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Earth, gypsum and cement-based plasters contribution to indoor comfort and health

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Abstract. Indoor air quality is important for comfort and health of buildings inhabitants. The use of environmentally friendly building materials is also very important for sustainable and green buildings. In the present study, mechanical characteristics of five mortars were comparably analyzed: two unstabilized earth mortars, one earth-air lime mortar, one cement mortar and other gypsum mortar. The earthen plasters are nowadays commonly applied unpainted. The gypsum plaster system is composed by the base mortar and a finishing layer; it can be applied unpainted or painted. The cement plaster is generally finished with a paint system. Therefore, the adsorption and desorption capacities were assessed for all the plasters and the influence of the paint system was evaluated for the cement and gypsum plasters. Results show that the earth mortar stabilized with air lime presents lower mechanical strength, in comparison to all other mortars, and lower adsorption capacity, similar to the gypsum system. The unstabilized earth plasters present high adsorption capacity, in comparison to the cement and gypsum plasters. The paint system does not have significant influence on the adsorption capacity of the gypsum plaster but reduced that capacity on the cement plaster. These results demonstrate the important contribution that unstabilized earth plasters may provide as passive indoor hygrothermal buffers, in comparison to other plasters.

Keywords: Air lime, Clay, Desorption, Mechanical strength, Mortar, Sorption.

Introduction

Plasters are applied to coat, protect and decorate indoor walls and ceilings, having a significant surface area. Currently, with existing energy and environmental problems and people's ecological awareness, it is increasingly necessary to use renewable and/or environmentally friendly building materials, with low CO_2 emissions and embodied energy, which may also contribute to improve the comfort and health of inhabitants.

Around the world, cement-based construction is very common. About 900 kg of CO_2 are emitted into the atmosphere during the production of 1 ton of cement [1]. Cement, after water, is the second most consumed substance in the world by weight [1].

Earth plastering mortars present several technical and environmental advantages: the raw material is a natural and abundant local resource; without need of transportation because it should be a local material; it is inexpensive, easy to work, non-toxic, not renewable but reusable (when not chemically stabilized); with low CO_2 emissions to manufacture and apply as a building material and, consequently, low embodied energy. Relatively small amount of energy is necessary to produce earth plasters, compared to conventional plasters, namely based on cement because the production of this binder requires very high temperature [2]. Thus, earth plasters can significantly contribute to the sustainability of buildings.

Furthermore, earth plasters are becoming recognized by their high hygroscopic capacities, conferred by clays, which provide an important contribution to act as passive humidity buffers, adsorbing and releasing a significant content of water vapor, contributing to balance indoor relative humidity (RH) and temperature [3–11]. Minke [10] and Morton [11] refer that the earth can absorb and bind pollutants dissolved in water, due to the hygroscopic capacity of the clay. Thus, it is deduced that the pollutants in the water vapor can be captured by the earth plasters.

The RH inside the buildings should vary from 40 % to 70 %, promoting the comfort and health of its occupants. In this range of RH there is a reduction of the fine dust content in the air, the protection mechanisms of the skin against microbes are active, and the life span of many bacteria and viruses is reduced. The mucous membranes of buildings´ occupants can dry, which causes a decrease of resistance to colds and related diseases when inhabitants are exposed to RH < 40 %, particularly if this occurs for long periods of time [10,12]. On the other hand, RH > 70 % promotes discomfort, increase of rheumatic pains and fungus formation in poorly ventilated spaces. When inhabitants are exposed to these environments for long periods, it can cause several kinds of disease and allergies [10,12].

Thermal comfort can be improved by regulation of RH, since the temperature increase as the RH decreases. Maskell et al. [4] analyzed the mass change of clayish earth, lime and gypsum plasters when exposed to different RH and constant temperature, and Minke [10] presents the adsorption curves of clayish earth, lime-cement and gypsum plasters. Nevertheless, earth plasters characteristics are not often tested and analyzed in comparison to common plasters, especially as regards adsorption and desorption capacity.

In this study five plastering mortars are formulated, specimens are produced and tested for shrinkage, dry bulk density, dynamic modulus of elasticity, flexural and compressive strength: two are unstabilized earth mortars; one is an air lime stabilized earth mortar; another is a cement-based mortar; and the last one is a gypsum-based mortar.

Nowadays earthen plasters use to be applied unpainted to profit from their colors and aesthetic appearance and cement plasters are generally finished with a paint system. The tested gypsum plaster system is composed by a base mortar and a finishing layer; it can be applied unpainted or painted. Therefore, the adsorption and desorption capacities were assessed for all the plasters unpainted (the gypsum plaster included the finishing layer) and the influence of the paint system was evaluated for the cement and gypsum plasters. Therefore, these two plasters were tested for hygroscopicity also painted.

1 Materials and methods

1.1 Materials

In the present study five mortars were analyzed with different formulation. One mortar was produced in the laboratory. Four other mortars were pre-mixed mortars that were produced only by water addition to an incompletely known formulation. Table 1 presents the description of tested mortars and plastering systems (when applicable).

Table 1. Description of mortars analyzed.

Mortars	Type of mortar	Production	Description	Water content [%]
E_L	Earth-based	Formulated in laboratory	Composed by a reddish clayish earth (RCE) – illitic-kaolinitc clayish earth, fine (FS) and coarse (CS) sand with volumetric ratio of 1:3:1.5 and mass ratio of 1:3.04:1.78 (RCE:FS:CS)	10
Em	Earth-based	Pre-mixed (Embarro Company – Universal)	Pre-mixed Ep earth product, composed by a reddish clayish earth – ilitic-kaolinitc clayish earth – from Algarve region, 0–2 mm fine sand and cut straw fibers (proportions of each constituent are not exactly known)	15
E+CL	Earth-air lime based	Pre-mixed (Aldeias de Pedra company)	Composed with yellow clayish earth (YCE) – kaolinitic clayish earth, provided by Sorgila company, coarse sand (CS), limestone powder (LP) and addition of air lime putty (ALP) (proportions of each constituent are not exactly known – supplied ready-mixed)	20
Cm	Cement-based	Pre-mixed (Secil Argamassas company – RHP Manual Interior)	Pre-mixed cementitious Cp product (formulation not known)	14
Gm	Gypsum-based	Pre-mixed (Sival company – Project 2010)	Pre-mixed gypsum-based Gp product; the system includes a finishing gypsum layer with 1 mm thickness that was applied only on the hygroscopicity specimens (formulations not known)	43

Loose bulk density and particle size distribution of raw materials used in the formulation of mortars and of the pre-mixed mortar products were determined and presented by Santos et al. [13]. In short, the constituent materials and pre-mixed products have the following loose bulk densities: 1.36 ± 0.01 kg/dm^3 for RCE, 1.38 ± 0.00 kg/dm^3 for FS, 1.61 ± 0.00 kg/dm^3 for CS, 1.40 ± 0.01 kg/dm^3 for Ep, 1.50 ± 0.00 kg/dm^3 for Cp and 0.81 ± 0.01 kg/dm^3 for Gp.

A standard plastic paint was used to paint some of the cement and gypsum-based specimens.

1.2 Mortars preparation and specimens production

Em, E+CL and Cm mortars (pre-mixed mortars) were produced only by addition of the water content indicated by each producer (Table 1). The producer of the Gm mortar did not define the water content and, therefore, the water content of Gm and E_L mortars (Table 1) was defined by an experienced craftsman to assure good workability.

All mortars were prepared using a mixed blade to reproduce, as much as possible, the method carried out on a construction site: the dry materials were placed in a bucket; water was slowly added; initial mixing of 8 minutes, approximately, was carried out; removal of mortar adhered to the bucket walls; final mixing of 3 minutes [13].

E+CL mortar was prepared (as described before) one day before the production of specimens and was supplied ready-mixed. All the remaining mortars were produced on the same day that specimens were prepared. Santos et al. [13] characterized each mortar in the fresh state.

Different types of specimens were produced for each mortar:

- Prismatic specimens, 40 mm x 40 mm x 160 mm, prepared in metallic molds, filled in two layers mechanically compacted with 20 stokes each and manually levelled. These specimens were demolded after 7 days.
- Planar specimens, 200 mm x 500 mm x 15 mm, prepared in metallic molds, and manually compacted and levelled. These specimens were not demolded. The finishing gypsum layer was applied on the Gm mortar planar specimens 24 hours after the base mortar. The planar specimens of the Cm and Gm mortars were tested unpainted, painted with two layers of paint after 9 months in laboratory conditions and tested painted.

All specimens were maintained in laboratory conditions of 20 ± 2 ºC and 65 ± 5 % RH.

1.3 Methods

Shrinkage

Linear shrinkage was determined by the difference of the linear geometrical length of the prismatic specimens before and after drying for 7 days, according to DIN 18947 [14]. During drying and before the hygroscopic test, specimens were visually observed to assess shrinkage.

Dry bulk density, dynamic modulus of elasticity and flexural and compressive strengths

Mortars were characterized for dry bulk density, based on EN 1015-10/A1 [15], dynamic modulus of elasticity (Ed), according to EN 14146 [16] with a ZEUS XRM equipment, and flexural (FStr) and compressive (CStr) strength, according to EN 1015-11 [17] with a Zwick Rowell Z050 equipment. Load cells of 2 kN and 50 kN and velocity of 0.2 mm/min and 0.7 mn/min were used for flexural and compressive tests, respectively. Tests were performed with 6 prismatic specimens and the results of each mortar are its average. Mortars were characterized after 1 month, by dry bulk density, and 2 months, by Ed, FStr and CStr – except E+CL mortar that was characterized after 4 months to assure air lime carbonation.

Adsorption and desorption

The dynamic vapor adsorption and desorption of plasters were determined with three planar specimens, according to DIN 18947 [14]. The specimens were kept in the metallic molds to ensure that adsorption and desorption occurs only on the top exposed surface of the specimens. Mortars were characterized after 4 months, except E+CL mortar that was characterized after 6.5 months.

The specimens were stabilized in a climatic chamber at 50 % RH and 23 ºC, for about 24 h. After stabilization, the climatic chamber conditions were changed from 50 % to 80 % RH, initiating the adsorption phase. The specimens were weighed at the following intervals: 0, 1, 3, 6, 12 and 24 h.

After 24 h the chamber conditions changed from 80 % to 50 % RH, initiating desorption phase, that was assessed with the same time interval protocol used in the adsorption phase.

2 Results and discussion

2.1 Shrinkage

Linear shrinkage of mortars (average and standard deviation) is presented in Table 2.

Table 2. Linear shrinkage, dry bulk density, dynamic modulus of elasticity (Ed) and flexural (FStr) and compressive (CStr) strengths.

Mortars	Linear shrinkage [%]	Dry bulk density [kg/dm^3]	Ed [N/mm^2]	FStr [N/mm^2]	CStr [N/mm^2]
E_L	0.1 ± 0.0	1.77 ± 0.04	3781 ± 316	0.20 ± 0.06	1.01 ± 0.20
Em	0.2 ± 0.1	1.82 ± 0.02	4267 ± 139	0.25 ± 0.06	0.96 ± 0.10
E+CL	1.4 ± 0.8	1.78 ± 0.07	2977 ± 101	0.17 ± 0.04	0.51 ± 0.03
Cm	0.1 ± 0.1	1.79 ± 0.01	5571 ± 243	0.84 ± 0.11	2.84 ± 0.17
Gm	0.2 ± 0.1	1.22 ± 0.03	4006 ± 161	1.51 ± 0.11	4.15 ± 0.58

By visual analysis of the hygroscopicity test specimens the presence of cracks was not observed (Fig. 1a), except in case of E+CL mortar which specimens had some cracks in the center (Fig. 1b). E+CL mortar has the higher linear shrinkage, which justifies the presence of cracks in these planar specimens.

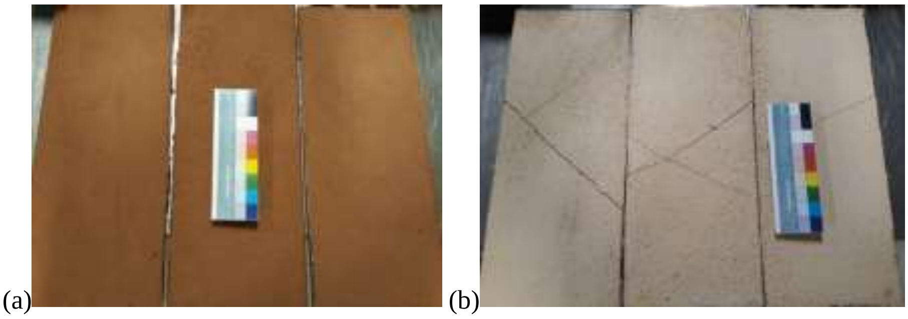

Fig. 1. Distinguish color and shrinkage in three planar specimens of Em (a) and E+CL (b) mortars.

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

Table 2 presents the dry bulk density, dynamic modulus of elasticity (Ed) and flexural (FStr) and compressive (CStr) strengths of mortars (average and standard deviation).

Some studies refer that the addition of natural fibers reduces shrinkage, dry bulk density and thermal conductivity [18,19] and eventually increases compressive strength [20]. But that should depend largely on the type and content of fibers [21]. Despite the presence of fibers, the earth mortar with fibers (Em) presents higher dry bulk density and lower compressive strength, compared to the other unstabilized earth mortar (E_L); however, the CStr values are very close. The Em mortar seems to have a good compactness and, therefore, lower porosity compared to the other analyzed earth mortar. However, this can only be further detailed through an analysis of the porous structure.

According DIN 18947 [14], the E_L mortar can be classified as class 1.8 and the Em mortar as class 2.0 of dry bulk density. Not considering that DIN 18947 [14] refers to unstabilized earth mortars only, the E+CL mortar can be classified as class 2.0. These mortars and the cement-based mortar present similar dry bulk density, while the gypsum-based mortar presents lower dry bulk density.

Dry bulk density of the mortars may be related to the loose bulk density of the raw materials and pre-mixed products (between 1.20–1.61 kg/dm^3) [13], which present similar values. The Gp is the exception and present lower loose bulk density (0.81 kg/dm^3) [13]. This can be justified by the lower dry bulk density of Gm mortar.

E+CL mortar presents the lowest strengths (Table 1). This reveals that the addition of air lime does not obligatory improve the mechanical strength of earth mortars. Similar results were obtained in previous studies: Santos et al. [22] concluded that the addition of 5 % of air lime in an illitic earth mortar (after 60 days) also decreased its mechanical strength; Gomes et al. [23] obtained similar results with air lime additions up to 15 % (after 90 days) in a kaolinitic earth mortar. Low contents of air lime seem to interrupt the clay matrix connection, without creating an air lime network strong enough to replace those clay connections [22,23][23][23][23][23]. In the present study, the same phenomena may have happened, although the content of air lime in the E+CL mortar is not known.

EN 998-1 [24] defines different classes for compressive strength, at 28 days, for plastering mortars: CS I for 0.4–2.5 N/mm^2; CS II for 1.5–5.0 N/mm^2; CS III for 3.5–7.5 N/mm^2 and CS IV for ≥ 6 N/mm^2. Although all the mortars were not tested at 28 days but at a higher age, earth mortars analyzed in the present study can be classified as CS I class and cement mortar as CS II, meeting the specifications defined by the pre-mixed product technical file. Although the standard [24] is not applied for calcium sulphate binder mortars, the Gm mortar could be also classified as CSII class. These results meet the requirements of mortars for interior and exterior plasters. Gm mortar meets the FStr and CStr defined by pre-mixed product technical file (FStr > 1 N/mm^2 and CStr > 2 N/mm^2) and by EN 13279 [25] (FStr of 1–2 N/mm^2 and CStr of 2–6 N/mm^2).

As expected, the earthen mortars (E_L, Em and E+CL) present lower mechanical strengths (Ed, FStr and CStr) when compared to hydraulic binder mortars (Cm and Gm), except for Em mortar Ed result. This is not necessarily negative if the application of these plasters on substrates with low mechanical properties is considered. In such cases, mortars should not exceed the characteristics of the substrates where they are applied in order to ensure long-term compatibility between the mortar and the substrate. If this compatibility is not verified, premature anomalies and detachment may occur. Other researchers concluded that earth plasters can be applied in different supports, for renovation or in new construction [26,27].

2.3 Adsorption and desorption

Fig. 2 presents the adsorption and desorption (average and standard deviation) of the plasters, unpainted and, for cement and gypsum-based plasters, also painted, and the limits of sorption classes defined by DIN 18947 [14]: WSI ≥ 35 g/m^2; WSII ≥ 47.5 g/m^2; WSI ≥ 60 g/m^2, after 12 hours.

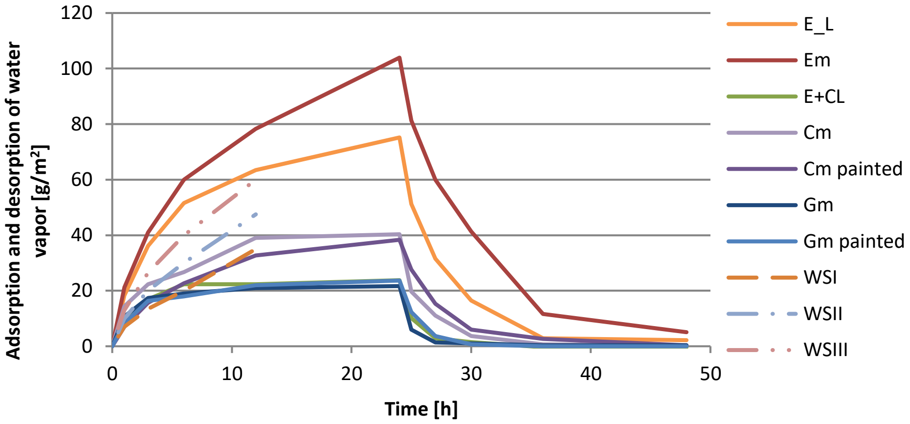

Fig. 2. Adsorption and desorption curves of plasters and sorption classes defined by DIN 18947 [14] (WSI, WSII and WSIII).

The unstabilized earth plasters (Em and E_L) present significantly higher adsorption and desorption capacity compared to plasters with common binders (cement, gypsum and even earth with added air lime). After 12 hours, the Em and E_L mortars present adsorption ≥ 60 g/m^2 and, therefore, are classified as WSIII class, by DIN 18947 [14]. Em and E_L plasters adsorb about 104 g/m^2 and 76 g/m^2 water vapor, respectively, after 24 hours, and the adsorption curves show an increasing trend at this time (Fig. 2). The presence of illitic clay can justify the higher sorption capacity of these plasters. Illitic clay is characterized by a significant water vapor absorption capacity [7], being only surpassed by montmorillonitic clay, which has a higher adsorption capacity than the illitic clay [28]. However, montmorilinitic earth mortars use to present very high shrinkage that enables its application [28].

The higher adsorption capacity demonstrated by Em plaster can also be due the presence of fibers, since fibers may increase the hygroscopicity, the water vapor permeability and the moisture buffering capacity of earth plasters [20,29]. Moreover, it is necessary to consider that the presence of fibers may also leads to mold growth [30]. For this reason, an adequate drying of plasters must be assured, promoting ventilation to avoid extended conditions of high RH, and prevent the proliferation of mold. Röhlen [31] showed that all earth mortars, with or without fibers, may have presence of fungi, since they can occur when the environment present high levels of humidity.

The adsorption of the Em and E_L plaster is not stabilized after 12 h and is still increasing up to 24 h (when the test stopped), contrarily to what happens with the earth stabilized with air lime, the gypsum and the cement-based plasters. That also confirms the important contribution that unstabilized earth plasters may provide as passive indoor buffers, in comparison to other plasters.

The analysis of the porous structure of the studied mortars may help to understand the differentiated adsorption of the mortars.

Em and E_L plasters also present a good desorption capacity, in comparison to the remaining mortars. However, these plasters present some desorption hysteresis of 3–5 %.

Comparing the results obtained with the cement plaster Cm, unpainted and painted (Fig. 2), it is possible to conclude that the painting partially blocked the adsorption and desorption capacity of the cement-based plaster. After 12 hours, Cm adsorbed about 39 g/m^2, while Cm painted just adsorbed about 33 g/m^2, 16% less. Nevertheless, after 48 hours, Cm and Cm painted desorbed the similar water vapor, about 38–40 g/m^2. The painted and unpainted cement plaster have a desorption hysteresis of about 1 %.

Both the gypsum plasters systems do not achieve the lowest sorption class of the DIN 18947 (after 24 hours only absorbed about 20 g/m^2 of water vapor). The adsorption capacity of unpainted and painted Gm plasters is similar, although slight differences can be observed: at the beginning and end of adsorption, from 0–9 h and 30–48 h, respectively, the unpainted Gm plaster has adsorption capacity slightly higher than the Gm painted plaster; in the intermediate period (9–30 h) the Gm painted plaster presents higher adsorption capacity (inverse behavior). Thus, it is verified that the painting causes a blockage of adsorption up to 9 hours and desorption from 30 hours. It is further observed that after 48 hours the Gm unpainted plaster presents a slight desorption hysteresis, about 2 %, while the Gm painted plaster does not.

Ramos et al. [32] evaluated the experimental mass variation for RH step of 33–75 % at 23 ºC of a gypsum plaster unpainted and painted (with acrylic and vinyl paints). After

8 hours the unpainted gypsum plaster adsorbed about 30 g/m^2, while the painted gypsum plasters adsorbed about 17.5–27.5 g/m^2. In the present study, for different RH variation (step of 50–80 %), Gm and Gm painted absorbed slightly less than 20 g/m^2. This can be due to possible admixtures of the pre-mixed gypsum plaster system. The different RH variation or different type of paint may also contribute to the different results obtained. As obtained in the present study (Fig. 2), Ramos et al. [32] also obtained higher adsorption capacity of the unpainted gypsum plaster in comparison to the painted gypsum plaster, after 8 hours.

Minke [10,12] analyzed the adsorption capacity at 21 ºC and RH variation from 50 % to 80 %, for 24 hours, in different materials with 15 mm of thickness and conclude that: undefined clayish earth absorbed about 200 g/m^2; lime-cement and gypsum plaster adsorbed only about 40 g/m^2 and 30 g/m^2 after 24 hours, respectively. In the present study, all plasters present lower adsorption capacity after 24 hours, except the pre-mixed Cm plaster that present similar adsorption capacity to lime-cement plaster analyzed by Minke [10,12]. Maskell et al. [4] analyzed the adsorption capacity of a clayish earth plaster, an air lime plaster and a gypsum plaster, at 23 ºC, RH variation from 50 % to 75 % and, after 12 hours, obtained adsorption of 30 g/m^2, 15 g/m^2 and 10 g/m^2, respectively. In the present study, the earthen plasters and the gypsum plaster adsorbed higher amount of water vapor (about 22–78.33 g/m^2), after 12 hours. The different results obtained in the present study and by these researchers [4,10,12] can be justified by eventual different types of clay minerals, formulation of plasters and environmental conditions (temperature and RH).

It is possible to make a comparison between the analyzed plasters when applied in common room during a daily cycle, considering a room with floor dimensions of 3 m x 3 m, with a ceiling height of 3 m, with a door of 2 m^2 and a window of 1 m^2, having walls and ceiling plastered with the seven different systems analyzed for hygroscopicity in the present study, with 15 mm of thickness (Fig. 2).

Considering the room occupied for 8 hours during the night at a high RH, the unstabilized earth plasters (E_L and Em) could adsorb about 2–3 l of moisture, whereas the mortars with binders, painted or unpainted (E+CL, Cm and Gm) could only adsorb about 1 l.

The present study demonstrates the ability of clayish earth plasters to adsorb and desorb moisture faster and to a greater extent than common pre-mixed plasters, such as cement and gypsum-based plasters. Nevertheless, the composition of the pre-mixed plasters is not known and eventual admixtures in the formulation may have a significant influence.

Conclusions

Plasters have a significant influence on buildings indoor environment. For this reason, plasters must meet some requirements, including aspects that contribute to a healthy indoor environment. Thus, the main objective of this study is to quantify some mechanical aspects, but mainly the adsorption and desorption capacity of different plaster systems in order to evaluate the benefits some may have for hygrothermal comfort and indoor air quality.

Analyzing the mechanical characteristics, it is possible to conclude that, as expected, earth mortars present lower mechanical strength comparing to cement and gypsum-based plasters. The addition of air lime does not seem to be mechanically advantageous for an earth mortar.

Unstabilized earth plasters validate their ability to regulate indoor RH since, in comparison to the other plasters, present: a high adsorption and desorption capacity; increasing adsorption after 12 h and at least up to 24 h (when the test stopped), contrarily to what happens with the lime stabilized earth, the gypsum and the cement-based plasters. Thus, the contribution of earth plasters, when applied on indoor walls and ceilings, to the indoor comfort of buildings can be significantly important compared to commonly used plasters, acting as passive hygrothermal buffer systems. This can have positive consequences on indoor air quality but also on energy saving to assure comfort. It was also proved that the painting has a negative influence on the adsorption and desorption capacity of the cement-based plaster; however, it does not cause significant influence on the gypsum-based plaster. Further study in needed to justify this different behavior, namely an in depth analysis of the mortars porous structure.

Tests are now being held to observe if the same plasters can capture pollutants, such as CO_2, when applied on indoor walls and ceilings. Plaster specimens of each type were applied covering five surfaces of air-tight cells, simulating a compartment such as a classroom or a room. The pollutant was injected and it is expected that, soon, results can be presented, hopefully showing a good capacity to capture CO_2.

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References

[1] Krejcirikova, B., Kolarik, J., Wargocki, P.: The effects of cement-based and cement-ash-based mortar slabs on indoor air quality. Build. Environ. 135, 213–223 (2018), doi:10.1016/j.buildenv.2018.03.011.

[2] Melià, P., Ruggieri, G., Sabbadini, S., Dotelli, G.: Environmental impacts of natural and conventional building materials: a case study on earth plasters. J. Clean. Prod. 80, 179–186 (2014), doi:10.1016/j.jclepro.2014.05.073.

[3] Maddison, M., Mauring, T., Kirsimäe, K., Mander, Ü.: The humidity buffer capacity of

clay-sand plaster filled with phytomass from treatment wetlands. Build. Environ. 44, 1864–1868 (2009), doi:10.1016/j.buildenv.2008.12.008.

[4] Maskell, D., Thomson, A., Walker, P., Lemke, M.: Determination of optimal plaster thickness for moisture buffering of indoor air. Build. Environ. 130, 143–150 (2018), doi:10.1016/j.buildenv.2017.11.045.

[5] Bruno, A.W., Gallipoli, D., Perlot, C., Mendes, J.: Effect of stabilisation on mechanical properties, moisture buffering and water durability of hypercompacted earth. Constr. Build. Mater. 149, 733–740 (2017), doi:10.1016/j.conbuildmat.2017.05.182.

[6] Randazzo, L., Montana, G., Hein, A., Castiglia, A., Rodonò, G., Donato, D.I.: Moisture absorption, thermal conductivity and noise mitigation of clay based plasters: The influence of mineralogical and textural characteristics. Appl. Clay Sci. 132–133, 498–507 (2016), doi:10.1016/j.clay.2016.07.021.

[7] Lima, J., Faria, P., Santos Silva, A.: Earthen plasters based on illitic soils from Barrocal region of Algarve: contributions for building performance and sustainability. Key Eng. Mater. 678, 64–77 (2016), doi:10.4028/www.scientific.net/KEM.678.64.

[8] Emiroğlu, M., Yalama, A., Erdoğdu, Y.: Performance of ready-mixed clay plasters produced with different clay/sand ratios. Appl. Clay Sci. 115, 221–229 (2015), doi:10.1016/j.clay.2015.08.005.

[9] Cagnon, H., Aubert, J.E., Coutand, M., Magniont, C.: Hygrothermal properties of earth bricks, Energy Build. 80, 208–217 (2014), doi:10.1016/j.enbuild.2014.05.024.

[10] Minke, G.: Building with earth. Design and Technology of a Sustainable Architecture. 1st edn. Birkhäuser - Publishers for Architecture, Berlin (2006).

[11] Morton, T.: Earth masonry. Design and construction guidelines. 1st edn. IHS BRE Press, UK (2008).

[12] Minke, G.: Earth construction handbook: The building material earth in modern architecture. 1st edn. WIT Press, Boston (2000).

[13] Santos, T., Gomes, M.I., Coelho, F., Faria, P.: Earth-based and current plasters: assessment of efficiency and contribution to indoor air quality. In: Álvarez, J.I., Fernández, J.M., Navarro, Í., Durán, A., Sirera, R. (eds.) HMC 2019 - RILEM Proceeedings PRO 130, pp. 5–20, RILEM Publications S.A.R.L. (2019).

[14] DIN 18947: Earth plasters – Terms and definitions, requirements, test methods (in German) (2013).

[15] EN 1015-10: Methods of test for mortars for masonry, Part 10: Determination of dry bulk density of hardened mortar (1999/2006).

[16] EN 14146: Natural stone test methods. Determination of the dynamic modulus of elasticity (by measuring the fundamental resonance frequency) (2006).

[17] EN 1015-11: Methods of test for mortar for masonry, Part 11: Determination of flexural and compressive strength of hardened mortar (1999/2006).

[18] Laborel-Préneron, A., Aubert, J.E., Magniont, C., Tribout, C., Bertron, A.: Plant aggregates and fibers in earth construction materials: A review. Constr. Build. Mater. 111, 719–734 (2016), doi:10.1016/j.conbuildmat.2016.02.119.

[19] Faria P., Lima, J.: Earth plasters (in Portuguese). Cadernos de Construção com Terra 3. 1st edn. ARGUMENTUM, Lisbon (2018).

[20] Palumbo, M., McGregor, F., Heath, A., Walker, P.: The influence of two crop by-products on the hygrothermal properties of earth plasters. Build. Environ. 105, 245–252

(2016), doi:10.1016/j.buildenv.2016.06.004.

[21] Lima, J., Faria, P.: Eco-efficient earthen plasters: The influence of the addition of natural fibers. In: Fangueiro, R., Rana, S. (eds.), Natural Fibres: Advances in Science and Technology Towards Industrial Applications, pp. 315–327, Springer Netherlands, Dordrecht (2016), doi:10.1007/978-94-017-7515-1_24.

[22] Santos, T., Nunes, L., Faria, P.: Production of eco-efficient earth-based plasters: Influence of composition on physical performance and bio-susceptibility. J. Clean. Prod. 167, 55–67 (2017), doi:10.1016/j.jclepro.2017.08.131.

[23] Gomes, M.I., Faria, P., Gonçalves, T.D.: Earth-based mortars for repair and protection of rammed earth walls. Stabilization with mineral binders and fibers. J. Clean. Prod. 172, 2401–2414 (2018), doi:10.1016/j.jclepro.2017.11.170.

[24] EN 998-1: Specification for mortar for masonry. Part 1: Rendering and plastering mortar (2010).

[25] EN 13279-1: Gypsum binders and gypsum plasters. Part 1: Definitions and requeriments (2008).

[26] Santos, T., Faria, P., Silva, V.: Can an earth plaster be efficient when applied on different masonries?. J. Build. Eng. 23, 314–323 (2019), doi:10.1016/j.jobe.2019.02.011.

[27] Delinière, R., Aubert, J.E., Rojat, F., Gasc-Barbier, M.: Physical, mineralogical and mechanical characterization of ready-mixed clay plaster. Build. Environ. 80, 11–17 (2014), doi:10.1016/j.buildenv.2014.05.012.

[28] Lima, J., Faria, P., Santos Silva, A.: Earth plasters: The influence of clay mineralogy in the plasters' properties, Int. J. Archit. Herit. (2020), doi:10.1080/15583058.2020.1727064.

[29] Ashour, T., Georg, H., Wu, W.: An experimental investigation on equilibrium moisture content of earth plaster with natural reinforcement fibres for straw bale buildings. Appl. Therm. Eng. 31, 293–303 (2011), doi:10.1016/j.applthermaleng.2010.09.009.

[30] Gomes, M.I., Faria, P., Gonçalves, T.D.: Rammed earth walls repair by earth-based mortars: The adequacy to assess effectiveness. Constr. Build. Mater. 205, 213–231 (2019), doi:10.1016/j.conbuildmat.2019.01.222.

[31] Röhlen, U.: Mould on clay renders. In: 6th International Conference on Building with Earth - LEHM 2012, pp. 113–121, Dachverband Lehm e.V., Weimar, Germany (2012).

[32] Ramos, N.M.M., Delgado, J.M.P.Q., de Freitas, V.P.: Influence of finishing coatings on hygroscopic moisture buffering in building elements. Constr. Build. Mater. 24, 2590–2597 (2010), doi:10.1016/j.conbuildmat.2010.05.017.