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Can an earth plaster be efficient when applied on different masonries?

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Abstract

Earth mortars are known for being ecological but also reversible, contributing to comfort and aesthetic. Nevertheless, compatibility with different masonries is scarcely assessed. A commercial unstabilised ready-mixed earth mortar was produced with an ilitic earth with addition of sand and oat straw fibres. It was used to plaster different experimental masonry walls, at protected outdoors environmental conditions. The plasters applied on the masonries were visually monitored and characterized *in situ* by non-destructive techniques and in laboratory by bulk density and microstructure. The same mortar used for the plasters was characterized in laboratory in fresh state and, after drying, on prismatic specimens and specimens composed by a mortar layer applied on hollow bricks. Some variation of results occurs when the same unstabilised ready-mixed earth mortar is used to plaster different masonries, what may be related to the water absorption of the masonry materials. However, after six months the earth plaster presented durability on the different masonries when protected from rain. It proves that this ecological mortar is technically efficient to plaster different types of masonry, historical or contemporary.

Keyword: clayish earth; durability; *in situ* test; masonry; mortar; plaster

1. Introduction

Earth plasters have been widely used in the past [1, 2]. Craftsman knowledge ensures its use in many regions of the world. Nevertheless, during the 20th century its use stopped for some decades across many countries. With the ecological interest that has emerged in recent decades and technical advantages of some earth-based building materials, the interest on earth plasters has been growing. Presently ready-mixed products for masonry plastering can be purchased and applied in many countries as high standard plasters. Nevertheless, to the authors' knowledge, there is only one standard about earth plastering - the German standard DIN 18947 [3] specifically for mortars without any chemical stabilization. This standard demonstrates the importance and need of defining requirements and test procedures for this type of mortars. Some of the DIN 18947 [3] requirements are defined in terms of the product itself, like the limit of salts: the earth mortar products must not have more than 0.02 % of nitrates, 0.10 % of sulphates, 0.08 % of chlorides and must not exceed a total salt content of 0.12 %. Other requirements are defined for hardened plastering mortars, for example linear shrinkage, dry bulk density, flexural, compressive and adherence strength, resistance to dry abrasion and hygroscopicity. Delinière et al. [4] described some of the test methods referred to in DIN 18947 [3], namely the procedure for the production of an earth mortar, and Faria et al. [5] discussed the influence that some variations on test procedures may have on results.

Earth, as a building material, offers many advantages. Many are ecological: although not renewable, earth is natural, non-toxic, with low energy intensity, low carbon emissions, reusable and recyclable (particularly when it is used without chemical stabilization with binders) [6]. Earth is a raw material that does not need energy for calcination like current binders, which can be found almost everywhere and sometimes can even be extracted from building sites, reducing costs and energy for transportation and production [6]. The previous confirms the sustainability of earthen mortars with a very positive life cycle. Earth plasters show a low environmental impact by life cycle assessment (LCA) methodology, in comparison with plasters based on current binders [7]. Only a limited energy is required for milling the clayish earth to be used on mortars.

The colour and texture resulting from the clay and application techniques offer infinitive aesthetic possibilities to plasters made with earth mortars. The addition of fibres may also contribute to the aesthetic characteristics of plasters. To keep not only these aesthetic aspects but also other technical characteristics, paint coat systems are not usually applied.

Furthermore, earthen plasters can contribute to improve the comfort in interior environments, complementing the masonry requirements: the earthen plastering mortars present hygroscopic inertia that, within specific ranges, can help regulating indoor relative humidity (RH), by their good capacity to absorb and give off moisture [8 – 14]. Nevertheless, unstabilised earth plasters are vulnerable to liquid water and, therefore, need to be protected from direct contact.

The application of plasters with hydraulic binders (mainly cement) in inefficient conservation and retrofitting interventions on historic and namely on earth constructions caused serious anomalies to these constructions. These anomalies are mainly due to differences in deformability and vapour permeability between the materials [6, 15]. The cement-based mortars promote temporary protection to low strength masonries but become potentially destructive in the long-term [6]. Earthen mortars seem to be the most suitable for the conservation and retrofit of earth walls and their characteristics seems to be compatible with low strength porous masonries (as the case of historic earthen-based walls and rubble stone masonry) since they have rigidity and water vapour permeability compatible with these supports. Moreover, earthen plasters are easily reversible once the clayish particles are water-soluble. Therefore, repairs are generally simple to undertake [16]. Consequently, it seems that earth plasters can be applied on earth walls [6, 17, 18, 19] but also in other types of walls that are protected from water, either for retrofitting or in new buildings [4, 15, 19].

Some studies characterized different mortars by different methods, as can be seen in Table 1; yet few studies characterized earth plasters *in situ*.

Table 1 – Synthesis of earth mortars studied and some *in situ* test methods used on several plasters.

Study	Mortars analysed	Methods
Gomes et al. [6]	Earth based mortars with local earths with volumetric ratio 1:0 and 1:1.5 (earth:sand) and with commercial kaolinitic earth with volumetric ratio 1:3 (earth:sand) without and with 5, 10 and 15 % of air lime, hydraulic lime, Portland cement and natural cement, and 5 % of hemp fibres	Bulk density Microstructure

Lima et al. [10]	Ilitic earth mortars with volumetric ratio 1:2, 1:2.5, 1:3 and 1:4 (earth:siliceous sand)	Linear shrinkage Bulk density
Santos et al. [15]	Earth-based mortars with volumetric ratio 1:3 (earth:unwashed sand) and 1:2 (earth:washed siliceous sand) without and with low addition of CL and NHL3.5	Surface hardness by durometer and sclerometer Sphere impact test Surface cohesion
Faria et al. [19]	Ready-mixed ilitic earth mortar with oat straw fibres	Fresh state (consistency, bulk density, air content) Shrinkage Bulk density Ultra-sound velocity Surface hardness by durometer and sclerometer
Lima and Faria [20]	Ilitic earth mortars with volumetric ratio 1:3 (earth:siliceous sand) with10 and 20 % of oat straw and 20, 40 and 80 % of typha	Linear shrinkage Bulk density
Santos et al. [21]	Ready-mixed ilitic earth mortar with oat straw fibres	Bulk density Microstructure
Palumbo et al. [22]	Earth mortars with barley straw fibres and corn pitch aggregates	Bulk density
Faria et al. [23]	Air lime mortars with volumetric ratio 1:2 (air lime:washed siliceous sand), with 25 % of the air lime replaced by a kaolinitic earth (in volume) applied as renders on an experimental rammed earth wall (outdoors conditions)	Ultra-sound velocity Surface hardness by durometer and sclerometer
Veiga et al. [24]	Renders (outdoor conditions) with mortars based on hydraulic lime and cement, natural and artificial pozzolans	Sphere impact test
Tavares et al. [25]	Old air lime mortars with consolidation	Surface hardness by durometer and sclerometer
Drdácký et al. [26]	Air lime mortars with volumetric ratio 1:2, 1:3, 1:4, 1:6 and 1:9 (lime:sand)	Surface cohesion

To assess if an earth plaster behaves suitably on different types of masonries, several masonry experimental walls were built at the Natural Exposition Experimental Station of Masonries and Coatings of NOVA University of Lisbon, in Caparica, Portugal, located approximately 3 km from the Atlantic coast. A commercial ready-mixed earth mortar was prepared and applied to plaster four different experimental walls. With the same ready-mixed mortar, from the same *in situ* batch, several mortar specimens were produced in laboratory.

Some of the results presented in this study were published in a conference article [19], with a brief description of DIN 18947 [3] and results of mechanical properties and thermal conductivity. In the present study the ready-mixed earth mortar and the plasters applied on the different experimental walls are characterized in terms of fresh state, visual observation during aging within natural conditions and other hardened state properties.

Therefore, the aim of the present study is to evaluate the effects of natural weathering on a ready-mixed earth mortar protected from rain when applied to plaster different types of masonries, historical or contemporary.

2. Materials and methods

2.1. Experimental masonries, materials and plaster

Without using any damp proof layer, four different masonry test walls were made on a concrete foundation: rubble stone with limestone and air lime mortar, concrete blocks with cement mortar, adobe with an earth mortar (the same clayish earth used to produce the blocks were used for the masonry mortar) and hollow bricks with cement mortar (Figure 1) [19]. The typologies of the walls were chosen to simulate diverse old to contemporary masonries. The rubble stone masonry simulated a historic wall, the adobe masonry simulated an earth wall and both the concrete and brick masonries simulated common contemporary walls. The dimensions of the experimental walls were 1.0 – 1.8 m height and 1.2 – 2.2 m length. The thickness of the rubble stone and concrete blocks walls is 45 cm and 20 cm, respectively, and the adobe and hollow bricks walls is 15 cm. No different mechanical behaviours or decays were expected depending on the types of masonries that were chosen.

Fig. 1 Surface of the masonry test walls before being plastered

A ready-mixed earth mortar from EMBARRO Company (Portugal and Spain) was used. The same ready-mixed earth mortar was characterized by Faria et al. [5] in laboratory conditions with a mixing preparation in controlled conditions. The dry ready-mixed earth mortar product was observed visually. It presents a reddish colour and it is possible to visually observe fibres. Including data provided by the producer, it is composed by a clayish earth, sand with particle size distribution 0 – 2 mm, both from Algarve region (South Portugal), and oat fibres cut with 1 – 2 cm length, from organic farming. No other additives or admixtures are used in the ready-mixed earth mortar formulation. However, since it is a ready-mixed mortar, the proportions of each constituent are not known, namely what is the composition of the raw earth (composed by sand, silt and clay), what is the sand content added and the one already in the raw earth and what is the exact fibres content. Therefore, a particle size distribution test of the ready-mixed mortar product was performed (dry method) according the EN 1015-1 [27] and is presented in Table 2 (average of three replicates). It also turned possible to assess the fibres content that is approximately 5% of the dry product volume.

Table 2 – Dry particle size distribution of the ready-mixed mortar product.

Sieves	Mesh [mm]	Passing [%]
3/8”	9.5	100.0
4	4.75	99.2
8	2.36	95.9
16	1.19	85.4
30	0.6	50.7
50	0.3	20.2
100	0.15	5.6
200	0.075	1.0
Residue		0.1

The ready-mixed earth mortar was also characterized by X-ray diffraction test (XRD), carried out with a Phillips PW3710 X-ray diffactometer with Co Kα radiation, speed of 0.05º/s and 2θ ranging from 3º to 74º. Two types of fractions of the ready-mixed product were analysed: fine fraction, with only the material passed on the 106 µm sieve, and global fraction, grinded and passed on the sieve of 106 µm [5]. By X-ray diffraction test it was possible to assess that the clayish earth is mainly illitic (Table 3).

Table 3 – XRD on global and fine fractions of ready-mixed earth mortar.

Identified crystalline compounds	Global fraction	Fine fraction
Quartz (SiO_2)	++/+++	+++
Feldspar ($KAlSi_3O_8$))	Vtg	?
Illite ($KAl_2Si_3AlO_{10}(OH)_2$)	++	+/++
Kaolinite ($Al_2Si_2O_5(OH)_4$)	+	+
Calcite ($CaCO_3$)	Vtg	?
Dolomite ($CaMg(CO_3)_2$)	++	+/++
Hematite (Fe_2O_3)	Vtg/+	Vtg/+

Peak intensity: +++ - high proportion (predominant compound); ++ - mean proportion; + - low proportion; Vtg - vestiges; ? - doubts in presence.

The loose bulk density of the ready-mixed mortar product, performed according EN 1097-3 [28] and by taking an average of three specimens of mortar, is 1.77 ± 0.01 kg/dm^3.

By indication of the producer the recommended water content is 20% (in volume of dry ready-mixed mortar), being this the water content used for the kneading of the analysed mortar.

The mortar was mechanically prepared *in situ* using a Putzmeister MP25 mixing equipment with a quantity of water that allows an easy application and was mechanically applied by pumping (Figure 2a). The mortar was directly applied on the four masonry test walls, which were previously sprayed with water. The plaster was easily levelled with a wood clapboard and finished with a trowel and a sponge (Figure 2b and 2c). The thickness of all the plasters was around 2 cm.

Fig. 2 Application of the earth plaster: (a) after mechanically application, (b) manual levelling and (c) finished surface; (d) protection of the experimental walls

The earth plasters can be affected by rainfall since earth mortars have not been chemically stabilized with any mineral binder. The ready-mixed product is commercialized for indoor or protected from water outdoor applications. For that reason, the plastered masonry test walls were protected by a continuous top covering 2.2 m large, two months after being completed (Figure 2d). Fortunately, during this two months period there was not much rainfall and the earth plasters were not damaged. Despite having a top covering, there is a very strong South wind at the Experimental Station. Therefore, with time, degradation occurred at the underside of the South facing plasters, due to insufficient protection from rainfall. For that reason, a protection net was vertically positioned on the lateral sides of the test walls´ covering (Figure 2d).

2.2. Mortar specimens preparation

For the characterization of the mortar in the fresh state, a portion was transported to the laboratory after *in situ* mixing, at a distance of about 30 m. After 10 minutes from mixing, flow table consistency, bulk density, water content and air content of the fresh mortar was assessed.

Several mortar specimens were produced with the same ready-mixed earth mortar, from the same *in situ* batch:

- Prismatic 40 x 40 x 160 mm specimens were mechanically compacted in two layers on metallic moulds and manually levelled.
- Specimens composed by a mortar layer applied on the surface of hollow brick with a thickness of 1.5 cm and 29.5 x 19.5 cm of area. The bricks were water sprayed and to simulate the *in situ* application energy, the mortar was left to fall from 70 cm height. The surface of the simulated plasters was then levelled.

The prismatic specimens were let to dry and then de-moulded. All the specimens were placed in a laboratory with 65 ± 5 % RH and 20 ± 3 °C temperature. The plaster applied on the different experimental walls was weathered in outdoors semi-protected conditions with 8.2 – 27.8 °C temperature and 65 – 80 % of RH.

2.3. Test methods

2.3.1. Water absorption of the masonry materials

The water absorption of the four masonry materials – hollow brick, adobe, concrete block and limestone – is analysed. The water absorption under low pressure is determined according the EN 16302 [27] and consists of measuring the water absorbed by the masonry materials over one hour, using *Karsten* tubes (Figure 3). The *Karsten* tubes are fixed and sealed to the masonry units be studied, with a certain contact area of the water with the surface. The results obtained are the average of adsorption obtained by three *Karsten* tubes applied in different areas of the masonry.

Fig. 3 *Karsten* tubes on hollow bricks

2.3.2. Characterization of the fresh state mortar

In the fresh state, the ready-mixed earth mortar is characterized by: the flow table consistency, determined according the EN 1015-3 [30]; the wet bulk density, based on the EN 1015-6 [31]; the air content, based on the EN 1015-7 [32]; the water content is obtained by the weight difference of fresh and dried specimens of the mortar [5].

The shrinkage of the ready-mixed earth mortar is determined based on the DIN 18947 [3], by the difference of the length of three prismatic specimens, with 40 x 40 x 160 mm, of mortar between the fresh and hardened state.

2.3.3. Bulk density and microstructure

The dry bulk density of the ready-mixed earth mortar is geometrically determined, using a 0.001 g precision digital scale and a digital calliper, with prismatic specimens, according the DIN 18947 [3] and EN 1015-10/A1 [33].

The open porosity and the pore size distribution are determined by mercury intrusion porosimetry (MIP) with a Micromeritics Autopore II equipment. The test specimens are stabilized at 40 °C and prepared (sculpted) to occupy the greater part of the 5 cm^3 bulb of the penetrometer volume. Testing begin at low pressures ranging from 0.01 MPa to 0.21 MPa, followed by high-pressure analysis from 0.28 MPa to 206.84 MPa, following a test procedure that is commonly used for lime mortar testing [5, 34]. MIP is applied to analyse the open porosity and the pore size distribution of: the prismatic specimen of the mortar, without influence of the substrate; the mortar applied on hollow brick, in controlled laboratory conditions; the mortar applied in two of the experimental masonry walls – on the hollow brick and on the rubble stone walls in the exterior environment protected from rain.

2.3.4. Ultra-sound velocity

The ultra-sound velocity of plaster applied on the experimental walls and specimens of mortar applied on brick, in laboratory, is determined with a Proceq Pundit Lab equipment and conic emitter and receiver transducers, with a frequency of 54 Hz, based on ASTM 12504-4 [35]. The compactness and the presence of eventual defects (like cracks or detachments) can be detected through this test. The thickness (from the surface) of the material that is analysed depends on the distance between the transducers; when transducers are farther from each other, the greater the thickness that is crossed by the ultra-sound waves. For determination of the ultra-sound velocity the indirect method is used on the plasters applied in the experimental walls. The emitter is placed at the 0 cm point and the receiver at points 6, 8, 10 and 12 cm along a straight line. The wave transmission time (in µs) is measured three times at each point. The ultra-sound velocity is the quotient between the distance travelled and the wave transmission time. The final result is obtained by the average of the measurements at the different points on three straight lines in three different areas of the plaster.

In the plasters applied on hollow bricks the same method is used in 10 different points. The ultra-sound velocity is the average of the three measurements in each point.

2.3.5. Surface hardness by durometer and sclerometer

The surface hardness by durometer is determined with a PCE durometer Shore A, based on ASTM D2240 [36], and by sclerometer with a pendular sclerometer Schmidt PT, based on ASTM C805 [37]. The durometer has a pin at the end which, when pressed against the material to be tested, by the action of a spring under a standard load, indicates the penetration strength, translated by the movement of the pointer along a scale of 0 a 100 [15, 38].

The sclerometer causes an impulse reaction that strikes against the surface of the material under analysis, through a known mass, thus allowing to measure the amount of energy recovered in the mass bounce, obtaining a hardness index (rebound value) on the graduated scale of the sclerometer [15, 38].

The surface hardness by durometer and sclerometer is the average of 12 measurements in different areas of each plaster applied on the masonries and on the mortar on hollow bricks.

On the brick-mortar specimens, the surface hardness by sclerometer was not evaluated because the impact of the test could damage them. This property has only been evaluated on the plaster panels.

2.3.6. Sphere impact test

The impact of a sphere is evaluated with a *Martinet-Baronnie* equipment (Figure 4a) based on Veiga et al. [24] and allows to evaluate the resistance and deformation capacity of the plaster through the impact of the sphere of this equipment, with defined mass and impact energy [15].

The body of the equipment is placed horizontally, perpendicularly to the wall, and then the arm of the apparatus, (0.6 m long) is dropped onto the plaster. The equipment arm has a 50 mm diameter steel sphere at its end, which strikes the wall with 3 J of energy [15, 38]. The behaviour of the plaster is evaluated by the diameter of the concavity caused by the sphere and by the possible cracking occurring in the area of the concavity resulting from the impact [38].

The impact strength of the sphere is the average of 5 measurements in different areas of each plaster.

Fig. 4 Sphere impact (a) and surface cohesion (b) tests on a plaster

2.3.7. Surface cohesion

The cohesion of the mortars results from the bond strength between the material particles that compose the mortars. Earth mortars generally present a good cohesion [39]. The surface cohesion is determined to evaluate the need to apply surface treatments to the plasters [16].

Drdácky et al. [26] defined a test for determination of the surface cohesion, which was adapted to earth mortars by Faria et al. [5] and applied. The surface cohesion is evaluated by the variation of mass of an adhesive tape with dimension of 70 x 50 mm (Figure 4b), pressed with a constant intensity on the surface of the plasters [5]. An increase of mass of the adhesive tape expresses the loss of particles of the plaster surface and consequently, its low surface cohesion. The loss of surface mass is obtained by average of 5 measurements in different areas of each plaster.

3. Results and discussion

All the tests (*in situ* and in laboratory) were performed in January 2014 with six months of aging. Visual observation continued after testing. The laboratory specimens were characterized in indoor conditions of 20 ± 3 ºC and 80 ± 5 % relative humidity (RH). The *in situ* tests were performed in outdoor conditions of 15 ºC and 92 % RH after a drying period without rain.

3.1. Water absorption of the masonry materials

The masonry materials water absorption after 1 hour test is registered in Figure 5. In comparison with the other materials, the concrete blocks absorption was so high that made it extremely difficult to assess the water intake: the 4 mL water of each *Karsten* tube was almost immediately absorbed by the concrete blocks. Therefore, the maximum water absorption presented in Figure 5 is only indicative; in fact, a much higher volume of water was absorbed after 1 hour test.

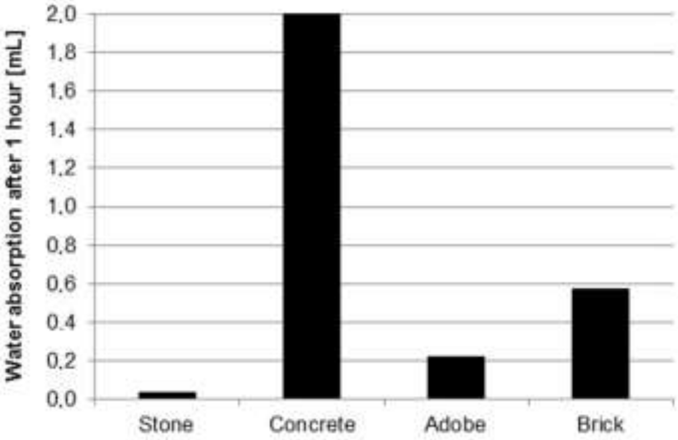

Fig. 5 Water absorption under low pressure of the masonry materials

The concrete blocks are the material with higher visible pores, which justifies the higher water absorption of this material. On the other hand, the stone is less porous leading to lower water absorption, as shown in Figure 5.

The masonries total water absorption will be affected by the water absorption of the masonry units but also of the correspondent masonry layering mortars. That may be more important for the rubble stone masonry, with a surface with higher percentage of masonry mortar. For that reason, the masonry units' water absorption (Figure 5) is only an indicative of the water absorption global behaviour of the masonries [19].

Ashour et al. [40] analysed the equilibrium moisture content (EMC) of four different compositions of earth plasters with addition of different percentage of three different natural fibre types: wheat straw, barley straw and wood shaving. These researchers concluded that the EMC of plasters increased with increasing RH and decreased with rising temperature. That EMC increase was gradual with increasing RH up to 65 % and this increase slowed down between 65 – 80 % RH and then increased again at RH higher than 80 %. In the present study, the water absorption of the different masonries can influence the higher or lower absorption of water from the fresh mortar and, consequently, influence the EMC of the earth plasters.

3.2. Characterization of the fresh state mortar

The characterization of the mortar in the fresh state - flow table consistency, wet bulk density, air content and water content – can be observed in Table 4.

Table 4 – Fresh state characterization of the earth mortar

Characteristics	Results
Flow table consistency [mm]	178.8 ± 2.8
Wet bulk density [kg/dm^3]	2.03
Air content [%]	2.8
Water content [%]	20.1 ± 0.1

DIN 18947 [3] defines that earth mortars must present consistency of 175 ± 5 mm and wet bulk density higher than 1.2 kg/dm^3. The ready-mixed earth mortar analysed in the present study complies with the standard requirements [3].

Some studies on some ancient and modern earth buildings reveal that the durability of these buildings may be reduced due to shrinkage cracks [41]. For this reason it is important to evaluate the shrinkage of earth mortars.

For shrinkage, DIN 18947 [3] defines that the earth mortars with addition of fibres may present a maximum shrinkage of 3 %. The ready-mixed earth mortar analysed presents shrinkage of 0.21 ± 0.08 % in prismatic specimens, which complies with the standard [3]. No shrinkage cracks could be observed in any of the plasters applied on the four masonry walls in external conditions and on the mortar applied on hollow bricks, in laboratory conditions. Therefore, in terms of shrinkage the earth plaster presents the same good behaviour when applied to the different experimental walls. The low shrinkage obtained in the plasters can be justified by the used of the illitic clayish earth, once this type of clays is characterized by their low swelling when wetted [10].

For earth mortars with different volumetric ratio (Table 1) and with an illitic clayish earth from the same region (Algarve), Lima et al. [10] obtained linear shrinkage (by the same method defined in DIN 18947 [3]) of 0.34 – 1.43 %. As expected the shrinkage increased with the clay content increase due to the swelling of the clays [17]. The ready-mixed earth mortar analysed in the present study shows low shrinkage in comparison with earth mortars of Lima et al. [10], which may be justify by the addition of the oat fibres or other unknown aspects of the ready-mixed product formulation. The different results obtained in the present study and by Lima et al. [10] can then be justified by the use of different clay contents and by the fact that no fibres have been used, thus promoting a greater shrinkage.

Lima and Faria [20] for earth mortars with volumetric ratio of 1:3 and addition of fibres (Table 1) with similar water content, obtained shrinkage of 0.13 – 0.62 % for addition of oat straw and of typha. In comparison with the earth mortar analysed in the present study, only the earth mortar with 10 % of straw analysed by Lima and Faria [20] presented lower shrinkage, what emphasizes the good behaviour concerning shrinkage of the mortar tested in the present study.

Ashour and Wu [41] analysed earth mortars composed by a cohesive earth, sand and three different fibre types: barley straw, wheat straw and wood shavings. These researchers concluded that shrinkage increased with temperature and this increase was more significant when the mortar presented lower fibre content. For 30 ºC temperature (similar to the temperature at which the plasters of the present study were submitted), Ashour and Wu [41] obtained shrinkage of 1 – 2 % and 3.5%, respectively for earth mortars with and without fibres. The earth mortars analysed in the present study present shrinkage much lower than the values obtained by Ashour and Wu [41].

3.3. Bulk density and microstructure

Dry bulk density of the mortar determined geometrically [19] and by MIP, and the open porosity determined by MIP of the prismatic specimen, the specimen of the mortar applied on the hollow brick and the specimen of the mortar applied on the brick and rubble stone masonry experimental walls are presented in Table 5.

Table 5 – Dry bulk density, open porosity and class of mortar [3] of the different specimens of the ready-mixed earth mortar.

Specimens	Method	Bulk density [kg/dm^3]	Open porosity [%]	Class [3]
Prismatic	Geometric	1.77 ± 0.02	-	1.8
	MIP	1.78	31	1.8
On brick	MIP	1.99	31	2.0
Plaster on brick masonry	MIP	1.81	30	2.0
Plaster on rubble stone masonry	MIP	2.02	34	2.2

All the MIP measurements were obtained by one test only for each specimen. Therefore, they do not result from an average, as for all the other tests.

The open porosity of the earth mortar presents similar values for different specimens of the same mortar analysed; the same results occurred for dry bulk density, presenting however, classes that vary between 1.8 and 2.2, defined by DIN 18947 [3]. There is a percentage variation of only 1 % between the bulk density values obtained by the geometric method and the MIP. Although all the analysed specimens were made with the same mortar, there is a variation on the bulk density determined by MIP for each type of specimen. The plaster applied on rubble stone masonry presents a variation on bulk density of 13 % in comparison to the prismatic specimens and a variation on porosity of 10 %. These results were not expected, since the masonry stone does not present high water absorption. The mortar applied on to brick in laboratory, presents a variation of 12 % in comparison to the prismatic specimen while the plaster on brick masonry, in outdoor conditions, presents a variation of only 2 %. These differences of variation of the specimens of the same mortar applied on the same brick support can be justified by different drying conditions of the specimens (outdoors and in laboratory), which may also change the microstructure of the mortar specimens.

Earth mortars usually have open porosity of 20 – 30 %, according to Röhlen and Ziegert [16]. All the analysed specimens of the ready-mixed earth mortar present open porosity close to that range.

Lima et al. [10] obtained, geometrically and with the same type of moulds, bulk densities of 1.84 – 1.96 kg/dm^3 of earth mortars with different volumetric ratios and without fibres (Table 1). The mortar analysed in the present study shows lower bulk density. Normally, the fibres increase their volume when wetted and, after drying, regain their initial volume [42], which may justify the density and porosity presented by the ready-mixed earth mortar analysed.

Again, geometrically and with the same type of moulds, Lima and Faria [20] obtained bulk density of 1.66 – 1.91 kg/dm^3, for earth mortars with fibres (Table 1). These values are similar with the values obtained in the present study, except the mortar applied on hollow brick in laboratory and the plaster applied on the concrete block masonry wall, that present higher bulk density.

Santos et al. [21] analysed a ready-mixed earth mortar produced by the same company (EMBARRO) with a clayish earth from the same pit and supposedly similar formulation (Table 1), but produced in laboratory controlled conditions and obtained the same bulk density (by geometric method) and the same open porosity obtained by the mortar analysed in the present study, evaluated by the same method. It can be concluded that, for these similar ready-mixed earth mortar, the different conditions of production of mortars did not influenced their bulk density and porosity.

For earth mortars with different percentages of fibres added (Table 1), Palumbo et al. [22] obtained a bulk density of 0.95 – 1.85 kg/dm^3. In the present study, all specimens of the earth mortar present bulk density in the same range of values obtained by Palumbo et al. [22], except the previously referred mortar applied on hollow brick in laboratory and the plaster of mortar applied on concrete block masonry, that present higher bulk density.

Gomes et al. [6] analysed earth-based mortars with a commercial kaolinitic earth, with and without addition of binders and fibres (Table 1), and obtained bulk density of 1.7 kg/dm^3 for mortar without additions, of 1.5 kg/dm^3 for mortar with addition of fibres, of 1.6 – 1.7 kg/dm^3 for mortars with addition of binders and of 1.5 – 1.6 kg/dm^3 for mortars with addition of fibres and binders. The mortar analysed in the present study shows higher bulk density for all specimens in comparison with all those mortars analysed by Gomes et al. [6].

Incremental mercury porosimetry curves for the different specimens of the same mortar that were analysed (prismatic specimen, mortar on brick and plasters applied in experimental walls) are plotted in Figure 6, presenting the pore size diameter, in µm, and each step of the mercury intrusion, in mL/g (Figure 6a) and each volume of pore, in % (Figure 6b), respectively.

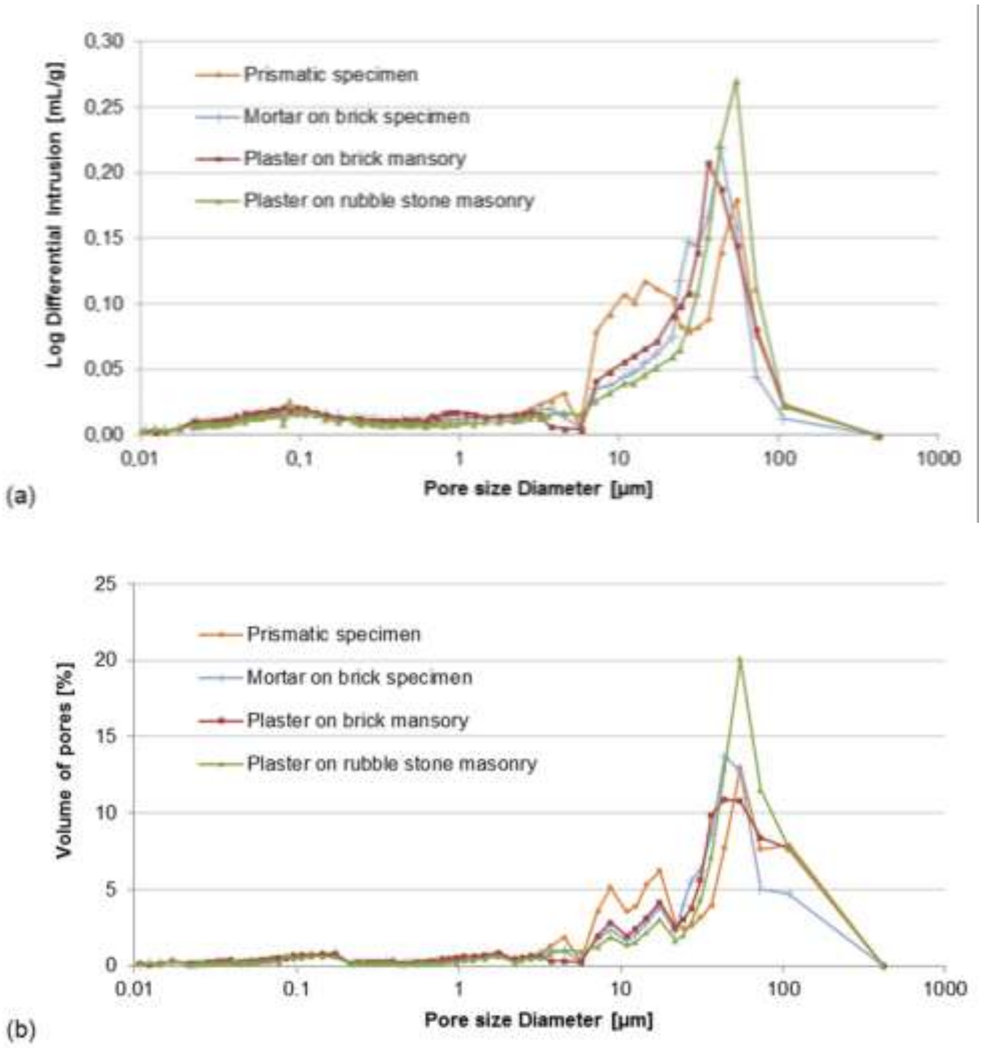

Fig. 6 Incremental mercury porosimetry curves: (a) differential intrusion and (b) volume of pores

The majority of the different specimens of earth mortar analysed presents a similar most frequent pore size diameter (in the range 36 – 55 µm) and differential mercury intrusion (in the range 0.20 – 0.27 mL/g). The only exception is the prismatic specimen, with a bi-modal frequent pore size diameter at 14 µm and 55 µm and differential mercury intrusion at 0.12 mL/g and 0.18 mL/g, respectively (Figure 6a). This differentiated microstructure may be justified by the absence of a porous substrate (the mould was metallic).

By the observation of Figure 6b it is possible to conclude that the occurrence of a main pore diameter at 55 µm is more evident for the plastering mortar applied on the rubble stone wall with 20 % of volume of pores. For the mortar applied on brick in laboratory and on the experimental wall, the main pore diameter at about 43.5 µm, occurs with 11 – 14 % of volume of pores. For the prismatic specimen, the occurrence of the main pore diameter at 55 µm was for 13 % of volume of pores.

The incremental mercury porosimetry curves of the mortar with and without the influence of the support shows that the latter has a notable influence on the mortar's microstructure. The application of the mortar on the brick and the rubble stone masonries produced an increase in the quantity of pores with larger diameter; simultaneously, decreases the quantity of pores with smaller diameters. When comparing the application on different supports, it is possible to conclude that the microstructure remains similar, although the mortar applied on the rubble stone wall presents a larger quantity of larger pores.

The microstructure presented by the same mortar applied on the same type of brick, in laboratory and plastering the wall, shows that this mortar' microstructure is not significantly influenced by the environmental conditions (in external conditions or in laboratory conditions). Nevertheless, the microstructure presents differences at pore sizes 3 – 7 µm.

Santos et al. [21] analysed the microstructure of a ready-mixed earth mortar from the same company (Table 1), with a clayish earth from the same region and a similar composition. These researchers analysed the microstructure of the mortar without influence of the support, with prismatic specimens and by the same procedure used in the present study and obtained an incremental mercury porosimetry curve similar with the curve obtained in the present study, with peak for pore diameters at around 10 – 100 µm and differential mercury intrusion of 0.10 – 0.15 mL/g. Similar results were obtained by Santos et al. [21] and in the present study prove the similarity of the composition of the analysed mortars and as previously mentioned, particularly the homogeneity of the microstructure of the earthen plasters when applied on different supports.

Gomes et al. [6] analysing earth mortars made with earths from old rammed earth walls without additions, obtained open porosity of 26 – 28 % – lower values in comparison with the open porosity by MIP obtained in the present study. When analysing earth-based mortars with volumetric ratio of 1:3 (commercial kaolinitic earth:sand) with and without the addition of hemp fibres and/or the addition of different percentages of binders (Table 1), these researchers obtained open porosity by MIP of 35 % for the mortar without additions, of 32 – 37 % for mortars with 15 % of binders and 38 % for mortar with 15 % of air lime plus 5 % of hemp fibres. The mortar analysed in the present study presents lower open porosity determined by the same method, in all specimens analysed, except in the case of the plaster applied on the rubble stone wall, which presents open porosity in the same range of the mortars with 15 % of binders analysed by Gomes et al. [6]. With regards to the microstructure, Gomes et al. [6] obtained main pore sizes around 108 – 109 µm for earth-based mortars both without and with addition of fibres and binders, much larger (almost double) than the ones of the present study. The use of a different type of clay, which may be slightly more expansible than the illitic clay used in the present study which may lead to the occurrence of larger pores. The chemical reactions that occur between the binders used as stabilizers and the other constituents of the earth mortars analysed by Gomes et al. [6] (clay and sand) may also have led to the occurrence of larger pores, compared to what occurred in the earth mortar analysed in the present study.

3.4. Ultra-sound velocity

The results of ultra-sound velocity in the specimens of mortar applied on brick in laboratory and in the plaster applied on the four experimental walls are presented in Figure 7 (average and standard deviation) [19].

For mortar applied on brick specimens and on brick masonry, the ultra-sound velocity is much higher. The decrease of 14 % of the ultra-sound velocity of the plaster applied on brick masonry, in comparison with the mortar on hollow brick, can be justified by the different drying conditions or the different application method. Comparing the ultra-sound velocity obtained by plasters applied on the experimental walls it is possible to concluded that the plasters applied in rubble stone, concrete blocks and adobe masonries, although presenting similar values, present ultra-sound velocity almost 40 % inferior (37 – 43 %) to the one obtained by the plaster applied on the brick masonry. The fact that stone and adobe are massive, compact walls may justify the variations obtained. The much higher thicknesses of the superficial face of concrete blocks, when compared to hollow bricks may also have an important influence. Comparing the ultra-sound velocity of the plaster applied on the brick masonry with the plaster applied on the concrete block masonry, the lower ultra-sound velocity of the plaster on concrete block can also be justified by the much higher water absorption under low pressure of the concrete blocks in comparison with brick (Figure 7). The higher water absorption of the concrete blocks may show a higher porosity of this masonry which in turn may have caused a fast drying of the plaster, possibly causing microcracking in the plaster thickness, thus justifying the low ultra-sound velocity presented by the plaster on the concrete block wall.

It can also be highlighted that the standard deviation is higher for mortar on brick specimens. The transducers being farther from each other turns more likely that the ultra-sound can reach the hollows of the individual bricks. The fact that the mortar layer on brick specimens is less thick in comparison to the plasters on the brick masonry wall may justify the difference.

Using the same methods, Faria et al. [23] analysed the ultra-sound velocity of air lime mortars with volumetric ratio of 1:2, with partial substitution of the air lime by a kaolinitic clayish earth (Table 1). These researchers obtained ultra-sound velocities of 918 – 1016 m/s for plasters applied on brick, and 551 – 775 m/s for plasters applied on rammed earth. In the present study, the plasters applied on brick in laboratory and on experimental walls present higher ultra-sound velocity, in comparison with Faria et al. [23], while the remaining plasters present lower ultra-sound velocity. When comparing the results of plasters applied on rammed earth obtained by Faria et al. [23] it is possible to conclude that once again, the plasters applied on hollow brick and on the brick masonry present higher ultra-sound velocity, while the remaining plasters present values in the same range. Nevertheless, it is important to refer that the mortars analysed by Faria et al. [23] were not protected from the incident rain. It is possible to conclude by comparison of these results, that the earth mortar applied on adobe and on brick masonries present similar result than the air lime mortar with earth, showing that the earth mortars may present compactness similar to conventional air lime-based mortars.

3.5. Surface hardness by durometer and sclerometer

The surface hardness by durometer and sclerometer (average and standard deviation) can be observed in Figure 7.

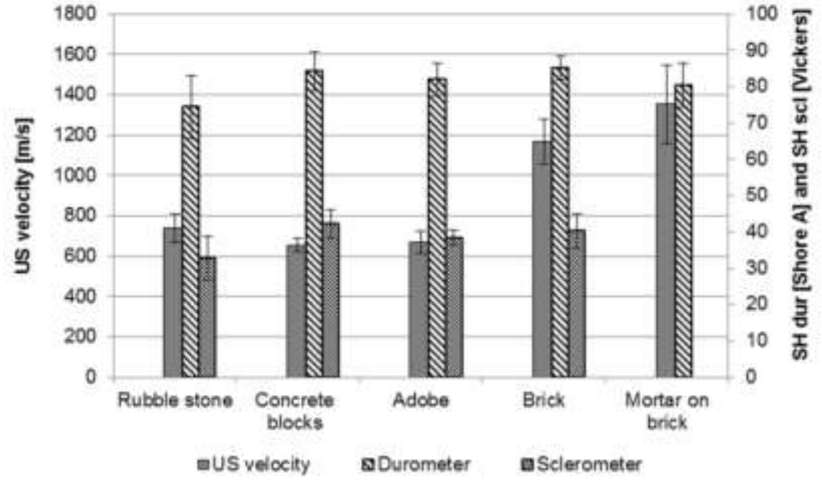

Fig. 7 Surface hardness by durometer (SH dur), sclerometer (SH scl) and ultra-sound velocity (US velocity) of the plasters on the masonry test walls and on specimens of mortar on brick

From Figure 7 it can be noticed that the surface hardness by durometer and sclerometer, although in different scales, indicates the same tendency, meaning that it does not change much with the type of support, application and drying conditions. The plasters applied on concrete blocks, adobe and brick walls present surface hardness about of 8 – 14 % higher than plaster applied on rubble stone masonry, which is within the range of standard deviation.

The pendular sclerometer test generates a high impact on the surface of the plasters applied on the masonries. This impact is generally enough to cause the detachment of plasters when adherence is not efficient [19]. Nevertheless, the sclerometer impact produced no degradation on any masonry plaster on the four masonry test walls. That indicates that the adherence of the plaster to all the four different types of masonry is efficient.

Santos et al. [15] analysed earth-based mortars with an unwashed and with a washed siliceous sand without and with low addition of CL and NHL3.5 (Table 1). These researchers analysed the surface hardness of the mortars and obtained 69 – 79 Shore A by durometer and 38 Vickers by sclerometer, for unstabilized earth mortars, and 50 – 70 Shore A and 25 – 42 Vickers, for earth-based mortars with addition of CL and NHL. The ready-mixed earth mortar analysed in the present study presents surface hardness by durometer slightly higher than the unstabilized mortars analysed by Santos et al. [15] and present surface hardness by sclerometer in the same range for the same mortars. When comparing the surface hardness obtained by earth mortar analysed in the present study with earth-based mortars with CL and NHL analysed by Santos et al. [15] it is possible to conclude that the earth-based mortars with addition of binders present lower surface hardness by durometer and sclerometer. These values show that the addition of binders does not improve the surface hardness of mortars. Nevertheless, opposing the mortar analysed in the present study, the earth-based mortars analysed by Santos et al. [15] were not protected from the incident rain, which may justify the low resistance of these mortars.

Faria et al. [23] analysed, by same methods, the surface hardness of air lime mortars applied on an experimental rammed earth wall outdoors (Table 1) and obtained a surface hardness by durometer of 70 Shore A and by sclerometer of 80 Vickers. In the present study all plasters of earth mortar present superficial hardness by durometer higher than the values obtained by Faria et al. [23] but, on the other hand, present lower superficial hardness by sclerometer. It was expected that air lime mortars would present higher surface hardness in comparison to earth mortars, due to a possible greater binding force of the lime. However, this is only true for the surface hardness by sclerometer. Nevertheless, when comparing results obtained outdoors consideration must be taken on the influence that different hygrothermal conditions may have had when the tests were performed.

To restore the cohesion of old air lime mortars Tavares et al. [25] analysed the use of consolidators (Table 1) and obtained surface hardness by durometer of approximately 59 – 68 Shore A and by sclerometer of 33 Vickers. The ready-mixed earth mortar analysed in the present study applied in the four experimental walls in outdoor conditions and applied in hollow brick in laboratory conditions, present a higher surface hardness by durometer. The low surface hardness obtained by Tavares et al. [25] may be related to a greater degradation of the old lime mortars analysed.

3.6. Sphere impact test

The results of sphere impact (average and standard deviation) of the plasters applied on experimental walls can be observed in Figure 8.

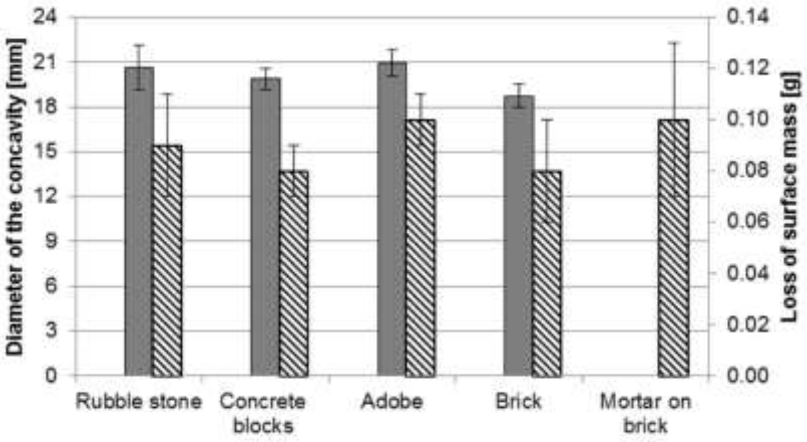

Fig. 8 Diameter of the concavity caused by sphere impact and mass loss by lack of cohesion

The plaster presents good deformability and good adherence when the diameter of the concavity is high, no cracking or loss of adhesion occurs. None of the plasters applied to the four experimental walls present cracking. The diameter of the concavity is similar for all plasters (between 19 and 21 mm) presenting the plaster applied on brick the smallest diameter. The low concavity presented by the plasters induces a good surface strength, which has already been demonstrated by the results of surface hardness by durometer and sclerometer.

By indirect testing – impact of the pendular sclerometer, sphere impact and ultra-sound tests – the adhesion of the earth plaster to the masonries proved to be efficient.

Santos et al. [15] when analysing earth-based mortars with and without the addition of the CL and NHL3.5 applied on an experimental brick wall outdoors (Table 1) obtained a concavity diameter of 17 – 24 mm, which is in the range obtained in the present study. These results show a good deformability and surface strength of the ready-mixed earth mortar analysed in the present study. Without addition of binders it presents sphere impact values in the same order of magnitude as mortars with addition of CL and NHL. When compared to earth plasters without addition of binders, it is possible to conclude that the addition of low amount of binders to earth plastering mortars does not change the deformability of the plasters.

Veiga et al. [24] analysed plasters based on several binders and additions (natural pozzolan and artificial pozzolans) applied on exterior renders (Table 1) and obtained diameters of the concavity of 10 – 16 mm, values lower than those obtained in the present study. These results were expected given the greater deformability of earth plasters compared to the deformability of common binder renders.

3.7. Surface cohesion

Figure 8 presents the surface cohesion (average and standard deviation) of the mortar applied on brick, in laboratory, and the plasters applied in the experimental walls in outdoor conditions.

All specimens of the mortar, in external conditions and in laboratory conditions, present similar loss of surface mass (in the standard deviation range). This demonstrates that the application of the plasters in external conditions or in laboratory conditions does not influence the surface cohesion of the mortar. However, some variation occurred in the results. The mortar on hollow brick and the plaster applied in adobe masonry present higher loss of surface mass and this shows a lower surface cohesion. The plaster applied in rubble stone masonry presents loss of surface mass 10 % lower and the plaster applied in concrete blocks and brick masonries 20 % lower in comparison to the plasters applied in adobe masonry and on hollow brick.

Santos et al. [15] on earth-based mortars with low addition of CL and NHL3.5 (Table 1), obtained loss of surface mass of 0.2 – 0.5 g. These values are higher than those obtained in the present study. It is possible to conclude that a low addition of binders to the earth mortars may not improve the surface cohesion of mortars. It is also important to remember that the earth-based mortars analysed by Santos et al. [15], although applied in external conditions which are similar to the mortar of the present study, do not have any protection from the incident rain.

Drdácký et al. [26], analysing air lime mortars (Table 1) by the same method but using a plastic tape with 25 mm width and 160 mm in length, obtained loss of surface mass of 0.017 – 0.020 g, values slightly higher than those obtained in the present study. These values demonstrate that the earth mortar analysed in the present study presents a good surface cohesion whatever the masonry on which is applied.

4. Conclusions

The earth plaster applied on the different masonries presents a good aesthetic appeal concerning its colour and texture, and do not need to be coated by a paint system. Not requiring a paint system, further consumption of resources is eliminated, making the earth plaster more eco-efficient, although less protected.

The earth mortar plastering different types of masonries present some differences but it was very easy to apply and proved to be efficient and durable when protected from rain. Although the application of unstabilized earth mortars as external plaster (render) is not recommended, due to its vulnerability in contact with water, the ready-mixed earth plastering mortar analysed in the present study shows a good behaviour when applied in outdoors but protected conditions. This protected outdoor exposure can simulate an earth render applied in a wall protected from rain or an earth plaster applied indoors but with aggressive cyclic changes of temperature, relative humidity and erosion that can frequently be found indoors, in private or public buildings.

Therefore, the results achieved by different tests show that this type of plaster can be applied on historic and earthen-based masonries but also that the application can be efficient on other types of masonry, extending their range of application to current hollow brick and concrete block masonries. So, without jeopardizing ecological aspects, the advantages of earthen plasters are also technical, reasons that can support more frequent applications of this type of eco-efficient mortars.

It is considered that the evaluation of the effects of natural exposure of the plasters after only six months only allows evaluating the first effects of the plasters degradations. Therefore, it is considered important and interesting to evaluate the effect of natural weathering with protection from rain for a longer period.

The results obtained in the present study refer to the use of a single ready-mixed mortar, formulated with a specific clayish earth, sand and fibres. In the future it is important to analyse the influence on physical-mechanical properties of earth plasters formulated with other types of clayish earths, type and content of sand and fibres.

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Declaration of interest: None

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