Evaluation of mechanical performance of thermal mortar applied in wall prototypes

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ABSTRACT

The performance of thermal mortars was studied through an experimental study on prototype walls. Nine types of mortars were studied, with different compositions and aggregates (expanded cork, expanded clay, silica aerogel). All the studied mortars have a thermal conductivity coefficient sufficiently low to be considered thermal mortars, according to EN 998-1 (CEN, 2010). Tests for determination of flexural and compressive strength of hardened mortars, dynamic Young's Modulus, adhesive strength, ultrasonic pulse velocity, *Martinet Baronnie*'s surface resistance and Pendulum rebound Hammer were carried out. Finally, a comparative study was carried out between the results of different properties. The mortars were used in prototypes of the wall placed in a climatic chamber for temperature control.

This work aimed to study the thermal mortars produced in the lab and others already on the market, as well as mortars that incorporate innovative materials, with the aim of understanding the mechanical performance of these mortar with different applications.

This study is part of the research project Nanorender PTDC/ECM/118262/2010 - performance of rendering mortar with silica nanoaerogel.

KEY-WORDS

Thermal mortars; Thermal insulating aggregates; Mechanical behaviour; Expanded cork; Expanded clay; Aerogel; Prototypes of wall.

1. INTRODUCTION

Today, the heating and cooling in buildings and industry are responsible for about 40% of final energy consumption, of these 70% comes from fossil energy sources. These end uses are estimated to have been responsible for 30% of global emissions of carbon dioxide (CO_2) in 2012. With this in mind, technological innovation is crucial to reduce energy consumption and by extension mitigate climatic changes while also supports economic and energy security objectives (IEA, 2015).

It is very important that all the components have adequate characteristics and contribute to the good performance and durability of the mortar (Veiga, 2010).

The actual performance of the rendering mortars is influenced by various factors, many of them related to their application. In particular, the support is a relevant factor to the good functioning of mortar/support system and its in-service mechanical performance.

According to Maciel *et al.* (1998), mechanical resistance is the property of coatings to resist to different actions, due to abrasion, impact and hygrothermal gradients. This property depends on the nature of the aggregates and binders and application conditions.

Thus, to properly perform the functions to which they are required, the renders must fulfill certain performance requirements, such as good workability, adherence, surface resistance, internal resistance, ability of deformation, and resistance to cracking, which were more demanding in the case of exterior renders (Silva, 2014; Flores-Colen, 2009).

Thermal mortars are an example of an existing solution to achieve the objectives with regard to energy efficiency and thermal behavior of buildings walls. They are characterised by having insulating aggregates with low thermal conductivity, for example cork, expanded clay, aerogel and EPS.

These thermal mortars have also to fulfill the minimum requirements for the mechanical performance. The application of the mortar in the wall can condition the mechanical performance of mortar, as also the prior preparation of the support.

The thermal conductivity is a material-specific thermal property and is equal to the heat flux per unit time and per unit area that flows through a layer of unit thickness with the faces differing by one unit of temperature (Moret Rodrigues et al., 2009; Rao *et al.,* 2009). In general, the thermal conductivity of building materials depends on the type of material, specific weight, porosity, temperature, moisture content, properties and internal structure of the material. The homogeneity and isotropy of material concerning the thermal conductivity should also be considered. Thus, the thermal conductivity indicates the ease of heat transfer, or more specific, of heat conduction by materials (Low *et al.,* 2010; Abdou *et al.,* 2013; Saleh, 2006).

The mortars with thermal insulating aggregates must have application thickness over 40 mm (Veiga *et al*., 2012). According to EN 998-1 (CEN, 2010), this mortars are characterized by having a coefficient of thermal conductivity (λ) lower than 0.1 and 0.2 (W/(m.K)), classified as T1 and T2, respectively. In accordance with EN 998-1 (CEN, 2010), the thermal mortars (T) should have compressive strength between 0.4 - 5 MPa (classes CS I and CS II), coefficient of permeability to water vapor (μ) less than 0.15 and water absorption by capillarity of W1 class ($C \leq 0.40$ kg/m^2. min^{0,5}).

Thermal mortars on the market, are classified as lightweight mortars, since the bulk density in hardened mortar is less than 1300 kg/m^3 (EN 998-1 (CEN, 2010)).

2. EXPERIMENTAL CHARACTERIZATION

2.1 MORTARS

The present experimental campaign aims comparing the performance of mortars in different type of models (standardized prismatic specimens, brick models and wall prototypes).

In this work, nine types of different mortars were studied. Six of which were dosed in the laboratory and three are industrial mortars. In the production of the dosed in the laboratory mortars, it was decide to introduce additions/admixtures for application improvement of these mortars, because these have been vertically applied. The characteristics of the different mortars used can be found in tables 1 and 2. The dosed in the laboratory mortars, contain all the same cement and vary its aggregates between granulated expanded cork, expanded clay and aerogel. A control mortar (A^{con} mortar) containing only sand as aggregate was produced, which serves as a reference for comparison purposes. The industrial mortars consisted of two mortars with cork as main aggregate ($H^{GC/T}$ and I^{GC} mortars) and one with EPS aggregate (G^{EPS} mortar). The production of dosed in the laboratory mortars were based on the rules set out in EN 1015-2 (CEN 1998).

Table 1 Constituents of mortar dosed in the lab

Dosed in the laboratory mortar	Binder	Admixtures (% by weight binder)		Aggregate in volume (%)				a/c
		Surfactants	Cellulose ether	Sand	GC	AE	Aerogel	
A^{con}	CEM II 32,5 N	0,05	0,075	100	-	-	-	0,57
B^{GC}	CEM II 32,5 N	0,05	0,075	-	100	-	-	0,77
C^{AE}	CEM II 32,5 N	0,05	0,075	-	-	100	-	0,78
$D^{Aero/AE}$	CEM II 32,5 N	1,00	0,075	-	-	40	60	1,25
$E^{GC/AE}$	CEM II 32,5 N	0,05	0,075	-	60	40	-	0,76
$F^{AE/GC}$	CEM II 32,5 N	0,05	0,075	-	40	60	-	0,76

Caption: GC-granulated Cork; AE-Expanded Clay; a/c – water/cement ratio.

Table 2 Constituents of industrial mortar

Industrial mortar	Binder	% of replacement (in volume)	Size of ag. insulator (mm)	Another aggregates	Amount of water (*l/kg*)	Additions/ Admixtures	Application
G^{EPS}	Lime/white cement and synthetic ligands	70 a 80% EPS	≤1,5	ni	0,7 a 0,8	ni	Ind/out
$H^{GC/T}$	Hydraulic lime NHL 3.5	Cork (ni)	≤3	Diatomaceous earth/clay	0,55	natural additions; polypropylene fibers;	Ind/out
I^{GC}	Portland cement	70-80% Cork	1,5 a 2	ni	0,5	reispercivel powder; water-repellent powder; air delivery agent and traction control; water retainers	Ind/out

Caption: ni – no information.

2.2 SUPPORTS

To better study the characteristics of the mortars, these were applied in wall prototypes that consist of brick models with 15 cm thick, with dimensions of 40x45 cm. The bricks were placed into openings in a wall (with U = 0.41 W/m^2 ºC) of an existing climate chamber in the Construction Laboratory of the Department of Civil Engineering, Architecture and Georesources (*DECivil*). It is possible to see the wall in Figure 1. The cure of the mortars was at room temperature (average 15ºC) for 28 days, putting a plastic in front of the wall, to avoid the shrinkage of the mortar in the early days of healing. Surface moisting of the mortar was made at regular intervals.

In addition to the prototypes, 3 standard 40 × 40 × 160 mm prismatic specimens (figure 2) and 2 ceramic hollow bricks (Figure 3) were produced for each mortar, to be tested at 28 days of age. Both elements were placed in polyethylene bags and stored in a curing chamber at a constant temperature of 20° C ± 2° C and a relative humidity of 50%. The demolding of the prismatic specimens and the release of the formwork of the bricks were done after 5 days of the mortar's application, being the mortars placed again in polyethylene bags, inside the curing chamber. The removal of the bags was made 7 days after the mortar's application, keeping the pieces in the curing chamber.

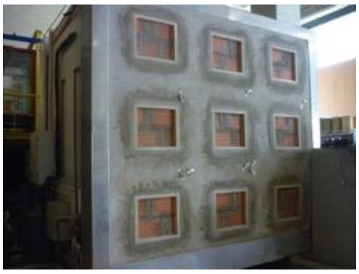

Figure 1 Wall prototypes

Figure 2 Standardized prismatic specimens molds

Figure 3 Brick with formwork

2.3 MORTAR APPLICATION

The thermal mortars have been applied with a minimum thickness of 4 cm, this thickness is also recommended by the manufacturers of industrial mortars. The application was made in two stages, i.e. two layers with a maximum of 2 cm thick each. The final result of the mortars applied in the prototypes is illustrated in the Figure 4.

The application of mortar in bricks models was carried out in only one layer of 4 cm, with the brick placed horizontally, based on EN 1015-21 (CEN, 2002). On the other hand, the application of mortar in the prismatic specimens followed the EN 1015-11 (CEN, 1998).

Figure 4 Prototypes of wall with mortar applied

2.4 TESTS

The main objective of the experimental campaign is to compare the mechanical characteristics of different thermal mortars produced and applied on different models. To this end, the following tests were performed on fresh mortar, first two tests, and hardened mortar:

- Bulk density of fresh mortar (EN 1015-6 (CEN, 1998));
- Consistence of fresh mortar (EN 1015- 3 (CEN, 1999);
- Dry bulk density of hardened mortar (EN 1015-10 (CEN, 1999));
- Ultrasonic pulse velocity (EN 12504-4 (CEN, 2004), equipment: PUNDIT LAB da PROCEQ);
- Adhesive strength of hardened rendering and plastering mortars on substrates (*Pull-off*) (EN 1015-12 (CEN, 2000), equipment: 58- C0215/T Pull-off digital tester, load capacity 16KN da Controls);
- Surface hardness with pendulum rebound hammer (equipment: Schmit Pendulum Hammer type P da PROCEQ);
- *Martinet Baronnie*'s surface resistance test (measurement of the diameter of the dint);
- Dynamic Young's Modulus (ASTM E1876-1 (ASTM, 2006), equipment: *GrindoSonic MK5 "Industrial"*, software: software*GrindoSonic*);
- Flexural strength of hardened mortars (EN 1015-11 (CEN, 1999), equipment: *Seidner Form+Test* (model 505/200/10 DM1) with a load cell of 10 kN);
- Compressive strength of hardened mortars (EN 1015-11 (CEN, 1999), equipment: Seidner Form+Test (model 505/200/10 DM1) with a load cell of 200 kN);

3. PRESENTATION AND DISCUSSION OF THE RESULTS

3.1 MORTAR APPLICATION ON WALL PROTOTYPES

In the application of the control mortar (A^{con}), there have been some difficulties, due to its predominantly coarse granulometry (aggregates between 0.5 to 2 mm), which possibly could be overcome with the adoption of more binder or another with more percentage of finer aggregates. As such, it was necessary to apply the mortar in thin layers and, instead of two layers, it was applied in four layers.

The B^{GC} mortar (with cork) was very elastic and unstable, resulting in detachment during application. The lack of cohesion has made the application more multi-layered and with thinner layers. Like the A^{con} mortar, it was applied in four layers, in which the last layers was no great difficulty of smoothing.

The C^{AE} mortar (with expanded clay) and $D^{Aero/AE}$ mortar had a good workability and application. The first mortar could have more fine aggregates. These mortars were applied in two layers of 2 cm as planned.

There have been some difficulties in applying the E$^{GC/AE}$ mortar (with cork and expanded clay), due to lack of adhesion and workability problems. This was applied in three layers, instead of the two initially planned layers. The F$^{AE/GC}$ (with expanded clay and cork) had good workability, but it was applied, like the E$^{GC/AE}$ mortar, in three layers.

The three industrial mortars (G^{EPS}, H$^{GC/T}$ and I$^{GC)}$ presented very good workability in terms of easiness of mixing and application on wall. This behavior might be expected, since these mortars are currently marketed and therefore with industrial application.

3.2 TEST RESULTS

The results of tests made on the fresh mortar and hardened mortar applied in bricks, wall prototypes and prismatic specimens can be consulted in Table 3.

Table 3 Mechanical characteristics of mortar produced (summary).

Mortar		**Model**	**Fresh mortar**		**Hardened mortar**							
			Consistence (mm)	**Mv,f (kg/m^3)**	**Mv,e (kg/m^3)**	**V$_{Média}$ (m/s)**	**Rt (MPa)**	**Rc (MPa)**	**Pendulum Hammer**	***Martinet Baronnie* (cm)**	**Ed (MPa)**	***Pull-Off* (KN/m^2)**
Dosed in the laboratory	A^{con}	PS	147,9	1885,7	1690,3	2941,22	2,257	6,608	x	x	13394,24	x
		B				3688,60	x	x	112,8	0,67	x	0,24
		W				2618,90	x	5,500	117,3	0,52	x	null
	B^{GC}	PS	139,0	560,4	443,1	1185,00	0,363	0,615	x	x	403,88	x
		B				2143,50	x	x	77,5	2,17	x	0,20
		W				1415,30	x	0,835	93,4	2,04	x	0,01
	C^{AE}	PS	144,1	787,8	721,8	2266,00	0,992	2,394	x	x	2889,84	x
		B				2823,80	x	x	82,8	1,63	x	0,11
		W				2470,10	x	2,879	91,1	1,4	x	null
	$D^{Aero/AE}$	PS	189,1	818,8	651,6	1586,44	0,365	1,323	x	x	1094,84	x
		B				2239,80	x	x	78,5	1,73	x	0,05
		W				2065,20	x	0,910	77,1	2,06	x	null
	$E^{GC/AE}$	PS	139,6	651,6	622,8	1760,00	0,737	1,752	x	x	1339,89	x
		B				2620,50	x	x	74,2	2,67	x	0,07
		W				1799,40	x	1,063	90,3	1,82	x	null
	$F^{AE/GC}$	PS	138,2	704,6	693,1	2032,00	0,867	2,221	x	x	2150,95	x
		B				2762,50	x	x	75	2,07	x	0,09
		W				1986,60	x	1,702	92,5	1,48	x	null
Industrials	G^{EPS}	PS	135,6	476,6	387,4	1404,00	0,647	0,917	x	x	526,51	x
		B				1711,80	x	x	79,3	2,67	x	0,14
		W				1566,30	x	0,788	83	2,48	x	0,08
	$H^{GC/T}$	PS	123,6	675,7	563,9	1266,00	0,693	1,302	x	x	554,44	x
		B				1926,50	x	x	80	1,57	x	0,30
		W				1406,90	x	1,973	96,5	1,18	x	0,10
	I^{GC}	PS	142,3	778,3	668,9	1330,00	0,698	1,556	x	x	870,43	x
		B				1994,90	x	x	77,5	1,93	x	0,29
		W				2138,70	x	2,885	100,2	1,72	x	0,29

Caption: PS – Prismatic Specimen; B – Brick; W – Wall; Rt – flexural strength; Rc – compressive strength; Ed – Dynamic Young's Modulus; Mv,f –density of fresh mortar; Mv,e – density of hardened mortar; V$_{Média}$ – ultrasonic pulse velocity.

In a first analysis, and taking into account the mechanical characteristics of thermal mortar applied in the different models, it is possible to verify that, in comparison with the prismatic specimens, the mortar applied on the wall prototype showed a better compressive strength, much due to the suction effect of the brick. In relation to the bricks, the tests on the wall obtained values less good, this time due to the difference of conditions of application and grip.

In terms of fresh mortars, the values of consistency vary between 123.6 and 189.1 mm, which shows that these mortars are quite fluid, especially the one that contains aerogel. This happens because of the introduction of adjuvants. The mortar that contains aerogel is the more fluid because it has more quantity of water than the other mortars. It was necessary for the aerogel to mix with the admixtures On the other hand, the bulk density had values between 477 and 891 kg/m^3, for thermal mortars. In the same way, the mortar that contains aerogel was the one that had the biggest value in the thermal mortars, for the same reason given to the consistency.

Concerning to the dry bulk density of hardened mortar of the insulating mortars it is possible to check that the values vary from 387 to 722 kg/m^3. According to EN 998-1 (CEN, 2010) these mortars can be classified as lightweight mortars (≤ 1300 kg/m^3). The C^{AE} mortar was the one that had more bulk density of all the thermal mortars, as a result of the aggregate's weight.

Regarding to the Dynamic Young's Modulus, the values of thermal mortars are the order of the 404-2890 MPa and as such, have a capacity of deformation exceeding current mortars, being less subject to cracking phenomena (Ed ≤ 10000 MPa, 427/05 report of LNEC (2005)). These mortars, although complying with the requirements of resistance to compression (CSI CSII classes according to EN 998-1), they feature low Dynamic Young's Modulus's values, conditioning their use, in specific situations, in particular in walls exposed to shocks (Ed ≥ 5000 MPa-MERUC CSTB (1993)). Thus, the mortar with more deformability is the B^{GC} mortar.

The compressive strength of hardened thermal mortars, vary between 0.6 and 2.2 MPa in the prismatic test specimens and 0.8 to 2.9 MPa in wall prototypes samples. It's possible to see in Figure 5 that the results of both tests are very different. However, the test of the prismatic specimen was made 28 days after the application of the mortars, and the test of the wall samples was made 10 months after the application. The best results in the wall prototypes due to the suction effect of the brick and greater tightness in the application. Flexural strength of the thermal hardened mortars vary, in general, between 0.4 and 1.0 MPa. In comparison with the control mortar (2,26 MPa), it's possible to see the decrease of the strength in about 50%.

It was possible to check that the values obtained for the surface resistance test (*Martinet Baronnie*), in the thermal mortars applied in the wall, were higher (between 1.2 and 2.5 cm) compared with the control mortar (0.5 cm). It was possible to verify also, as illustrated in Figure 6, that the values of the test in mortars applied in bricks were higher (between 1.6 and 2.7 cm).

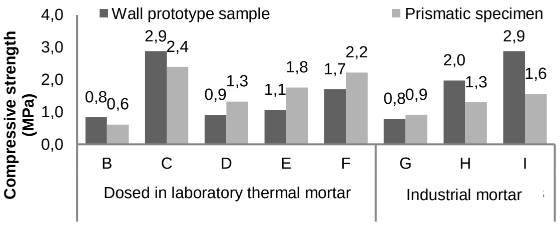

Figure 5 Compressive strength of test specimens prismatic and samples taken from the prototypes of the wall

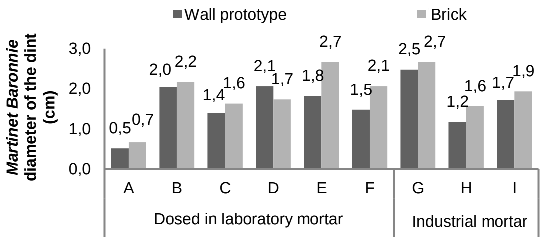

Figure 6 Diameters of the dint impact of the *Martinet Baronnie* in mortar applied in brick and wall prototypes

In the Pendulum Hammer test, the thermal mortars had a Pendulum Hammer' value under 100 (between 100 and 77.1) in the tests on the wall. The values obtain in the test done in the mortar applied in brick (between 74.2 and 82.8) were smaller than the results of the test in the wall (Figure 7), where the rigidity of the support was higher.

In relation to the values of adhesive strength to support, in applied thermal mortar to brick, ranged from 0.05 to 0.30 MPa. In prototypes of the wall it was found the impossibility of conducting some tests, but those that were possible to obtained, the values were between 0.01 and 0.29 MPa. It's difficult to compare both models (Figure 8), whereas there aren't values for all mortars applied in the wall; it is only possible to check that the industrial mortars are prepared to be applied in walls. Taking into account existing requirements and fields of application recommended by the manufacturers of the respective industrial mortars (can be used for the rehabilitation), the values obtained can be considered acceptable in some cases (0.1-0.3 MPa to adhesive ruptures). It is still possible to conclude that in the mortars assessed in the laboratory, there is lack of adhesive strength, soon need an improvement in this respect.

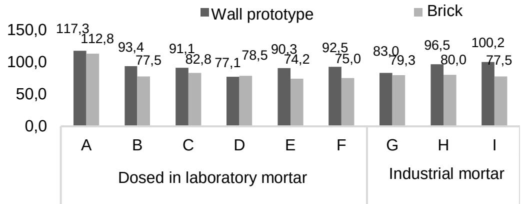

Figure 7 Pendulum Hammer values in the mortar applied in prototypes and brick wall.

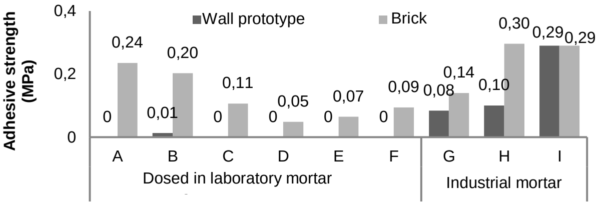

Figure 8 Comparison of the mortars adhesive strength applied in brick and in wall prototypes

Seen to have conducted the determination of ultrasonic pulse velocity in all of the models (with direct and indirect method), it is possible to check that in direct method of this test (1185 to 2266 m/s) (Figure 9), the velocity is smaller than the values obtain in the wall and bricks, much due to the mortar applied in wall and brick have received greater tightness in their application.. The thermal mortars applied in the wall prototypes had an average velocity of propagation (1175.5 to 2395.0 m/s) lower than the velocity obtained in thermal mortars applied in bricks (1413.2 to 2544.9 m/s) (Figure 10). This result happens because it’s difficult to have the same grip in the wall as in the brick, so the mortars applied in the wall have less compactness.

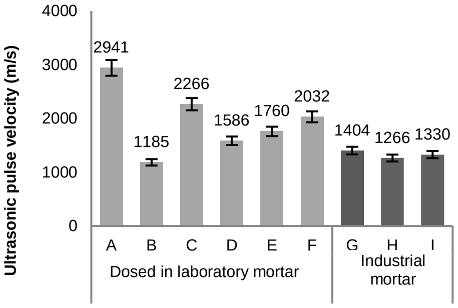

Figure 9 Values of the ultrasonic pulse velocity (direct method)

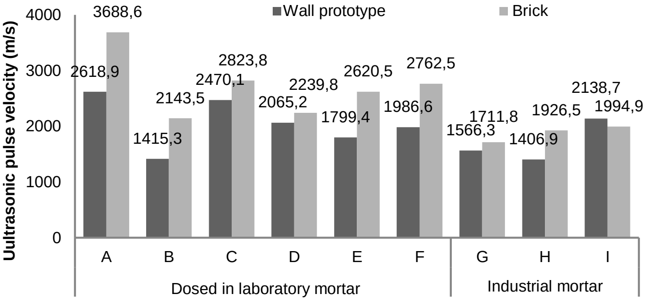

Figure 10 Comparison of ultrasonic pulse velocity in mortar applied in brick and prototypes

3.3 CORRELATION BETWEEN RESULTS

For a better interpretation of the results, were made several correlations (Table 4) between the results of different test techniques, in order to complement the results obtained. Note that these relations take into account only the thermal mortars, excluding the reference mortar, and results obtain in the wall prototypes, whenever possible.

Table 4 Correlations between results of different tests

Measurement parameters	**Comparison parameter**	**Type of regression**	**R^2**
Ultrasonic pulse velocity (m/s)	Compressive strength (MPa)	Polynomial	0,46
	Bulk density (kg/m^3)	Exponential	0,68
Pendulum Hammer	Compressive strength (MPa)	Power	0,43
	Superficial resistente *Martinet Baronnie* (cm)	Linear	0,38
	Bulk density (kg/m^3)	Potency	0,04
Superficial resistente *Martinet Baronnie* (cm)	Compressive strength (MPa)	Power	0,59
	Bulk density (kg/m^3)	Linear	0,42
Compressive strength (MPa)	Bulk density (kg/m^3)	Linear	0,61

Once the waves propagate by vibration of solid particles, the ultrasonic pulse velocity depends on the constitution of the mortar analyzed. Knowing that the less compact the materials are, lower the ultrasonic pulse velocity values are, it is possible to establish a parallel between these results and the apparent density values. As can be seen in Figure 11, in general, the higher the density faster is the ultrasonic pulse velocity.

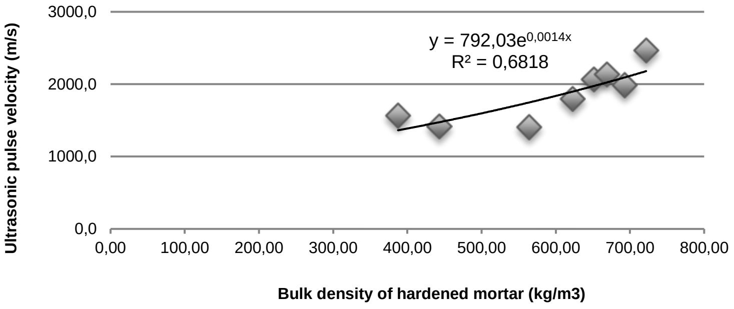

Figure 11 Correlation of the results of ultrasonic pulse velocity with bulk density

4. CONCLUSION

In the present study, nine types of mortars were studied, with different compositions and three types of aggregates: expanded cork; expanded clay and silica aerogel.

The mechanical behavior of the studied improved thermal mortars was strongly influenced by the incorporation of thermal insulating aggregates, as well as by the use of admixtures.

Concerning all the tests, it should be noted that the mortar with expanded clay have better results in terms of mechanical resistance. The incorporating of expanded cork showed less good results of mechanical resistance, but a better application on the masonry wall.

The mortar with aerogel and expanded clay ($D^{Aero/AE}$) presented acceptable mechanical resistance's values, but it was concluded that these results were influenced by the presence of expanded clay in the mortar mixture. The application on the wall was quite good, having been one of the best in terms of workability, but after the application, shrinkage cracks have emerged due to the greater amount of water that is required to add this mortar, due to the aerogel and surfactants.

In short, taking into account the purpose of the verification of the mechanical characteristics and thermal improvement of mortars, it is possible to note that with the introduction of these insulating aggregates, the mechanical performance of mortar is changed and significantly affected. Regarding to the comparison of the applications of the mortar, it can be concluded that the application of the mortar on prototypes of the wall increases the Pendulum Hammer's values, reduce the notch diameter caused by the equipment of Martinet Baronnie and decreases the ultrasonic pulse velocity in relation to the application in the brick. Which translates in increased hardness and surface resistance and increased of voids or internal cracking.

Thus, the industrial mortars showed a better mechanical behavior than the produced in the laboratory, showing the importance of additions in cement and a good formulation of these. In general, the application of the industrial mortars was better, as the obtained results in the tests, regardless of the type of support.

In conclusion, it was found that the thermal mortars could constitute a solution of thermal insulation, through a careful choice of the mixture of aggregates and admixtures. Through this dissertation it was possible to observe a trend towards an improvement in the mechanical behavior in mortar with expanded clay. However, the mechanical behavior of mortar with thermal insulating aggregates is a complex subject and is dependent on many factors, so that more studies are needed to evaluate the influence of these aggregates on performance of these mortars.

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