MECHANICAL BEHAVIOR OF THERMAL MORTARS WITH EXPANDED POLYSTYRENE AGGREGATES

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1. Introduction

With the awareness for the concern of the thermal comfort of buildings and the appearance of thermal requirements and regulations [1], of successive increasing demands, there is a need for developing new and better products able to follow the current and next demands. It is in the field of sustainable wall coatings that appear the thermally enhanced mortars, with the purpose of obtaining a product able to place itself in the middle of the conventional coating mortars and thermal insulation system ETICS.

The use of these mortars at the construction site in Portugal is still suspicious due to the poor knowledge and large uncertainty regarding to their behavior and performance as coating mortars. This study intends to contribute to a better understanding of the behavior and characteristics of these mortars and consequently resulting in their better insertion in the Portuguese market of construction.

The characteristics of these mortars, in order to classify them as thermal mortars, are described in the European standard EN 998 – 1 (2010) [2], and they have to present themselves as mortars able to display a thermal conductivity of less than 0.10 and 0.20 W/m.K, respectively T1 and T2 type, a coefficient of water absorption due to capillary forces not greater than 0.20 and 0.40 kg/m^2.min$^{0.5}$, respectively W1 and W2 class, a water vapor permeability coefficient lower than 15 and their compressive strength classified as CS I or CS II (from 0.4 to 5.0 MPa).

As it has been said before, it is noticeable the appearing of numerous thermal mortars in the Portuguese market of construction over the last years, differing essentially in field of application (interior/exterior), type of lightweight insulating material (essentially expanded polystyrene, EPS, and cork) and the percentage of substitution of mineral aggregates by those and also the binder used.

The EPS, a polymer with closed cells, nearly composed by 2 % of plastic and 98% of air is able to perform a thermal conductivity as low as 0.033 to 0.057 W/m.K, is already vastly used in several construction works. As so the aim of this study has been set to characterize the mechanical behavior of two of the most used industrial thermal mortars at the construction site in Portugal, intended for the use as coatings of exterior walls and also incorporating EPS as the insulating aggregate.

2. Experimental work

For the purpose of this study, two of the most used thermal mortars in the market, aside with one industrial and another traditional cementitious mortars, were produced in the laboratory with the purpose of comparing and evaluating their mechanical behavior.

The two chosen industrial mortars were the Weber.Therm Aislone, from Weber Saint-Gobain, and Isodur, from Secil Martingança, their known characteristics are displayed in the Table 2.1. Aside with those, another industrial mortar has been selected for the purpose of comparing, the Weber.Rev Classic, also from Weber Saint-Gobain, characterized to be a commonly used industrial cement-based coating mortar at the Portuguese market. The traditional reference mortar has been produced with the 1:4 volumetric ratio, as it is one of the most frequently used ratios at the Portuguese construction site regarding to cement-based coating mortars, using as a binder the Portland cement of the CEM II B/L 32.5 N type, and as mineral aggregates, the mixture of fine and thick grade silty sand from the Portuguese riversides, granting the use of right amounts of water according to the EN 1015-2 [3] standard of consistency.

Table 2. 1 - Composition of the mortars produced.

Mortars	*IS*	*AW*	*RC*	*TD*
Binder	Lime / White Cement	Lime / White Cement / Synthetic binder	Cement / Lime	Cement (CEM II B/L 32.5 N)
Percentage of water to dry constituents mass / Water to binder ratio	85%	120%	16%	0.70
Insulating material, EPS, in percentage of substitution	70-80%	100%	0%	0%
Other Aggregates	Limestone and silty sand	Without other aggregates	Silty sand of fine grade	Silty sand: 35% of fine grade and 65% of thick grade
Admixtures/ Additions	Not specified	Re-dispersible polymer, hydrophobic, expansive and water-retaining agents	Synthetically fibers and other not specified	None
Field of application	As a coating of exterior/interior, new or old walls	As a coating of exterior/interior, new or old walls	As a coating of exterior/interior, new or old walls	As a coating of exterior, new or old walls

Notes: IS = Isodur; AW = Aislone; RC = Rev.Classic; TD = Reference 1:4 mortar.

In order to produce the required specimens for the aimed test, the storage and curing conditions specified by their standards [4] are exposed on the Table 2.2.

As it can be seen on the Table 2.2, the laboratory tests performed for the purpose of this study were the compressive, tensile and corner strength, hardened bulk density, dynamic modulus of elasticity, ultrasonic pulse velocity, water absorption due to capillary forces and under low pressure, accelerated erosion under the spray test, adhesion to the substrate, shrinkage and constrained shrinkage, sclerometric pendulum and the impact of a pendulum sphere transmitting 2J of energy, proceeded by the tests performed in the fresh conditions.

Regarding the corner strength test, which did not followed any standard, it consisted in an incorporation of a PVC corner with 15 mm of width at the edges of the prismatic 160x40x40 mm^3 so called "strengthened" specimens, which will serve as an intermediate for the transfer compressive force applied to the specimen.

The restrained shrinkage test was performed with the use of a one meter of length mold with a triangular section area of 4.27 cm^2 and with restraining movement bolts applied to both ends. The test consisted in a periodic observation of the shrinkage and eventual cracking of the mortar under the test time of 28 days. Regarding the other tests their procedures followed the standard procedures specified in each standard.

Table 2. 2 - Necessary curing conditions for the tests performed.

Test	***Curing conditions***	***Geometry of specimens***
Hardened bulk density Compressive and tensile strength Dynamic modulus of elasticity Water absorption due to capillary forces Corner strength	7 days of wet curing in a chamber of 95% ± 5% of relative humidity and a temperature of 20 °C ± 2 °C followed by 21 days of dry curing in a climatic chamber of 60% ± 5% of relative humidity and a temperature of 20 °C ± 2 °C	Prismatic (160x40x40 mm^3)
Drying Shrinkage	28 days of dry curing in a climatic chamber of 60% ± 5% of relative humidity and a temperature of 20 °C ± 2 °C	Prismatic (160x40x40 mm^3)
Restrained shrinkage		Triangular section, 1 meter of length mold
Water absorption under low pressure Adhesive strength (pull-off) Sclerometric pendulum Sphere impact [2J] Accelerated erosion (spray test)	28 days of curing in the laboratory ambient with variable conditions of relative humidity and temperature	Mortar with 25 mm of width applied on a 300x200x110 mm^3 brick

3. Results

All the tests were performed under the standard procedures displayed at the Table 3.1. It also can be found at the Table 3.1 the average results obtain in each test performed at the 28 days of age.

Regarding the hardened bulk density, both the thermal mortars show a density below 1300 kg/m^3 and so are classified as lightweight mortars according to the EN 998-1 [2]. This result is obviously expected because they present themselves with high percentage of substitution of mineral aggregates by EPS of low density. The result obtain for the RC mortar is similar to the obtained by Ferreira [5] (1567 kg/m^3) and within the range specified by the manufacturer. The incorporation of lime and other unspecified additives justifies the lower density verified at the RC mortar when compared to the TD.

The direct ultrasonic test shows a greater compactness in the IS mortar when comparing it to the AW mortar, probably due to the smaller incorporation of EPS, displaying both a smaller velocity when compared to the industrial and traditional cement-based mortars. The traditional mortar displays the greatest value, which was expected, due to its greater mass and compactness. It displays a velocity of 3650 m/s which is a value commonly obtained in this type of mortars, as Vale [6] obtained 3285 m/s and Martins [7] obtained 3486 m/s. The results of this test shows that thermal mortars with lower bulk density display much lower values of the ultrasonic velocity than the reference mortars, these results are similar to the obtained by Vale [6] e Melo [8] where they obtained a velocity of 1412 m/s and 889 m/s at the IS and AW mortar, respectively, revealing the correct production of the studied mortars.

Table 3. 1 - Mechanical results at 28 days of age.

Tests		***Standards***	***Mortars***			
			IS	AW	RC	TD
Hardened bulk density [kg/m^3]		EN 1015-10 [9]	438	208	1522	2083
Direct ultrasonic pulse velocity [m/s]		EN 12504-4 [10]	1416	925	1930	3650
Dynamic modulus of elasticity [MPa]		ASTM E 1876-1 [11]	764	80	5125	24896
Compressive strength [MPa]		EN 1015-11 [4]	1.24	0.35	3.86	22.88
Tensile strength [MPa]			0.70	0.23	1.56	5.20
Corner Strength [MPa]	Regular	-	1.67	0.40	6.32	36.99
	Strengthened	-	2.83	0.85	6.91	38.06
Drying shrinkage [m/m x 10^{-6}]		LNEC E 398 [12]	-2391	-1643	-563	-445
Adhesive strength [MPa] - Fracture		EN 1015-12 [13]	0.20 - b	0.06 - b	0.39 - b	0.38 - a
Sclerometric pendulum [PT]		-	23	35	52	70
Sphere impact [2J]	ϕ [mm]	LNEC Fe Pa 25 [14]	26.0	35.6	13.4	4.8
	Δ [mm]		4.3	5.9	1.9	0.4
C_{abs}^1 [kg/m^2.min$^{0.5}$]		EN 1015-18 [15]	0.45	0.38	0.44	0.44
C_{abs}^2 [kg/m^2.min$^{0.5}$]		LNEC Fe Pa 39.1 [16]	0.18	0.20	0.48	0.48

Notes: Pattern a = adhesive; Pattern b = cohesive; C_{abs}^1 = Water absorption due to capillary forces; C_{abs}^2 = Water absorption under low pressure (Karsten pipe).

The deformability rate was measured by the dynamic modulus of elasticity and it was found that the thermally enhanced mortars present themselves as more deformable than the regular cement-based mortars, the AW being the most deformable with an average value of 80 MPa similar to the value obtained by Vale [6] (70 MPa). It was also found that when we increase the incorporation of insulating aggregates it reveals a decrease in the E_d value, the same was also recorded by Vale [6]. According to the 427/05 LNEC's [17] report, the dynamic modulus of elasticity of render mortars should be below 10 GPa, which is essentially intended to allow a better elastic compatibility of the deformations of the support reducing the probability of mortar cracking. Regarding this report only the TD mortar isn't fit for its use as render, being too much rigid, the rest three mortars are.

Regarding the compressive strength it was found that both thermally enchased mortars display a sufficient resistance in order to classify them in the CS I class according to the EN 998-1 [2] standard.

However, these values are significantly lower than the rate of compressive strength displayed by the traditional reference mortar (22.9 MPa). The same was also recorded regarding the tensile strength. As Vale [6] and Leal [18] also recorded in their studies, the increase of incorporation of insulating aggregates reveals a great decrease in tensile and compressive strength. Considering the density of the mortars produced, which is directly related to its thermal performance, the best resistance/density ratio was reached for the traditional mortar, being about 4.5, 6.6, and 3.9 times higher than the RC, AW and IS mortars respectively. In other words, the lower strength of non-traditional mortars may compromise their performance in situations where mechanical characteristics may be important, such as shock or abrasion.

As it was expected, the use of the PVC corner reinforcement in the strengthened specimens revealed an increase in the resistant capacity of all four types of mortars. However it was observed that this increase was much higher in the thermal mortars (70% for the IS and 113% for the AW) when compared to a slight increase of the corner resistance in the reference mortars (3% for the TD and 9% for the RC). In fact, regarding the IS and AW mortar, during the test it was verified that the PVC corner was mobilized and began to deform until entering into plastification, taking advantage of its maximum resistant capacity and allowing a greater distribution of the point load by the area of the specimen, this was also possible due to the lower modulus of elasticity of those mortars when compared to the reference ones, where this wasn't recorded due to their higher rigidity where the PVC corner wasn't able to mobilize its maximum deformation capacity, leading to a lower increase of corner resistance. However when comparing the strength displayed by the TD mortar with the IS and AW it was about 22 and 93 times higher, respectively. This substantially decreases with the addition of the PVC corner, reducing the difference between those to about a half.

The results of the drying shrinkage show an average value for the TD mortar of -445 x 10^{-6} m/m at 28 days of age, placing it between the results obtained by Martins [7] (-530 x 10^{-6} m/m) regarding a similar composition but of 1:3,5 volumetric ratio, and Braga [19] (-403 x 10^{-6} m/m) in an identical volumetric ratio of 1:4. Regarding the industrial cement-based mortar, RC, the shrinkage was only slightly higher (-563 x 10^{-6} m/m), however this product presents the incorporation of synthetic fibers in its composition, which contributes to the reduction of this property. As expected, the thermally enhanced mortars with a low modulus of elasticity showed a much higher average shrinkage, -2391 x 10^{-6} m/m for the IS and -1643 x 10^{-6} m/m for the AW, this phenomenon is commonly seen in mixtures with high percentages of EPS incorporation due to its very low stiffness and, consequently, poor capacity of strain restriction.

The restrained shrinkage test showed that under the 28 days of testing in the specified specimens, the thermal mortars characterized by a higher shrinkage and lower modulus of elasticity presented a lower amount of cracking when compared to the TD mortar of lower shrinkage and much higher modulus of elasticity. Regarding the AW mortar, its lowest modulus of elasticity and relatively high shrinkage was found to be sufficient in order to not display any cracking during the test period, also the RC mortar didn't displayed any cracking due to its incorporation of synthetic fibers in its composition. The IS mortar displayed 2 cracks on the 1 meter of length mold showing that its relatively low modulus of elasticity wasn't able to accommodate its high shrinkage.

Regarding the adhesive strength test and inherent fracture pattern, the TD mortar displayed an adhesive strength of 0.38 MPa and adhesive fracture pattern, higher than the minimum value define at the LNEC's 427/05 [17] report of 0.30 MPa for cementitious renders. The RC mortar also displayed a higher value than the minimum specified at the report (0.39 MPa and cohesive fracture), and also its manufacturers specification ($f_u \geq 0.25$ MPa). Within the industrial mortars there is a trend of reducing the adhesion tension with the increase of the percentage of substitution of the mineral aggregate by EPS, although the type of binder in all those mortars is not identical. The IS mortar developed a mean adhesive tension of 0.20 MPa similar to the value obtained by Vale [6] (0.21 MPa). The AW mortar, with a lower strength and density, displayed a lower adhesive stress of only 0.06 MPa which was only slightly lower than the obtained by Vale [6] (0.08 MPa). It should be noted that industrial mortars may incorporate additives in their constitution which promote and improve its adhesion capabilities, leading to higher bond stresses than the traditional mortars.

It should be noted that the sclerometric pendulum (PT) test presents a high variability, reporting values of rebounds quite different depending on the region where the test is performed, being very sensitive to slight variations in the characteristics of the carrier. This test intends to estimate the strength of a material by measuring its surface hardness, noting that the greater the absorption of the acting force is, the lower the rebound of the impact mass will be. The value obtained for the TD mortar is very similar to the value reporter by Gonçalves [20] on a similar cementitious composition (IE = 70). In relation to the RC mortar, the value obtained falls within the limit reported by Galvão [21] for pre-dosed cementitious mortars (IE ≥ 50). Both the thermal mortars presented a reduced sclerometric index values, indicating a low surface hardness and modest resistance to impact. Contrary to what might be expected, the AW mortar with lower density and strength capacity showed a higher sclerometric index than the IS mortar, this might be due to a greater compaction of the AW mortar when it was applied fresh to the mold.

The sphere impact test measures the impact depth and diameter of a sphere of known impact energy on a render (in this case 2 Joules). According to the LNEC's 115/2008 [22] report, formulated for a 3 Joules impact energy, a depression diameter of less than 20 mm is considered adequate. As we are testing for a 2 Joule energy impact, it makes it difficult to classify the mortars analyzed. Nevertheless, it is considered that the cementitious mortars TD and RC presented a high resistance to shock. On the other hand the thermal mortars exhibit modest shock resistant values. The AW mortar, presented the worse shock performance, showing mean depressions of 7.4 times greater than those of the TD mortar.

The Spray-test performed under the New-Zeeland's standard, NZS 4298 [23], intender for earth brick under heavy rains, displayed in general positive results placing all four mortars tested in the class 1 of the erosion indexes. The TD mortar didn't displayed any detachments under the 60 minutes of testing, similar to the result displayed by the RC mortar which displayed a single detachment in depth below 1 mm. In relation to the thermal mortars, the IS, with higher density, had much better performance than the AW mixture, showing that the percentage of substitution of mineral aggregate by EPS appears to be preponderant in the cohesion of the hardened mortar. The AW with the worst behavior suffered some superficial degradation during the test period. After 15 minutes, it displayed central detachments with depths up to 3.5 mm reaching the depth of 5 mm after 30 minutes.

The water absorption due to capillarity and the water absorption under low pressure tests intend to obtain the water absorption coefficient regarding the period of fast water absorption. Regarding the water absorption due to capillarity coefficient, all the different mortars display similar results. Only the AW mortar, associated to a higher percentage of EPS, showed absorption coefficients 10% to 13 % lower than the other mortars. Considering the long-term absorption, the thermal mortar present values about 25% lower than those of the RC and TD cementitious mortars, showing a lower porosity accessible to water, this might be justified by the incorporation of water-repellent agents in the composition of these mortars. Both the thermal mortars seems to be able to be classified as W1 (C_{abs} < 0.4 $kg/m^2min^{0.5}$) class according to the EN 1015-18 standard [15]. Regarding the coefficients obtained under the water absorption under low pressure test, the IS mortar results are similar to those of Melo [8] were he obtained a value of 0.21 $kg/m^2min^{0.5}$ for an average absorption of 0.93 cm^3 under 60 minutes. The AW showed a behavior similar to the IS mortar, with slightly higher absorption and absorption coefficient (about 10%) which is contrary to the observed trend in the capillary absorption. This may result from the effect of water permeability also assuming some relevance in this test, being less affected by the action of the water repellent products. It is important to note that the results of both these tests may be altered by the use of water repellents in the composition of those industrial mortars in the order to display better characteristics.

By the end of this study it was possible to identify some correlations between the different tests performed. It was possible to verify a large logarithmic relationship between the hardened bulk density and the compressive strength (R^2 = 0.93), an even larger relationship between the compressive and tensile strength (exponential of R^2 = 0.99). It was also found a linear relationship between the dynamic modulus of elasticity and the compressive strength (R^2 = 0.99) and finally an exponential relationship between the dynamic modulus of elasticity and the result of the sphere impact test (diameter, R^2 = 0.99 and depth, R^2 = 0.98 of the impact). It is displayed at the Table 3.2 the approximation equations found between the different tests performed.

Table 3. 2 - Approximation equations found between the different tests.

Approximation relations	Hardened bulk density [kg/m^3]	Compressive strength [MPa]	E_d [MPa]
Compressive strength [MPa]	$B_d = 484.6 \ln (C_s) + 620.9$	-	-
Tensile strength [MPa]	-	$C_s = 2.274 (T_s)^{1.3469}$	-
E_d [MPa]	-	$E_d = 1095.4 C_s - 41.78$	-
Sphere impact (ɸ) [mm]	-	-	$E_d = 62499 e^{-0.182ɸ}$
Sphere impact (Δ) [mm]	-	-	$E_d = 38563 e^{-0.1004Δ}$

Notes: E_d = Dynamic modulus of elasticity; B_d = Hardened bulk density; Cs = Compressive strength; Ts = Tensile strength; ɸ = Diameter of the sphere impact [mm]; Δ = Depth of the sphere impact [mm].

4. Conclusions

The present study intended to characterize the mechanical behavior of thermally enchased mortars. In order to make this possible it was found to be interesting to produce an additional traditional cementitious mortar and another cement-based pre-dosed industrial mortar alongside with two of the most used thermal mortars in Portugal in order to lately compare their properties.

As a summary of this study, it was concluded that in order to obtain mortars with improved thermal behavior, there is a natural accelerated decrease in their rigidity and resilient capacity. Although thermal mortars generally meet the minimum requirements defined in standardization [2], their poor mechanical strength may compromise their use in coating systems subject to relevant impact or abrasion actions.

Taking into account the tests of sphere impact and accelerated erosion (spray test) carried out in this work, the application of thermal mortars in coatings subject to these actions is extremely discouraged. The low integrity of these thermal mortars results in a very susceptible product to degradation when applied in areas with sharp edges, and it is advisable to apply reinforcement angles to the corners of this type of coatings. The high shrinkage of these thermal mortars seems to be compensated by their weak rigidity when analyzing their susceptibility for the development of cracking by restriction. The incorporation of water repellents and other additives allows these mortars to demonstrate adequate water resistance and better adhesion to the support, facilitating their application in outdoor environments. The durability of these additives in mortars was not analyzed.

5. References

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