Experimental characterization of an earth eco-efficient plastering mortar

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ABSTRACT

Earthen plastering mortars are becoming recognized as highly eco-efficient. The assessment of their technical properties needs to be standardized but only the German standard DIN 18947 exists for the moment. An extended experimental campaign was developed in order to assess multiple properties of a ready-mixed earth plastering mortar and also to increase scientific knowledge of the influence of test procedures on those properties. The experimental campaign showed that some aspects related to the equipment, type of samples and sample preparation can be very important, while others seemed to have less influence on the results and the classification of mortars. It also showed that some complementary tests can easily be performed and considered together with the standardized ones, while others may need to be improved. The plaster satisfied the requirements of the existing German standard but, most importantly, it seemed adequate for application as rehabilitation plaster on historic and modern masonry buildings. Apart from their aesthetic aspect, the contribution of earthen plasters to eco-efficiency and particularly to hygrometric indoor comfort should be highlighted.

Subject headings from the ASCE's Civil Engineering Database

Mortar; Prefabrication; Test procedure; Standardization; Classification

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Introduction

Mortars are building products that are widely used in construction, principally being applied as rendering and plastering systems to protect the walls. While renders have to resist the action of rain water, plasters must contribute to the indoor air quality and comfort. Therefore plastering mortars must fulfill predetermined requirements.

After being neglected for decades, earth-based plastering mortars are nowadays becoming recognized as highly eco-efficient (Maddison et al., 2009; Darling et al., 2012). When compared to other types of mortars the sustainability of earth mortars is well known, mainly in terms of embodied energy (Swan et al., 2011). In fact, this type of mortar does not contain binders that have to be specifically produced and thus involve stone mining, transport and energy consumption. Melià et al. (2014) compared the environmental impacts of earthen plasters with those of conventional plasters based on common binders (like cement or hydraulic lime) using the LCA methodology. Their research showed that earth plasters outperformed the others with respect to all the indicators considered: cumulative energy demand, greenhouse gas protocol, ecological footprint and ReCiPe indicators (Melià et al., 2014). Aesthetic aspects, like color and texture, were also recognized. However, the technical characteristics and efficiency of these mortars has not often been scientifically proved; their technical efficiency needs to be evidenced by testing.

Compared to other types of earth-based products, as the case of earth blocks that have been deeply studied (Danso et al., 2014; Cagnon et al., 2014; Silveira et al., 2014), and other types of plastering mortars, such as air lime-based products (Veiga et al., 2010; Faria et al., 2008), earth-based mortars have been characterized in very few scientific studies (Pkla et al., 2003; Azeredo et al., 2008; Hamard et al., 2013; Delinière et al., 2014). There are few codes and standards for earth building materials (Swan et al., 2011). The recent German standard DIN 18947 (DIN, 2013) is the first standard specifically devoted to earth mortars. It defines some requirements and test methods. Many test methods are based on parts of the EN 1015 standard, developed for masonry mortars, mainly hydraulic binder-based, while others are specific to the DIN standard (DIN, 2013). Delinière et al. (2014) have recently applied this standard to characterize five ready-mixed earth plasters.

The experimental study presented in this paper involved a ready-mixed earth plastering mortar based on natural earth, sand and plant fibers. The dry ready-mixed product was characterized in the laboratory. The same ready-mixed product was used to produce two sets of mortars. The first was prepared in the field with current mechanical equipment while the second was prepared in controlled laboratory conditions. The mortar prepared on site was used to plaster an experimental brick masonry wall that was being non-destructively tested (Faria et al., 2014), and a portion was reserved. Both mortars were characterized in the fresh state and measurements included drying shrinkage. Samples with different dimensions and methods of preparation were produced in the laboratory. The wall plaster and the samples were tested. Characterization of the hardened mortar included visual observation of the plaster applied to the brick masonry test wall and several tests performed on mortar samples to evaluate the mechanical, physical and microstructural properties of the mortar. Hygrothermal properties of the hardened mortars were also studied (sorption–desorption isotherms, vapor diffusion and thermal conductivity). The characterization and the test procedures were based on the German standard (DIN, 2013) but also included other standards and specific test procedures implemented by the authors. The influence of differences in the dimensions of samples and the methods for preparing them were assessed. The characteristics of the plaster are presented and, whenever possible, compared with the DIN (DIN, 2013) requirements and with other studies (Delinière et al., 2014; Gomes et al., 2012; Veiga et al., 2010). The aim is to contribute to the setting up of test procedures, including the validation of existing ones and the development of complementary procedures to characterize earth plasters. These indicative results should be useful for a future international standard for earthen plastering mortars.

Materials and methods

Materials

The experimental study presented in this paper was carried out with a ready-mixed earth plastering mortar from the Embarro company (Portugal and Spain), based on natural clayish earth and siliceous sand, both from the Algarve region (South Portugal), and cut oat fibers 1-2 cm long. The ready-mixed mortar was mechanically produced on site using a Putzmeister MP25 mixing and pumping equipment. The same equipment was used for the application of mortar as a plaster on an experimental hollow brick masonry wall having a surface area of 2.2 m x 1.8 m with rain protected exposure to the outdoor environment (Fig. 1). A portion of this mortar was transported to the laboratory (30 m distance – 2 minutes), where it was tested in fresh state conditions and samples were prepared: prismatic samples 40 mm x 40 mm x 160 mm were prepared in metallic molds and a 15 mm-thick mortar layer was applied to the surface of ceramic hollow brick of surface area of 29.5 cm x 19.5 cm (Fig. 1). The same ready-mixed mortar product was mixed in the laboratory for 5 minutes with a mixer blade (commonly used on site), using the same water content as for the on-site mortar. It, too, was tested in fresh state conditions and samples were prepared: disk samples 90 mm in diameter and either 15 mm or 20 mm thick were prepared in PVC molds over a polyethylene base and rectangular samples with 200 mm x 500 mm surface and 15 mm thick were prepared in metallic molds (Fig. 1). All the samples were manually compacted and leveled. The prismatic samples were de-molded when hardened and all the samples were allowed to reach equilibrium in controlled environmental conditions at 20±3°C and 65±5% relative humidity (RH).

Methods

Characterization of ready-mixed product and fresh state mortar

The dry ready-mixed mortar product was observed visually and characterized in terms of loose bulk density, based on EN 1097-3 (CEN, 1998c), dry particle size distribution, based on EN 1015-1 (CEN, 1998/2006) and by X-ray diffraction test (XRD). XRD was carried out with a Phillips diffractometer with Co Kα radiation, speed of 0.05 º/s and 2θ ranging from 3 to 74. Two types of fractions were analysed: a fraction designated as fine fraction, which has a higher binder concentration and was obtained from the fines of the ready-mixed product passing a 106 µm sieve and a fraction designated as global, obtained by grinding the ready-mixed product as collected, to pass in the 106 µm sieve.

The two batches of mortar were tested by: flow table consistency, based on standard EN 1015-3 (CEN, 1999/2004/2006); bulk density, following standard EN 1015-6 (CEN, 1999/2006a); air content, according to standard EN 1015-7 (CEN, 1998b); and water content, determined by weight loss after oven drying.

The laboratory mortar was also tested for water retention based on draft standard prEN 1015-8 (CEN, 1999). To determine water retention, the weight increase of filter papers in contact with the fresh mortar specimen for 5 minutes was considered, in relation to the mortar solid and liquid compositions. Consistency was assessed also by penetrometer, based on standard EN 1015-4 (CEN, 1998a), and by the slump occurring in the flow table test sample. For the latter test, the slump of the mortar specimen was determined by the difference between the height of the mold and that of the highest point of the slumped test specimen.

Drying shrinkage

For the mortar mixed on site, linear drying shrinkage was determined on the basis of standard DIN 18947 (DIN, 2013) by the linear geometrical length reduction due to drying of six mortar samples 40 mm x 40 mm x 160 mm, assessed when they were de-molded. For the laboratory mortar, shrinkage was determined by the geometrical reduction of the surface of three 200 mm x 500 mm mortar samples 15 mm thick when hardened on metallic molds, compared with the dimensions of the molds.

Surface cohesion and dry abrasion resistance

The superficial cohesion and dry abrasion resistance were determined to assess the surface resistance and the eventual necessity for surface hardening (Röhlen and Ziegert, 2011). Superficial cohesion was determined by the weight increase of an adhesive tape 70 mm x 50 mm, after it had been pressed with constant intensity on the surface of the samples of mortar layer on ceramic brick, using the method of Drdácký et al. (2014), which expresses the loss of particles from the surface of the mortar. The average and standard deviation of results obtained with six adhesive tapes applied in two bricks was used.

Dry abrasion resistance was determined according to DIN 18947 (DIN, 2013), by the weight loss of mortar samples after 20 rotations of three different circular polyethylene brushes 65 mm in diameter, applied to the sample surface with a pressure of 2 kg. Samples with mortar on hollow brick and samples of 90 mm diameter and 20 mm thickness were tested.

Mechanical characterization

The mechanical characteristics were evaluated using the six prismatic, 40 mm x 40 mm x 160 mm samples. The dynamic modulus of elasticity was determined based on standard EN 14146 (CEN, 2004), defined for natural stone, using a Zeus Resonance Meter. The flexural and compressive strengths were determined according to standards DIN 18947 (DIN, 2013) and EN 1015-11 (CEN, 1999/2006c) using a Zwick Rowell Z050 machine, with load cells of 2 kN, for bending loads and 50 kN for compression.

The adhesive strength was determined with the pull-off adhesion test equipment PosiTest AT-M and pull-head plates 50 mm in diameter, based on standards DIN 18947 (DIN, 2013) and EN 1015-12 (CEN, 2000).

Sorption–desorption isotherms and vapor diffusion

Water vapor permeability of the mortar was determined according to DIN 18947 (DIN, 2013), EN 1015-19 (CEN, 1998/2004), EN ISO 12572 (CEN, 2001) and EN 15803 (CEN, 2009b) using the 90-mm-diameter, 20-mm-thick laboratory mortar samples. The wet method was used and the mortar specimen systems were placed in a climatic chamber at 23ºC and 40% RH.

The sorption of the mortar was determined with the 15 mm x 200 mm x 500 mm rectangular samples in metallic molds initially in equilibrium at 50% RH, according to DIN 18947 (DIN, 2013). A climatic chamber was programmed for 80% RH and the water vapor gain after determined periods of time in the climatic chamber (from 0.5 h up to 12 h) was assessed using a scale of 0.1 g precision. It was also determined by the same method but using a scale of 0.001 g precision with the 90-mm-diameter circular samples with thicknesses of 15 mm and 20 mm. The samples were water-vapor proofed with a polyethylene film on all surfaces except the top one. Both types of samples were made with the laboratory mortar. The desorption of the mortars, initially at equilibrium at 80% RH, was also determined. The climatic chamber was programmed for 50% RH and the weight decrease of the same samples after the same defined periods of time (from 0.5 h up to 12 h) were determined.

Capillary absorption and drying

The analysis of capillary rise is not a general requirement for non-stabilized earth mortars because they are intended to be applied for plastering the internal surfaces of walls or as renders but in areas protected from rain. Nevertheless, if the wall where the mortar is applied presents problems of capillary rise from the ground, the mortar may need to resist capillary absorption. Therefore the capillary absorption of the mortar was assessed, using EN 15801 (CEN, 2009a) and EN 1015-18 (CEN, 2002), by sequential weighing of the samples in contact with water to a height of 5 mm. Cubes 40 mm x 40 mm x 40 mm were cut from the prismatic samples, prepared and tested. Three different types of sample preparation were used: waterproofing the lateral faces of the cubic samples with an epoxy resin (resin), waterproofing the lateral faces with a polyethylene film (polyeth.), and without any material to waterproof the lateral faces (simple). A thin cotton cloth was placed on the bottom face of each sample, to avoid loss of fines, and was maintained by a thin elastic band. Each sample was placed inside a net basket and handled in the basket throughout the test (Fig. 2).

The capillary curve, with water capillary absorption by contact area with water in ordinate (in kg/m^2) and the square root of time in abscissa (in $min^{0.5}$), was plotted. The capillary coefficient, CC, which represents the initial capillary absorption, was determined by the slope of the most representative initial segment of the capillary curve.

The drying capacity of the mortar was assessed after samples had been wetted by the capillary test, as described by EN 16322 (CEN, 2014), but without complete saturation of the samples and in slightly different environmental conditions. The same samples, with the three types of lateral surface treatment mentioned above, were used. The drying curve was plotted with time in abscissa and water content in ordinate (weight / drying surface, in kg/m^2) and was used to calculate the drying rate (DR) and the drying index (DI). The DR represented the initial drying of the mortar and was determined by the slope of the initial portion of the drying curve for each type of sample preparation. A higher slope of the curve with respect to the horizontal axis reflected a high drying rate and faster initial drying. The DI represented the difficulty of achieving complete drying, in equilibrium with the environment, and was calculated following the simplified procedure presented by Grilo et al. (2014). It was determined for a period of 137 h.

All the tests were carried out in a conditioned room at 20±3ºC and 65±5% RH.

Thermal conductivity and microstructure

Thermal conductivity was determined using six prismatic samples and the samples with a 15-mm mortar layer on hollow brick, from the mortar mixed on site, and also using the 15 mm and 20 mm thick circular samples with and the 15 mm x 200 mm x 500 mm in metallic molds rectangular samples of the laboratory mixed mortar. Tests were performed after drying of the samples and at equilibrium with the laboratory conditions (20ºC, 65% RH). An Isomet 2104 Heat Transfer Analyzer was used with a 60-mm-diameter contact probe, API 210412. The equipment requires a minimum surface of 60 mm in diameter and a height of 15 mm. The prismatic sample type did not satisfy the recommendations for using the test equipment as the surface area of the contact probe exceeded the surface area of the sample.

The bulk density was geometrically determined according to DIN 18947 (DIN, 2013) and EN 1015-10/A1 (CEN, 1999/2006b) on the same prismatic samples, by means of a digital caliper and a 0.001 g precision digital scale.

The open porosity was determined by mercury intrusion porosimetry (MIP) and the same technique was used for the determination of pore size distribution. MIP was applied to specimen taken from among the prismatic samples, without the influence of the substrate, but also to specimen of the mortar layer on hollow brick produced in controlled laboratory conditions and samples of the plastering mortar applied on the experimental hollow brick masonry wall, conditioned in the exterior environment protected from rain. It was determined with a Micromeritics Autopore II mercury porosimeter. The masses of the test specimens were stabilized at 40°C and the mortar specimens were prepared so as to occupy the greater part of the 5 cm^3 bulb of the penetrometer volume. Testing began 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 (Grilo et al., 2014).

Results and discussion

Ready-mixed product and fresh state mortar characterization

The average value of loose bulk density and its standard deviation was 1.17±0.01 kg/dm^3. The ready-mixed product had a reddish color and the dry particle size distribution (average of three samples) is presented in Fig. 3.

The results obtained by XRD are shown in Fig. 4. The main minerals detected on ready-mixed product were quartz (SiO_2), K-Feldspar ($KAlSi_3O_8$), dolomite ($CaMg(CO_3)_2$), illite ($(K,H_3O)Al_2Si_3AlO_{10}(OH)_2$) and kaolinite ($Al_2(Si_2O_5)(OH)_4$). Other minerals were detected in low proportions, like calcite ($CaCO_3$) and hematite (Fe_2O_3). The fine fraction presented an increase of the proportions of clay minerals (illite and kaolinite), which is accompanied by k-feldspar, dolomite, calcite and hematite minerals.

The mortar (two batches, produced on site and in the laboratory) showed very good workability when handled. The plaster applied to the brick masonry wall (Faria et al., 2014) gave a reddish colored surface without shrinkage cracks. Some dispersed plant fibers could be seen. The average values (and, whenever at least three samples were tested, the standard deviation) of fresh mortar properties are presented in Table 1.

From Table 1, it can be observed that the fresh state characteristics of the mortars mixed on site and in the laboratory were quite similar, namely in terms of flow table consistency, bulk density and water content, despite the different equipment and conditions used for the mortar production. It is probable that the slightly higher air content and lower bulk density of the mortar mixed on site were due to the mechanical equipment that produced (and projected) the mortar.

Another fact that could have influenced the fresh state characterization was the time that elapsed between the contact of the clayish mortar product with water and the moment the tests were performed. In fact the mortar mixed on site was prepared and applied as plaster on several walls before being transported to the laboratory and tested. However, tests performed on samples from both the site and the laboratory batches did not reveal differences that could be directly attributed to that situation. This is very positive because it indicates good stability of the product when fresh.

Compared with earth mortars characterized by Gomes et al. (2012), the mortars considered in the present study had higher bulk density. When the consistency, wet bulk density and water content of the earth mortar tested here were compared with those tested by Delinière et al. (2014), the results were observed to be in the same range.

Drying shrinkage

The average and standard deviation of shrinkage measured on samples 40 mm x 40 mm x 160 mm was 0.21±0.08%. In the case of 200 mm x 500 mm laboratory rectangular samples 15 mm thick the average and standard deviation length changes of the shorter and longer sides of the rectangle were 0.32±0.00% and 0.58±0.23%. As these samples were not de-molded, it was harder to measure shrinkage in this case than for prismatic molds. It seemed that shrinkage was proportional to the measured dimension and, for that reason, another mold was filled with laboratory mortar but only one sample was tested, using a film-faced plywood mold 40 mm x 40 mm x 600 mm generally used for testing earth for building purposes and following the Alcock test (Gomes et al., 2014). Drying shrinkage was 0.61% and no crack was observed inside the mold. No cracking due to drying shrinkage was observed on the plaster applied to the experimental wall. The drying shrinkage was very low regardless of the samples used, including the plaster applied to the experimental wall. The shrinkage measured on the prismatic samples, according to DIN 18947 (DIN, 2013), was well beyond the maximum of 3% defined for mortars with fibers. Comparison with the results obtained with samples of other dimensions suggests that the shrinkage increases in direct relation with the length of the sample.

Surface cohesion and dry abrasion resistance

The cohesion test was easily performed and allowed the superficial loss of material to be assessed quantitatively, by weighing. It was 0.10±0.03 g.

It seems that, even if a precision scale is not available, the visual observation of the material sticking to the adhesive tape can be qualitatively compared (Fig. 5). In real conditions, this easy test can, therefore, be used for comparison between plasters and between different areas of the same plaster. Comparing the results obtained by Drdácký et al. (2014) for lime mortars using the same test methods, it is possible to conclude that the loss of material obtained with the clayish plaster is higher, showing a lower surface cohesion.

The abrasion relief formed on disk samples with the three brushes can be seen in Fig. 6. The soft brush, when pressed, exceeded the diameter of the disc. As the abrasion with that brush was almost inexistent, it could not be measured with the mortar on brick sample because of the scale precision.

The average and standard deviation of weight loss by abrasion on circular mortar samples and on mortar-on-brick samples after testing with hard, medium and soft brushes are presented in Table 2. The standard DIN 18947 (DIN, 2013) defines two classes, SI and SII, for mortars considering their weight loss by abrasion and their lower limits are also given in Table 2.

The differences of weight loss by abrasion of the mortar obtained with different brushes are noteworthy. With the soft brush, the mortar would be classified in class SII, while with the other two brushes the mortar does not meet the standard requirement. Bearing in mind that DIN 18947 (DIN, 2013) only defines a plastic brush, it seems that the hardness of the brush should be defined with more precision. The DIN standard also defines that, instead of measuring the weight loss, the disaggregated material should be weighed. That procedure would appear to be less accurate because, due to the abrasion of the brush, some of the material would be scattered and, therefore, it would be difficult to gather and weigh the totality.

Mechanical characterization

The average and standard deviation of the dynamic modulus of elasticity (Ed), flexural and compressive strength (FStr and CStr), and adhesive strength (AStr) of the mortar are presented, together with the lower limits of DIN 18947 (DIN, 2013) strength classes SI and SII, in Table 3. The fracture pattern of the adhesion test was an adhesive rupture at the interface between mortar and brick, effectively representing the adhesive strength.

The results presented in Table 3 show that this mortar can be classified as SI because its flexural strength is not less than 0.3 N/mm^2, its compressive strength is not less than 1.0 N/mm^2 and its adhesive strength is not less than 0.05 N/mm^2 (DIN, 2013). Compared with earth mortars characterized by Gomes et al. (2014), the mortars analyzed in the present study have higher dynamic modulus of elasticity, flexural strength and compressive strength. Compared with five earth mortars characterized by Delinière et al. (2014) the tested mortar presents flexural and compressive strengths that are lower (though only slightly). Nevertheless the mortar tested has a higher adhesive strength, which may show the influence that different supports can have on this test. In fact, not only the support but also its preparation may have a huge influence on results (Delinière et al., 2014). Different, simple tests may be considered to assess adhesion, such as the one established by Hamard et al. (2013), which can be easily applied on site to evaluate the compatibility of plasters with the substrate.

Veiga et al. (2010) suggest a range of mechanical characteristics of plastering mortars to ensure compatibility with historic masonry: dynamic modulus of elasticity 2000-5000 N/mm^2, flexural strength 0.2-0.7 N/mm^2 and compressive strength 0.4-2.5 N/mm^2. Although the range was defined for lime-based mortars, it seems acceptable that the same range should be also considered for plastering mortars to be applied to other masonries with similar mechanical characteristics. It can be noted that the mechanical characteristics of the ready-mixed earth mortar are all within the suggested range.

Sorption–desorption isotherms and vapor diffusion

The water vapor resistance factor, µ, was 8.0±0.3 and the water vapor diffusion equivalent air layer thickness, Sd, was 0.16±0.01 m (average and standard deviation). The DIN 18947 (DIN, 2013) states that a value of 5 - 10 can generally be adopted for the water vapor resistance factor of earth mortars (dry and wet method, respectively). The mortar analyzed confirmed that assumption.

Cagnon et al. (2014) obtained values of µ between 3 and 6 with different types of earthen bricks, in a chamber at 50% RH and 20ºC. Although bricks and plasters were applied and tested with different thickness, a comparison of the results stressed the remarkable water vapor permeability of the ready-mixed plaster.

The water vapor weight gain and release are presented in Fig. 7. When comparing the adsorption of the mortar by the standardized rectangular sample with 1000 cm^2 surface area with the lower limits of classes defined by DIN 18947 (DIN, 2013) (WSI, WSII and WSIII) it can be seen that the mortar can be classified in class WSIII. Nevertheless, and despite the apparently different results obtained with the other samples, for a much smaller surface of 28.3 cm^2, the same class would be obtained for both types of samples with 90 mm diameter and 15 mm or 20 mm thickness. Although the rectangular samples show an initial increase on adsorption, their following behavior is parallel to that of the circular samples. There is no difference in sorption between circular samples, regardless of their thickness.

Concerning desorption, behavior is similar for the circular and rectangular samples, particularly during the first half of the test.

Capillary absorption and drying

The capillary curves of the mortar tested for each type of sample preparation is presented in Fig. 8, with the most representative segments of capillary absorption and their equations. As explained in Methods the slope of those segments represents the capillary coefficient.

The drying curve of the mortar for each type of sample preparation is presented in Fig. 9, with the segments of initial drying for the determination of the drying rate (DR).

The average and standard deviation of capillary coefficient, CC, drying rate, DR, and drying index, DI, of the mortar samples prepared in different ways – waterproofing of lateral surfaces with resin or polyethylene film and simple (without waterproofing) - are presented in Table 4.

The capillary test showed that the preparation of the samples (without lateral waterproofing or with polyethylene film or with resin) has an important influence on results. For that reason, it seems to be very important to define the sample preparation procedure if capillary requirements are considered. In terms of sample preparation, DR results show the same tendency as CC; simple samples and resin samples show the same tendency for DI and CC, while the samples with polyethylene present a different tendency.

The mortars without mineral binder and with resin preparation used by Gomes et al. (2012) presented a CC of 0.14 kg/(m^2.$s^{0.5}$) without fibers and 0.23 kg/(m^2.$s^{0.5}$) with hemp fibers; their DI was 0.11 without fibers and 0.13 with hemp fibers. The period of time for the determination of DI by Gomes et al. (2012) was not the same as that of the present study and, also, the samples of the present study were not totally capillary saturated before starting the drying test (for that reason, DI is not strictly comparable). Nevertheless, when comparing the mortars characterized by Gomes et al. (2012) with the ones of the present study, it can be observed that the latter have a much lower capillary coefficient (0.5 kg/(m^2.$min^{0.5}$) corresponding to 0.06 kg/(m^2.$s^{0.5}$)), meaning that the rising water progresses more slowly, but a higher drying index of 0.18, meaning that total drying is achieved later.

Thermal conductivity and microstructure

The thermal conductivity results (average and standard deviation for each type of sample) are presented in Table 5.

Independently of their type, all the samples had a value close to 0.9 W/(m.K), which seems to be interesting for non-thermal plasters. Considering a 2-cm-thick plaster and comparing it with a plaster with chemical binder (with thermal conductivity around 1.3 W/(m.K), the thermal resistance increase due to the earth plaster presented here would be 0.04 (m^2.K)/W.

Bulk density determined geometrically and from open porosity measured by MIP for the prismatic samples, and MIP determinations for the mortar layer on brick and the plaster on the outdoor protected experimental wall are given in Table 6.

The plastering mortar can be placed in class 1.8 in terms of dry bulk density (DIN, 2013) because the bulk density is between 1.61-1.80 kg/dm^3. The porosity determined by MIP is quite similar for the different types of samples of the same mortar.

Incremental mercury porosimetry curves for specimens of prismatic mortar, mortar on brick, and brick masonry plaster – for the whole range and only the lower part of the range - are plotted in Fig. 10. The pore size diameter is expressed in microns and each step of the mercury intrusion is in ml/g.

It can be observed from the curves of Fig. 10 (a) that both the mortar plaster on brick masonry and the mortar on laboratory brick samples present almost the same microstructure in terms of most frequent pore diameter (approximately 40 µm) and differential mercury intrusion (approximately 0.20 ml/g). This shows that the mortar's microstructure is not influenced by the environmental conditioning (in outdoor protected conditions or in laboratory conditions) for the higher range of pores. The mortar specimen from a prismatic sample presents a quite different microstructure, with most frequent pore diameters at around 55 µm and 14 µm, with 0.18 ml/g and 0.12 ml/g respectively. This bi-modal microstructure of the mortar applied without the influence of a porous support, compared with samples of the same mortar but applied in contact with ceramic brick, shows that the support has a notable influence on the mortar’s microstructure. In fact the brick support increases the quantity of pores with larger diameter while decreasing the quantity with smaller diameters.

When the lower range of pores (Fig. 10b) is studied, two peaks can be observed: around 6 µm mainly for the specimen from the prismatic sample and around 0.1 µm for all samples. This is the range commonly recognized to have the most influence on the capillary absorption of building materials (Mindess et al., 1981). However, this statement is based on studies for cement-based materials and not specifically those on earth mortars. For the latter type of mortars, the influence of the microstructure needs to be studied in greater depth.

Conclusions

The workability achieved by both batches of the ready-mixed earth mortar was excellent. Results of flow table consistency, wet bulk density and drying shrinkage satisfied the requirements of DIN 18947 (DIN, 2013) for earth plasters even with different mixing procedures. These tests seem appropriate for fresh state characterization and demonstrate good stability of the characteristics with different types of mixing equipment.

The mortar presents good mechanical characteristics when compared to air lime mortars. It seems appropriate for application on historic walls (Veiga et al., 2010). The resistance to abrasion is an issue that it is important to address for this type of mortars but it is necessary to increase the detail of the test procedure mentioned in the DIN 18947 (DIN, 2013), namely in terms of the hardness of the brush used and the assessment of the loss of weight, for comparability.

The mortar showed a very high adsorption capacity, and also the ability to desorb all the water vapor adsorbed. The hygroscopic behavior of the mortar, and of similar mortars analyzed by other authors, leads to the conclusion that this type of earth mortars can indeed contribute to the hygrometric equilibrium and comfort inside buildings.

The capillary absorption measurement is not a common requirement for this type of mortars but it enables the assessment of their behavior to be broadened, which may be important for some applications and uses. The definition of the lateral waterproofing of the samples is crucial for comparison, as the results are more favorable when the lateral waterproofing seems more efficient. Drying capacity can also be easily assessed. The thermal conductivity does not seem as important for common plaster, where the layers are not thick.

The dry bulk density determined geometrically is quite reliable. The microstructure is also quite stable when the plaster is applied to different substrates (porous or metallic) and under different environmental conditions (protected exterior or laboratory).

The ready-mixed mortar tested fulfilled all the DIN 18947 (DIN, 2013) requirements assessed and showed an appropriate behavior when applied to a hollow brick test wall in protected outdoor conditions.

It is expected that the results will contribute to a more generalized use of earth mortars as plasters, or as renders in areas protected from rain, on historic but also on modern masonries. The implementation of an international standard, where test procedures and requirements were defined, would also help to achieve this goal.

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Figure captions

Fig. 1. Samples and tests performed.

Fig. 2. Capillary samples prepared with resin and cotton cloth (left) and with polyethylene film inside the net basket (right).

Fig. 3. Dry particle size distribution of the ready-mixed mortar product.

Fig. 4. X-ray diffraction of global and fine samples of the ready-mixed product (Q - quartz, F - K-Feldspar, D - dolomite, M – illite, K – kaolinite, C – calcite, H - hematite).

Fig. 5. Visual result of the cohesion test with material sticking to the adhesive tape.

Fig. 6. Abrasion relief of the circular mortar samples tested with brushes of different hardness.

Fig. 7. Sorption and desorption of mortar samples.

Fig. 8. Capillary curves of mortar samples with different preparation, representative segment of capillary absorption, their equation and correlation coefficient.

Fig. 9. Drying curves of mortar samples with different preparations, segments of initial drying, their equation and correlation coefficient.

Fig. 10. Incremental mercury porosimetry curves – whole range (a) and only lower part of the range (b).

Table 1. Characteristics of fresh mortars.

Fresh Mortar	On site	Laboratory
Flow table consistency [mm]	178.8±2.5	182.3±2.5
Slump by flow table [mm]	-	14.2
Penetrometer consistency [mm]	-	2.4±0.1
Wet bulk density [kg/dm^3]	2.03	2.11
Air content [%]	2.8	2.5
Water retention [%]	-	67.5±1.3
Water content [%]	20.1±0.1	19.4±0.3

Table 2. Weight loss by abrasion and standard lower limits.

∆Wt [g]	Ø9cm, 2cm			Mortar on brick		
	Hard	Medium	Soft	Hard	Medium	Soft
Average	18.1	3.9	0.3	11.2	4.5	-
StDv	3.1	0.5	0.0	2.2	0.5	-
SI (DIN, 2013)	≤1.5					
SII (DIN, 2013)	≤0.7					

Table 3. Dynamic modulus of elasticity, flexural, compressive and adhesive strength of the mortar (average and standard deviation) and standard lower limits.

Dry Mortar	Ed	FStr	CStr	AStr
	[N/mm^2]	[N/mm^2]	[N/mm^2]	[N/mm^2]
Average	3610	0.3	1.1	0.15
Stdv	128	0.0	0.1	0.03
SI (DIN, 2013)	-	≥0.3	≥1.0	≥0.05
SII (DIN, 2013)	-	≥0.7	≥1.5	≥0.1

Table 4. Capillary coefficient, CC, drying rate, DR, and drying index, DI, of the mortar (average and standard deviation).

Dry mortar	CC [kg/(m^2.min^{0,5})]			DR [kg/(m^2.h)]			DI [-]		
Prepar.	Resin	Polyeth.	Simple	Resin	Polyeth.	Simple	Resin	Polyeth.	Simple
Average	0.50	0.86	1.84	0.30	0.33	0.64	0.18	0.22	0.14
Stdv	0.06	0.04	0.34	0.01	0.02	0.07	0.01	0.02	0.03

Table 5. Thermal conductivity of mortars for different types of samples (average and standard deviation).

Sample	λ [W/(m.K)]				
	Ø9cm 1.5cm	Ø9cm 2.0cm	Rectangular 1.5cm	1.5 m on Brick	Prismatic
Average	0.8	0.9	0.9	0.9	1.0
Stdv	0.0	0.0	0.0	0.1	0.0

Table 6. Open porosity, bulk density and standard class of mortar on a prismatic sample, a plaster-on-brick sample and from the brick masonry plaster.

Sample		Bulk density [kg/dm^3]	Porosity [%]	Class (DIN, 2013)
Prismatic	Geometric	1.77 ±0.02	-	1.8
	MIP	1.78	31	
Plaster (MIP)		1.81	30	2.0
On brick (MIP)		1.99	31	