EXTENDED ABSTRACT

Evaluation of the physical performance of thermal mortars in wall prototypes

Ana Rita Inácio da Silva Santos

Supervisor: Prof.ª Maria da Glória de Almeida Gomes

Co-supervisor: Prof.ª Inês dos Santos Flores Barbosa Colen

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1. Introduction

Nowadays the environmental impact is a huge concern in construction sector. That's why the necessity to improve the technologies used, to search for new and ecologic materials and to implement measures and incentives to reduce energy consumption and waste.

The thermal mortars are a possible solution to reduce the costs of energy consumption in buildings. Therefore it's essential to study their mechanical and physical characteristics aiming the knowledge of their behavior if they were applied in buildings facades.

This dissertation included an experimental campaign carried out in laboratory, in order to study the physical characteristics of improved thermal performance mortars with incorporation of insulating aggregates (such as expanded clay, granulated cork, EPS and silica aerogel), applied in standard and cylindrical specimens, brick models and wall prototypes. The characteristics studied are superficial temperature and humidity, thermal conductivity, water absorption under low pressure and due to capillary, drying index and thermal behavior.

2. Improved thermal performance mortars

The mortars are for plastering the walls, protecting the masonry from the external actions like the rain and humidity, contributing to the buildings aesthetic aspect, and helping in the salubrity, durability and resistance of the walls. Besides those functions, the thermal mortars have smaller thermal conductivity, induced by its constituents.

Thermal mortars are constituted by binders, aggregates, water and addition/adjuvant, just like the conventional mortars. But, the aggregates used are insulating and light weighting contributing to lower the conductivity, instead of stony aggregates used in traditional mortars. Table 1 shows the classification for hardened thermal mortars properties according to standard EN 998-1 (CEN 2010).

Table 1 Classification for hardened thermal mortar properties

Properties	Categories	Values
Range of compressive strenght at 28 dias	CS I	0,4 a 2,5 MPa
	CS II	1,5 a 5 MPa
	CS III	3,5 a 7,5 MPa
	CS IV	≥ 6 MPa
Capillary water absorption	W0	Non especified
	W1	C ≤ 0,4 $kg/m^2.min^{0,5}$
	W2	C ≤ 0,2 $kg/m^2.min^{0,5}$
Water vapour permeability		≤ 15
Thermal conductivity	T1	≤ 0,1 W/m.K
	T2	≤ 0,2 W/m.K

Mortars can be classified according to their design (improved or formulated), properties and use (interior or exterior mortars) and local where they are produced (industrial – at the factory –, or traditional – in the local where they will be applied) (Nascimento, 2006). The traditional mortars present variability in their behavior because of the choice of materials and particle size curve, relations between the binders and aggregates and binders and water, and storage, manufacture, application and cure conditions. On the other hand, the industrial mortars present more stability in their behavior because of the mix's quality for the different purposes.

The mortar's thermal behavior is influenced, not only by their constituents, and type of mortar but also by the set mortar and substrate, and by the application made in that substrate. That is why is so important to study the mortar's physical behavior when applied in different substrates. In this dissertation, the substrate used was only the ceramic brick.

3. Experimental campaign

3.1. Characterization of the mortars

In this experimental campaign were produced, according with standard EN 1015-2 (CEN, 1998a), nine types of mortars with different composition and types of aggregates, being six of them dosed in laboratory (Table 2), with the incorporation of adjuvants, and the other three made industrially (Table 3). All the mortars are improved thermal performance mortars, except one that has stony aggregates and it was produced to be a traditional mortar reference. Tables 2 and 3 show mortar's formulations.

Table 2 Constituents of the mortars dosed in laboratory

Mortars dosed in laboratory	Designation	Binder	Adjuvants (% of the binder mass)		Volume of aggregate (%)				Granulometry (mm)	w/c
			S	C	Sand	GC	AE	Silica aerogel		
Control	$A^{controlo}$	CEM II 32,5 N	0,05	0,075	100	-	-	-		0,57
100%GC	B^{GC}	CEM II 32,5 N	0,05	0,075	-	100	-	-		0,77
100%AE	C^{AE}	CEM II 32,5 N	0,05	0,075	-	-	100	-	0,5 – 1	0,78
60%Isogel 40%AE	$D^{Aero/AE}$	CEM II 32,5 N	1,00	0,075	-	-	40	60	1 – 2	1,25
60%GC 40%AE	$E^{GC/AE}$	CEM II 32,5 N	0,05	0,075	-	60	40	-		0,76
40%GC 60%AE	$F^{AE/GC}$	CEM II 32,5 N	0,05	0,075	-	40	60	-		0,76

Subtitle: S – surfactants; C – cellulose ether; GC- granulated cork; AE- expanded clay; w/c – relation water-cement

Table 3 Summary of industrially mortars characteristics

Designation	Binder	S (% in volume)	D (mm)	Other aggregates	Quantity of water (l/kg)	Additions/Adjuvants
G^{EPS}	Lime / White cement and synthetic binders	100% EPS	1,5 a 2	si	0,7	ni
H^{GC}	Hydraulic Lime NHL 3.5	Cork (ni)	≤ 3	Diatomaceous earth/clay	0,55	Natural additions; polypropylene fibers; water introducers
I^{GC}	*Portland* Cement	70-80% Cork	1,5 a 2	Calcareous and siliceous aggregates	0,3	ni

Subtitle: ni – no information; D – insulating aggregate's dimension; S - % of substitution

3.2 Characterization of the test specimens

A wall prototype was executed for each of the mortars with the dimensions of 40x45 cm, mortar's thickness of 4 cm and with ceramic bricks with 15 cm of thickness as masonry substrate. Those prototypes were made in the wall of the climatic chamber in the Construction Laboratory of the Civil Engineering, Architecture and Georesources Department of the IST, and mortars were applied in the exterior of the chamber. The application of mortars was adapted according the standard EN 1015-21 (CEN, 2002b) and the cure was made at laboratory temperature.

Two reduced brick models with 20x25 cm size were produced for each mortar with a thickness of 4 cm. The application and cure of mortars was based on the standard used for the wall prototypes (EN 1015-21), but the cure chamber was at conditions of 20ºC ± 2ºC and 50% of relative humidity.

There were produced three standard specimens with the dimensions of 4x4x16 cm^3 and three cylindrical specimens with 6 cm of diameter and 2 cm of thickness for each mortar, although the cure conditions were the same for the brick models.

3.3 Test Plan

The characterization of the mortars started after mixing their constituents, with the determination of bulk density of fresh mortar, according to the standard EN 1015-6 (CEN, 1998b), and the determination of consistence of fresh mortar, based on the standard EN 1015-3 (CEN, 1999a).

When the mortars on the specimens achieved their hardened state were made many tests, such like:

- Mortar's surface humidity measurement at 28 days, using *TRAMEX* humidifier;
- Mortar's surface temperature measurement at 28 days, using *TRAMEX* 's *IRTX* equipment;
- Thermal conductivity measurement at 28 days, using *ISOMET 2114*;
- Water absorption under low pressure at 28 days, using *Karsten* tubes and according to the LNEC Fe Pa 39.1 (LNEC, 2002);
- Thermal behavior characterization tests, divided into two experimental campaigns, one with constant temperature and another with variable temperature, using a climatic chamber, thermocouples, heat flow meters and a logger;
- Water absorption due to capillary according to the EN 1015-18 (CEN, 2002a);
- Drying tests;
- Water content measurements.

4. Analysis of the results

4.1 Tests of fresh mortar

In the Table 4 there are showed the values obtained for the bulk density and consistency for the fresh mortars studied.

Table 4 Results of bulk density and consistence tests on the fresh mortars

Mortar's designation	Bulk density (kg/m^3)			Consistency (mm)		
	Average	DP	CV (%)	Average	DP	CV (%)
$A^{controlo}$	1885,7	60,0	3,2	147,9	19,2	13,0
B^{GC}	560,4	63,9	11,4	139,0	9,3	6,7
C^{AE}	787,8	24,5	3,1	144,1	14,7	10,2
$D^{Aero/AE}$	818,8	48,9	6,0	189,1	18,8	9,9
$E^{GC/AE}$	651,6	39,0	6,0	139,6	14,1	10,1
$F^{AE/GC}$	704,6	46,2	6,6	138,2	9,4	6,8
G^{EPS}	476,6	80,5	16,9	135,6	7,2	5,3
H^{GC}	675,9	72,5	10,7	123,6	4,6	3,7
I^{GC}	778,3	41,9	5,4	142,3	8,9	6,3

Subtitle: DP – standard deviation; CV – coefficient of variation

According to the standard EN 998-1 (CEN, 2010), all the mortars studied constituted by insulating aggregates are classified as light mortars because they have fresh bulk densities under 1300 kg/m^3. For the mortar $A^{controlo}$, the bulk density is 45% bigger than the limit value referred before, what means that this mortar isn't a light mortar, as expected.

Analyzing the values obtained for the consistency of the mortars, its possible verify that they have values within ranges showed in EN 1015-2 (CEN, 1998a), for their obtained fresh bulk density. Mortars which consistency values aren't included in the ranges correspondents for their bulk density are $A^{controlo}$ and $D^{aero/AE}$, that have bigger values because of more mixing time and the incorporation of more quantity of surfactants, respectively.

4.2 Temperature and humidity

Were measured the surface temperatures of the wall prototypes, brick models and cylindrical specimens and the surface humidity of the wall prototypes and brick models.

Mortars constituted by granulated cork (I^{CG}, B^{GC} e H ^{GC}) and also the mortar with aerogel ($D^{Aero/AE}$) had surface humidity in wall prototypes higher than 40% because of the hydrophobicity of their aggregates that contributes for the superficial water retention. Almost all the mortars have different values in their surface humidity for both of the applications because they were measured in different days, with ambient conditions very distinct. The only mortar that has stability in their results it's the one that has stone aggregates ($A^{controlo}$), and it is caused only by the humidity of the paste, because the sand have lower porosity.

The surface temperature of the mortars depends of the ambient conditions, that is why the comparison for the both applications of the mortars isn't conclusive.

4.3 Thermal conductivity

Thermal conductivity was calculated for each mortar in different ways and specimens. It was used an equipment (*ISOMET 2114*) to measure this property at 28 days in applied mortar on wall prototypes and brick models and in cylindrical specimens with different water contents, and a climatic chamber and all equipment necessary to calculate this characteristic trough the equations 1 and 2 in wall prototypes. The results obtained for all tests referred above are in the Table 6.

$$q = U \cdot (T_i - T_e) \tag{1}$$

where:

q = density of heat flow (W/m^2);

U = coefficient of thermal transmission ($W/m^2.^oC$);

T_i = ambient temperature inside the climatic chamber (ºC);

T_e = ambient temperature outside the climatic chamber (ºC);

$$q = \frac{\lambda_{argamassa}}{e_{argamassa}} \cdot (T_m - T_e) \tag{2}$$

where:

q = density of heat flow (W/m^2);

$\lambda_{argamassa}$ = mortar thermal conductivity (to be calculated) ($W/m^2.K$);

$e_{argamassa}$ = thickness of the applied mortar on wall prototypes of 0,04 m;

T_m = temperature at the interface between the mortar and the brick (ºC);

T_e = ambient temperature outside the climatic chamber (ºC);

According to the thermal conductivity values obtained at 28 days and with the climatic chamber in the Table 6, and to the standard EN998-1 (CEN, 2010), all mortars with insulating aggregates are classified as thermal mortars because their values are less than 0,2 W/m.K. Despite variations in values, mortars such as B^{GC}, G^{EPS} and H^{GC} are classified as T1 due the values lower than 0,1 W/m.K, while the others thermal mortars are classified as T2 due the values under 0,2 W/m.K. $A^{controlo}$ mortar don't have improved thermal performance because thermal conductivity values obtained at 28 days and with the climatic chamber are around 0,9720 to 1,6058 W/m.K.

Table 5 Thermal conductivity (λ – W/m.K) on the different mortar specimens

Mortar's designation	Cylindrical specimens			Brick models	Wall prototypes	
	28 days	Dry	Saturated	28 days	28 days	Climatic chamber
	λ_{Isomet}					$\lambda_{Fourier}$
$A^{controlo}$	1,6058	1,4023	2,0354	0,9488	1,4358	0,9720
B^{GC}	0,0899	0,0768	0,4674	0,0915	0,1008	0,1319
C^{AE}	0,2007	0,1705	0,5519	0,1415	0,1359	0,2029
$D^{Aero/AE}$	0,1930	0,0964	0,5691	0,1148	0,1200	0.1653
$E^{GC/AE}$	0,1323	0,1107	0,5165	0,0991	0,1065	0,1714
$F^{AE/GC}$	0,1501	0,1274	0,5547	0,1187	0,1217	0,1632
G^{EPS}	0,0909	0,0736	0,2956	0,0804	0,0868	0,1285
H^{GC}	0,1080	0,0895	0,6508	0,0911	0,0887	0,1574
I^{GC}	0,1218	0,0967	0,6527	0,1218	0,1339	0,2094

Industrial mortar G^{EPS} had values between 0,0804 to 0,0909 at 28 days and in climatic chamber test, being nearly of the value assigned by the manufacturer (λ_G^{EPS} = 0,07 W/m.K), which is the value obtained in the dry test ($\lambda_G^{EPS}{}_{, dry}$ = 0,0736 W/m.K). Industrial mortar H^{GC} had more than double of the value assigned by the manufacturer (λ_H^{GC} = 0,045 W/m.K), in the range of 0,0887 to 0,1080 W/m.K.

Industrial mortar I^{GC} was classified as T2 in the information given by the manufacturer like the results obtained.

Analyzing Table 6 and Figure 1, it's possible to verify that larger quantities of cork incorporated in mortars improve their thermal performance, lower their thermal conductivity.

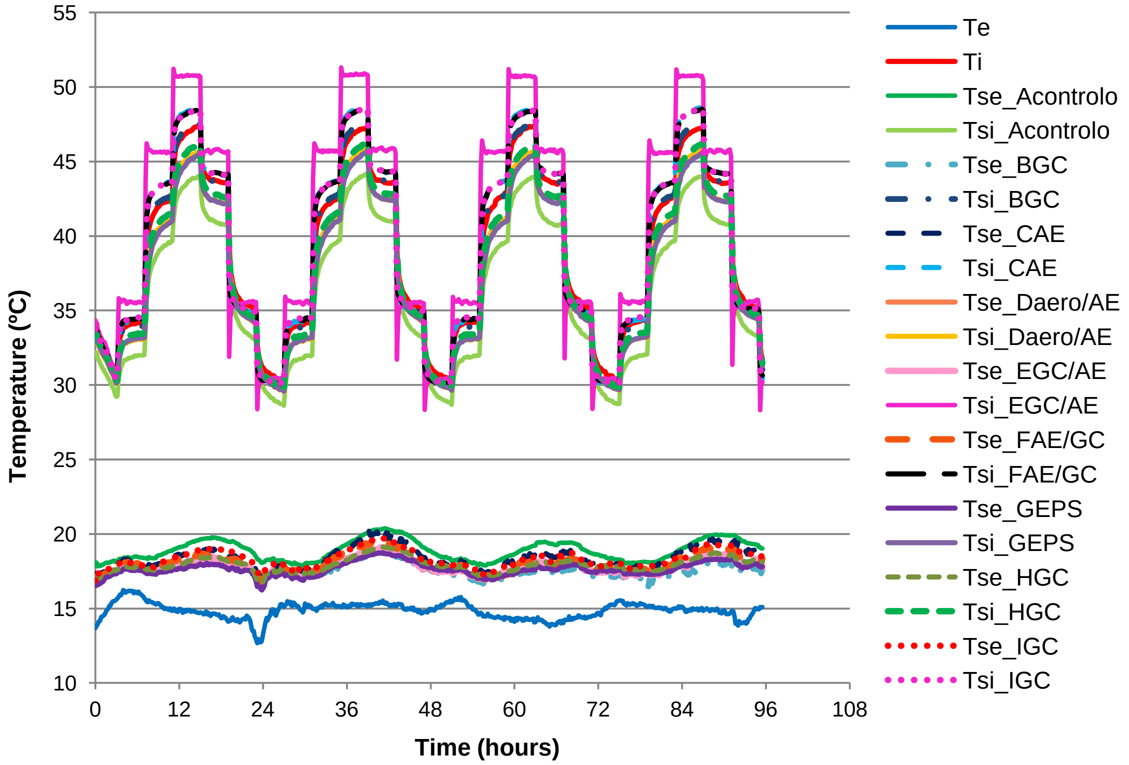

Figure 1 Representation of the surface temperatures of the campaign at variable temperature of thermal behavior characterization tests

Wall prototypes and brick models have a good correlation, around 0,9094, because mortars are applied on the same substrate (brick). A reasonable correlation is between brick models and cylindrical specimens, proximately 0,7029 and the worse correlation is between wall prototypes and cylindrical specimens (0,5369).

The values collected from climatic chamber test are 30 to 60% higher than the values obtained with the equipment ISOMET, except in mortar which presents a decrease of 30%. These differences are caused by the error associated to the equipments. Figure 2 presents the relation between both methods used, which is around 0,7186, a reasonable correlation as expected.

Table 6 presents lower thermal conductivity when mortars are dry and higher when they are saturated, meaning that thermal conductivity increases proportionally with water content (Melo, 2014). The values of thermal conductivities can increase around 325 to 725% in thermal mortars while in mortar with stone aggregates ($A^{controlo}$), only increase around 25%. Figure 3 demonstrate the proportionality between water content and thermal conductivity, which is around 0,8318.

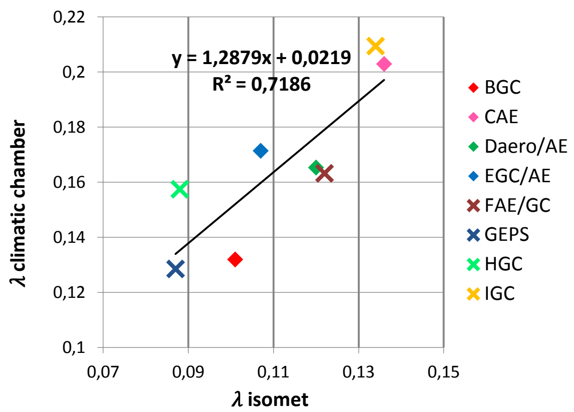

Figure 2 Relation of thermal conductivities measured in wall prototypes with *ISOMET* and climatic chamber

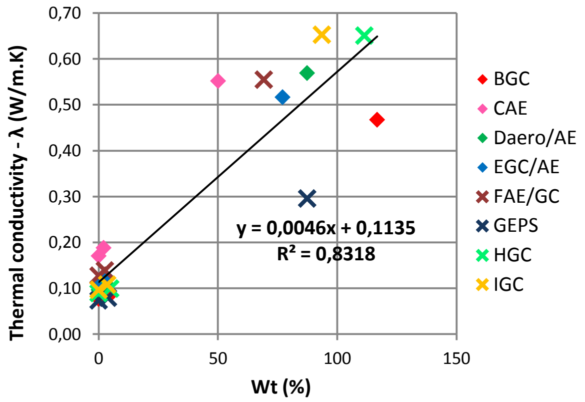

Figure 3 Relation between thermal conductivities measured with *ISOMET* and water content in cylindrical specimens

4.4 Water absorption under low pressure

In this test were measured the volume of water absorbed by the mortars in 60 minutes trough the *Karsten* tubes and then calculated the water absorption coefficients for those mortars, using the equation 3. The volume absorbed and the water absorption coefficient for each mortar are shown in the table 7.

$$C_a = \frac{Q \cdot 10^{-3}}{D^2 \cdot \left(\frac{\pi}{4} \cdot 10^{-6} \cdot \sqrt{t}\right)} \quad (3)$$

where:

Q = volume of water absorbed (ml);

D = surface diameter where the water penetration is made which is 25 mm;

t = period test, which in this case is at 60 minutes.

Table 6 Results of water absorption under low pressure of applied mortars on wall prototypes and brick models

Mortar's designation	Wall prototypes				Brick models			
	Volume of water absorbed at 60 min (ml)	DP (ml)	CV (%)	C_a (kg/m^2.min^{0,5})	Volume of water absorbed at 60 min (ml)	DP (ml)	CV (%)	C_a (kg/m^2.min^{0,5})
$A^{controlo}$	-	-	-	-	11,25	8,39	74,58	2,96
B^{GC}	10,37	6,16	59,41	2,73	12,03	4,70	39,04	3,16
C^{AE}	-	-	-	-	5,07	0,66	13,10	1,33
$D^{Aero/AE}$	2,67	0,55	20,74	0,70	7,65	0,42	5,55	2,01
$E^{GC/AE}$	-	-	-	-	-	-	-	-
$F^{AE/GC}$	-	-	-	-	-	-	-	-
G^{EPS}	4,62	1,61	34,93	1,21	2,80	1,94	69,18	0,74
H^{GC}	17,77	12,39	69,75	4,67	8,45	0,95	11,29	2,22
I^{GC}	1,57	0,10	6,64	0,41	1,60	0,18	11,27	0,42

Subtitle: DP – standard deviation; CV – coefficient of variation; C_a – Surface water absorption coefficient; - – measure impossible to do because of the higher water absorption during the test period

Analyzing the Table 7, it was verified that in some mortars the water was quickly absorbed because of the insulating aggregates they had, especially the mortars which have expanded clay, making impossible to test them in the established test period. The mortar $A^{controlo}$ was one of the mortars which it was impossible to test in the wall prototype because of the incorporated surfactant which increases mortar porosity, according Gominho *et al.* (2016).

The mortars constituted with only cork as aggregate, EPS and aerogel had an expected behavior related to water absorption, being that a slower absorption due to the hydrophobic characteristics of the materials constituents of mortars. I^{GC} mortar has water absorption coefficients very lower and closed for the wall prototype and brick model, meaning that their results shown stability because it is a finishing grout.

4.5 Water absorption due to capillary

Water absorption occurred in standard specimens and specimens of mortar which are removed from wall prototypes and brick models. These last two types of specimens had a reduced thickness, around 2,6 to 3,9 cm, causing a quickly water absorption in mortars, and inferior water absorption coefficients calculated according to EN 1015-18 (CEN, 2002a) (C_1) because they were calculated at saturated state. The water absorption coefficients calculated by the slope of initial phase of water absorption process were higher because of the quickly water absorption. The summary of this test is presented in Table 8.

Table 7 Water absorption coefficients for capillary in the different specimens tested

Mortar's designation	Wall prototypes				Brick models				Standard specimens			
	C_1	C_2	R^2	t_2 (min)	C_1	C_2	R^2	t_2 (min)	C_1	C_2	R^2	t_2 (min)
$A^{controlo}$	0,05	2,32*	0,922	10	0,10	1,31*	0,956	10	0,22	0,53	0,910	30
B^{GC}	0,08	3,22*	0,923	10	0,15	1,53*	0,941	15	0,45	0,30	0,896	1570
C^{AE}	0,06	2,52*	0,911	10	0,13	1,78*	0,901	15	0,35	0,21	0,853	1570
$D^{Aero/AE}$	0,62	0,63	0,954	400	0,46	0,50	0,964	180	0,70	0,44	0,901	1325
$E^{GC/AE}$	0,05	3,22*	0,932	10	0,03	3,55*	0,928	10	0,40	0,49	0,865	180
$F^{AE/GC}$	0,14	3,08*	0,923	10	0,07	2,90*	0,926	10	0,29	0,19	0,912	3025
G^{EPS}	0,43	0,58	0,930	90	0,61	0,58	0,956	180	0,60	0,61	0,965	180
H^{GC}	0,48	0,69	0,876	90	0,55	0,76	0,906	90	0,72	0,46	0,967	1510
I^{GC}	0,15	0,60	0,905	15	0,17	0,13	0,935	1165	0,52	0,35	0,962	1510

Subtitle: C_1 e C_2 of unities kg/m^2.min^{0,5}; R^2 – correlation coefficient; t_2 – duration of fast phase of water absorption; * - measurements not considered due to the reduced thickness of test pieces

Industrial mortars and $D^{Aero/AE}$ had an exponential behavior due to their hydrophobic materials in all the pieces tests.

According to EN 998-1 (CEN, 2010), mortars with granulated cork and expanded clay (B^{GC}, C^{AE}, $E^{GC/AE}$, $F^{AE/GC}$) had values under 0,4 kg/m^2.min^{0,5}, what means they are classified as W1, as well as mortar with stone aggregates ($A^{controlo}$) thanks to paste porosity caused by surfactants. Mortars $D^{Aero/AE}$, G^{EPS} and H^{GC} had values higher than 0,4 kg/m^2.min^{0,5}, so they are classified as W0, although these last two should had less thant 0,2 and 0,35 kg/m^2.min^{0,5}, respectively and according with the information assigned by the manufacturer. I^{GC} mortar had values under 0,2 and 0,4 kg/m^2.min^{0,5} depending on tests made in which specimens, so in some of the tests this mortar was classified as the manufacturer signed in the information files (W2).

4.6 Drying tests

This test consists in weighing the standard specimens and the wall prototypes and brick models removed specimens, in order to calculate their water content and drying indexes using the equations 4 and 5, respectively.

$$w_t = \frac{m_h - m_{dry}}{m_{dry}} \cdot 100 \quad (4)$$

where:

m_h = mass of wet specimen (kg)

m_{dry} = mass of dry specimen (kg)

w_t = water content of the specimen (%)

$$I_s = \frac{\int_{ti}^{tf} f\left(\frac{m_x - m_{dry}}{m_{dry}}\right) dt}{\left(\frac{m_{saturated} - m_{dry}}{m_{dry}}\right) \cdot t_f} \quad (5)$$

where:

m_x = mass of specimen registered during drying process (g);

m_{dry} = mass of dry specimen (g);

$m_{saturated}$ = mass of saturated specimen (g);

t_f = ending time of drying test (h);

I_s = drying index.

The stopping criterion for this test was the duration of 30 days, resulting in final water contents of thermal mortars under 56%. The drying indexes obtained for mortars were not conclusive because of the high values of final water content in mortars, result of the stopping criterion which should have been when was verified the stabilization of the final masses with variation up to 2%. That is why the drying rates were calculated for each mortar in all specimens.

It was noted that the lower drying velocities were of industrial mortars and $D^{Aero/AE}$ mortar due their hydrophobic materials. However, mortar with stone aggregates had even lower velocity than those which are constituted by hydrophobic materials, caused by its reduced thickness.

5. Conclusions

In summary, the insulating aggregates incorporated in the mortars imply a reduction of their masses and thermal conductivities and an increase of their capacity of water absorption, showing high water indexes when saturated compared to mortars of stone aggregates.

The reference mortar is useful for comparing the thermal behavior of a conventional mortar with stone aggregates and of improved thermal performance mortars, although the introduction of adjuvants in reference mortar alter some of its properties as the water absorption capacity.

Industrial mortars have better results and consistency of them, showing greater stability for the different types of application due to the industrial formulation with adjuvants. Only one mortar dosed in the laboratory has similar behavior to industrial mortars due to the hydrophobic capacity of its aggregate that is silica aerogel.

The application of the mortars in different types of support led to different results in most of the tests. Although suction phenomenon was expected in mortars applied to the brick, decreasing the number of voids and leading to higher values of thermal conductivity of the mortar in comparison to the values obtained in the cylindrical specimens, this did not occur, meaning that the type of compaction carried out modifies the characteristics of the mortar.

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