Experimental characterization of thermal mortars after exposure to elevated temperatures

Extended Abstract

Manuel António Mendonça da Cunha Pereira

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Department of Civil Engineering, Instituto Superior Técnico, Universidade de Lisboa, Portugal

1. Introduction

In the recent years, the concern with environmental impact and thermal comfort is assuming an increasing relevance in the design and construction of buildings. The new national regulation for buildings (REH [1], among others) have boosted the use of new technologies for the production of new materials and coating systems that are able to ensure a high thermal performance, without compromising their mechanical resistance. Among these solutions are the thermal mortars [2], obtained through the incorporation of insulating aggregates. It is also important that this type of mortars can maintain their properties, and fulfil their initial functions even when exposed to high temperatures, namely in industrial applications or after accidental actions, such as fire.

According to standard EN 998-1 [3], the maximum thermal conductivity coefficient of thermal mortars is 0.1 W/m·K (Class T1) and 0.2 W/m·K (Class T2). They are also characterized by the CS I and CS II strength classes (0.4 to 5 MPa), capillary water absorption coefficient lower or equal to 0.40 kg/m^{2}min^{0,5} (W1 class) and water vapour permeability coefficient of 15.

The incorporation of insulating aggregates improves the renders' thermal performance and significantly reduces their bulk density in the hardened state, allowing them to be classified as lightweight aggregates according to BS EN 13055-1 and BS EN 206-1, with a density lower than 1200 kg/m^3 [4,5]. In this study, expanded clay, granulated cork and silica aerogel were the thermal insulating aggregates tested.

Expanded clay combines good thermal resistance (up to 1000ºC), high porosity and low bulk density (300 to 700 kg/m^3), with high structural strength and low cost production, that makes it a valid solution to be used as an insulating material in construction. Expanded clay has a high percentage of semi-closed pores (up to 90% of its volume), contributing to its low thermal conductivity (approximately 0.10 W/m·K) [6-8].

Silica aerogel is a nanostructured material characterized by an open pore structure with 95% of air content, with bulk density of 3 to 500 kg/m^3, and very low thermal conductivity (0.01 to 0.02 W/m·K) [6]. It is an extremely light, hydrophobic, non-flammable and high heat resistant material, with cost and difficulty of production being its main obstacles, limiting it to high technology uses [8-10].

Cork is a very low density material (between 100 and 140 kg/m^3), with low thermal conductivity (0.035 to 0.070 W/m·K) and good mechanical properties. Is also an organic and cellular material [11-13]. In this study expanded granulated cork was used as an aggregate.

In the present study an experimental campaign was conducted to characterize the physical and mechanical behaviour of thermal mortars incorporating these aggregates after exposure to elevated temperatures. Traditional formulations of thermal mortars were produced, then exposed to different elevated temperatures and finally subjected to various tests, with the following main objectives:

- to evaluate the influence of the incorporation of insulating aggregates (expanded clay, expanded granulated cork, silica aerogel) and admixtures (air entrainer agent, liquid resin, and rheological agent) in the composition of the thermal mortars;
- to study the influence of exposure to high temperatures in the different mortars produced, namely on their physical and mechanical properties, by testing bulk density, ultrasonic pulse velocity, dynamic elasticity modulus, dynamic shear modulus and *Poisson* coefficient, compressive strength and thermal conductivity;
- to compare the behavior of the different mortars and understand the effects of exposure to high temperature on their performance and on the correlations between the most affected parameters.

2. Experimental work

In order to characterize the effect of high temperatures in the properties of thermal mortars, seven mortars (three thermal mortars, one reference mortar and three sand mortars with admixtures) were produced, with each mortar's composition being shown in table 1.

Table 1 - Mortars' composition

Mortar	Aggregate	Binder	Water/cement ratio	Aggregate dimensions (mm)	Admixtures (% binder's mass)		
					Air entrainers	Rheological agent	Resin
A^{AE}	100% expanded clay	CEM II 32,5N	0,90	0,5 to 2	-	-	-
B^{GC}	100% granulated cork		1,00		-	-	-
C^{AERO}	100% aerogel		0,90		0,5	0,075	-
D^{REF}	100% sand		0,65		-	-	-
E^{CT}			0,55		0,5	0,075	-
$F^{5\%RES}$			0,65		-	-	5
$G^{10\%RES}$			0,65		-	-	10

A 1:4 volumetric ratio was used for the production of all mortars, since it is the most commonly used ratio for traditional cement-based mortars in Portugal [14]. In addition the same binder was used in all mortars (Portland cement of the CEM II B/L type 32,5 N class) and the water/cement ratio used for each mortar was

selected according to EN 1015-2 standard, in order to meet the requirements necessary for ensuring the right workability [15].

Three thermal mortars were produced: one containing 100% of expanded clay (A^{AE} mortar), one containing 100% of granulated cork (mortar B^{GC}) and one containing 100% of aerogel (C^{AERO} mortar). One reference sand mortar was produced (mortar D^{ref}), and three sand mortars were produced using admixtures (mortars E^{CT}, $F^{5\%res}$ and $G^{10\%res}$). In total, 5 batches were produced for each mortar, each for a given target temperature. The particle grading sizes used for the studied mortars were selected according to "Curve 2" with fraction sizes from 0.5 to 1 mm and from 1 to 2 mm, in agreement with the grain sizes of the thermal insulating aggregates. For each mortar 5 prismatic samples measuring 160x40x40 mm were produced for mechanical strength tests and 2 cylindrical samples with 60 mm of diameter and 20 mm of thickness were produced for thermal conductivity tests (figure 1).

Figure 1 – Prismatic sample mold with 160x40x40mm (left); cylindrical sample mold with 60mm diameter and 20mm thickness (right)

All the samples were stored and cured following the EN 1015-11 standard [16], according to which they were wet first cured in polyethylene bags (7 days) and then subjected by dry curing (21 days) in a climatic chamber under controlled conditions of 20ºC ± 2ºC and relative humidity of 65% ± 5%.

After mold releasing and completing the curing process, the samples were placed in a thermal chamber. Each production of mortars was heated at a rate of 2,5ºC/min up to a target temperature, for which it was subjected during a period of one hour, and finally cooled to ambient temperature at a rate of -1,5ºC/min, in order to minimize the internal stresses due to temperature variations (figure 2). Each mortar was exposed to the following temperatures: 100ºC, 150ºC, 200ºC and 250ºC. Then, they were placed back in the climatic chamber for 24 hours.

Figure 2 – Thermal chamber *Tinius Olsen Environmental Chamber* before and during the tests (left and center); metallic structure to hold samples during high temperatures exposure (right)

In order to characterize physically and mechanically the mortars exposed to high temperatures and the mortar at room temperature (for comparison purposes), a set of tests were performed to evaluate the bulk density, ultrasonic pulse velocity, dynamic modulus of elasticity, dynamic shear modulus, *Poisson* ratio, compressive strength, and thermal conductivity according to European and American standards [17-22]. This way, it was possible to measure and evaluate the influence of the high temperatures in the properties of the studied mortars.

3. Results and discussion

Table 2 lists the results of the experimental tests and indicates the test standards that were followed.

It is important to note that the sand mortar with 10% resin was poorly produced because an excessive amount of resin was used, which led to a consequent segregation of the material. For this reason, the results obtained from this mortar are not considered to be representative due to its heterogeneity.

For mortars exposed to higher temperatures (150ºC, 200ºC and 250ºC) one observed the occurrence of condensations inside the thermal chamber. These condensations occur due to the evaporation of water from the mixture, leading to an increase of the mortar's porosity [23].

The bulk density in hardened state of mortars incorporating insulating aggregates range between 432 and 737 kg/m^3, and between 1590 and 1749 kg/m^3 for sand mortars. For the temperature range studied, exposure to high temperatures had a significant effect in reducing the bulk density in the hardened state, with variations around 10%, except for the aerogel mortar (C^{AERO}), which achieved a reduction of about 25% for the temperature of 250ºC (figure 3). According to EN 998-1 [3], these thermal mortars can be classified as lightweight mortars, since their bulk density is lower than 1300 kg/m^3.

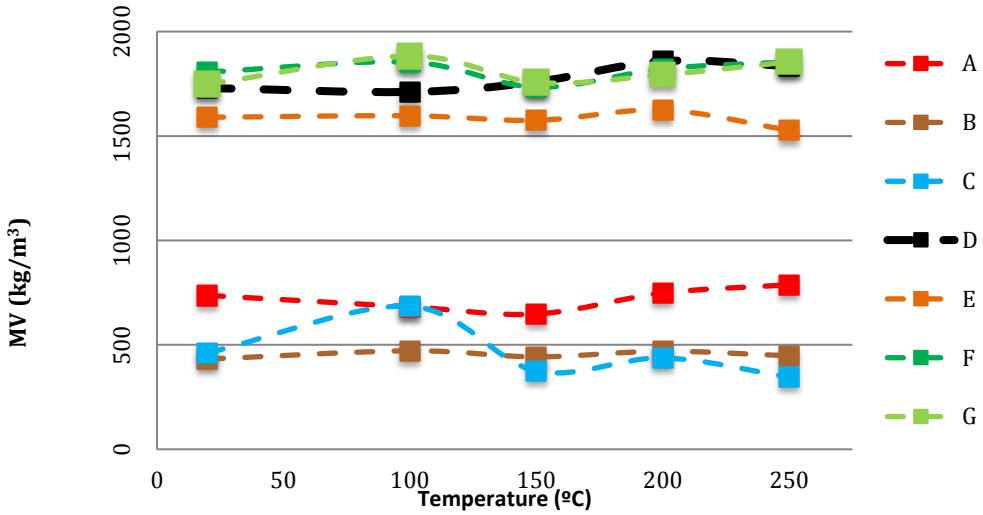

Figure 3 - Bulk density (kg/m^3)

Table 2 - Test results

Mortars	MV (kg/m³)	V (m/s)	E_d (MPa)	G_d (MPa)	ν	Cs (MPa)	λ (W/m·K)
Standards	EN 1015-10 [17]	EN 12504-4 [18]	ASTM E 1876-01 [19]			- [20]	ASTM C518 [21]
$A^{AE}_{control}$	737	2379	3152	1349	0,17	3,99	0,202
$A^{AE}_{100ºC}$	682	2201	2239	955	0,18	3,27	-
$A^{AE}_{150ºC}$	648	2065	2033	888	0,15	3,09	0,142
$A^{AE}_{200ºC}$	748	2279	2631	1177	0,12	3,59	-
$A^{AE}_{250ºC}$	788	2335	3144	1379	0,14	3,98	0,04
$B^{GC}_{control}$	432	994	238	98	0,23	0,89	0,102
$B^{GC}_{100ºC}$	472	1112	379	124	0,29	1,16	-
$B^{GC}_{150ºC}$	443	1083	332	128	0,2	1,07	0,078
$B^{GC}_{200ºC}$	470	1020	327	140	0,17	1,06	-
$B^{GC}_{250ºC}$	448	1072	281	99	0,31	0,97	0,075
$C^{AERO}_{control}$	462	1094	290	66	0,3	0,99	0,074
$C^{AERO}_{100ºC}$	684	968	261	122	0,08	0,93	-
$C^{AERO}_{150ºC}$	375	973	292	64	0,3	1	0,062
$C^{AERO}_{200ºC}$	437	837	192	99	0,3	0,78	-
$C^{AERO}_{250ºC}$	346	813	184	86	0,16	0,76	0,06
$D^{ref}_{control}$	1730	3081	12310	2826	0,3	8,83	1,987
$D^{ref}_{100ºC}$	1711	3010	10984	3369	0,24	8,26	-
$D^{ref}_{150ºC}$	1760	2732	10454	2606	0,3	8,02	1,338
$D^{ref}_{200ºC}$	1858	2852	11718	5213	0,12	8,58	-
$D^{ref}_{250ºC}$	1836	2597	9891	4455	0,11	7,77	1,247
$E^{CT}_{control}$	1590	2551	6944	3230	0,13	6,32	1,326
$E^{CT}_{100ºC}$	1597	2298	7095	3000	0,18	6,4	-
$E^{CT}_{150ºC}$	1575	2010	4939	2223	0,11	5,18	1,122
$E^{CT}_{200ºC}$	1624	2003	4890	2178	0,12	5,15	-
$E^{CT}_{250ºC}$	1528	1681	3111	1387	0,05	3,96	0,956
$F^{5\%res}_{control}$	1806	3357	15353	4278	0,3	10,04	1,385
$F^{5\%res}_{100ºC}$	1853	3358	16773	3708	0,3	10,57	-
$F^{5\%res}_{150ºC}$	1734	2885	11335	5032	0,13	8,41	1,618
$F^{5\%res}_{200ºC}$	1822	2823	11059	5013	0,1	8,29	-
$F^{5\%res}_{250ºC}$	1854	2507	8842	4138	0,07	7,28	1,364
$G^{10\%res}_{control}$	1749	3474	10713	2904	0,28	8,14	-
$G^{10\%res}_{100ºC}$	1883	3470	18714	4356	0,3	11,27	-
$G^{10\%res}_{150ºC}$	1756	3021	12160	4542	0,32	8,76	-
$G^{10\%res}_{200ºC}$	1793	2845	8593	3753	0,14	7,16	-
$G^{10\%res}_{250ºC}$	1854	2195	8842	4138	0,07	7,28	-

Legend: MV – bulk density in hardened state; V – ultrasound pulse velocity; E_d – dynamic elasticity modulus; G_d – dynamic shear modulus, ν – Poisson coefficient; Cs – compressive strength; λ – thermal conductivity

The strength of a mortar can be estimated based on the principle that more compact materials feature higher wave propagation speeds and resistance values. Therefore, with the ultrasonic pulse velocity test, it is possible to assess the state of compactness of mortars and consequently its state of internal degradation (discontinuities, voids). As expected, the values of the values of the ultrasound pulse velocity of thermal mortars are lower than those of sand mortars. Exposure to high temperatures had a reduced influence in the ultrasound pulse velocity of the expanded clay (A^{AE}) and granulated cork mortars (B^{GC}). The aerogel mortar (C^{AERO}) was sensitive to temperatures from 200ºC, with a reduction of ultrasound pulse velocity of 25% after exposure to 250ºC. Sand mortars experienced ultrasound pulse velocity reductions with exposure to high temperatures, mainly for mortars with admixtures from 100ºC, with maximum reductions of 34% (E^{CT}) and 25%($F^{5\%res}$) for 250ºC (figure 4). This parameter reduction confirms the presence of mortar discontinuities with increasing porosity and micro-cracking [24].

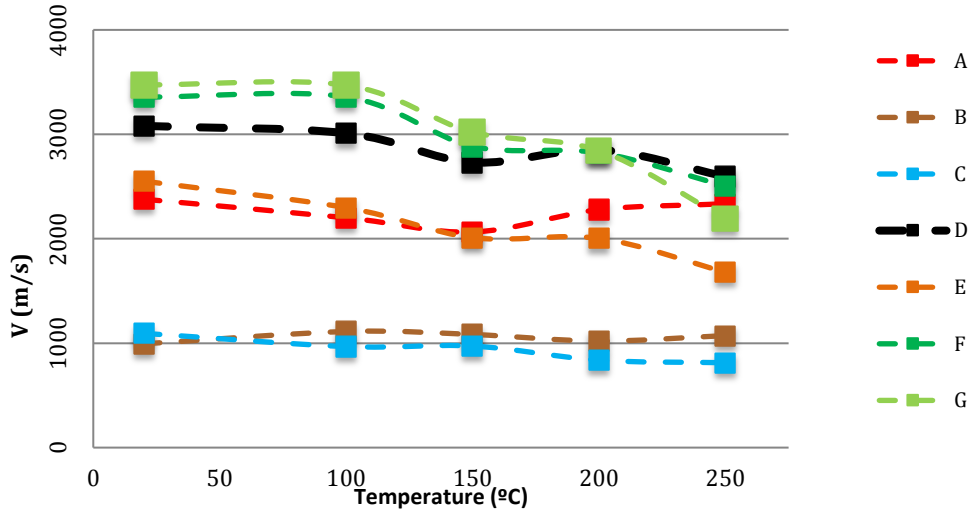

Figure 4 - Ultrasound pulse velocity (m/s)

Regarding the mortars' dynamic modulus of elasticity after exposure to high temperatures, from 200ºC there were reductions for the aerogel mortar (C^{AERO}), and reductions of up to 37% for 250ºC. With the increase of temperature, the expanded clay (A^{AE}) and reference mortars (D^{ref}) showed reductions between 17% and 29%, and between 5% and 20%, respectively. The granulated cork mortar (B^{GC}) dynamic modulus of elasticity increased, apparently due to the effect of the cell walls' straightening of cork, influenced by high temperatures [25]. As for the mortars with admixtures (E^{CT} and $F^{5\%res}$), these showed reduced susceptibility until 150ºC, but from this temperature, their dynamic modulus of elasticity reduced between 29% and 55% and between 26% and 42%, respectively (figure 5). In general, the dynamic shear modulus and *Poisson* coefficient had similar behaviour to the dynamic modulus of elasticity, decreasing with the increase of temperature. This behaviour can be associated with a loss of stiffness and compactness of the mortars.

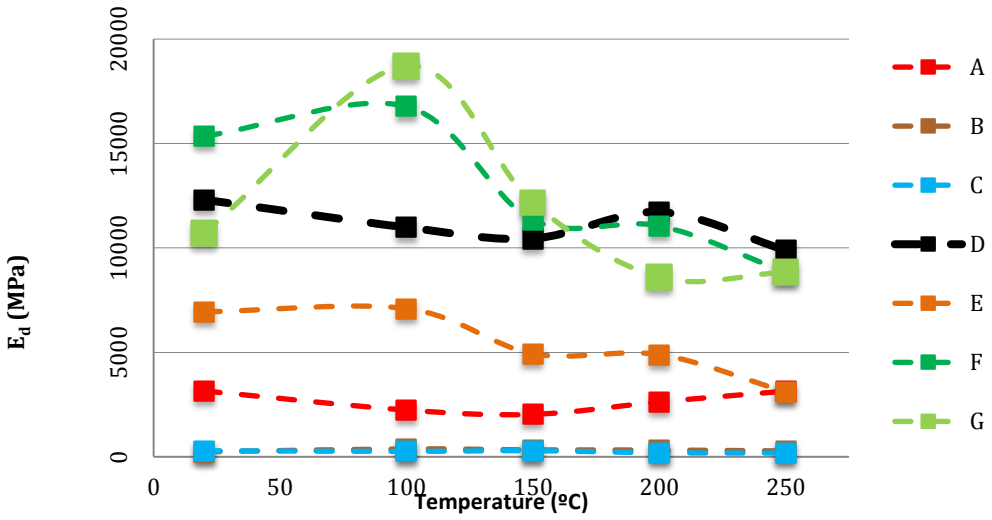

Figure 5 - Dynamic modulus of elasticity (MPa)

Analysing the compressive strength (obtained by a non-destructive method through the dynamic modulus of elasticity [26]), the aerogel mortar (C^{AERO}) had reductions from 200ºC and the sand mortars with admixtures (E^{CT}, $F^{5\%res}$ and $G^{10\%res}$) from 150ºC. As expected, due to the aforementioned effect of straightening of the cork's cell walls, the compressive strength of granulated cork mortar (B^{GC}) increased around 21% from 100ºC exposure (figure 6). After exposure to high temperatures, and despite the loss of mechanical characteristics, the thermal mortars studied showed compressive strength values between 0.76 MPa and 3.09 MPa, being classified as CS I and CS II mortars, thus complying with the 998-1 standards applied for thermal mortars [3].

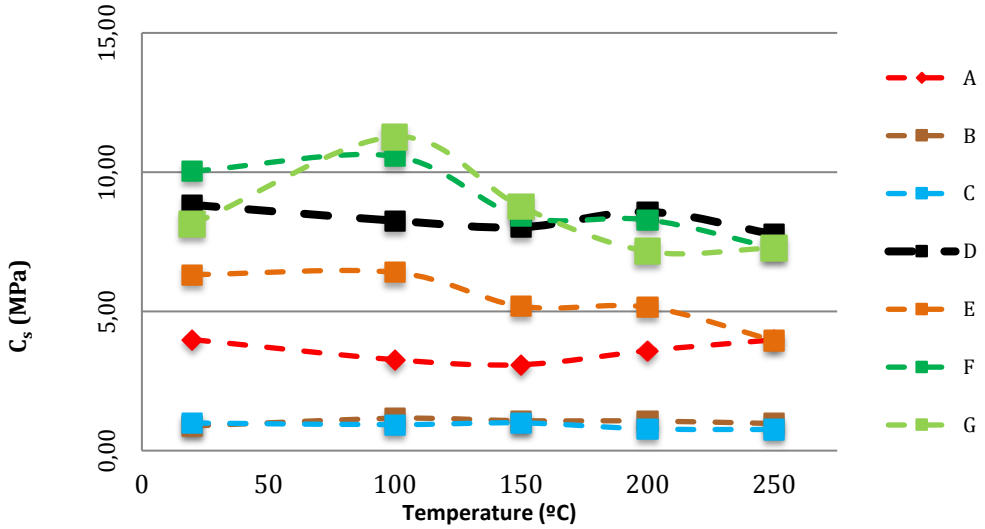

Figure 6 - Compressive strength (MPa)

In terms of thermal performance, after exposure to the temperature of 250ºC, all the mortars suffered a thermal conductivity reduction. This improvement might be associated with possible changes in the internal structure of the mortars causing an increasing porosity and micro-cracking. In this context, it is

possible to say that these mortars continue to have a good thermal performance even after being exposed to high temperatures (figure 7). After exposed to 250ºC, mortars with thermal insulating aggregates presented a thermal conductivity coefficient between 0.04 W/m.K and 0.075 W/m.K; therefore, since their thermal conductivity coefficient is below 0.1 W/m.K (T1), they may be classified as thermal mortars according to standard EN998-1, even after being exposed to high temperatures.

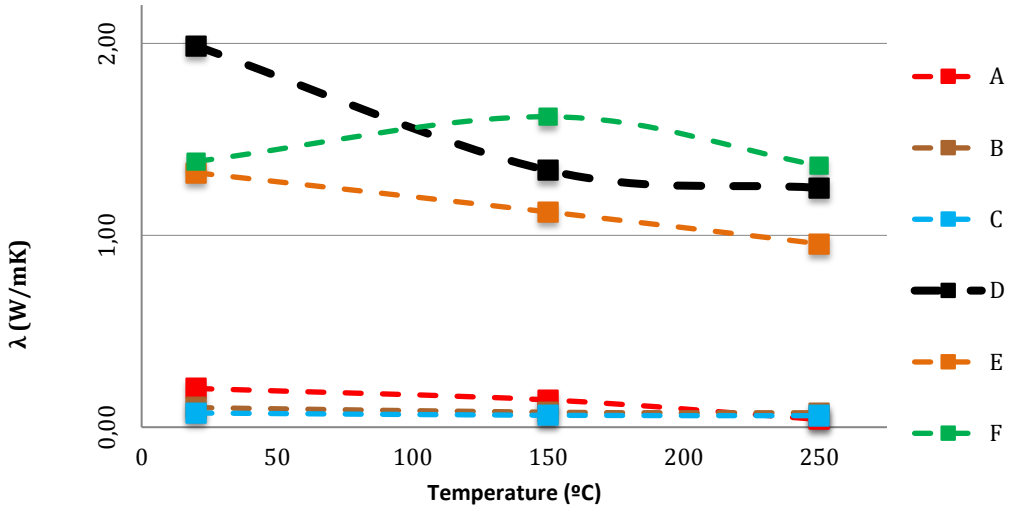

Figure 7 - Thermal conductivity coefficient (W/m·K)

4. Conclusions

This main objective of study was the experimental characterization of thermal mortars after being subjected to high temperatures. To this end, a set of mortars produced in the laboratory were exposed to temperatures between 20ºC and 250ºC. Bulk density, ultrasound pulse velocity, dynamic modulus of elasticity, dynamic shear modulus and *Poisson* coefficient, compressive strength and thermal conductivity tests were conducted before and after thermal exposure. Taking into account the literature review, the work in the experimental campaign and the results obtained are an important contribution to the development of knowledge about thermal mortars.

In general, the physical and mechanical behaviour of the thermal mortars was influenced by the exposure to high temperatures. This influence has its possible causes in the increase of porosity of the mortars with the water's evaporation, which leads to an increase of its empty pores; the increase of micro-cracking due to different expansion coefficients of the materials that constitute the mortar; and the deterioration of admixtures, in particularly, those used in sand mortars with 5% and 10% of resin ($F^{5\%res}$ and $G^{10\%res}$).

On the other hand, the exposure to high temperatures had a reduced influence on the correlations between the different mortar parameters studied, showing in a general way, that it affects in a similar and linear way the mortars properties. Only the relations between the bulk density and ultrasound pulse velocity, and between thermal conductivity and ultrasound pulse velocity were affected by high temperatures, largely

due to the characteristics of the aggregates.

To sum up, the thermal mortars studied are thermal insulation renders suitable for exterior and interior walls. Besides being able to maintain their insulating characteristics when exposed to high temperatures, thermal mortars experienced internal damage and mechanical strength loss for exposure to temperatures above 100ºC. In this context, it might be necessary to incorporate specific materials (additions, among others), in order to guarantee enhanced resistance to high temperatures that can be caused by fires in current buildings or more aggressive industrial applications.

The results of this experimental program show that the most sensitive mortars to the effect of high temperatures are the one with aerogel (C^{AERO}) and sand mortars (E^{CT}, $F^{5\%res}$ and $G^{10\%res}$), both with admixtures in their composition, and that the most critical temperature for these mortars is 150ºC.

Regarding the aerogel mortar (C^{AERO}), despite incorporating an aggregate which resists by itself to about 1600ºC, its binder paste (that incorporates admixtures) led to a lower performance after exposure to high temperatures. The improvement of this mortar can be made by adjusting the amount of air entrainers, consecutively reducing its water, and minimizing the estimated increase of porosity, and number of voids after exposure to high temperatures.

5. References

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