Eco-efficient Earth Plasters: Influence of Clay Content, Sand Particle Size, and Support

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Abstract: Earth construction, including the use of earth mortars, has been extensively used in the past. However, with the appearance of hydraulic binders, the use of earth strongly decreased for new construction and even to repair old earth buildings, whose best solution would be the use of compatible materials such as earth mortars. Due to the innumerable advantages of earth and with the growing concern on eco-efficient construction, the interest on earth construction has resurfaced, namely on earth mortars. To optimize the composition of an earth plastering mortar made with a defined clayish earth and two siliceous sands with different particle sizes, six compositions were assessed. Mortars with different volumetric ratios were applied in two different supports (on the back of a tile and on a brick) and planar specimens were also produced. Distinct characteristics were assessed, such as their visual appearance, shrinkage, surface cohesion, surface hardness, dry abrasion resistance, ultrasonic velocity, adhesive strength, and thermal conductivity. It is possible to conclude that a higher clay content in the earth mortar composition increases the shrinkage and occurrence of cracking, the use of fine sand promotes high mass loss by abrasion, and the same mortar applied in different supports behaves differently in terms of durability.

Keywords: clayish earth; formulation; mortar; optimization; shrinkage; non-destructive test

0 Introduction

Building techniques that use earth as construction material have been used since prehistoric time[1]. This type of construction encapsulates several and varied forms of techniques and applications. Earth mortars are one of those applications. They can be applied as masonry mortars, namely to produce mortar joints, as repair mortars for earth-based monolithic walls such as cob or rammed earth walls, and as plastering mortars for protection of walls and ceilings. Earth plasters played an important role in the past and can be found in important buildings such as noble residences, public buildings, churches, and monasteries[2]. With the recent interest in sustainable and ecological construction, earth plasters have promoted the interest of the owners, contractors, builders, and scientific community. Thus, earth plasters are nowadays becoming recognized as highly eco-efficient[3,4].

Earth plasters present many advantages, due to the characteristics of the earth: It is natural, non-toxic, reusable, and recyclable – although not renewable – with low emissions of CO_2 and low embodied energy. Frequently, it can even be extracted from building sites, reducing costs, and energy for transportation and production[5]. Melià *et al*.[6] concluded that earth plasters have a low environmental impact through a life-cycle assessment as compared to other plasters based on current binders. This conclusion also confirms the sustainability of earth plasters.

Due to the hygroscopic capacities of clay, earthen plasters can also contribute to indoor comfort of inhabitants, since they can contribute to regulate indoor

relative humidity, due to its capacity to adsorb and release moisture[7-13].

Earth as a building material is composed of different contents of clay, silt, sand, and gravel, with different particle size distribution and types of minerals. To produce earth plastering mortars, the gravel needs to be removed from the earth, acting the clay as a binder. A high content of clay promotes a greater resistance of the mortar; however, it increases shrinkage. Therefore, if the content of clay is too high, the addition of supplementary sand is necessary. Not only the percentage but also the type of clay varies considerably the characteristics of the mortars, unlike standardized building materials. Clays that are dimensionally more stable (do not present great volumetric variation when in the presence of water) are more adequate for plastering. An earth plaster is considered acceptable when, after drying, there are no visible cracks and good adhesive strength (AStr) to the support[14].

In recent times, several authors have conducted some studies on earth-based mortars. Table 1 summarizes some of these studies and the main results.

The aim of the present study is to preliminary evaluate the influence of the mortars formulation – using a clay, fine, and coarse sands – in an attempt to determine the best behavior to avoid shrinkage and cracking of the plaster, achieving the optimum formulation. Therefore, mortars were applied in two different supports (on the back of a tile and on a ceramic hollow brick). Visual color and cracking assessment, shrinkage, AStr, dry abrasion resistance, surface hardness, ultrasound pulse velocity, and thermal conductivity were the characteristics assessed. For this purpose, six mortars were formulated under laboratory conditions with different volumetric ratios.

1 Materials and methods

1.1 Characterization of materials

Six earth-based mortars were analyzed in the present study with different proportions of a clayish earth and two types of siliceous sand (fine and coarse sand) [Figure 1].

The clayish earth was provided by Cerâmica Torreense Company and was previously disaggregated to eliminate big clods. Both of the fine and coarse siliceous sands were commercialized by Areipor Company.

The clayish earth and the two sands were characterized by loose bulk density, taking an average of three specimens of each material, based on EN 1097-3[23]. Particle size distribution was performed, according to EN 1015-1[24], by wet method for the clayish earth and dry method for both the sands. The sedimentation test was also analysed, according to LNEC specification E196[25], to complement the particle size distribution of the clayish earth because it presents particles lower than 0.075 mm. The results are presented in Table 2 and Figure 2, respectively.

The fire behavior classes for these building materials – clayish earth and sands – were determined based on DIN EN 4102-1[26] and EN 998-1[27]. All mortars were classified as non-inflammable, Class A by DIN EN 4102-1[26] and Class A1 by EN 998-1[27], since they do not contain organic material.

1.2 Mortar preparation and specimens

The earth-based mortars were produced with different volumetric ratios of clayish earth: fine sand: coarse sand (Cl: FS:CS) [Table 3]. All the mortars present in their formulations fine sand, but coarse sand only appears in some of them, as it is shown in Table 3. The water content (as a percentage of the total dry components) used in each earth mortar is also presented in Table 3. The final particle size distribution of the six mortar dry components is shown in Figure 2.

The first four volumetric ratios of the earth mortars (1:2:0, 1:1:1, 1:3:0, and 1:1.5:1.5) were initially defined to evaluate the shrinkage and cracking occurrence. Each pair of formulations has the same earth: sand ratio (1:2 and 1:3), differing the second formulation from the first just by having a mix of both sands. The sand mixture aims to reduce the porosity but was important to observe the mortars behavior when applied on the support. Some cracks were observed in these four compositions; therefore, it was decided to increase the amount of sand, and two more volumetric ratios were defined with earth: sand ratios of 1:4, with higher content of fine sand (1:3:1) and 1:5, also maintaining the high content on fine sand (1:3:2).

The earth mortars were mixed in laboratory conditions, based on the method defined by DIN 18947[28] with some adjustments: The materials (clayish earth and
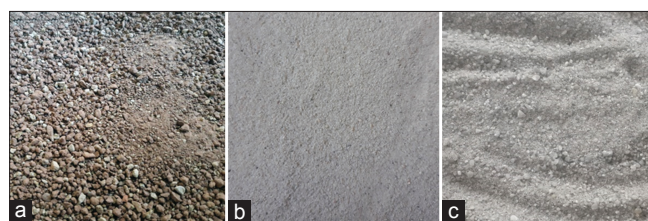

Figure 1. Clayish earth (a), fine (b), and coarse (c) sands

Table 1. Summary of some studies on earth-based mortars

Author	Mortar analyzed	Results
Gomes et al.[5]	Kaolinitic and illitic earth mortars with the addition of siliceous sand. Volumetric ratios 1:0, 1:1.5, and 1:3 (clay: sand). Earth mortars 1:3 were also analyzed with and without the addition of 5% of hemp fibers.	LS <1.5%; **VS** 0–4% (with and without fibers) - 300×300×30 mm specimens λ: 0.9–1.35 W/(m.K) – mortars without fibers; 0.78 W/(m.K) – mortar with fibers
Emiroğlu et al.[8]	Earth mortar with different clay: sand ratios with two different types of clay.	VS: 22 and 27% (high value obtained for different types of clay)–50×50×50 mm specimens
Lima et al.[9]	Illitic earth mortars, with different clayish earth; sand volumetric ratios (1:2, 1:2.5, 1:3, and 1:4) with a water content of 18 – 20% (in volume).	LS: 0.34–1.43% – 40×40×160 mm specimens λ: 1.00–1.25 W/(m.K) - being the lower thermal conductivity for mortars with lower clay content AStr: 0.07 N/mm^2
Delinière et al.[15]	Five earth mortars with different proportions of clay and sand (two ready-mixed and three formulated), with different types of clay (four with montmorillonite and illite and one with kaolinite) and with 17–20% of water content.	LS: 1.6–2.1% for ready-mixed earth mortars and 1.5–2.5% for formulated earth mortars – 40 mm×40 mm ×160 mm specimens AStr: 0.11–0.14 N/mm^2
Faria et al.[16]	An illitic ready-mixed earth mortar with fibers and water content of 20% (in volume).	LS: 0.21% – 40 mm×40 mm×160 mm specimens; 0.32% and 0.58% – 500×200×15 mm specimens Cohesion: 0.10 g Abrasion: 4.5 g – mortar applied on brick; 3.9 g – circular specimens λ: 0.9 W/(m.K) on different types of specimens, including specimens of mortar applied on hollow brick. AStr: 0.15 N/mm^2
Faria et al.[17]	An illitic ready-mixed earth mortar with fibers and water content of 20% (in volume), applied on different experimental external masonry walls and in laboratory conditions applied on bricks and circular specimens.	US velocity: 1350 m/s – mortar applied on brick in laboratory conditions λ: 0.9–1.3 W/(m.K) SH: 80 Shore A - mortar applied on brick in laboratory conditions
Lima and Faria[18]	Illitic earth mortars with volumetric ratio of 1:3 and addition of 10 and 20% of oat straw and 20, 40, and 80% of typha fiber-wool (in volume) with a water content of 19.6 – 25.6%.	LS: 0.85% for earth mortar without fibers and 0.13–0.62% for mortars with fibers – 40×40×160 mm specimens λ: 0.99–1.45 W/(m.K) – circular specimens AStr: 0.07–0.11 N/mm^2
Santos et al.[19]	Earth-based mortars with volumetric ratio of 1:3 (earth: unwashed sand) and 1:2 (earth: washed sand) without and with low addition of CL90 S and NHL3.5 (building limes classified by EN 459-1[20]).	Cohesion: 0.20–0.50 g SH: 69–79 Shore A – unstabilized mortars; 50–70 Shore A – stabilized mortars
Gomes et al.[21]	Earth mortars with volumetric ratio of 1:0 and 1:1.5 (with local earth) and 1:3 (with a reference earth). The earth mortar with 1:3 volumetric ratio was also analyzed with and without the addition of 5% of hemp fibers and/or addition of 5, 10. and 15% of CL90 S, HL5 (EN 459-1[20]), Portland cement. and natural cement.	LS: 0–2% – mortars with and without fibers and binders VS: 0–8% – mortars with and without fibers and binders
Faria et al.[22]	Mortars with 25% of the air lime replaced by kaolinitic earth (in volume) applied on brick in laboratory conditions and applied as plaster outdoors on an experimental rammed earth wall.	SH: 63 Shore A – mortars applied on brick; 70 Shore A – mortars applied on a rammed earth wall US velocity: 918 m/s – mortar applied on bricks; 775 m/s – mortar applied on a rammed earth wall λ: 0.43–0.52 W/(m.K)

LS: Linear shrinkage, VS: Volumetric shrinkage, λ: Thermal conductivity, AStr: Adhesive strength, SH: Surface hardness by durometer, Cohesion: Loss of surface material by cohesion, Abrasion: Loss of material by abrasion, US velocity: Ultrasonic pulse velocity

sands) were manually homogenized for 30 s; the water was placed on a mechanical mixer equipment followed by the homogenized material; the water and the materials were subjected to a mechanical mixing for 90 s; the mixing was suspended for 5 min, after which it was resumed for an additional period of 60 s.

To evaluate the influence of the formulation, the mortars were applied with 20 mm of thickness, with a previous

application of a clay suspension, on two different supports [Table 4]:

- On ceramic hollow bricks, with an area of 300 mm × 200 mm – one specimen of each type of mortar was produced;
- On the back of ceramic tiles, with an area of 450 mm × 212.5 mm – one specimen of each type of mortar was produced.

Ceramic hollow bricks are more porous than ceramic tiles.

Planar specimens were also produced in metallic molds, with the dimensions of 200 mm × 237.5 mm × 15 mm [Table 4]. One specimen was produced for each type of mortar.

The EM5 and EM6 mortars were not applied on the bricks since EM4 mortar already showed insignificant shrinkage and cracking, as well as good adhesion to the support. For this reason, it was decided to apply these mortars only on the tiles that needed more conditioning characteristics of the mortars due to their dimension. The EM4 mortar was not applied in the metallic mold
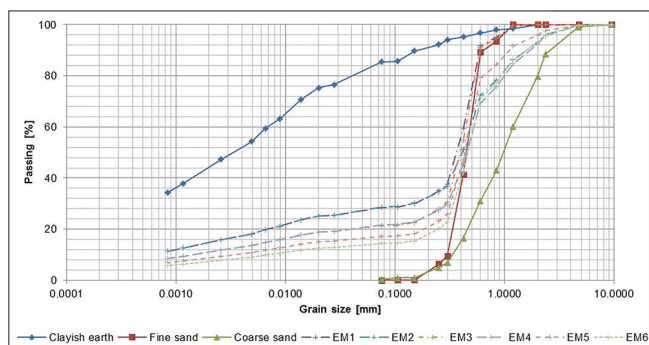
Figure 2. Dry particle size distribution of the materials (clayish earth by wet method and sands by dry method) and earth mortars

Table 2. Loose bulk density of the materials

Materials	Loose bulk density (kg/dm^3)
Clayish earth (Cl)	1.36±0.01
Fine sand (FS)	1.38±0.00
Coarse sand (CS)	1.61±0.00

since it presented a bad behavior on the tile in terms of cracking, although good behavior on the brick.

1.3 Methods

Characterization tests were performed after 28 days of drying of the all specimens, with laboratory conditions of 22 ± 2°C and 60 ± 5% of RH.

1.3.1 Visual analysis

The visual analysis of plastering mortars consists on the observation of characteristics such as color and/or their alteration, cracking, loss of adhesion (between mortar and support), and development of molds, which can be influenced by climatic or curing conditions. These characteristics were evaluated for earth mortars applied on the brick and on the tile through photographic capture of the surface of the mortars.

1.3.2 Shrinkage

The shrinkage of the plastering mortars was determined by the reduction of the size of the specimens in the metallic molds. For earth mortars, the DIN 18947[28] defines that the shrinkage must be determined by reduction of linear length of prismatic specimens of 40 mm × 40 mm × 160 mm and must be <3%. Gomes *et al.*[21] refered that linear shrinkage does not appear to be representative of total shrinkage; volumetric shrinkage presents a more sensitive and complementary parameter. However, normative documents only mention linear shrinkage. In the present study, the shrinkage was determined by reduction of linear length in the planar specimens of 200 mm × 237.5 mm × 15 mm, which was considered more representative. In addition to linear shrinkage, the volumetric shrinkage was also determined, evaluating the shrinkage in the three dimensions.

1.3.3 Surface cohesion

The bond strength between the particles of the materials that compose a mortar is described by the cohesion

Table 3. Volumetric and mass proportion of mortars and water content

Designation of the mortar	Volumetric proportion (Cl: FS: CS)	Mass proportions (Cl: FS: CS)	Water content (%)
EM1	1:2:0	1:2.03:0	20
EM2	1:1:1	1:1.01:1.18	20
EM3	1:3:0	1:3.04:0	18
EM4	1:1.5:1.5	1:1.52:1.78	18
EM5	1:3:1	1:3.04:1.61	20
EM6	1:3:2	1:3.04:2.3	20

Table 4. Specimens of each mortar

Mortar	On hollow bricks (200 mm×300 mm×20 mm)	On tiles (212.5 mm×450 mm×20 mm)	Planar specimens (200 mm×238 mm×15 mm)
EM1	✓	✓	✓
EM2	✓	✓	✓
EM3	✓	✓	✓
EM4	✓	✓	x
EM5	x	✓	✓
EM6	x	✓	✓

✓: Specimen was produced, x: No specimen was produced

between those materials. In general, earth plasters present a good cohesion[29].

The surface cohesion was determined on the plastering mortars, applied on the brick and tile, through the variation of the mass of an adhesive tape with the dimension of 70 mm × 50 mm[16,17,30]. When a mass increase exists in the adhesive tape, it means that there is a loss of particles on the surface and, consequently, a weak cohesion.

The adhesive tape was previously pressed with a constant intensity of 4 kg by 1 min on the surface of the mortar [Figure 3a]. The values for surface cohesion were obtained by the average of three measurements, on different non-cracked areas of each specimen.

1.3.4 Dry abrasion resistance

The dry abrasion is one of the standard tests performed on plasters and was determined according to DIN 18947[28], on the mortars that were applied on the bricks and tiles. A 65-mm diameter brush was preloaded with a force of 20 N against the mortar surface until 20 rotations were obtained in 15–25 s [Figure 3b]. Due to the size of the specimens and the dust losses that may occur during the test, the specimens were weighed before and after the test being performed; the loss of material was determined by the difference of mass. For each mortar, the dry abrasion resistance was obtained by the average of three measurements at three different areas.

1.3.5 Surface hardness by durometer

The surface hardness by durometer was determined based on ASTM D2240[31], with the PCE durometer Shore A equipment, being performed in non-cracked areas on the mortars applied on the hollow brick and the tile. The durometer has a pin which, by the action of a spring under a standard load, when pressed against
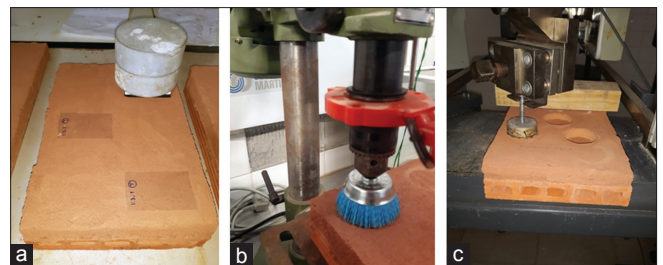

Figure 3. Surface cohesion test on the EM3 mortar applied on the ceramic hollow brick (a), brush and dry abrasion resistance test on the EM2 mortar on the brick (b), load cell and AStr test on the EM1 mortar (c)

the surface indicates the penetration strength by the movement of the pointer on a scale of 0–100[19,32].

1.3.6 Ultrasonic pulse velocity

The determination of the ultrasonic pulse velocity by indirect method was based on EN 12504-4[33] using a Proceq Pundit Lab equipment, with a conic emitter and receiver transducers. The conic emitter was placed in a defined point and the receiver was placed at a distance of 6, 8, 10, and 12 cm, along a straight line on non-cracked visible areas of the mortars applied on brick and tiles. The wave transmission time (µs) was measured 3 times at each point, and the ultrasonic velocity was determined by the quotient between the distance traveled and the wave transmission time. The results are an average of the measurements, in each point and in three different areas of the mortars, applied on the brick and tile.

1.3.7 Thermal conductivity

Thermal conductivity was performed with an ISOMET 2104 Heat Transfer Analyzer using a contact probe API 210412 with 60 mm of diameter. The equipment requires a minimum surface of 60 mm of diameter and a height of 15 mm[16]. For this reason, this test was determined only in mortars which were applied on the

bricks and tiles. The average of the measurements at six different points was considered.

1.3.8 Adhesive Strength

Adhesive Strength (AStr) of the mortars was determined based on DIN 18947[28] and EN 1015-12[34]. Nevertheless, instead of a conventional pull-off equipment, a Zwich Rowell Z050 equipment, with a load cell of 50 kN and 3 min/m of velocity, was used [Figure 3c]. This option was justified by a higher sensibility and precision that can be obtained, important for low adhesive materials, such as earth plasters. The test was performed on the plastering mortars that were applied on the ceramic hollow brick. This was carried out on the central area of the ceramic brick and cracked areas were avoided.

For each mortar, three specimens with 50 mm of diameter were cut and glued 24 h before performing the test, with an epoxy glue. The AStr value for each mortar is the average of the three measurements. The type of rupture (adhesive – by the contact surface of the mortar with the support – or cohesive – within the mortar) was also assessed.

2 Results and discussion

2.1 Visual analysis

Analyzing the specimens of the plastering mortars, it is possible to observe that there was no visual change of color between them. Therefore, the increase of the sand content, differences on fine and course sand contents, and application in different supports had no influence on esthetic color [Figure 4].

Regarding the cracking, it was possible to observe that mortars applied on the ceramic hollow bricks (with 200 mm × 300 mm × 20 mm) do not present cracks – except the EM2 mortar, which presents a slight crack, as shown in Figure 4a. Regarding mortars applied on the tiles with 212.5 mm × 450 mm × 20 mm [Figure 5], it was possible to observe cracks in compositions containing higher clay content, such as EM1 and EM2. The EM3 and EM4 mortars also present some cracks although less visible. The remaining mortars, with lower clay content, do not present cracks [Figure 5]. It is possible to achieve that the support in which the mortars are applied strongly influences the behavior of these mortars. The same mortar when applied in different supports behaves differently. It seems that a more porous support, such as the brick, reduces shrinkage. Nevertheless, a higher area of the mortar
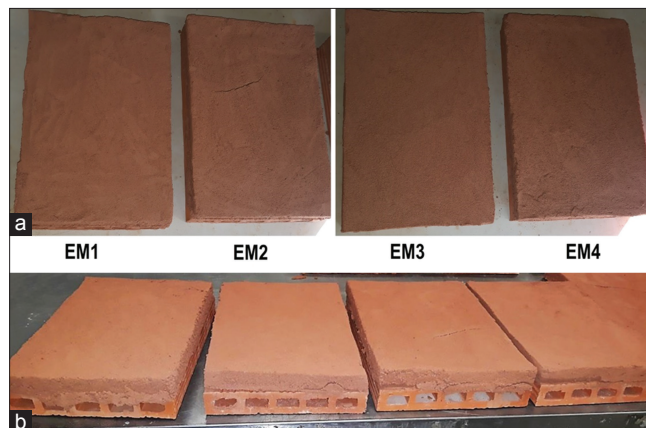
Figure 4. Visual appearance of the mortars on the hollow bricks (from left to right: EM1, EM2, EM3, and EM4 mortars): (a) the presence of cracks and (b) loss of adherence
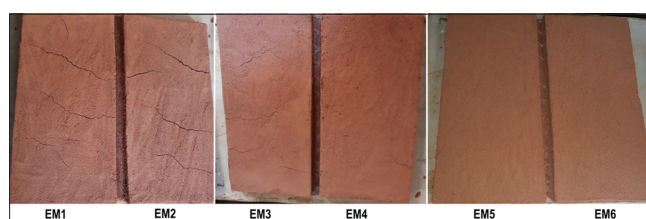
Figure 5. Visual appearance of the mortars on the tiles (from left to right: EM1, EM2, EM3, EM4, EM5, and EM 6 mortars)

specimen, such as the specimens on tile, may also have influence.

Emiroğlu et al.[8] realized a visual analysis of the earth mortars [Table 1] relative to the occurrence of cracks and concluded that mortars with the highest clay content showed a higher occurrence of cracks, as happened in the present study in mortars applied on the tiles. However, the occurrence of cracking is much lower when compared with some mortars analyzed by Emiroğlu et al.[8]. Santos et al.[19] also performed a visual analysis of the earth mortars with low addition of lime applied on external conditions [Table 1] and did not observe the occurrence of cracking for any of the mortars analyzed, unlike what happened with the EM1, EM2, EM3, and EM4 mortars applied on the tiles analyzed in the present study.

It is possible to conclude that mortars with high percentage of clay fraction tend to develop more cracks. The type of clay is also important since there are different types of clay and some are less stable than others. The type of support where the mortar is applied is also other important issue, since after a mortar application and due to evaporation of the water contained on that mortar, shrinkage starts to appear and it will lead to the development of tensile stresses between the mortar and support.

Shear stresses in the plane of contact between the mortar and the support may also appear which may lead to the detachment of the mortar[35]. This was verified on the mortars applied on the bricks: They show prominence in the lateral zones maintaining the adherence to the support in the central zone [Figure 4b]. Development of biological contamination was not observed in any mortar specimen. However, Gomes et al.[21] also analyzed visual observation earth mortars with the addition of hemp fibers [Table 1] and concluded that mortars with the addition of fibers showed the development of biological contamination after performed accelerated aging test by wetting-drying cycles. Furthermore, Röhlen[36] observed fungi and molds in an environment with high humidity levels, in both earth mortars with and without fibers. It can be concluded that the presence of fibers and high levels of humidity can aggravate the appearance of biological contamination. Hence, ventilation is needed, to avoid high relative humidity and consequently biological growth.

2.2 Shrinkage

The values for shrinkage, linear and volumetric, can be observed in Table 5. The shrinkage is an important characteristic to be evaluated in plastering mortars since cracks can turn plasters esthetically unacceptable and also reduce their protective effect, therefore reducing the durability of ancient and modern earth buildings[37].

By observation of Table 5, it can be detected that lower clay content promotes lower shrinkage, taking into account that water content is approximately the same [Table 3]. Observing the limits mentioned by the DIN 18947[28], the six mortars comply with the standard (<3%), but they present high values for volumetric shrinkage. It is important to note that the dimensions of the specimens referred in the standard are not the same as the present ones (see 2.2): In this study, two of the dimensions are much higher than those recommended. As a consequence, the results observed may be higher given the largest dimension of the specimens. Emiroğlu et al.[8] analyzed earth mortars with different clay: sand ratio, and as in the present study, these researchers obtained higher values of volumetric shrinkage for mortars containing lower clay content [Table 1], decreasing with the decrease of clay content. Delinière et al.[15] analyzed linear shrinkage of earth mortars [Table 1]. In the present study, only the EM1 and EM2 mortars present higher linear shrinkage, the

EM3 mortar presents linear shrinkage in the same range, and the remaining mortars present lower linear shrinkage, in comparison with Delinière et al.[15] [Table 1]. The linear shrinkage difference can be justified by the use of different types of clay, which have different swelling.

Lima et al.[9] analyzed linear shrinkage of illitic earth mortars [Table 1]. The lowest shrinkage stands for the mortar with lower clay content. In the present study, earth mortars with the same volumetric ratio and water content presented higher linear shrinkage than that obtained by Lima et al.[9] [Table 1]. This can be justified by probably using a different type of clayish earth, which promoted a higher shrinkage of the mortars.

Gomes et al.[5] analyzed linear and volumetric shrinkage of earth mortars [Table 1]. In the present study, earth mortars with the volumetric ratio of EM1 and EM2 present higher linear and volumetric shrinkage, while the remaining mortars present linear shrinkage within the range of values obtained by Gomes et al.[5] and lower volumetric shrinkage [Table 1].

2.3 Surface cohesion

The superficial loss of material by surface cohesion test in each earth mortar is shown in Figure 6.

Observing Figure 6, it is possible to conclude that EM1 and EM5 mortars applied on tiles present the highest superficial loss of material. Consequently, they present

Table 5. Linear and volumetric shrinkage of planar specimens

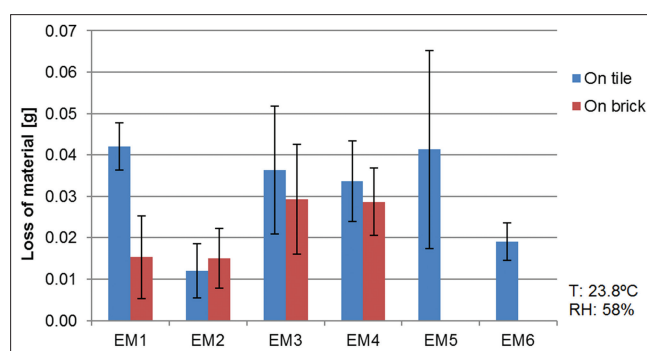| Mortar	Linear shrinkage (%)	Volumetric shrinkage (%)
EM1	2.9	6.3
EM2	2.9	4.9
EM3	1.3	2.2
EM5	0.8	1.3
EM6	0.0	0.0

Figure 6. Loss of material by surface cohesion test.

the lowest surface cohesion, followed by the EM3 and EM4 mortars. Nevertheless, standard deviation of EM5 is particularly high. On the other hand, the EM2 mortar presents the lowest superficial loss of material; therefore, it has the highest surface cohesion, followed by EM6 which presents a slightly higher superficial loss of material and, consequently, lower surface cohesion.

In mortars applied on ceramic hollow brick, the tendency is different since the EM3 and EM4 mortars present a greater loss of material and the EM1 and EM2 mortars present lowest superficial loss of material and, consequently, greater superficial cohesion. In the ceramic brick, it can be clearly observed that cohesion decreases with the increase of volumetric sand content from 1:2 (EM1 and EM2) to 1:3 (EM3 and EM4).

In the tile support, the same trend as in the ceramic support did not occurred; there is no clear evidence on the influence of the sand content.

Faria *et al*.[16], with an ready-mixed earth mortar with oat fibers, analyzed the surface cohesion of the mortar [Table 1]. In the present study, all mortars applied on the two different supports present lower loss of surface mass, which represents a better surface cohesion [Table 1].

Santos *et al*.[19] analyzed the loss of surface material of the earth-based mortars with low addition of CL90 and NHL3.5 [Table 1], by a similar method. The mass loss values are much higher than those obtained in the present study [Table 1]. It is important to refer that the earth-based mortars analyzed by Santos *et al*.[19] were exposed to natural atmospheric external conditions [Table 1]. This, as well as a probable different type of clay, may justify the lower surface cohesion of these mortars in comparison with the ones of the present study.

2.4 Dry abrasion resistance

Figure 7 presents the loss of mass by abrasion of the studied earth mortars.

By Figure 7, it is possible to conclude that the earth mortars applied on the tiles always present greater loss of material by abrasion in comparison with the same mortars applied on the bricks which can be due to the more porous structure of the brick in comparison with the tile. With a higher water absorption by the support, it is probable that the plaster hardens more compact and, therefore, more resistant to abrasion.

The earth mortars with only fine sands (EM1 and EM3) and applied on tiles present a greater loss of material by

abrasion when compared to mortars with a mix of both fine and coarse sands (EM2, EM4, EM5, and EM6). The EM2 and EM4 mortars present similar loss of material by abrasion when applied on the tiles and on the bricks which shows that the sand mix most probably allows a more dense mortar structure, therefore justifying a higher resistance and durability.

The DIN 18947[28] classified the earth mortars for their dry abrasion resistance in two classes: SI when loss of material by abrasion is ≤1.5 g and SII when this loss is ≤0.7 g. All mortars are classified as SII class, except the EM1, EM3, and EM5 mortars applied on tiles.

Faria *et al*.[16], analyzing the loss of material by abrasion of a ready-mixed earth mortar [Table 1] applied on bricks by the same method and type of brush, obtained a higher loss of material in comparison with the present study [Figure 6], which shows an improved durability of the studied mortars.

2.5 Surface hardness by durometer

The surface hardness by durometer of each earth mortar can be observed in Figure 8.

By Figure 8, it can be concluded that the EM3 (on tiles and on brick) and EM5 (on tiles) mortars present
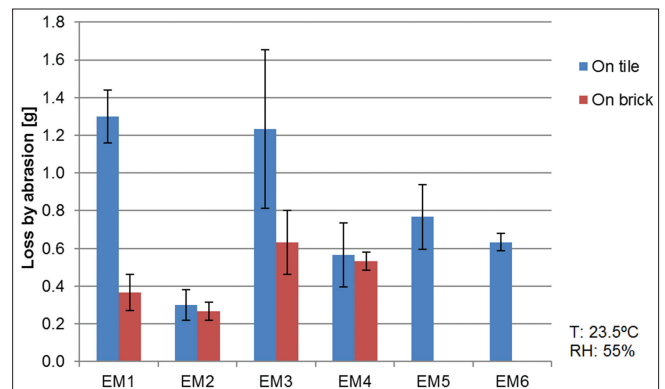

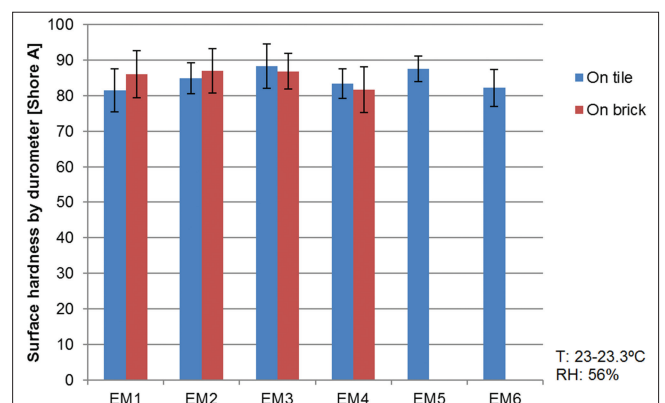**Figure 7.** Loss by abrasion of earth mortars

Figure 8. Surface hardness by durometer of earth mortars

the greater surface hardness. However, the values are very similar between the mortars. It is also possible to conclude that the content of clay does not influence the surface hardness of the mortars.

Santos et al.[19], analzing the surface hardness by durometer of earth-based mortars without and with low addition of CL90 S and NHL3.5[20] in natural outdoor conditions [Table 1], obtained lower surface hardness. These lower results can be justified by the weathering that these mortars were subjected.

Faria et al.[17] analyzed the surface hardness by durometer of the ready-mixed earth mortar and obtained values approximately in the same range of obtained in the present study [Table 1].

Comparing another study performed by Faria et al.[22] but with air lime-earth mortars [Table 1] applied on brick in laboratory conditions and as plaster outdoors on an experimental rammed earth wall, it was observed that mortars of the present study exhibit higher surface hardness [Table 1].

2.6 Ultrasonic pulse velocity

The ultrasonic pulse velocity of earth mortars is shown in Figure 9.

Observing Figure 9 and comparing the ultrasonic pulse velocity of the mortars applied on the two supports, it is possible to conclude that the higher values can be observed on the ceramic hollow bricks. Despite the cracking of some plasters, there were no large variations on ultrasonic pulse velocity of the mortars, which were around 1000 m/s in mortars applied on the tiles and 1200 m/s in mortars applied on the bricks.

Faria et al.[17], for a ready-mixed earth mortar with oat fibers applied on ceramic hollow brick in laboratory conditions, obtained higher ultrasound velocity than the mortars of the present study applied on bricks [Table 1]. The same method was used by Faria et al.[22] who obtained lower ultrasonic pulse velocity when compared with values obtained in the present study [Table 1]. These results can be justified by the higher compactness and presence of less microcracking of the mortars analyzed in the present study.

2.7 Thermal conductivity

Figure 10 presents the thermal conductivity of earth mortars. It is possible to conclude that there is a small difference in the thermal conductivity of the mortars applied on the tile and brick. This can be justified by the influence of the support with different characteristics in
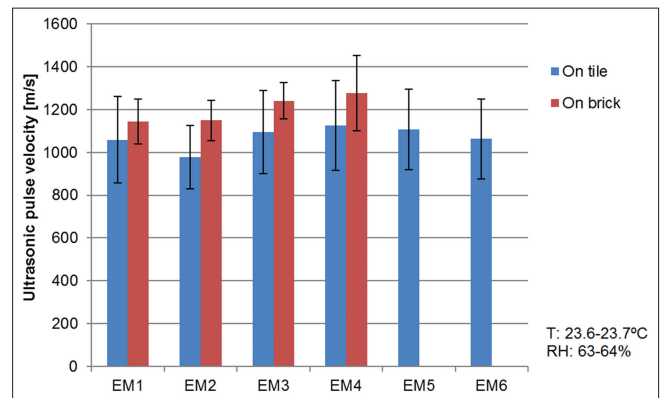

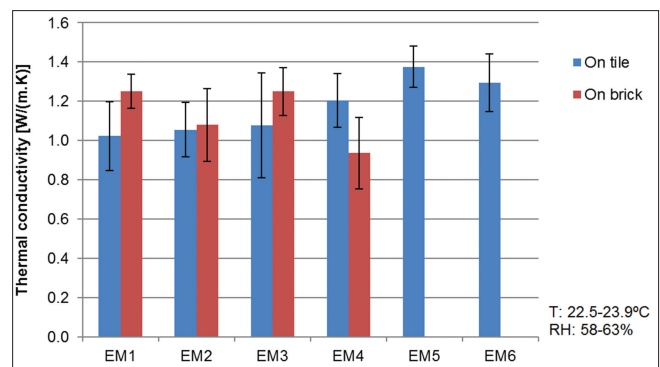**Figure 9.** Ultrasonic pulse velocity of earth mortars

Figure 10. Thermal conductivity of earth mortars

terms of porosity and water absorption. The EM1, EM2, and EM3 mortars present higher thermal conductivity when applied on the brick, while when applied on the tiles present lower thermal conductivity, in comparison with the EM4 mortars. It is verified that, in the mortars applied on the brick, the addition of coarse sand promotes a reduction of the thermal conductivity, which may be related to a porosimetric change.

The EM5 and EM6 mortars present higher thermal conductivity. However, the results of the same mortar applied on the brick for comparison are not available. The high thermal conductivity presented by these mortars shows a lower capacity of thermal insulation.

Faria et al.[16], analyzing the thermal conductivity of ready-mixed earth mortar with oat fibers [Table 1], observed lower values when compared with the present study. This can be justified by the presence of fibers in the earth mortar since fibers promote the reduction of thermal conductivity[38].

Lima et al.[9] analyzed thermal conductivity for circular specimens of earth mortars [Table 1] and obtained values in the same range when compared with the present study, except the EM4 mortar applied on the brick that presents lower values and the EM5 and

EM6 mortars that present higher values for thermal conductivity.

For earth mortars with the addition of different percentage of two different fibers, Lima and Faria[18] concluded that thermal conductivity decreases with the increasing of fiber content [Table 1]. The mortars analyzed in the present study (without fibres) present thermal conductivity in the same range of earth mortars analysed by Lima and Faria[18].

Gomes et al.[5] studied earth mortars without and with hemp fibers [Table 1] and, for mortars without fibers, obtained values for thermal conductivity approximately in the same range of the mortars analyzed in the present study.

For air lime-earth mortars applied on bricks in laboratory conditions, Faria et al.[22] [Table 1], obtained values for thermal conductivity much lower than those presented in this study.

2.8 Adhesive strength

Adhesive strength (AStr) of mortars is one of the most important characteristics of plasters since it guarantees the correct fixing of the plaster to the support. The adhesive strength it is the ability of the plaster to resist to normal and tangential stress in plaster/support interface. This property depends on the penetration of the mortar matrix into the support and the physical connections between the plaster and the support that depend on its roughness.

During the cutting of the circular specimens, there was a detachment of the specimen, in EM2 and EM3 mortars [Figure 11]. For this reason, it was not possible to perform the adhesion test in these mortars and it was concluded that they have low adhesion to the support. Nevertheless, several studies performed for lime-based mortars[39] or earth-based mortars[14,15] have discussed this problem, showing that this type of test (involving the cut of samples) is not adequate to these types of mortars.

The AStr obtained for EM1 and EM4 mortars is present in Table 6. The EM1 mortar presents AStr higher than 0.14 N/mm^2 since the rupture of two specimens occurred in the mortar layer.

DIN 18947[28] classifies earth mortars in two classes: SI when AStr $\geq$0.05 N/mm^2 and SII when AStr $\geq$0.10 N/mm^2. Analyzing Table 6, EM1 and EM4 can be classified as SII. It is important to note that, despite good AStr in the central part of the specimen, some detachment occurred in the lateral zones.

Figure 11. (a) Detachment of specimen being cut of EM3 plaster and (b) detachment of the part of the EM2 plaster

Table 6. Adhesive strengths of earth mortars

Mortars	AStr (N/mm^2)
EM1	$\geq$0.14±0.00
EM2	–
EM3	–
EM4	0.15±0.04

Mortar not tested by low adhesion to the support

Faria et al.[16], for a ready-mixed earth plaster [Table 1], analyzed the AStr and obtained AStr lower than the present study. In another study performed by Lima and Faria[18] which analyzed the AStr of the earth mortars with addition of two different types and percentage of fibers [Table 1], these researchers obtained values lower than the present study.

Delinière et al.[15] analyzed the AStr of earth mortars applied on the concrete panels [Table 1]. It consisted first on covering the surface of the concrete panel using a suspension of the clay plaster tested (liquid mixture of earth and water)[15], as used in the present study. Both the studies present similar values for AStr to the support.

3 Conclusion

This study analyzed six different mortars formulated with the same clayish earth but with variation of the clay: sand ratio (1:2, 1:3, 1:4, and 1:5), with only fine sand and with a mix of both fine and coarse sands. With these mortars, three different specimens were produced: Planar specimens in metallic molds and specimens simulating plasters applied on ceramic hollow brick and on the back of a ceramic tile. Visual assessment and some physical-mechanical characteristics of each mortar were evaluated, mainly by non-destructive testing.

The earth mortars analyzed do not present color changes or the development of biological contamination. By the results of linear and volumetric shrinkage, it is possible to conclude that lower clay content promotes a reduction of the mortars shrinkage. When applied on the tiles, some cracks appear on the plaster specimens formulated with higher clay content.

It can be concluded that the different clay: sand ratio and the different supports do not promote significant changes in the surface hardness of the earth mortars. The same occurs for ultrasonic pulse velocity, in which approximately 1000–1300 m/s are obtained for all earth mortars.

For dry abrasion resistance, it is possible to conclude that earth mortars applied on the tiles always present greater loss of material in comparison with the same mortars applied on the bricks. That fact induces that a more porous structure (the brick in comparison with the tile) absorbs a higher content of water from the fresh mortar when in contact with the support, therefore leading to a denser hardened mortar when applied on the brick. In comparison with the mortars formulated with a mixture of both sands, the mortars formulated with only the fine sand have lower dry abrasion resistance.

Although a suspension of clay was applied on the brick and tile supports before the application of the mortars, a low adherence to the support was verified for two of the mortars analyzed, on which there was detachment from the support during the cutting of the specimens. This shows that this test is not adequate to this type of mortars and an alternative test should be pursued.

The results obtained in the present study refer to the use of a single type of clayish earth. In the future, it is important to continue to analyze the influence on properties of earth mortars formulates with other types of clayish earth.

Conflicts of interest

No conflicts of interest were reported by all authors.

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