heat Flow Meter (HFM) method. The goal of both methods

was to determine the thermal conductivity of the industrial mortar and compare the values obtained. For these productions, the mortars $A^{100}, A^{133}, S^{100}$ e S^{133}, were chosen because they fit the intended objectives (figure 4).

3. Physical performance/results

The results obtained with this experimental work can be consulted on the table 2, where are indicated the most significance values for each mortar studied. In order, from the left to the right the values are as follow: the bulk density in the fresh state (right after the mortar production), the bulk density in the hardened state (after 28 days under dry cure chamber conditions), and bulk density in the hardened dry state (after being dried in an oven for 3 days). In regards to the thermal conductivity, the results shown were measured in the same conditions as the bulk density: in other words, they were measured on the 28th day (hardened state) and 31st (hardened dry state). The other properties were all determined in a hardened state after 28 days.

Table 2 Meaningful values obtained during the experimental work.

Mortars		ρ^{fresh}	$\rho^{hardened}$	ρ^{dry}	$\lambda^{hardened}$	λ^{dry}	f_c	Ed	G
		[kg/m³]	[kg/m³]	[kg/m³]	[W/m.K]	[W/m.K]	[MPa]	[MPa]	[MPa]
Industrial mortar A^{EPS}	A^0	378,25	234,75	226,80	0,0542	0,0507	0,31	144,9	59,8
	A^{25}	336,50	195,41	181,70	0,0452	0,0425	0,20	44,6	20,8
	A^{56}	329,50	186,56	172,86	0,0430	0,0405	0,12	23,5	11,1
	A^{100}	323,50	102,62	*	*	0,0230	*	*	*
	A^{119}	268,00	137,05	124,23	0,0343	0,0272	0,05	3,9	4,2
	A^{133}	313,75	159,15	154,73	0,0346	0,0274	0,09	7,0	2,0
	A^{181}	280,00	127,32	123,35	0,0288	0,0256	0,05	4,2	1,4
Industrial mortar $A^{Perlite}$	S^0	435,00	202,92	200,71	0,0547	0,0540	0,09	85,4	12,6
	S^{25}	306,75	158,27	153,85	0,0484	0,0478	0,09	*	*
	S^{56}	303,00	175,95	180,38	0,0465	0,0460	0,06	6,0	2,0
	S^{100}	262,75	*	*	*	*	*	*	*
	S^{119}	232,00	129,98	123,79	0,0307	0,0266	0,01	51,3	10,7
	S^{133}	266,50	149,87	148,99	*	*	0,03	2,6	1,2
	S^{181}	249,25	141,03	137,49	0,0264	0,0226	0,04	3,1	1,6

Legend: ρ – bulk density; λ – thermal conductivity coefficient; f_c – compression strength; Ed – modulus of elasticity. G – modulus of torsion. *Values that were not obtained due to the rupture of the samples.

In general, the addition of aerogel to the industrial mortars led to the following results: an improvement to the thermal conductivity, and a decrease of the bulk density, compressive strength, modulus of elasticity and modulus of torsion.

Values for the bulk density in the fresh state range from about 280-378 kg/m³ for A^{EPS} mortars and from 249-435 kg/m³ for $A^{Perlite}$ mortars. The reference sample value for A^{EPS}, 378.25 kg/m³, is within the range provided by the manufacturer, which can be found in the material data sheet, and has a range of 350 ± 75 kg/m³ (WSG, 2016). In regards to the reference mortar (0% aerogel) of the $A^{Perlite}$ there is no defined value, since it is a mortar currently under development.

Comparing aerogel mortars with reference mortars, it is verified that, the addition of aerogel results in a decrease of the bulk density by 26% for mortars with A^{EPS} as base and a decrease of 43% for the mortars with $A^{Perlite}$. Although the reference sample of $A^{Perlite}$ is higher than A^{EPS}, the trend for higher percentages of aerogel is reversed, where lower values for $A^{Perlite}$ were obtained, around 10% less.

After hardened and dried (dry state), a great decrease in the bulk density of the samples was observed, as shown on the table 2. The addition of the aerogel allowed a variation between the reference sample (0% aerogel) and the lower bulk density sample of around 45% and 30%, for A^{EPS} and $A^{Perlite}$ respectively. Comparing the reference sample of the two industrial mortars, the $A^{Perlite}$ mortar reveals a lower bulk density, however, for values of 181% addition of aerogel, the value is higher by approximately 11%. In general, the trend remains like in the fresh state, meaning, the higher the aerogel quantity the lower the bulk density. For the mortars produced, the best values obtained were 123,35 kg/m³ for A^{EPS} and 137,49 kg/m³ for $A^{Perlite}$, which are very reasonable results when compared to the values obtained by other authors, more precisely, Archard *et al* (2011) and Stahl *et al* (2012), which reached values of about 156 kg/m³ and 200 kg/m³, respectively, within their mortars.

To obtain the thermal conductivity of the mortars, two models of the ISOMET equipment were used, 2114 and 2104, with two different probes, the contact and the needle probes, and the equipment required for the HFM method (this last method was just used to validate the needle probe tests). The thermal properties of the mortars were evaluated after two different moments, namely at 28 days, and after the samples had oven dried at 31 days. For the purpose of this discussion only the dry state samples will be discussed as these samples resemble the closest to those seen in practice in construction. In any of the tests carried out, the thermal conductivity obtained was always less than 0.1 W/m.K, which means, all mortars produced are category T1, according to the classification of thermal conductivity for thermal mortars at 28 days specified in the standard EN 998-1 (CEN, 2010). The first tests were conducted using the contact probe, which has a range of 0.04-0.30 W/m.K, that is, values close to 0.04 may be unrealistic (such as A^{119}, A^{133}, A^{181}, S^{119}, S^{133} and S^{181}) . For this reason, for mortars with a higher percentage of aerogel and values close to or below the probe range, new samples were tested with the needle probe, which is capable of determing lower values, and can calculate values within the magnitude of the expected results (0.015-0.05 W/m.K).

When analyzing the results, the reference sample value, A^0 (0.0507 W/m.K), is similar to the one reported by the manufacturer in the product datasheet, 0.0420 W/m.K. However, this approximation has an associated error of 17%, which is still higher than expected. This discrepancy of values may be related to differences in the production process of the manufacturer compared to laboratory processes, such as the mixing time and the compaction of the mortar. In regards to S^0 (0.0540 W/m.K) there is no comparison data, since it is a mortar under study and without a defined technical file.

The minimum values reached for the maximum percentages of added aerogel can be considered sizable values, 0.0256 W/m.K for A^{181} and 0.0226 W/m.K for S^{181}, when compared with values usually obtained in high performance thermal mortars. This comparison argues the accuracy of this experimental work. The results obtained are similar to the aerogel mortar already marketed in Switzerland, such as FIXIT 222 (FG, 2013), which has a thermal conductivity of 0.0280 W/m.K. Other studies, such as Stahl *et al*. (2012) and Archard *et al*. (2011) reported values around the same greatness, 0.025 W/m.K and 0.0268 W/m.K, for mortars with aerogel in their constitution. The samples were tested at a temperature of 23°C and with a relative humidity of approximate 50%. For mortars with a maximum percentage of aerogel addition, a reduction of 53% and 59% was obtained for reference mortars A^{EPS} and $A^{Perlite}$ respectively.

It should also be noted that mortars with an Aerogel/Industrial mortar ratio bigger than 1.0, which means, a 50/50 blend, display a thermal conductivity lower than 0.035 W/m.K for both industrial mortars. Thus, there is a direct relation between the addition of aerogel and the decrease in value of the thermal conductivity of the mortar. The higher the amount of aerogel, the lower the thermal conductivity. These facts can be observed in figure 5, which shows the trend of the thermal conductivity, with the aerogel addition. However, the results do not allow us to conclude the main cause for the thermal improvement obtained throughout this experimental procedure. The improvement may in fact be due to the impact of the bulk density decrease. Similarly, the improvement may be due to the introduction of a more insulated material in and of itself or it may be for both causes.

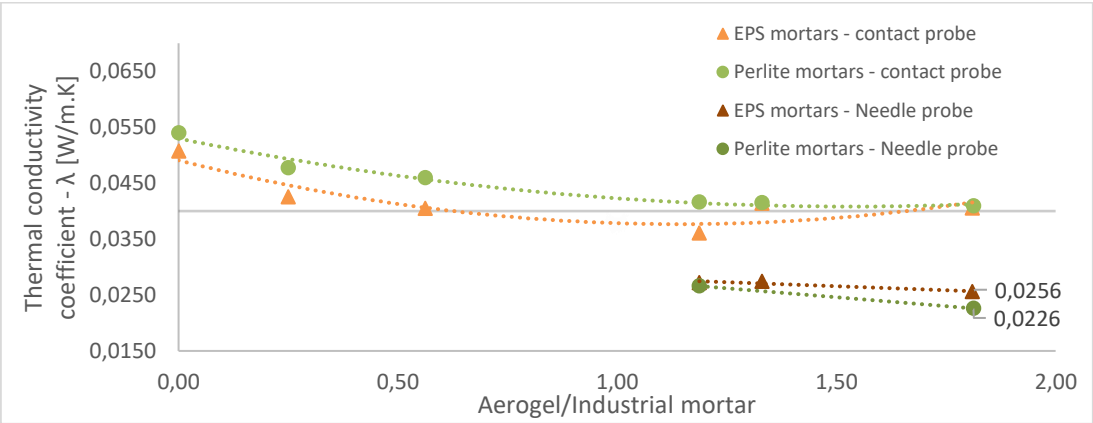

Figure 5 Thermal conductivity variation with aerogel percentage increase on a dry hardened state.

According to standard EN 998-1 (CEN, 2010) there are four classes related to the compressive strength of mortars at 28 days, where the minimum class is CSI and comprises values between 0.4 and 2.5 MPa. Even though every test carried out obtained a resistance lower than 0.4 MPa, the issue of resistance can be solved by utilizing a system where those thermal mortars will always be protected by a higher resistance layer.

As would be expected, in both industrial mortars, there was a decrease in compressive strength with the increase of aerogel percentage (figure 6), reaching 84% comparing to the reference sample for A^{EPS} and for $A^{Perlite}$ a decrease of 75%. The percentages mentioned are related to very low compressive strengths, which range from 0.01-0.05 MPa and should not be directly compared, since the perlite mortars have lower original values (reference samples).

Since perlite mortars presented low mechanical strength and were also difficult to produce, it is concluded that for these mortars, coupled with the addition of aerogel, require an increase in the amount of binder materials used, such as cement or hydraulic lime, to the detriment of other components, in order to impart a greater mechanical resistance.

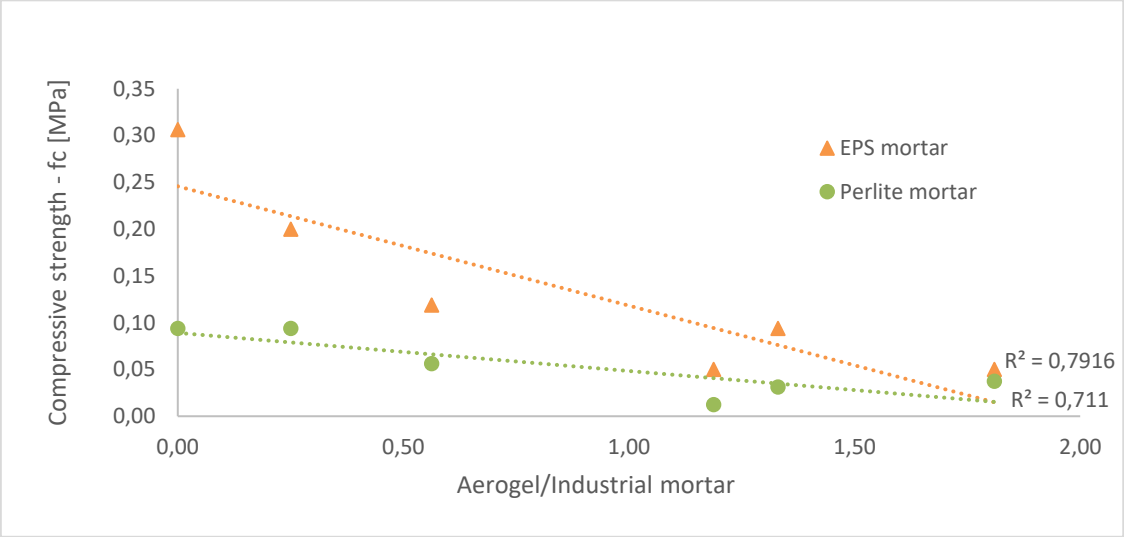

Figure 6 Compressive strength variation with aerogel percentage increase on a hardened state.

With the analysis of the results it was observed that, for the dynamic modulus (E), values between 4.2 and 144.9 MPa were obtained for the A^{EPS} mortars and values between 3.1 and 85.4 MPa were found for the $A^{Perlite}$. For the modulus of torsion (G) the results were between 1.4 and 59.8 MPa for the mortars A^{EPS} and for the $A^{Perlite}$ the values were between 1.6 and 12.6 MPa. There is a clear decrease in both properties for both EPS and perlite mortars, trending to very low values when higher percentages of aerogel were reached. With this sharp decrease in the characteristics of the materials, values in the order of 2-5 MPa were obtained for both E and G, which corresponds to decreases of approximately 90% when compared with the values of the reference mortars.

4. Conclusions

With this study, it is possible to conclude that the addition of aerogel (at least 25% of the powdered mass of the industrial mortar) in industrial thermal mortars has an immediate influence on the thermal and mechanical behavior of these mortars, decreasing the values of all the

properties studied. As expected, the lightweight aggregate of aerogel proved to be a very efficient aggregate for the improvement of mortar's thermal performance. However, this wasn't the case for the compressive strength, which showed a considerable decrease.

Based on the reference thermal mortars (industrial mortars A^{EPS} and $A^{Perlite}$ with 0% aerogel), a comparative analysis was made with mortars that are comprised of aerogel aggregates. It was concluded that, for aerogel additions greater than 100% of the industrial mortar powdered mass, were obtained values for the bulk density that range 100-150 kg/m³, which means a decrease of about 40-55% over the reference samples (227 and 201 kg/m³ for A^{EPS} and $A^{Perlite}$ respectively). In regards to the thermal conductivity and for the same mortars (aerogel additions greater than 100%), values below 0.030 W/m.K were obtained, reaching a minimum of 0,023 W/m.K for mortar A^{100}, which means the same quantity of A^{EPS} industrial mortar and aerogel. This aerogel addition (greater than 100%) positively influenced the thermal performance of the mortars, allowing the thermal properties to reach reductions between 50 to 60% when compared to the reference samples (0% of aerogel). It should be noted that all mortars produced are thermal class T1, according to EN 998-1 (CEN, 2010). When concerning the compressive strength, again for additions of aerogel above 100%, there were quite considerable decreases. For A^{EPS} industrial mortars, values between 0.05-0.1 MPa were obtained, which corresponds to a reduction of 70 to 85%. For $A^{Perlite}$ industrial mortars, a reduction was also observed, values reached lower than the first and ranged between 0.01-0.05 MPa, noting a decrease of 60 to 80%. Due to the fact that $A^{Perlite}$ industrial mortars are shown to have very low strength, an increase on the binder quantity should be considered when high percentages of aerogel are added. The classification of the mortars is in accordance to EN 998-1 (CEN, 2010); as such, all mortars have lower compressive strength than CSI class, which means that these mortars are only classified according to the pre-standard, Fpr EN 16025-1 (CEN, 2012). The decrease of the modulus of elasticity and modulus of torsion with the increase of aerogel in the mixture was also notable. The reductions reached about 90%; in other words, the incorporation of aerogel made the mortars more deformable.

In general, when the two industrial mortars (A^{EPS} and $A^{Perlite}$) are compared, for the same quantities of added aerogel, their behavior is similar (for properties, such as, bulk density, thermal conductivity, modulus of elasticity and modulus of torsion), except for the compressive strength, where the $A^{Perlite}$ mortars had a lower strength than A^{EPS}.

After analyzing all the tests and results obtained within this experimental procedure, and understanding the ultimate goal of reducing the thermal conductivity as much as possible, while not greatly reducing the compressive strength, it is concluded that from the mortars analyzed, the ideal mortar for combating the energy problems today, would be closer to A^{119} (perhaps A^{100}, although it is not fully characterized). This mortar has an apparent bulk density of 124 kg/m³, a thermal conductivity of 0.0272 W/m.K, a compressive strength of 0.05 MPa, a modulus of elasticity of 3.9 MPa and a modulus of torsion of 4.2 MPa.

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