Experimental characterization of the physical behavior of mortars with improved thermal performance

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1. Introduction and Objectives

In order to improve buildings´thermal performance, not only in terms of their thermal properties, but also regarding the indoor environmental quality and the environmental impact, a need for improvement of the properties of thermal insulation materials has arisen. Such a need is reflected in the requirements and regulations [1, 2] with more stringent demands for buildings´thermal performance [3]. In order to meet such a goal, and taking into account the importance of today´s energy issues, a number of production methods and products with improved thermal performance have been developed [4].

In this regard, studies in the field have brought in new materials as mortars´components, aiming to improve their thermal performance, while maintaining acceptable physical properties in order to fulfil their original functions [5]. Thermal renders are one of the available solutions meeting the objectives regarding building´s enhanced thermal performance. These are made of lightweight materials, and their application thickness should be above 40 mm [6].

According to EN 998-1 standards [7], thermal mortars are characterized by thermal conductivity (λ) of less than 0.1 and 0.2 (W/m.K), categorized respectively as T1 and T2. They are also characterized by a capillary water absorption coefficient less than 0.2 and 0.4 $kg/(m^2.min^{0.5})$, categorized respectively W1 and W2 classe, by a water vapour permeability coefficient lower or equal to 15, and by the CS I or CS II strength classes (0.4 to 5 MPa).

In order to improve mortars thermal properties, innovative solutions have been developed incorporating lightweight insulating materials, whose densities are typically below 150 kg/m^3 and whose thermal conductivity is below 0.05 W/m.K [8].

In this study mortars incorporating organic aggregates are tested, in particular expanded polystyrene and cork, because these materials are more frequently found as components of mortars available on the market, and which contribute to an improved thermal performance of building walls.

Expanded Polystyrene (EPS), figure 1.1, is a rigid and resistant thermoplastic polymer, with closed cells, and which is usually white. Given that it is composed of 98% air and 2% plastic with low thermal conductivity ((≈ 0.04 W/m.K), it features outstanding thermal insulation properties, and is usually used in construction work [9-12].

Figura 1.1- Expanded Polystyrene (EPS)

Figura 1.2 - Cork granulate

Cork, figure 1.2, is a cellular, natural and renewable material, featuring low thermal conductivity (≈ 0.039-0.045 W/m.K), slow combustion (despite being an organic material), and good physical and mechanical properties [5, 9, 13].

In order to better understand the physical behavior of thermal mortars, it was performed in this paper an experimental campaign to study both traditional and industrial mechanical characteristics of thermal mortars or improved thermal performance incorporating insulating aggregates (cork and EPS), having the following as main objectives:

- to understand the influence of the incorporation of insulating aggregates (cork and EPS) in the formation of thermal mortars;
- characterize the physical behavior of these mortars and see what features most influenced by insulating materials;;
- to compare the physical performance of traditional mortars (without additions) with industrial mortars, which are considered thermal or with improved thermal performance;
- to evaluate possible applications or restrictions of these mortars.

2. Experimental Programme

The aim of the experimental programme was to make a comparative analysis of the physical characteristics of different mortars with improved thermal performance. In order to achieve this goal, three traditional and four industrial mortars were produced, all of which are shown in Table 2.1.

The 1:3 volumetric ratio was chosen for producing traditional mortars; because it is one of the most frequently used ratios for producing traditional cement-based mortars, in Portugal [14]. This volumetric ratio was maintained throughout the production of all traditional mortars, thus enabling one to compare the results according to the incorporation of different aggregates.

In the course of the experimental programme, a cork mortar and an EPS mortar were produced. Producing the first mortar replacing sand with cork, by 80% of the volume, and a bulk density of 101 kg/m^3 (mortar F^{Trad}_{Cort}), while producing the EPS mortar involved replacing sand with EPS, by 85% of the volume, and a bulk density of 11 kg/m^3 (mortar G^{Trad}_{EPS}), according to the incorporation percentage values found in the works of Brás et al. [9], and Ali [15], respectively.

Apart from these mortars, a reference mortar was also produced (E^{Ref} mortar). It should be noted that, in all of traditional mortars, Portland cement of the CEM II B/L type 32,5 N class was used as the binder, while the amounts of water used met the requirements necessary for ensuring a consistence according to the EN 1015-2 standard [16].

Table 2.1 – Render composition

Mortars		Binder	% (by volume)	$D_{máx}$ (mm)	Other materials	Water / binder ratio	Water / dry constituents ratio	Additions / Admixtures
Industrial	A^{Ind}_{EPS}	Lime / cement	100% EPS	≤ 3	without incorporation	not specified	1.14	Re- dispersible polymer; hydrophobic agent; expansive agent; water-retaining agents
	B^{Ind}_{EPS}	Lime / cement / synthetic binder	70-80% EPS	1.5 - 2	Sand (silica and calcareous)	not specified	0.7	Not specified
	C^{Ind}_{Cort}	Cement	70-80% cork	1.5 - 2	Sand (silica and calcareous)	not specified	0.33	Re- dispersible powder; air entraining agent; hydrophobic powder; shrinkage control agent; water retaining agents
	D^{Ind}_{Cort}	Natural hydraulic lime	cork	≤ 3	Diatomaceous earth and clay	not specified	0.55	Natural additions; fibres, air entraining agent
Traditional	E^{ref}	Cement	-	-	Sand (quartz, quartzite, feldspar)	0.8	-	With no additions
	F^{Trad}_{Cort}	Cement	80% cork	1 - 2	Sand (quartz, quartzite, feldspar)	0.7	-	With no additions
	G^{Trad}_{Cort}	Cement	85% EPS	3.4 - 4	Sand (quartz, quartzite, feldspar)	0.5	-	With no additions

As shown in Table 2.1, the production of dry industrial mortar (supplied in bags) followed manufacturers´ instructions, particularly, regarding the amounts of water that should be added to the powder product.

The storage and curing of the samples were performed according to EN 1015-11 standard [17]. Wet curing in polyethylene bags (7 days) was followed by dry curing (21 days) in a climatic chamber under controlled conditions, corresponding to 65% ± 5% of relative humidity and a temperature of 20 °C ± 2 °C.

To characterize these mortars physically, bulk density in hardened mortars, air contend, open porosity, water absorption under low pressure, water absorption coefficient due to capillary, drying rate and thermal conductivity tests were performed in all mortars.

3. Physical performance/results

The physical performance tests were conducted according to standard procedures shown in Table 3.1, which also presents the respective results, at the 28 days.

Table 3.1 – Physical performance, at the 28 days (mean values)

Mortars		B.d. (kg/m^3)	Air content (%)	Open Porosity (%)	C1 (kg/m^2.min$^{0.5}$)	C2 (kg/m^2.m$^{0.5}$)	Drying rate	ʎ (W/m.K)
Standard		EN 1015-10 [18]	EN - 1015-7 [19]	NP EN 1936 [20]	EN 1015-18 [21]	Ficha Lnec Fe Pa 39.1 [22]	-	*Isomet 2114* [23]
Number of tests		21	14	12	21	28	21	21
Industrial	A^{Ind}_{EPS}	237	9.6	-	0.9	11.7	0.23	0.06
	B^{Ind}_{EPS}	432	5.2	-	0.3	1.63	0.23	0.1
	C^{Ind}_{Cort}	863	6.6	46.4	0.13	0.75	0.45	0.23
	D^{Ind}_{Cort}	642	6	47.3	0.67	2.33	0.31	0.14
Traditional	E^{ref}	1885	4.7	25.6	0.74	2.82	0.32	1.3
	F^{Trad}_{Cort}	855	5	37.5	0.64	0.66	0.28	0.27
	G^{Trad}_{EPS}	683	6.2	-	0.23	1.45	0.29	0.23

Notes: B.D.- Bulk density - hardened state (kg/m^3); C1 - Water absorption due to capilary action (kg/m2.min$^{0.5}$); C2 - Water absorption under low pressure - *Tubo Karsten* (kg/m2.m$^{0.5}$).

Through this first analysis, and taking into account the objective of improving the thermal mortars, you can check that with the introduction of insulating aggregates (cork and EPS), the physical performance of mortars changes. There are significant decreases in the values of all physical characteristics, except in air content and open porosity.

Regarding the bulk density in the hardened state of mortars incorporating insulating aggregates is possible to estimate the values range between 237-863 kg/m^3. According to EN 998-1 [7] these mortars can be classified as light mortars (bulk density ≤ 1300 kg/m^3). Tend mortars with incorporation of granulated cork have bulk density values higher than mortars with incorporation of granulates EPS, as was expected, given the granulated cork have a bulk density higher to the EPS (cork-> 101 kg/m^3; EPS -> 11 kg/m^3). The introduction of granulated cork and EPS caused a decrease in the bulk density of the order of 55% and 65%, respectively, compared to the reference mortar.

The experimental results show that, in general, the rate of air content in fresh state in industrial mortars ranges between 5 and 7%, except for the A^{Ind}_{EPS} mortar, where this value is close to 10%. As a side note, EPS was the only aggregate used in this mortar; its composition also contains lime, and the amount of water used in the mixture was greater than that used in other industrial mortars. In traditional mortars, the values for air content are also close to those found in industrial mortars, ranging between 5 and 6%, thus being slightly higher than those in the reference mortar (with air content close to 5%). The air content in cementitious materials normally ranges between 3% and 5% in mortars [24]. To sum up, mortars incorporating a high percentage of insulating aggregates trend to contain greater amounts of air. Unfortunately, works of other authors referring to mortars of this type are scarce.

Regarding the capillary water absorption coefficients of all mortars were in the range of 0.13 to 0.67 kg/(m^2.min$^{0.5}$), thus being lower than that of reference mortar (0.74 kg/(m^2.min$^{0.5}$). This study has shown that the A^{Ind}_{EPS} and D^{Ind}_{Cort} mortars have higher values than those reported by the manufacturers (class of capillary water absorption W1 → capillarity coefficient ≤ 0.40 kg/(m^2.min$^{0.5}$), in accordance with EN 998-1 [7]). As discussed earlier, there were already differences in these mortars mechanical characteristics, when compared to those declared by respective manufacturers. Therefore, changes in physical characteristics may also be related with mortar mixing and application process. Despite the high porosity of $\mathbf{C^{Ind}_{Cort}}$ mortar (about 46.4%), it has shown a low coefficient of capillary water absorption. However, according to the information provided by the manufacturer, this mortar has a hydrophobic agent as one of its components.

In traditional mortars incorporating EPS (mortar $\mathbf{G^{Trad}_{Cort)}}$), there was a significant reduction in the coefficient of capillary water absorption, while the traditional mortar incorporating cork had a significantly lower capillary water absorption coefficient than that of the reference mortar. Other authors have concluded that the capillary water absorption values tend to remain close to those of the reference mortar, in cases of 80% EPS incorporation [12]. However, in producing mortars, these authors have used a high range water reducer (HRWR), while the particle diameter (max. 2mm) was lower than that in this study. When comparing the cork mortar with the reference mortar, Martins [25] has found that capillary water absorption tends to decrease in cases of incorporation rate of 60%, and when particle size is greater than 0.5 mm. In making this comparison, Bras et al. [12] have also observed the same tendency of decrease of capillary water absorption, in cases when cork incorporation was made by 80%, and when particle size ranged between 0.5 and 2mm.

Open porosity could only be ascertained in cork mortars, because the reduced density of some mortars - especially those incorporating EPS, - made the hydrostatic weighting of samples unfeasible. The results for mortars' open porosity have shown that cork incorporation rates higher than 70% result in open porosity values between 38 and 47%, while the value for porosity in the reference cement-based mortar is close to 26%. The significant difference found in mortars with approximate open porosity $\mathbf{C^{Ind}_{Cort}}$ and $\mathbf{D^{Ind}_{Cort}}$ mortars with open porosity about 47% in terms of water absorption, can also be explained by particular differences of formulations, by the presence of hydrophobic agents in mortar $\mathbf{C^{Ind}_{Cort}}$, by the variations of the binder, non-insulating aggregate, and by the percentage variation of aggregate incorporation (absent in the case of $\mathbf{D^{Ind}_{Cort}}$ mortar).

Regarding the low pressure water trial, a 75% and 50% decrease can be seen in the cork mortars (F^{Trad}_{cort})' and EPS'(G^{trad}_{EPS}) absorption rate respectively, when compared with the reference mortar's rate. Other articles where this trial was made in thermal improved mortars were not found, so, water absorption coefficients due to capillary were compared with water absorption under low pressure coefficients, being both, in the industrial mortars, controlled by the hydrophobic agents. Analyzing industrial mortars, there's a tendency for the same mortar to show higher values of both coefficients (A^{ind}_{EPS}) while the opposite can also be found (C^{ind}_{Cort}).

With the introduction of granulated cork and EPS, there was a decrease in the rate of drying of 13% and 10% compared to the reference mortar. This tred was also observed by Leal [26] who obtained decreases of 25% and 14% when tested with mortar mergers similar of cork and EPS. The mortars which absorb more water tend to be the ones that also expel more water. In this article this same tendency can be seen in the A^{ind}_{EPS}, B^{ind}_{EPS} and F^{Trad}_{Cort} mortars, these being the mortars that absorb the bigger amount of water while showing the smallest drying rate. The inverted effect can also be seen in the C^{ind}_{Cor} mortar, that while having the smallest water absorption coefficient due to capillary under low pressure also has the highest drying rate. According to Páscoa [27], the bigger the porosity of a certain mortar, the bigger its ability to dry, i.e. the smaller the I_s. The C^{ind}_{Cort} mortar doesn't show this tendency, i.e. despite its high open porosity (46%), around 45% higher than the benchmark mortars' porosity, its drying rate is also high, specifically, around 40% higher than the benchmark mortars' drying rate.

In what concerns to the thermal performance, values from 0.06 to 0.28 W/m.K were obtained to the coefficient of thermal conductivity (λ) of the insulating mortars incorporating aggregates.

When evaluating the thermal conductivity of mortars B^{Ind}_{EPS} and C^{Ind}_{Cort} containing the same percentage of incorporation of insulation aggregate, one concludes that the mortar incorporating EPS has a better thermal performance than the mortar incorporating cork. However, the specifics of the B^{Ind}_{EPS} mortar formulation may provide an explanation for different results. In particular, in what concern the binders, which, apart from cement, also include lime and synthetic binders; and the admixtures (whose specifications were not provided by the manufacturer), and all of which were added to the mixture.

When comparing traditional mortars with the reference mortar, the addition of thermal insulation materials has resulted in a substantial reduction (about 80%) of the value of thermal conductivity (values close to 0.3 W/m.K, as opposed to 1.34 W/m.K for the reference mortar). This was also accompanied by a substantial decrease in apparent bulk density. Still, despite the high percentages of incorporation of these materials (80-85%), none of the traditional mortars produced met the thermal mortar requirements as in EN 998-1 [7]. Bras et al. [12] have also concluded that mortars' thermal conductivity decreases with the introduction of the cork and EPS. However, these authors have also observed that, in contrast with cork aggregates, where an increase of amounts of cork results in a significant decrease of thermal conductivity, an increase of the proportion of EPS aggregates in mortars does not contribute to such a substantial decrease in thermal conductivity. Ali [15] noticed a decrease of 89% in thermal conductivity with the addition of EPS aggregates. It was possible to observe a better thermal performance for industrial mortars compared to the traditional. Note that some industrial mortars, in particular mortar D^{Ind}_{Cort} and C^{Ind}_{Cort}, contain in its composition air introducing agents that improve heat resistance [5].

Finally, with the results obtained, it was possible to identify correlations between the different physical characteristics of industrial and traditional mortars studied. These correlations are presented in Table 3.2.

Table 3.2 – Matrix of correlations between properties of mortars with improved thermal performance

	A.C.	C2.	C1.	B.D..	D.R.	C.S.	ʎ	P
A.C..		Lin.	Lin.	Exp.	Pot.	Exp.	Pot.	Log.
C2	**0.74**		Lin.	Exp.	Pot.	Exp.	Pot.	Lin.
C1	-	0.46		Exp.	Log.	Log.	Exp.	Lin.
B.D.	0.57	0.43	0.34		Exp.	Pot.	Pot.	Exp.
D.R..	-	0.28	0.51	0.42		Log.	Pot.	Log.
C.S..	0.47	0.82	0.61	**0.95**	**0.86**		Pot.	Log.
ʎ	0.46	**0.75**	0.35	**0.88**	0.20	**0.74**		Pot.
P	**0.82**	0.21	0.32	**0.90**	0.51	**0.79**	**0.94**	

Legendas: Lin.-Linear; Exp.- Exponencial; Pot.-Potencial; Log.- Logarítmica; A.C. – Air content; C2 - Water absorption under low pressure - Tubo Karsten (kg/m2.m$^{0.5}$).; C1 Water absorption due to capilary action (kg/m2.min$^{0.5}$);M.V.. B.D. - Bulk density - hardened state (kg/m^3) ; D.R. - Drying rate; R.C.- Resistência compressão; ʎ Thermal conductivity (W/m.K); P- Open Porosity; C.S. - Compressive strength [MPa].

It is possible to identify a direct relationship between the thermal conductivity (λ) and the bulk density in the hardened state (Bd) (R^2=0.88). In general, for smaller values of thermal conductivity correspond mortars with lower densities, as well as reduced compressive strength. Panesar et al. [5] also observed a direct relationship between thermal conductivity and bulk density of mortars incorporating cork aggregates.

Although it is not possible to obtain a porosity value of all mortars, this parameter was examined with the values obtained. It should be stressed the fact that this parameter having a relationship with the high apparent density in the hardened state, that is, the higher the porosity of mortar, the lower its apparent density in the hardened state.

The parameter drying also has a relationship with the high compression resistance which in turn has a good relationship with the porosity, probably due to the fact that the mortars are more porous and less resistant to have the greatest ease in drying.

The remaining correlations were not relevant, especially those that relate to the absorption of water by capillarity and low pressure, possibly because of the presence of the water-repellent mortar industrial changing the normal behavior, despite its high porosity.

Note the weak correlation coefficient capillary absorption, the content of air and liquid water permeability with other tests. The test of the density in the hardened state is strongly correlated with other tests

4. Conclusions

When analyzing the physical characteristics, significant improvements in thermal performance were found, such as a decrease by 80% of the coefficient of thermal conductivity in comparison to the reference mortar, with values lower than or equal to 0.2 W/m.K in industrial mortars, and 0.3 W/m.K in traditional mortars. This has resulted in more porous mortars (open porosity values ranging between 38 and 47% in mortars with cork), with a significant decrease in bulk density values (between 642 and 863 kg/m^3), and a slight increase in air contents of fresh mortar (most values ranging between 5 and 7%).

Regarding to the influence of the incorporation of the insulating aggregates (cork and EPS), it can be seen that to obtain mortars with improved thermal performance greater quantities, over 80% by volume of incorporation of these aggregates, are required. However, it appears that for traditional mortars, without any additions, the introduction of these aggregates by itself, allows for thermal improvements, but not enough to be classified as thermal mortars according to EN 998-1 ($\lambda \leq 0.1$ to 0.2 W/m.K) [7]. The values for thermal conductivity of industrial mortars are in the range of 0.1 to 0.2 W/m.K, and falling into the category of thermal mortars (T1 or T2 rating, in accordance with the European standard EN 998-1 [8]).

It is possible to observe that with the introduction of insulating aggregates the physical performance of mortars is affected/changed. You can get lighter mortars (Bulk density ≤ 863kg/m^3) compared to standard mortars. Thus, in general, lower values of thermal conductivity are found in mortars with lower values of bulk density, which also explains lower values regarding mechanical strength.

Regarding the coefficient of capillary water absorption, the values for the studied mortars varied significantly, something which may be related to the effects of addition/admixtures (such as hydrophobic agents) on industrial mortars' water absorption parameters. In general, the experimental results have shown good correlations between some physical characteristics.

The differences found between traditional and industrial mortars with high percentages of insulation material incorporation call for a more comprehensive study of the effects of different components on mortars with enhanced thermal performance. In particular, this concerns different binder types, the size of thermal insulation aggregates, and different types of additions and admixtures used. There is also a need for further research regarding EPS mortars, in terms of the impact of its production process on the physical and mechanical properties in the hardened state.

In short, it can be seen that the mortars with incorporation of insulating aggregates, either cork or EPS, are a good solution to obtain mortars with improved thermal performance.

In general, these mortars, due to the low coefficient of thermal conductivity, promote effective treatment to combat thermal bridges, decisively contributing to the prevention of defects in the construction. They can also be used for dehumidifying walls. These mortars are suitable for carrying out wall thermal insulation coverings, for interior and exterior. Regarding the application of the mortars abroad it must be aware of the following aspects: C^{ind}_{cort} mortar is the only one that can be applied in walls exposed to shock or in regions with adverse weather conditions, the A^{ind}_{EPS}, D^{ind}_{Cor}t and F^{trad}_{Cort} mortars need additional coating that gives it a greater protection for water suction and B^{ind}_{EPS} and G^{trad}_{EPS} mortars can be applied in moderate weather conditions. They are also suitable for insulation of new or rehabilitated walls, with special emphasis on the rehabilitation of used/old walls.

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