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Comparison of mineralogical, mechanical and hygroscopic characteristic of earthen, gypsum and cement-based plasters

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Abstract

It is important to ensure indoor comfort by passive methods, avoiding mechanical equipment that has energy costs. To assess plasters common efficiency but also its contribution as moisture buffers, five different plastering mortars, including unstabilized and stabilized earth-based plasters, gypsum and cement-based pre-mixed plasters, were analyzed and their chemical, mechanical and hygroscopic characteristics compared. The materials and mortars were analyzed by X-ray diffraction and simultaneous thermal analysis. Linear shrinkage, dry bulk density, dynamic modulus of elasticity, flexural and compressive strengths, dry abrasion resistance, surface cohesion, surface hardness and sorption and desorption of mortars and plasters were also evaluated. The mechanical strength of earthen mortars is lower than gypsum and cement-based mortars. However, earth plasters show the highest hygroscopicity, acting as moisture passive buffers, improving thermal comfort and contributing to occupants´ health.

Keywords: abrasion; air lime; cohesion; compression and flexural strength; laboratory testing; mortar; sorption; XRD; TGA/DSC

1. Introduction

Cement-based construction is very common around all the world. In consequence, cement is the second most consumed substance in the world by weight [1]; just after water. During the production of 1 ton of cement, around 900 kg of CO_2 are emitted into the atmosphere [1]. Given the environmental issues of cement production, whenever possible it is important to use environmentally friendly building materials, with low CO_2 emissions and embodied energy, which may also contribute to improve indoor air quality (IAQ) of buildings.

The technical and environmental advantages of earth plastering mortars promoted an increase of interest of the scientific community: the earth raw material is natural, available without need of transportation, inexpensively, not renewable but reusable (when not chemically stabilized), non-toxic, involving low CO_2 emissions to be manufactured and applied as a building material – due to all these features earth plasters presents low embodied energy. The production of earth plasters requires a relatively small amount of energy, when comparing with conventional plasters – based on cement and lime, for example – because the production of these materials requires very high temperature [2]. Earthen plasters can contribute to the comfort of buildings inhabitants and IAQ

due to their high capacity to adsorb and release water vapor, due to the high hygroscopic capacity of clays, contributing to balance indoor relative humidity (RH) and temperature [3–10].

Earth plasters characteristics are not often tested and analyzed in comparison to common plasters, using the same test procedures, especially as regards sorption and desorption capacity as a way to analyze the hygrothermal balance. To the authors knowledge only Maskell et al. [9] present the mass change of clayish earth, lime and gypsum plasters when exposed to different relative humidity and constant temperature, and Minke [3] present the sorption curves of clayish earth, lime-cement and gypsum plasters. However, many doubts still subsist when considering the choice of an eco-efficient plaster.

To contribute to a deeper knowledge, in the present study three earth-based plastering mortars were characterized: a laboratory formulated earth mortar (E_L), a commercial pre-mixed earth plastering mortar commercialized by Embarro company (Em) and a pre-mixed earth-air lime plastering mortar being developed by Aldeias de Pedra company (E+CL). Two other commercial pre-mixed plastering mortars commonly used in Portugal were also characterized: cement-based and the other hemi-hydrated gypsum-based, identified respectively as Cm and Gm mortars.

Mineralogical characteristics, such as X-ray diffraction (XRD) and thermogravimetric and differential scanning analysis (TGA/DSC), were used to characterize the constituent materials and the mortars. Mechanical and physical characteristics of the mortars, such as linear shrinkage, dry bulk density, dynamic modulus of elasticity (Ed), flexural (FStr) and compressive (CStr) strengths, dry abrasion resistance, surface cohesion and hardness, sorption and desorption capacity, were also determined; the results are presented and discussed.

2. Materials, mortars and methods

2.1. Materials characterization

Table 1 shows the description of mortars and systems (when applicable) with their various constituents and manufacturing type (laboratory or pre-mixed formulation). Loose bulk density values of the eight raw materials used in the mortars formulation analyzed by EN 1097-3 [11] (taking an average of three specimens of each material) are also presented in Table 1, as well as technical characteristics of Cm and Gm mortars.

Table 1. Description of mortars analyzed.

Mortars	Type of mortar	Production	Materials constituents	Technical characteristics
E_L	Earth-based	Formulated in laboratory	Composed with red clayish earth (RCE), fine (FS) and coarse (CS) sand with volumetric ratio of 1:3:1.5 and mass ratio of 1:3.04:1.78 (RCE:FS:CS)	LBD* of the materials RCE: 1.36 ± 0.01 kg/m^3 FS: 1.38 ± 0.00 kg/m^3 CS: 1.61 ± 0.00 kg/m^3
Em	Earth-based	Pre-mixed (produced by Embarro company)	Produced using the pre-mixed earth product (Ep), composed by a reddish clayish earth from Algarve region, 0–2 mm fine sand and cut straw fibers (proportions of each constituent are not exactly known)	LBD* of Ep: 1.40 ± 0.01 kg/m^3
E+CL	Earth-air lime based	Pre-mixed (produced by Aldeias de Pedra company)	Composed with yellow clayish earth (YCE), provided by Sorgila company, coarse sand (CS), limestone powder (LP) and addition of air lime putty (ALP) (proportions of each constituent are not exactly known because the mortar arrived ready to apply)	LBD* of the materials YCE: 1.20 ± 0.00 kg/m^3 CS: 1.61 ± 0.00 kg/m^3 LP: 1.37 ± 0.02 kg/m^3

Cm	Cement-based	Pre-mixed (produced by Secil Argamassas company – RHP Manual Interior)	Produced using Cp product (proportions of each constituent are not exactly known because the mortar arrived ready to apply); the plaster is commonly painted, but that finishing coat was not included	LBD* of Cp: 1.50 ± 0.00 kg/m^3; CS II class for CStr; 0.2 MPa of AStr; BD of 1650 ± 150 kg/m^3; Wvp ≤ 15 μ; class A1 for FB; 0.61 W/(m.K) for λ
Gm	Gypsum-based	Pre-mixed (produced by Sival company – Project 2010)	Produced using Gp product; the system includes a finishing gypsum coat that was applied only on the planar (in metallic mold) and on the brick specimens (proportions of each constituent are not exactly known because the mortar arrived ready to apply)	LBD* of Gp: 0.81 ± 0.01 kg/m^3; FStr > 1 MPa; CStr > 2 MPa; SH > 50 Shore C; class A1 for FB (after 28 days)

Notation: LBD* – loose bulk density (determined in the present study); FStr – flexural strength; CStr – compressive strength; AStr – adhesive strength; BD – bulk density; Wvp – water vapor permeability; FB – fire behavior; SH – surface hardness; CS sand used for E_L mortar was supplied by Aldeias de Pedra company, guaranteeing that it was the same one used for E+CL mortar production

Particle size distribution of the raw materials, shown in Figure 1, were characterized by EN 1015-1 [12]. The fine and coarse siliceous sands (FS and CS) were analyzed by the dry method, while the clayish earths (RCE and YCE), the Ep pre-mixed earth product and the limestone powder (LP) were analyzed by the wet method [12]. The sedimentation was also analyzed, according to LNEC specification E196 [13], to complement the particle size distribution of RCE, YCE, Ep and LP, since these materials present particles lower than 0.075 mm. The particle size distribution of the E_L mortar was calculated from the particle size distribution of its constituent materials (RCE, FS and CS). The cement-based product (Cp) present particle size lower than 1.2 mm, by EN 1015-1 [12], according to the producer's indication. Particle size of the gypsum-based product (Gp) was not determined nor is it shown in the producer's indications.

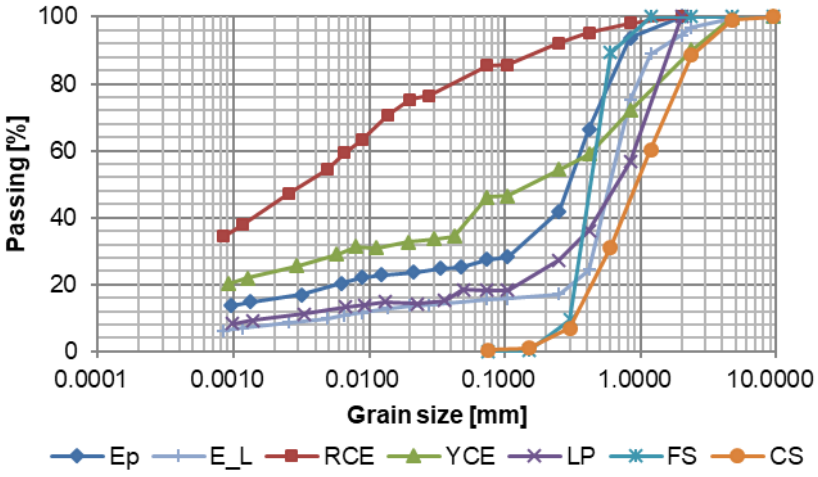


Figure 1. Particle size distribution of mortars (E_L and Ep) and raw materials (RCE, YCE, LP, FS and CS).

2.2. Mortars preparation, fresh state characterization and specimens production

The pre-mixed mortars (Em, E+CL and Cm) were produced only by addition of the water content indicated by each producer (Table 2). The water content of E_L and Gm mortars (Table 2) was defined by an experienced craftsman to assure good workability. Although Gm is a pre-mixed material, water content was not indicated by the producer.

Table 2. Water content, fresh state characterization and linear shrinkage of the plastering mortars.

Mortars	Water content [%]	Flow table consistency [mm]	Plunger penetration consistency [mm]	Wet bulk density [kg/dm^3]	Linear shrinkage [%]

E_L	10	136 ± 19	0.85 ± 0.49	1.56 ± 0.06	0.1 ± 0.0
Em	15	125 ± 8	0.65 ± 0.21	2.03 ± 0.02	0.2 ± 0.1
E+CL	20	153 ± 1	1.70 ± 0.00	1.99 ± 0.02	1.4 ± 0.8
Cm	14	138 ± 14	0.75 ± 0.07	1.90 ± 0.00	0.1 ± 0.1
Gm	43	-	2.20 ± 0.00	1.58 ± 0.05	0.2 ± 0.1

Mortars were manufactured using a mixer blade, in order to reproduce, as much as possible, the method carried out on construction site: dry materials were placed in a bucket and the water was slowly added; initial mixture of 8 minutes, approximately, was carried out; after this period, the mortar adhered to the bucket edges was removed and added to the remaining mortar, followed by a further 3 minutes of mixing. The E+CL mortar was manufactured one day before the production of specimens – to improve the connection between earth and lime. The remaining mortars were produced the same day their specimens were molded.

Before molding, the fresh mortars were characterized by the flow table consistency (EN 1015-3 [14]), by plunger penetration consistency (EN 1015-4 [15]) and wet bulk density (EN 1015-6 [16]). Results are presented in Table 2. The flow table consistency of the Gm mortar was not determined due to it adhesion to the wall of the cone-shaped mold.

For each mortar different specimens were produced:

- prismatic (40 mm x 40 mm x 160 mm), prepared in metallic molds; the mortar was placed in two layers and mechanically compacted with 20 stokes/layer and manually levelled; the prisms were demolded when dried, in laboratory conditions, after at least 7 days (Figure 2a);
- planar (200 mm x 500 mm x 15 mm), prepared and tested in metallic molds as a plaster; the plaster was manually compacted and levelled; the specimens were dried in the same temperature and RH conditions as the prismatic (Figure 2b);
- mortar with 20 mm of thickness applied as a plaster on hollow fired brick (200 x 300 mm area); the brick surface was previously sprayed with water; the plaster was manually compacted and levelled (Figure 2c).

a)  b)  c) 

Figure 2. Prismatic specimens of Em mortar (a), planar specimens of Cm mortar (b) and E+CL mortar specimens on hollow brick (c).

Commonly gypsum plaster system is composed by a mortar layer and a finishing coat. So, the finishing gypsum coat, with 1 mm of thickness, was only applied on the planar and on the brick specimens of the Gm mortar; the application was done after 24 hours of the mortar.

Before the characterization tests, all specimens were maintained in laboratory conditions of 20 ± 2 ºC and 65 ± 5 % relative humidity (RH).

Table 3 presents the age of testing of each mortar. In E+CL mortar a longer testing age was justified due to their slow hardening reaction.

Table 3. Age, number and type of mortar specimens for each test.

Test	Age of testing (months)		Number of specimens	Type of specimen
	E_L, Em, Cm, Gm	E+CL		
XRD, TGA/DSC	6	9	1	Powder
Linear shrinkage	0.5	3	6	Prismatic
Dry bulk density	1	3.5	6	Prismatic
Dynamic modulus of elasticity and flexural and compressive strength	2	4.5	6	Prismatic

Dry abrasion resistance	10	12	1**	Planar on the brick
Surface cohesion and surface hardness by durometer	1	3.5	2**	Planar on the brick
Sorption and desorption	4	6.5	3	Planar on metallic mold

Note: *RCE, YCE, LP, FS, Gp and Ep raw materials also were analyzed; *3 measurements were made in different areas of specimen

2.3. Test methods

Some characterization tests analyze the mortar materials; others analyze the mortars itself, as the case of linear shrinkage, dry bulk density, dynamic modulus of elasticity and flexural and compressive strength tests. Other tests analyze the plasters produced with the mortars, as the case of dry abrasion resistance, surface cohesion, surface hardness by durometer and sorption and desorption tests. For this reason, there is a distinction between the term mortar and plaster, depending on the characterization test.

2.3.1. X-ray diffraction (XRD) and simultaneous thermal analysis (TGA/DSC)

The mineralogical analysis using the X-ray diffraction (XRD) technique, on non-oriented (random) powder sample, was performed on a Philips X'Pert PRO MPD diffractometer, with operational conditions: CuKα radiation, 50 kV, 30 mA, scan rate 0.02 °θ/s in the range 4°–70° 2θ. The identification of the crystalline phases was made according the powder diffraction files (PDF) from the International Centre for Diffraction Data (ICDD).

The thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) were carried out by simultaneous thermal analysis (STA) in powder sample using a TA Instruments SDT Q600 equipment. The heating rate was 10 ºC/min, from ≈25 ºC to 1000 ºC, in air atmosphere.

Tests were performed on the raw materials and the mortars itself. All samples analyzed were first dried at 40ºC and ground to pass a 0.150 mm sieve. Since FS and CS are from the same mineral source, only FS sample was tested.

2.3.2. Linear shrinkage

Linear shrinkage was determined, according to DIN 18947 [17], by the difference of the linear geometrical length of mortar between the fresh and hardened state (Table 2).

2.3.3. Dry bulk density, dynamic modulus of elasticity and flexural and compressive strength

The dry bulk density was determined based on the EN 1015-10/A1 [18], by the ratio between the mass in laboratory conditions, assessed with a 0.001 g precision, and the geometrical volume of the mortar, determined with 0.01 mm precision. The dynamic modulus of elasticity (Ed) was determined in accordance with EN 14146 [19], using a Zeus XRM equipment. The flexural (FStr) and compressive (CStr) strengths were determined in accordance with EN 1015-11 [20], using a Zwick Rowell Z050 equipment, with load cells of 2 kN and velocity of 0.2 mm/min for flexural strength and 50 kN and velocity of 0.7 mm/min for compressive strength. Six halves of the prismatic specimens resulting from the FStr test with about 80 mm long were used to determine the CStr for each mortar, with a compressive area of 40 mm x 40 mm, as defined by EN 1015-11 [20].

2.3.4. Dry abrasion resistance

The dry abrasion resistance was determined in accordance with DIN 18947 [17] by the weight loss of the plaster specimens on the bricks, after 20 rotations of a circular polyethylene brush with 65 mm of diameter, applied to the specimen surface with a pressure produced by a weight of 2 kg. The weight loss was obtained as the average of 3 measurements in different areas of the plaster surface.

2.3.5. Surface cohesion and surface hardness by durometer

The test for determination of the surface cohesion defined by Drdácky et al. [25] was applied as adapted by Faria et al. [26]. In this method the surface cohesion was determined by the variation of mass of an adhesive tape with dimension of 50 mm x 70 mm, pressed with a constant intensity produced by a 4 kg weight applied on top of a resilient material placed on the surface of specimens, after 1 minute. The surface lack of cohesion was defined by the increase of mass of the adhesive tape. The surface lack of cohesion is determined by the average of 3 measurements in different areas.

The surface hardness was determined in accordance with ASTM D2240 [21] using a PCE durometer Shore A. The durometer has a pin at the end which when pressed against the plaster indicates the penetration strength. The surface hardness by durometer was determined on the brick specimens and corresponds to the average of 12 measurements in different plaster areas.

2.3.6. Sorption and desorption

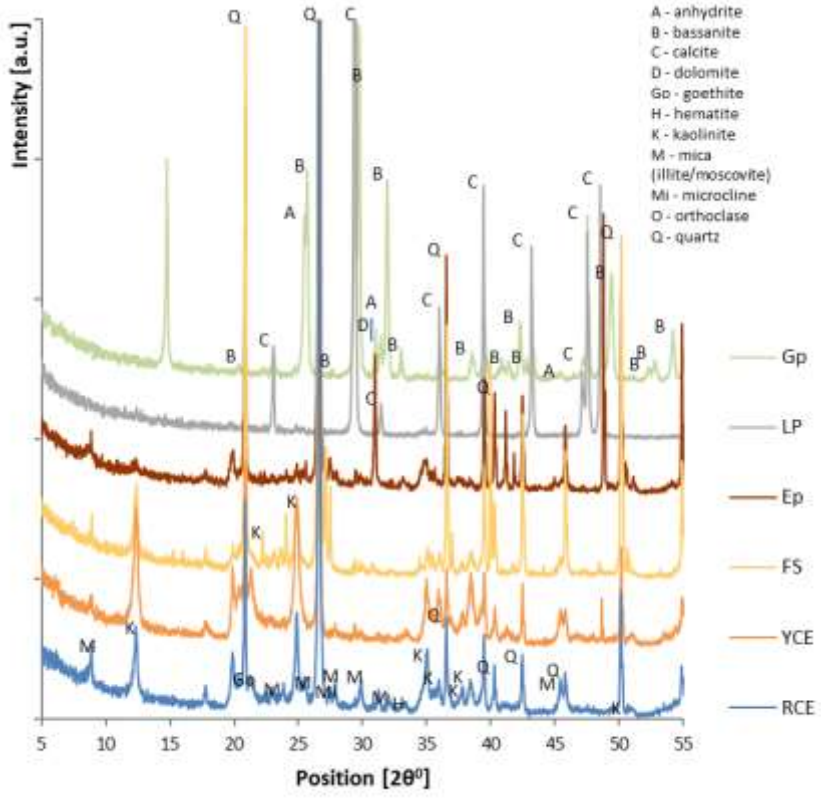
The sorption capacity was determined in accordance with DIN 18947 [17], with some complements. The specimens were placed, until constant mass (less than 2 % of variation), in a climatic chamber at 23 ºC and 50 % RH. Then the specimens were exposed to 80 % RH maintaining the temperature at 23 ºC. The water vapor gain by the plaster (in g/m^2) was determined by weighing the specimens after 1, 3, 6, 12 and 24 hours. According to DIN 18947 [17] the test must end at 12 hours. However, in the present study, the test was extended until 24 hours in order to better understand the sorption behavior of the plasters, as has already been done by some authors [6,22,23].

For determination of the desorption capacity the reverse process was used. The RH inside the climatic chamber was decreased to 50 %, evaluating the decrease of water vapor content of the plasters (in g/m^2); at the same defined periods of time (from 1 up to 24 hours).

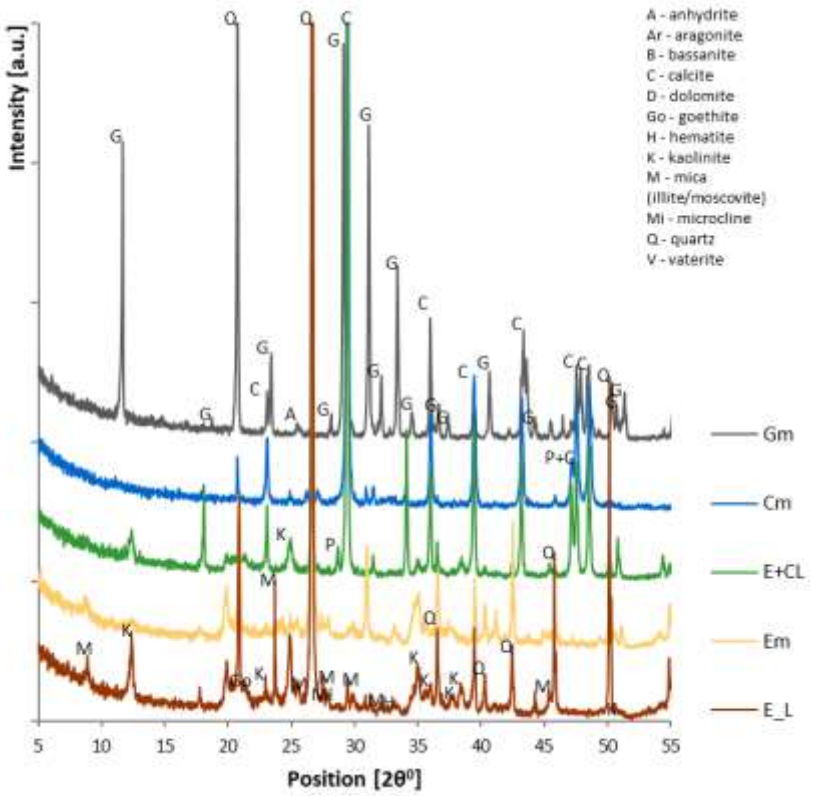
3. Results and discussion

3.1. XRD and TGA/DSC

Figure 3a shows the mineralogical composition of the raw materials used in mortars preparation.



a)



b)

Figure 3. Mineralogical composition of the samples: a) RCE, YCE, LP, FS, Gp and Ep raw materials; b) Em, E_L, E+CL, Cm and Gm mortars.

RCE sample is mainly composed by quartz, residual kaolinite and illite, and vestigial goethite, microcline hematite and calcite. YCE presents a similar composition with the referred RCE sample, without microcline. LP shows calcite as principal phase, as expected, and quartz as vestigial. FS is fundamentally composed by quartz, as expected, with minor quantities of orthoclase and microcline, residual kaolinite and vestigial illite/moscovite. The compounds presented in Gp sample are bassanite and calcite as main phases, anhydrite as minor, quartz and dolomite as vestigial. Ep product show quartz as main mineral, dolomite and illite as minor, kaolinite, hematite, microcline and calcite as vestigial minerals.

The mineralogical composition of the studied mortars is presented in Figure 3b. Em mortar presents a similar composition with the Ep, being mainly composed by quartz, dolomite and illite as residual, kaolinite, microcline and hematite as vestigial minerals. E_L mortar presents quartz as main mineral, kaolinite and illite as residual, and dolomite, microcline, goethite and hematite as vestigial minerals. E+CL mortar shows major calcite, minor quartz and portlandite, residual kaolinite and vestigial goethite. The cement-based mortar (Cm) presents calcite as main phase, gypsum as vestigial, and portlandite, quartz, vaterite and aragonite as vestigial phases. The gypsum-based mortar (Gm) is mainly composed by gypsum, as expected, calcite as minor, and bassanite, anhydrite and quartz as vestigial minerals.

The TGA curves of the raw materials and the mortars are presented in Figure 4.

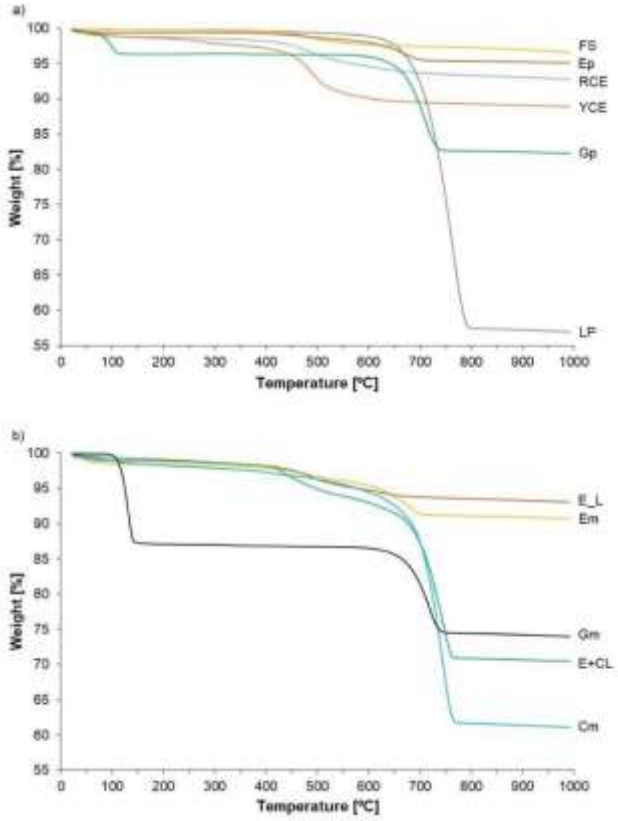


Figure 4. TGA of the samples: a) RCE, YCE, LP, FS, Gp and Ep raw materials; b) E_L, Em, E+CL, Cm and Gm mortars.

The samples RCE and YCE show a similar decomposition pattern. In both samples it is observed a slight weigh loss ~285 ºC (for RCE) and ~277 ºC (for YCE) that can be assigned to the dehydration of illite. The most expressive weight loss with the correspondent endothermic reaction, occurs between ~400 ºC and ~650 ºC (for RCE) and between ~400 ºC and ~700 ºC (for YCE) with values of 7.7 %wt. and 4.5 %wt., respectively. This weight loss is mainly related with the dehydroxylation of kaolinite. To the end of the test, it is noted a slight weight loss of 0.6 %wt. (for RCE) and 0.9 %wt. (for YCE) that could be ascribed to the complete decomposition of illite and eventually to the formation of high temperature phases.

The LP sample clearly presents the thermal decomposition of calcium carbonate with the release of CO_2, between ~600 ºC and ~800 ºC (maximum at ~768 ºC), with a weight loss of 41.1%wt and the corresponded intense endothermic reaction.

The thermal decomposition of Gp sample occurs in two steps: the first, up to ~115 ºC, with a weight loss of 3.2 %wt., related with the dehydration of bassanite and eventually moisture; and the second one from ~600 ºC to ~750 ºC (maximum at ~712 ºC), with a weight loss of 13.2 %wt., that could be associated with the decomposition of calcite and some dolomite.

The FS sample show, from ~300 ºC to the end of the test, lower weight loss of 3.2 %wt. that is mainly related with the decomposition of kaolinite and illite.

The Ep product and Em mortar presents similar behavior, as expected, with an incipient weight loss, from ~300 ºC to ~580 ºC (for Ep) and from ~300 ºC to ~560 ºC (for Em), that could be due mainly to the dehydration of kaolinite and a noted weight loss of 4.5 %wt. from ~580 ºC to ~720 ºC for Ep and of 4.3 %wt., from ~560 ºC to ~715 ºC for E mortar, respectively, that can be associated essentially to the decomposition of dolomite.

E+CL sample show a thermal decomposition is two main steps: the first, not well resolved, from ~400 ºC to ~600 ºC, with a weight loss of 5.4 %wt., that is related the decomposition of kaolinite and portlandite; and the second well resolved step, from ~600 ºC to ~775 ºC (maximum at ~746 ºC), with a weight loss of 21.9 %wt., associated to the decomposition of calcite.

The Gm mortar presents a thermal decomposition in two distinct steps, similarly to the Gp raw product. The first one, from ~100 ºC to ~160 ºC, with a weight loss of 12.5 %wt., assigned to the decomposition of gypsum and bassanite and the second step, between ~600 ºC and ~760 ºC, with 21.9 %wt. of weight loss, connected with the decomposition of calcite.

Finally, the Cm sample presents an incipient step up to ~115 ºC, ascribed to the decomposition of some hydrated compounds and a wide thermal decomposition step, beginning ~375 ºC and ending ~780 ºC (maximum at ~749 ºC), with a weight loss of 35.8 %wt., associated to the decomposition of calcium carbonate polymorphs and portlandite. All the mineralogical phases referred were identified by XRD (Figure 4a and Figure 4b).

3.2. Linear shrinkage

Table 2 presents the linear shrinkage results (average and standard deviation). It is possible to conclude that unstabilized earth mortars E_L and Em present very low linear shrinkage. This can be justified for the low swelling of the clayish earth used namely, illite (present in E_L and Em) and kaolinite (present in E_L). Kaolinites and illites minerals have linear drying shrinkage on the rage of 3–11 % [24]. However, all mortars analyzed in the present study present lower linear drying shrinkage. The E+CL mortar, despite containing kaolinite minerals, presents higher linear shrinkage. This result can be due to the use of air lime, which shrinks during the carbonation. All the earth mortars present linear shrinkage below 3 % in accordance with the DIN 18947 [17] and the New Zealand standard [25]. According Röhlen and Ziegert [26] the shrinkage of earth and cement mortars can be 0.5 % and 0.09 %, respectively, nevertheless shrinkage in earth mortar should not be more than 2 %. This value depends on the type of clay used for earth mortars. In the present study, all mortars are within the requirements (Table 2), including the Gm mortar.

The cement and gypsum mortars (Cm and Gm, respectively) present low linear shrinkage, similar to the unstabilized earth mortars.

3.3. Dry bulk density, dynamic modulus of elasticity and flexural and compressive strength

Figure 5 reports the dry bulk density, dynamic modulus of elasticity (Ed), the flexural (FStr) and compressive (CStr) strengths results (average and standard deviation). It should be remembered that mechanical characterization tests in E+CL mortar were performed after 4.5 months – more than twice the time for the remaining mortars (Table 3) – to assure the lime carbonation.

Observing Figure 5, it is possible to conclude that earthen mortars (E_L, Em and E+CL) present similar dry bulk density (1.77–1.82 kg/dm^3). The cement mortar (Cm) presents similar bulk density (1.79 kg/dm^3) to earth mortars and the gypsum mortar (Gm) presents lower values (1.22 kg/dm^3). E_L and Em mortars can be classified as class 2.0 by DIN 18947 [17]. Although not applicable because the DIN standard is only for unstabilized earth plasters, E+CL mortar would be classified as class 1.8 by the same standard [17].

The dry bulk density of each mortar can be justified by the loose bulk density of each constituent material (Table 1): all raw materials and pre-mixed mortar products present similar loose bulk density; the gypsum-based pre-mixed product is the exception, which has the lowest loose bulk density and, consequently, the Gm mortar presents the lowest dry bulk density. Cm mortar meets the dry bulk density defined by the pre-mixed product technical file, considering standard deviation (Table 1). Slight differences in dry bulk density can be due to the compaction of the specimens.

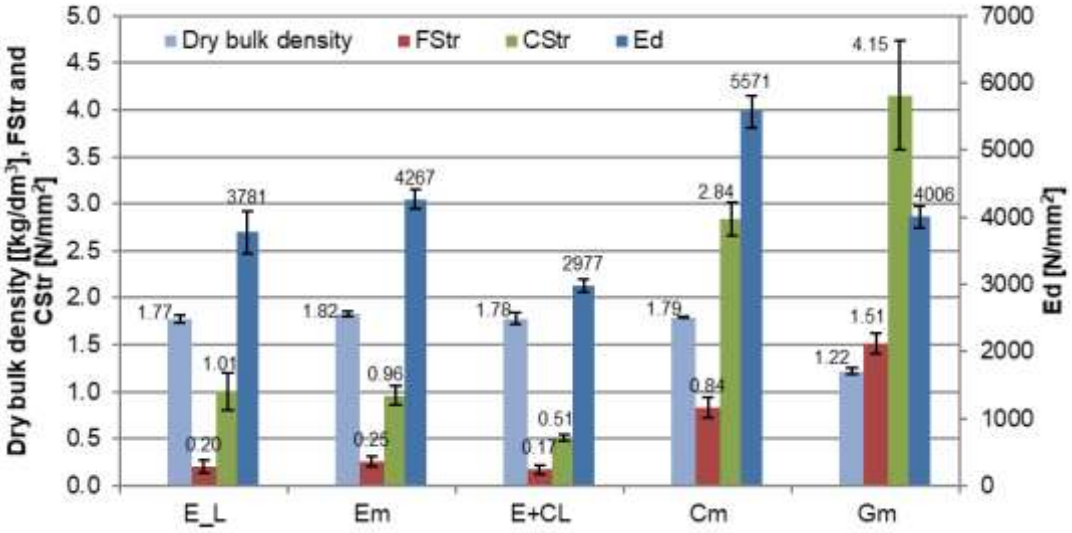


Figure 5. Dry bulk density, flexural (FStr), compressive (CStr) strengths and dynamic modulus of elasticity (Ed) of the mortars.

Dry bulk density of earth mortars is in the range of 1400 – 1800 kg/m^3, according to Röhlen and Ziegert [26]. This is confirmed by the earth mortars analyzed in the present study.

By Figure 5 it can be concluded that the E+CL mortar presents the lower strengths. In this case, this means that the addition of air lime does not improve the mechanical strength of the earth mortar. This can be due to incomplete carbonation, as XRD has showed before. Similar results were obtained in previous studies of the authors.

According to Houben and Guillaud [24], compressive strength tends to increase with aging of earth-lime mortars and values of 2–5 N/mm^2 can easily obtained. The researchers refer that the optimum proportion of lime should be determined and for lime addition of 2–6 % the compressive strength tends to rise and for higher additions tends to fall. In the present study, since the E+CL mortar is a pre-mixed mortar, the percentage of lime added is not known, so it is not possible to conclude on the effect of the lime percentage on the mortar compressive strength.

Walker and Australia [27] refer that air lime stabilization improve dimensional stability and increase strength and that 3–12 % (by mass) of air lime should be added to dry clayish earth. Despite this affirmation, it was verified in the present study that air lime stabilization of the E+CL mortar did not seem to improve the dimensional stability or increase strength in comparison to other unstabilized earth mortars. Different percentages of added air lime could justify this condition, once, as mentioned previously, the air lime content of E+CL mortar is not known.

However, Santos et al. [28] concluded that the addition of 5 % of air lime in an earth mortar (after 60 days) also decreased its mechanical strength. Gomes et al. [29] obtained similar results with air lime additions up to 15 % (after 90 days). According to these studies lime interrupts the clay matrix connection, without creating an air lime network strong enough to replace those clay connections.

Röhlen and Ziegert [26] refer that a value of 1–3 N/mm^2 and 3 N/mm^2 of CStr is more typical for earth mortars and gypsum plaster mortars, respectively. E_L and Em mortars present 1 N/mm^2 of CStr, approximately, and meet this value. E+CL does not meet this value, probably due to the weak lime network (according to the timeline of testing performed). Gm mortar presents higher CStr. For earth materials, the same authors [26] refers that Ed typically lies in the range of 450–3000 N/mm^2. All earth mortars present higher Ed, except E+CL mortar that presents 2977 N/mm^2.

For plastering mortars, the EN 998-1 [30] defines different classes for compressive strength, at 28 days: CS I for 0.4–2.5 N/mm^2; CS II for 1.5–5.0 N/mm^2; CS III for 3.5–7.5 N/mm^2 and CS IV for ≥ 6 N/mm^2. The earth mortars analyzed in the present study can be classified as CS I class, the cement mortar as CS II, although all the mortars were not tested at 28 days. This proves that these mortars meet the requirements of mortars for interior and exterior plasters. According to Röhlen

and Ziegert [26] earth plasters should be made with earth mortars of compressive strength mortar class CS II.

The German Lehmbau Regeln [31] refer that earth mortars must have a compressive strength above 0.5 MPa when applied in secondary spaces (test according to EN 1015-11 [20]). It is possible to conclude that all the earth mortars of the present study fall within the regulated.

Cm meets the CSII class of compressive strength (according by EN 998-1 [30], CStr of 1.5–5.0 N/mm^2), defined by the pre-mixed product technical file (Table 1). As expected, the earthen mortars (E_L, Em and E+CL) present lower mechanical strengths (Ed, FStr and CStr) when compared to Cm and Gm mortars, except for Em mortar in Ed result. This conclusion is not entirely negative if we want to apply mortars on supports with low mechanical properties. Mortars must not exceed the mechanical characteristics of the support to which they are applied, must be compatible, ensuring long-term compatibility between the mortar and the support. Otherwise, there may be premature anomalies and mortar detachment due to lack of compatibility with the substrate. Veiga et al. [32] defined general requirements for plastering mortars for application on old buildings concerning some characteristics of mortars: Ed of 2000–5000 N/mm^2; FStr of 0.2–0.7 N/mm^2; CStr of 0.4–2.5 N/mm^2. Unlike cement and gypsum mortar, earth mortars meet the flexural and compressive strength requirements and can be applied to repair old buildings. Regarding the dynamic modulus of elasticity, only the cement mortar (Cm) with 5587 MPa does not meet the limit defined by Veiga et al. [32] nevertheless is not far.

Gm mortar meets the FStr (> 1 N/mm^2) and CStr (> 2 N/mm^2) defined by pre-mixed product technical file (Table 1). The EN 13279 [33] defines that gypsum plasters must meet at least a flexural strength of 1–2 N/mm^2 and a compressive strength of 2–6 N/mm^2; the Gm mortar is in that ranges.

Santos et al. [28] analyzed a pre-mixed earth mortar similar with the Em mortar, produced by the same producer, with dry bulk density of 1.54 kg/dm^3 and water content of 20 %, and obtained dynamic modulus of elasticity of 4331 N/mm^2, flexural strength of 0.24 N/mm^2 and compressive strength of 0.55 N/mm^2. In the present study, the Em mortar presents lower Ed, similar FStr and higher CStr. A decrease of the water content of the mortars may lead to the increase of compressive strength.

3.4. Dry abrasion resistance

The mass loss of the surface by dry abrasion (average and standard deviation) can be observed in Figure 6.

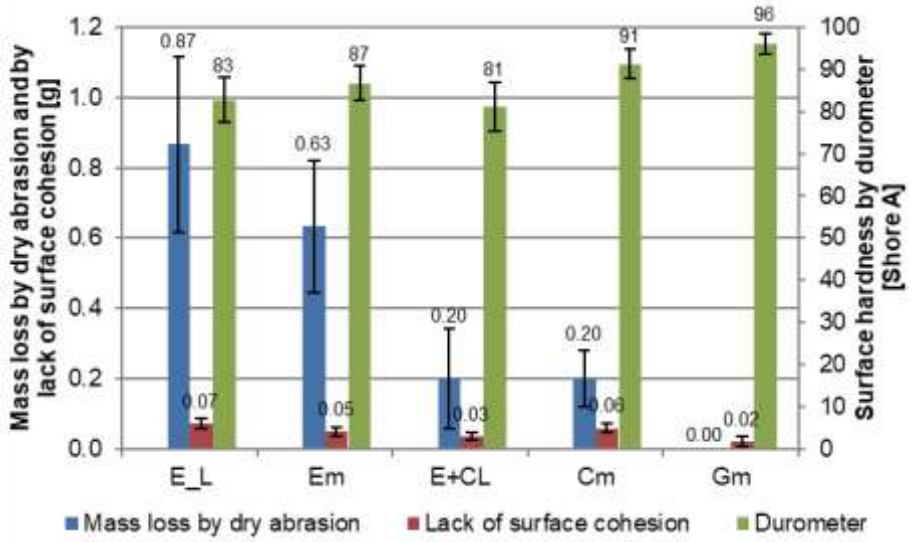


Figure 6. Mass loss by dry abrasion and by lack of surface cohesion, and surface hardness by durometer of the plasters.

Observing the Figure 6 and analyzing only the earth plasters, is possible to observe that E_L plaster presents the higher mass loss by dry abrasion (0.87 g), consequently, the lower dry

abrasion resistance. This result can be justified by the presence of higher content of coarse sand. The use of fine sand and the addition of fibers in the Em plaster, as well as the addition of air lime in the E+CL plaster can promote a decrease of mass loss by dry abrasion in comparison with the E_L plaster, assuring a better bond between the mortar constituent particles.

The Cm and E+CL plasters present the same mass loss by dry abrasion. The Gm plaster presents excellent resistance to dry abrasion because no mass was lost.

Faria et al. [34] analyzed by the same method a pre-mixed earth mortar similar to the Em plaster and obtained a much higher mass loss by dry abrasion of 4.5 g. In fact, all mortars analyzed in the present study present a lower mass loss by dry abrasion, consequently these plasters present a better dry abrasion resistance, what was already expected for the hydraulic plasters but not for the earth plasters.

3.5. Surface cohesion and surface hardness by durometer

Figure 6 presents the loss of surface cohesion of mortars (average and standard deviation).

All plasters analyzed in the present study show similar mass loss on the surface cohesion test (0.02–0.07 g); due to this condition there is a similar lack of surface cohesion. However, some variation occurred. The E_L plaster presents higher mass loss on the surface (0.07 g) and, consequently, lower surface cohesion. The Em plaster shows slightly lower mass loss (0.05 g) than the E_L plaster: this can be due to the addition of fibers. The earth plaster with air lime presents reduced mass loss (0.03 g) relatively to unstabilized earth mortars and, consequently, an increase of the surface cohesion: this can be justified by the air lime. The Cm plaster presents similar mass loss (0.06 g) in comparison to the E_L plaster. The Gm plaster presents the lower mass loss (0.02 g) and, consequently, the best surface cohesion.

Santos et al. [35] analyzed a pre-mixed earth mortar, similar to the Em mortar, applied in different supports and in external and laboratory conditions. The results show mass loss by surface cohesion of 0.08 g and 0.10 g for earth mortar applied on the brick in external and laboratory conditions, respectively. The earthen plasters analyzed in the present study present lower mass loss by surface cohesion. These results can be due to the good surface cohesion of common gypsum and cement-based plasters, but for the earthen plasters these can be due to a still short aging and to indoor environment. In another study, Santos et al. [36] analyzed earth-based renders with a washed siliceous sand with volumetric ratio of 1:2 (clayish earth:sand) with low addition of air lime CL (5–8 %, approximately), applied outdoors, and obtained mass loss of surface cohesion of 0.5 g. E+CL plaster, as well as the other plasters analyzed in the present study, presents lower mass loss of surface cohesion. These results may be due to the fact that in Santos et al. [36] the plasters were applied and aged outdoors, while the plasters of the present study were analyzed under laboratory conditions, without natural aging.

Drdácky et al. [37] analyzed air lime mortars, by a similar method but using a plastic tape with 25 mm x 160 mm, and obtained mass loss by surface cohesion of 0.017–0.020 g. All plasters analyzed in the present study present higher mass loss by surface cohesion, except the Gm mortar that presents surface mass loss in the same range. However, the values obtained in this study do not exceed 0.07 ± 0.01 g.

The surface hardness by durometer (average and standard deviation) can be observed in Figure 6. It is possible to conclude that earthen plasters (Em, E_L and E+CL) present similar surface hardness by durometer. The plasters with common binders (Cm and Gm) present slightly higher surface hardness than earthen plasters.

Santos et al. [35] analyzing a pre-mixed earth mortar, similar to the Em plaster and produced by the same company, obtained a surface hardness by durometer about 80 Shore A for the earth plaster applied on brick in laboratory conditions. Comparing with Em mortar, and considering the standard deviation of the results obtained, in the present study the values are slightly above. These results may be justified by a slight change in the mortar formulation made by the producer and of which the authors are unaware. The E_L mortar presents surface hardness slightly above and E+CL mortar presents similar surface hardness when comparing with Santos et al. [35]. The different type of clayish earth and the presence of coarse sand can justify the higher surface

hardness of E_L mortar: kaolinites has high dry strengths than illites [24]. In another study, Santos et al. [36] obtained surface hardness by durometer of 50 Shore A for an earth-based plaster with air lime. E+CL plaster presents higher surface hardness and this may be related, once again, to the fact that Santos et al. [36] mortars were applied and aged outdoors.

3.6. Sorption and desorption

Figure 7 presents the average curves of sorption and desorption of the plasters and the limits of sorption classes (WSI, WSII and WSIII) defined by DIN 18947 [17]: WSI for sorption ≥ 35 g/m^2; WSII for ≥ 47.5 g/m^2 and WSIII ≥ 60 g/m^2, after 12 hours.

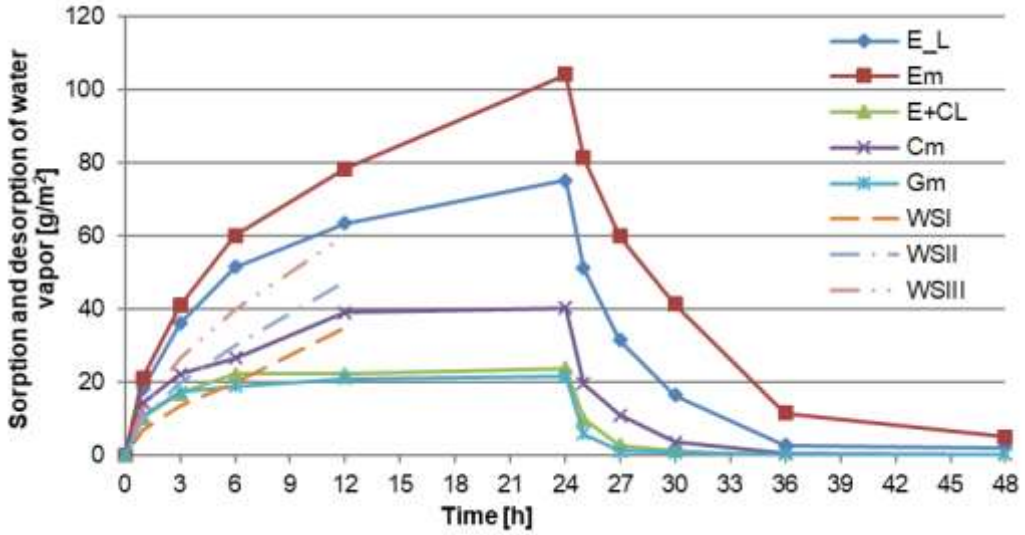


Figure 7. Sorption and desorption curves and sorption limits (WSI, WSII and WSIII) defined by DIN 18947 [17].

Analyzing the results, it is possible to conclude that both unstabilized earth plasters Em and E_L present significantly higher sorption and desorption capacity in comparison to all the plasters with common binders. The Em and E_L plasters present the higher sorption (≥ 60 g/m^2) after 12 hours and can be classified in WSIII class, by DIN 18947 [17]. After 24 hours, the Em and E_L plasters adsorbed about 104 g/m^2 and 76 g/m^2 water vapor, respectively. It is possible to conclude that the Em and E_L plasters could adsorb higher amount of water vapor since the sorption curves still show a growing trend at 24 hours (Figure 7). The high sorption capacity demonstrated by these plasters may be related to the main type of clay (illite) present in these plasters (Figure 3b): E_L and Em are characterized by a significant water vapor absorption capacity, promoted by illite mineral [6]. The natural fibers can be responsible for the higher sorption capacity of the Em plaster [38]. However, natural fibers enhance the growth of mould [39]. To avoid the proliferation of mould adequate drying must be ensure, promoting ventilation to avoid extended conditions of high relative humidity. However, a study conducted by Röhlen [40] found that all mortars show the presence of fungi (with or without fibers). Fungi can also occur when the environment presents high levels of humidity.

The low hygroscopicity of E+CL plaster may be due to the air lime (Figure 7). After 24 hours, the E+CL plaster only absorbed about 24 g/m^2. The low water vapor sorption capacity of this plaster also may be related to the higher content of kaolinitic clay presented in this sample (Figure 3b), because kaolinite mineral present poor surface adsorption. The addition of air lime also promoted a decrease of hygroscopicity of this mortar because the binder seems to block the clay structure, inhibiting the hygroscopic characteristics of the clay, thus creating a new structure in which the behavior of the mixture becomes representative of the binder and not of clay [41]. The E+CL plaster is impossible to classify by DIN 18947 [17] since at 12 hours this plaster presents a sorption lower than the limit for the lower class (WSI ≥ 35 g/m^2); nevertheless, the standard is only for unstabilized earth plasters. The E+CL plaster presents stable adsorption behavior after 6 hours of testing, unlike the Em and E_L plasters without mineral binders. This behavior demonstrated that the air lime contributes to block the hygroscopic behavior of the clayish particles. As happened

with mechanical strength, the air lime structure most probably interrupts the clay matrix connection.

The Cm and Gm plasters present lower sorption capacity in comparison with the unstabilized earth plasters, Em and E_L. The Cm plaster absorbed about 40 g/m^2, higher than the E+CL plaster sorption. The Gm plaster absorbed about 22 g/m^2 and present similar (and the lowest) sorption behavior to the E+CL plaster.

Relative to desorption, all plasters present a good behavior, having desorbed almost the entire water vapor that had been adsorbed. The unstabilized earth plasters (Em and E_L) desorb little less water vapor than they adsorbed, after 24 hours: they show a downward trend and for this reason they would probably reach the same initial values if the test continues for a longer period. The E+CL, Cm and Gm plasters desabsorb all the water vapor they had adsorbed in a similar period of time: after performing the desorption these plasters present similar water vapor content in relation to 0 hours.

Minke [3,42] analyzed the sorption capacity of different materials with 15 mm of thickness for 48 hours, at 21 ºC, raising the relative humidity from 50 to 80 %, and conclude that the clayish earth (undefined) sorption was about 300 g/m^2 (and about 200 g/m^2 after 24 hours). For lime-cement and gypsum plasters the sorption was only about 75 g/m^2 and 40 g/m^2 after 48 hours (and about 40 and 30 g/m^2 after 24 hours), respectively. In the present study, after 24 hours, E_L and Em plasters present lower water vapor sorption, Cm plaster presents similar water vapor sorption to lime-cement plaster analyzed by Minke [3,42] and the others plasters have lower values. In another study, Maskell et al. [9] evaluating the sorption and desorption capacity of a clayish earth plaster, an air lime plaster and a gypsum plaster, at 23 ºC, for relative humidity from 50 to 75 %, obtained a sorption of 30, 15 and 10 g/m^2, respectively, after 12 hours. In the present study, after 12 hours, the earthen and gypsum plasters present higher water vapor sorption. The variation of results obtained in the present study in comparison to others researchers [3,9,42] can be justified by the different types of clay minerals and formulation of the plasters, as well as the different environmental conditions namely relative humidity.

The hygroscopicity results obtained by the different plasters analyzed confirmed the ability of the clayish earth plasters to absorb and desorb humidity faster and to a greater extent than other building materials, as cement or gypsum plasters, as noted by other researchers [3,43]. This ability of earth plasters contributes to create a healthy environment inside buildings, through the passive moderated regulation of relative humidity of indoor air, reducing the peak of high moisture promoted by cooking and washing or the low moisture associated with central heating of buildings [43]. This regulation of relative humidity occurs in a similar manner to heat storage by thermal mass, i.e., reducing the moisture flux that the buildings have to deal with. It is very important for occupants' comfort and health that the relative humidity inside the buildings is kept between 40 and 70 %. These range of relative humidity has positive consequences because it reduces the fine dust content in the air, activates the protection mechanisms of the skin against microbes, reduces the life of many bacteria and viruses and reduces odor and static charge on the surfaces of objects in the room [3,42]. Relative humidity below 40 % for long periods of time can dry the mucous membranes of people, which can decrease its resistance to colds and related diseases. Relative humidity more than 70 % promoted discomfort, increase of rheumatic pains, fungus formation in closed rooms that, in large quantities, can lead to various kinds of pain and allergies. The regulation of relative humidity in a relatively low range in winter in Mediterranean countries, without continuous heating, also contributes to improve the thermal comfort inside those buildings. For the same total moisture, temperature increases when relative humidity decreases, as can be easily seen through the analysis of a psychrometric diagram [44]. On the contrary, a high relative humidity increases the thermal conductivity of the air and restricts evaporation by the skin, increasing the sensation of discomfort [44].

The porosity of clayish earth allows it to absorb indoor air pollutants, although the mechanism is not well known. Minke [3] and Morton [43] refer that the clayish earth can absorb and bind pollutants dissolved in water. This can be related with hygroscopic capacity of earth plasters: the pollutants dissolve in water/water vapor that is absorbed by the plasters. Nevertheless, this aspect was not assessed in the present study and requires further research.

In addition to the advantages of earthen plasters for the indoor environment of buildings, it is also important to remember that the clayish earth is a natural building material, with lower CO_2 emissions and embodied energy, which are important factors for the sustainability of the building.

4. Conclusions

With the current problems and climate change worldwide, the concern and interest of the scientific community in eco-efficient building materials is increasing. The indoor air quality of buildings is also extremely important and, therefore, it is paramount to be aware of the influence building materials have on the health and comfort of inhabitants. Plasters may have a significant area indoors and, apart from aspects that contribute to a healthy indoor environment, they must fulfil plasters requirements. Therefore, this paper aims to help answering some of these aspects, trying to quantify not only general requirements of plasters but also possible improvements that may be beneficial to indoor comfort presented by different types of earth plasters compared to other plasters commonly used in Portugal, based on gypsum and cement mortars.

This paper presents a comparison of the mineralogical, mechanical and hygroscopic characteristics of these mortars:

- The clayish fraction in the studied earth mortars contain illite and kaolinite minerals, being illite the dominant in Em, and kaolinite in E_L and E+CL mortars. As expected, the mineralogical composition of Cm and Gm mortars, based on cement and gypsum respectively, reflects the binder composition.
- All mortars (earth and hydraulic mortars) present similar and acceptable linear shrinkage, except the earth mortar with addition of air lime that presented higher linear shrinkage, but far below regulatory limits.
- As expected, earth mortars present lower mechanical strength when compared to mortars with current mineral binders (cement and gypsum). The addition of air lime decreases their mechanical strength.
- Earth plasters presents slightly lower surface hardness than current cement and gypsum plasters. However, the addition of fibers promotes a slight increase on this characteristic in the earth plasters. Therefore, the addition of fibers and air lime to earth plasters seem to promote an increase in the resistance to dry abrasion and a higher surface cohesion. Natural fibers enhance the growth of mould – care should be taken when using fibers if proper ventilation is not considered or if the relative humidity in the environment is too high.
- Unstabilized earth plasters present, in comparison to the other plasters, a high capacity of sorption and desorption, validating their ability to regulate indoor RH. Therefore, when applied on indoor walls and ceilings, the contribution of unstabilized earth plasters to indoor comfort can be significantly important, acting as a passive hygrothermal buffer system.

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