Chapter 20
The Benefits of Eco-efficient Plasters for Occupant's Health—A Case Study

Maria Idália Gomes, José Lima, Tânia Santos, João Gomes, and Paulina Faria

Abstract The health and comfort of building inhabitants are significantly affected by indoor air properties. Currently, there is sufficient scientific evidence associating discomfort and unpleasant indoor environment, reported by building occupants, with construction materials used inside those buildings. Hygienic and human-toxicological aspects need to be further studied in buildings to guarantee the existence of pleasant and comfortable built environments, but mainly healthy ones. Plasters, coating the surface of indoor walls and ceilings, can perform an important role on indoor conditions. In this chapter, the contribution of different plasters to the interior comfort, namely regarding the ability to regulate relative humidity by its hygroscopic capacity, is analyzed. The drying shrinkage, bulk density and mechanical performance are also compared to ensure that all the mortars can perform well when used as plasters. The analyzed plasters are made of earth, without and with low content of air lime and gypsum addition, as well as lime, gypsum and cement. It is shown that earth plasters have a more active effect on the hygrothermal balance when compared to air lime, gypsum and cement plasters, and that the addition of low binder content to earth plasters seems to be negative.

Keywords Adsorption · Air lime · Cement · Earth · Gypsum · Hygroscopic capacity · Mechanical performance · Plasters

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20.1 Introduction

Throughout history, humanity has noticed that polluted air can be harmful to health and wellbeing indoors, due to the emissions from indoor sources, as well as too humid or too dry environments. The energy crisis of the 70's of last century resulted in more airtight buildings, having low air intakes, thus increasing occupants' exposure to pollutants and lowering the quality of the indoor air. The Sick Building Syndrome (SBS) identified by the World Health Organization (WHO 1999), in the 70s of the past century is characterized by several symptoms and diseases due to inadequate ventilation. Low indoor air quality (IAQ) is recognized as one of the worst threats to human health, as humans spend around 80–90% of their lifetime inside buildings, and the indoor air can be more contaminated than outdoors (WHO 2010; EEA 2013; Al Horr et al. 2016). According to an environmental report issued by OCDE (2012), by 2030 indoor air pollution will be one of the major casualties caused by environmental issues, resulting in 2.3 million deaths. Although there are several sources of indoor pollutants, indoor air quality is also influenced from numerous factors that are bound to affect health and wellbeing of occupants, such as the building conservation state, ventilation air renovation ratio, temperature and relative humidity, pollutant emission rate, existence of indoor sources, maintenance and cleaning, outdoor air quality, number of occupants and their activities indoors. As referred, air temperature clearly affects indoor air quality: if occupants are subjected to conditions such as hot/dry as well as cold/humid, these conditions are not favorable to the human respiratory system and could induce lung infections, as well health problems in occupants having asthma. The excess heat also affects, negatively, persons with health conditions such as cardiovascular disease, diabetes, Alzheimer and epilepsy (Ormandy and Ezratty 2012). Low humidity promotes dermatological conditions, namely dry skin and associated diseases, dryness of eyes and nose, and vocal problems. These negative effects are also increased by high temperature with high humidity, which are also favorable to microbial growth, such as fungi and bacteria (Reinikainen and Jaakkola 2003; CCRSA 2008; FPP 2015). Microbial growth is also responsible for the emission of spores, cells, microparticles and volatile organic compounds (VOCs), which negatively affect indoor air quality (APA 2010; US-EPA 2010). VOCs emitted from microbial agents also result in malodorous environments. International standard ISO 7730 (2005) defined the optimal range for relative humidity of 30–60%. However, relative humidity lower than 50% inhibits growth of fungi, mites and bacteria (Pegas et al. 2011). Therefore, the range of 30–50% of relative humidity, usually recommended for housing (US-EPA 2010).

Nevertheless, according to WHO (2009), fungi do not appear for relative humidity lower than 75%, if the air temperature is within the range 5–40 °C, whereas the development of mites requires a relative humidity in the range 45–50% (WHO 2009).

It is also important to consider that a high relative humidity also influences the chemical degradation of the materials, contributing to increase the degradation of indoor air quality, and these concentrations can still increase with inadequate ventilation (Bornehag et al. 2005). Furthermore, high relative humidity can contribute to decreasing mechanical performance of building products and elements.

Hygienic and human-toxicological aspects are currently being studied in the built environment, to guarantee the health and comfort of the indoor environments.

Plasters, coating the surface of indoor walls and ceilings, can perform an important role in indoor conditions. When plasters have a hygroscopic capacity, i.e., ability to absorb and release the moisture, they can make an active contribution in the regulation of the RH of the indoor environments where they are applied. It has been shown that earth plasters have a more active effect on the hygrothermal balance when compared to other plasters.

The interest in earth plastering mortars in the scientific community has been growing. Some studies were carried out about the behavior of earth plasters with addition of binders, such as lime and gypsum, and other types of additions, such as geopolymers and enzymes (Rescic et al. 2021).

According to the authors' knowledge, there are few studies analyzing the mechanical and hygroscopic characteristics of earth-based plasters compared to current binder plasters. The same for the ability to regulate IAQ by plasters' contribution to a healthy indoor environment.

To prove this statement, different types of plaster will be analyzed, consisting of earthen plasters, without and with low content of air lime and gypsum addition, as well as lime, gypsum and cement-based plasters.

The present study intends to analyze the contribution of each plaster to indoor comfort, namely regarding the ability to regulate RH through its hygroscopic capacity, promoting the comfort of building occupants. In addition, the drying shrinkage, bulk density and mechanical strengths will also be compared to ensure that the mortars have mechanical performance adequate for plastering.

20.2 Materials, Mortars Composition and Test Methods

20.2.1 Materials and Mortars Composition

In this study, eleven different mortars were analyzed, consisting of: earth plasters ($E_{1\_f}S$; $E_{1\_m}S$; $E_{2\_f1c}S$; $E_{3\_f}S\_Fib$); earthen plasters with the addition of low contents of air lime ($E_{1\_m}S + CL$; $E_{4\_c}S + CL_p$); earthen plaster with the addition of a low content of gypsum ($E_{1\_m}S + G$); air lime plaster ($CL\__fS$); gypsum plasters ($G\__fS$ and G_m); and cement plaster (C_m).

The mortar composition and fresh state characterization are presented in Table 20.1. The reddish clayish earth (E_1) is from Algarve, the southernmost region of Portugal; it was studied (Lima and Faria 2016; Lima et al. 2016). The remaining clayish earths (E_2, E_3 and E_4) were characterized by Santos et al. (2020), wherein: E_2 is a clayish earth, also reddish, from the center of Portugal; E_3 is a pre-mixed earth

Table 20.1 Mortars composition and fresh state characterization

Mortar's name	Volumetric proportions									Weight proportions		Wet density^{c} (kg/m^{3})	Consistency^{d} (mm)
	E (%)	$_{f}S$ (%)	$_{m}S$ (%)	$_{c}S$ (%)	CL (%)	G (%)	C (%)	Volumetric ratio	Water^{a} (%)	Mass ratio	Water^{b} (%)		
$E_{1}\_{}_{f}S$	25	75	–	–	–	–	–	1:3 (E_{1}:$_{f}S$)	24.6	1:3.42 (E_{1}:$_{f}S$)	16.9	2018.8 ± 9.0	173.2 ± 1.2
$E_{1}\_{}_{m}S$	25	–	75	–	–	–	–	1:3 (E_{1}:$_{m}S$)	19.6	1:3.63 (E_{1}:$_{m}S$)	12.8	2130.7 ± 0.0	173.2 ± 0.0
$E_{2}\_{}_{f1c}S$	18.2	54.5	–	27.3	–	–	–	1:3:1.5 (E_{2}:$_{f1}S$:$_{c}S$)	11.7	1:3.04:1.78 (E_{2}:$_{f}S$:$_{c}S$)	9.5	1555.9 ± 56.7	136.0 ± 19.0
$E_{3}\_{}_{f}S\_F_{ib}$	Pre-mixed earth product							nk	20	nk	14.7	2033.3 ± 19.0	125.0 ± 8.0
$E_{1}\_{}_{m}S$ + CL	25	–	75	–	5.0$^{(e)}$	–	–	1:3 + 5%CL (E_{1}:$_{m}S$ + 5%CL)	24.6	1:19.43:70.45 (CL:E_{1}:$_{m}S$)	15.9	2052.1 ± 0.0	176.0 ± 0.0
$E_{4}\_{}_{c}S$ + CLp	Pre-mixed earth product							nk	–	nk	20	1988.8 ± 20.3	153.0 ± 1.0
$CL\_{}_{f}S$	–	75	–	–	25	–	–	1:3 (CL:$_{f}S$)	25.4	1:12.88 (CL:$_{f}S$)	20.9	1958.4 ± 10.3	169.6 ± 3.4
$E_{1}\_{}_{m}S$ + G	25	–	75	–	–	5.0$^{(e)}$	–	1:3 + 5%G (E_{1}:$_{m}S$ + 5%G)	20.4	1:10.08:36.54 (G:E_{1}:$_{m}S$)	13.1	2073.9 ± 8.9	168.8 ± 4.8
$G\_{}_{f}S$	–	75	–	–	–	25	–	1:3 (G:$_{f}S$)	24	1:6.90 (G:$_{f}S$)	18.6	1936.3 ± 3.0	175.9 ± 3.5
Gm	Pre-mixed mortar, produced using Gp product							nk	nk	nk	43	1578.9 ± 50.3	–

(continued)

Table 20.1 (continued)

Mortar's name	Volumetric proportions									Weight proportions		Wet density[c] (kg/m^3)	Consistency[d] (mm)
	E (%)	$_f$S (%)	$_m$S (%)	$_c$S (%)	CL (%)	G (%)	C (%)	Volumetric ratio	Water[a] (%)	Mass ratio	Water[b] (%)		
Cm	Pre-mixed mortar, produced using Cp product							nk	22	nk	14	1896.4 ± 3.5	138.0 ± 14.0

Notation: E_1—Illitic clayish earth; E_2 and E_3—reddish clayish earth; E_4—yellow clayish earth; $_f$S—fine sand (washed); $_m$S—medium sand (not washed); $_c$S—coarse sand (washed); CL—Calcitic air lime (powder); CLp—calcitic air lime (putty); G—Gypsum; Gp—pre-mixed product; Cp—pre-mixed product; nk—not known

[a] Volume of water added, considering the total volume of mortar dry components without additions

[b] Mass of water added, considering the total mass of mortar dry components including additions

[c] Fresh state density

[d] Flow table consistency

[e] Volume of binder added, considering the total volume of mortar dry components;

mortar product from Embarro company, formulated with a reddish clayish earth from the region of E_1, sand and vegetable fibers, and E_4 is a yellowish clayish earth supplied by Sorgila company, located in the center of Portugal. Illite is the predominant mineral in all clay soils (E_1, E_2, E_3 and E_4), but E_2 also contains kaolinite minerals.

The sands used are all siliceous, namely fine sand (${}_{f}S$ and ${}_{f1}S$), medium sand (${}_{m}S$)—used unwashed—and coarse sand (${}_{c}S$). The hydrated calcitic air lime (CL) used, is a commercial product designated as "H100" from Musical company (Lhoist group), distributed in a form of powder. CLp is a calcitic air lime hydrated with abundant water and used as a putty, provided by a builder (Aldeias de Pedra company). The hemi hydrated gypsum (G) designated "Gesso Estuque" and the pre-mixed product (G_p) designated "PROJECT 2010" are commercial products from Sival company, both supplied in powder. The mortar C_p is a commercial pre-mixed product provided by SecilArgamassas company, designated "RHP Manual Interior", provided in powder.

The distribution curves for the raw materials particle size were characterized by EN 1015-1 (1998); these results are available in Santos et al. (2020) and Lima et al. (2016). The gypsum-based product (G_p) was characterized regarding the distribution of the particle size nor the product date sheet presents that information. According to the producer, the particle size of the cement-based product (C_p) is lower than 1.2 mm, according to EN 1015-1 (1998).

Table 20.2 presents the loose bulk density for the raw materials that are part of the mortar´s formulation. They were determined in accordance with EN 1097-3 (2002), considering the average of three samples for each material.

20.2.2 Mortars Characterization and Preparation, Characterization in Raw and Specimen Obtention

Eleven studied mortars are formulated as explained below:

- $E_1\_{}_{f}S$ was formulated considering a volume ratio of 1:3, respectively of clayish earth E_1 and fine sand (${}_{f}S$)
- $E_1\_{}_{m}S$ was formulated considering a volume ratio of 1:3, respectively of clayish earth E_1 and medium sand (${}_{m}S$)
- $E_2\_{}_{f1c}S$ was formulated considering a volume ratio of 1:3:1.5, respectively of clayish earth E_2, fine sand (${}_{f1}S$) and coarse sand (${}_{c}S$)
- $E_3\_{}_{f}S\_F_{ib}$ was a pre-mixed product of earth materials, composed of the clay earth E_3, fine sand (${}_{f}S$) and cut straw fibers (proportions for each constituent are unknown)
- $E_1\_{}_{m}S + CL$ and $E_1\_{}_{m}S + G$ have the same base formulation of $E_1\_{}_{m}S$ but with 5% volumetric addition of hydrated calcitic air lime (CL) and hemi hydrated gypsum (G), respectively

Table 20.2 Materials, pre-mixed products loose bulk density (kg/m^3)

E_1	E_2	E_3	E_4	$_{f}S$	$_{f1}S$	$_{m}S$	$_{c}S$	CL	LP	G	Gp	Cp
1317.0 ± 1.8	1359.8 ± 8.1	1396.7 ± 5.5	1201.5 ± 4.2	1500.0 ± 2.0	1384.2 ± 4.3	1591.8 ± 0.6	1606.2 ± 4.9	350.7 ± 1.7	1374.6 ± 19.4	652.1 ± 4.7	810.9 ± 11.0	1502.0 ± 1.2

- $E_{4}\_{}_{c}S + CL_p$ has in its composition the clayish earth E_4, coarse sand ($_cS$), limestone powder (LP) and some addition of hydrated calciticair lime putty (CL_P); however, the content of each constituent are unknown as the mortar was delivered already pre-mixed
- $CL\_{}_fS$ and $G\_{}_fS$ were formulated considering a volume ratio of 1:3, respectively of the corresponding binder, hydrated calcitic air lime (CL) or hemi hydrated gypsum (G), and fine sand ($_fS$)
- Gm and Cm mortars were prepared based on the pre-mixed products G_p and C_p, respectively, requiring only water to mix; the proportions of constituents and other components are not known.

To produce the mortars containing the clayish earth E_1 the German standard DIN 18947 (2018) for earth plasters was followed, except the preparation of the mortar with E_1 and G addition which followed the EN 1015-2 (1998). In all these mortars the volume of water added to the mortars' mixture was the minimum required to achieve a flow table consistency in a range defined by the DIN 18947 (2018) and to ensure adequate workability.

All other mortars preparation tried to mimic, as much as possible, the procedure usually executed on construction sites. The mortars were prepared by means of a mixer blade system. First, the dry materials were put in a vase and water was added in order to obtain a first mixture, during a period of about 8 min. Then, the mortar adhering to the walls of the vase was removed and put together with the remaining mortar, and a second mixture was carried out for 3 min. To achieve a better connection between earth and the hydrated calciticair lime putty the $E_{4}\_{}_{c}S + CLp$ mortar was prepared one day prior to the production of the specimens. All other mortars were prepared on the same day of the molding of specimens. Pre-mixed mortars, $E_{3}\_{}_{f}S\_F_{ib}$, $E_{4}\_{}_{c}S + CL_p$ and C_m, were prepared only by addition of the water content indicated by their producer. It should be noticed that Gm is made with a pre-mixed material (G_p product), and the water content was not indicated by the manufacturer. Therefore, the water content of Gm mortar was, then, defined by an experienced craftsman in order to assure an acceptable workability. The same procedure was followed for the preparation of mortar $E_{2}\_{}_{f1c}S$.

The obtained mortars were characterized as raw (Table 20.1) in terms of wet density, according to standard EN 1015-6 (1998) and flow table consistency according to standard EN 1015-3 (1999). Table 20.1 allows to see that flow table consistency varies significantly between the different binder mortars, what can thus influence the hardened state properties of the mortars and plasters, and particularly its porous structure, also depending on their type of curing: just drying for the earth plasters, by carbonation for the plasters with air lime, hydrating for the hydraulic plasters.

Each plastering mortar resulted in different types of specimens which were produced in metallic molds:

- for carrying out tests of bulk density, linear shrinkage, elasticity dynamic modulus and flexural and compressive strength, 6 prismatic specimens having dimensions 40 mm × 40 mm × 160 mm, molded as two layers mechanically compacted at 20 strokes/layer and leveled manually and were finally demolded when dried, after 7 days, at least.

- for carrying out adsorption and desorption tests, 3 planar specimens having dimensions 200 mm × 500 mm × 15 mm were compacted manually and leveled; the metallic mold ensures that adsorption/desorption cycle occurs only in the top exposed surface; in the Gm planar specimens a gypsum finishing coat designated "Massa de acabamento", provided by Sival, having a thickness of 1 mm, was applied; this application was done 24 h after these mortars were applied in the planar specimens.

Specimens were placed in environmental conditions of 20 ± 2 °C and 65 ± 5% RH prior to the execution of the characterization tests.

The specimens' age of each plastering mortar for all the tests and the type of specimen is shown in Table 20.3. The aging process for prismatic specimens of mortar $CL_{\_f}S$ included a period of accelerated carbonation comprising 30 days in a CO_2 rich confined environment. The specimens' carbonation was confirmed through a phenolphthalein test, carried out on the fracture surface of the specimens, immediately after the flexural strength test. The specimens of mortar $E1_{\_m}S$ + CL were tested after an aging of 1.5 months. The specimens' carbonation was not confirmed after flexural strength test due to the mortar's reddish color. A longer aging period of 4.5 months was allowed for the specimens of mortar $E_{4\_c}S$ + CLp to compensate for the lime's slow carbonation reaction.

Table 20.3 Number, age and type of specimens for each performed test

Test	Testing age (months)				Minimum number of specimens	Type of specimen
	$E_{1\_f}S$ $E_{1\_m}S$ $E_{1\_m}S$ + CL $E_{1\_m}S$ + G $G_{\_f}S$	$CL_{\_f}S$	$E_{2\_f1c}S$ $E_{3\_f}S\_F_{ib}$ Gm Cm	$E_{4\_c}S + CL_p$		
Linear shrinkage	When demolding				6	Prismatic
Bulk density, dynamic modulus of elasticity, flexural and compressive strength	1.5	2	2	4.5	6	Prismatic
Sorption and desorption	1.5	6.5	4	6.5	3	Planar on metallic mold

20.2.3 Test Methods

Mortars were assessed in terms of linear drying shrinkage, dry bulk density, dynamic modulus of elasticity, flexural and compressive strength and water vapor adsorption and desorption capacity. First tests characterize the mortars' physical and mechanical performance while the adsorption/desorption test allows to assess the contribution of plasters to balance indoor RH. Thus, there is a clear distinction between "mortar" and "plaster", depending on the characterization test performed.

20.2.3.1 Linear Shrinkage, Bulk Density, Dynamic Modulus of Elasticity and Flexural and Compressive Strength

Linear shrinkage was determined on the prismatic specimens, in accordance with DIN 18947 (2018), by measuring the difference of the linear geometrical length of mortar between the raw and hardened state. The dry bulk density was determined geometrically in accordance with standard EN 1015-10/A1 (1999), by measuring the ratio between the dry mass and the volume of each specimen. The dynamic elasticity modulus (Ed) was determined according to standard EN 14146 (1414), by using Zeus XRM equipment. Flexural (FStr) and compressive (CStr) strengths were determined according to standard EN 1015-11 (1999), by using a ZwickRoell Z050 equipment, using load cells of 2 kN and a velocity of 0.2 mm/min for flexural strength and 50 kN and a velocity of 0.7 mm/min for compressive strength. 6 halves of the prismatic specimens, after subjected to the FStr test, having about 80 mm long, were used in the determination of the CStr for each mortar, having a compressive area of 40 mm × 40 mm, as specified by standard EN 1015-11 (1999).

20.2.3.2 Adsorption and Desorption

According to DIN 18947 (2018), absorption capacity was determined with some complements based on (Santos et al. 2020). In the climatic chamber at 23 °C and 50% relative humidity the specimens were placed until they reached constant mass (that is, mass less than 2%). The adsorption phase of the plasters it was achieved at the expense of an increase to 80% of relative humidity inside the climatic chamber, keeping the temperature at 23 °C. By weighing the specimens after 1, 3, 6, 12 and 24 h, the water vapor gained (in g/m^2) by the plasters was determined. The absorption test must end at 12 h by DIN 18947 (2018). Nonetheless, to better understand the adsorption effect on plasters, this test was extended to 24 h. The standard also reported a first weighing at 30 min, but this was not carried out, the first weighing was performed at 1 h after the test started. It was considered that if the first weighing was at 30 min it would result in a negative effect and destabilize the climatic chamber, since 30 min is considered a very short period of time to stabilize the climate chamber.

Although DIN 18947 (2018) just define the analysis of the adsorption capacity of plasters, the reverse process was used to determine the desorption capacity, since it is considered important to evaluate the water release (Schroeder 2018; Maddison et al. 2009; Veiga et al. 2010). To evaluate the decrease of water vapor content, relative humidity was decreased to 50%. This parameter was also measured in g/m^2, from 1 up to 24 h in the same time periods defined in the previous test.

20.3 Results and Discussion

20.3.1 Dry Bulk Density and Linear Shrinkage

The dry bulk density of each mortar is presented in Fig. 20.1, and is related to the loose bulk density of the materials that comprise its composition (Table 20.2). Loose bulk density is equivalent in all raw materials and pre-mixed mortar products, exception made too hydrated calcitic air lime (CL), hemi hydrated gypsum (G) and gypsum-based pre-mixed product (Gp); these materials exhibit low loose bulk density and, consequently, $\mathrm{CL\_}_{f}\mathrm{S}$, $\mathrm{G\_}_{f}\mathrm{S}$ and Gm mortars, present low dry bulk density. However, although Table 20.1 shows that flow table consistency varies significantly between the different binder mortars, the differences in terms of dry bulk density are not very high, considering the different types of hardening the mortars have.

Observing in Fig. 20.1 the dry bulk density, and taking into account DIN 18947 (2018), the mortars $\mathrm{E}_{1\_m}\mathrm{S}$ and $\mathrm{E}_{3\_f}\mathrm{S\_F}_{ib}$ fall within bulk density class 2.0 (from 1.81 kg/dm^3 till 2.00 kg/dm^3), and $\mathrm{E}_{1\_f}\mathrm{S}$, $\mathrm{E}_{2\_f1c}\mathrm{S}$ can be classified as class 1.8

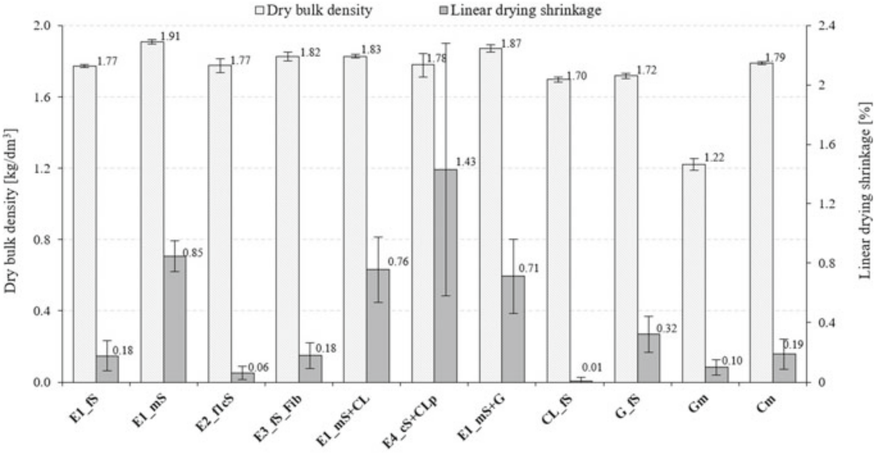

Fig. 20.1 Dry bulk density and linear drying shrinkage

(which is considered between 1.61 and 1.80 kg/dm^3); these classification are only applicable for unstabilized earth plasters.

All the remaining earth mortars that are stabilized with lime or gypsum, namely $E_{1\_m}S$ + CL, $E_{4\_c}S$ + CLp, $E_{1\_m}S$ + G and the cement mortar (Cm)exhibit high values for dry bulk density (between 1.78 and 1.87 kg/dm^3).

Regarding linear drying shrinkage, all mortars presented in this study show significantly low linear drying shrinkage (Fig. 20.1). Unstabilized earth mortars, $E_{1\_f}S$, $E_{1\_m}S$, $E_{2\_f1c}S$, $E_{3\_f}s\_F_{ib}$, exhibit very low linear shrinkage.

According to Röhlen and Ziegert (2011), earth mortars present a dry bulk density around 1400–1800 kg/m^3. All earth-based mortars analyzed in the present study have a dry bulk density in this range of values. In addition, the mortars with sand with different particle size distribution and with the addition of fibers and air lime show higher results. The high dry bulk density can be justified by a better packaging obtained with the different grains of sand and the air lime; the influence of the fibers cannot be compared because of the use of a different type of earth.

The low linear shrinkage found, may be due to the low swelling characteristic of the clay mineral that is present in the earths used, namely illite (which is present in $E_{1\_f}S$, $E_{1\_m}S$, $E_{2\_f1c}S$, $E_{3\_f}s\_Fib$) and kaolinite (also presented in $E_{2\_F1C}S$). The mortars $E_{1\_m}S$ + CL and $E_{4\_c}S$ + CLp, that are stabilized with lime, present the highest value for linear shrinkage (excluding the mortar $E_{1\_m}S$). The observed result may be due to the use of air lime (powder and putty), known by shrinking during carbonation. It is important to highlight the high standard deviation value in $E_{4\_c}S$ + CLp mortar, leading to a maximum value of 2.3% for linear shrinkage.

However, the earth mortars exhibit linear shrinkage less than 3%, taking into account DIN 18947 (2018) and the NZS (1998). Röhlen and Ziegert (2011) also refer that shrinkage in earth mortars should not be more than 2%. The average values of all mortars were found to be within the requirement (Fig. 20.1). For cement mortars, Röhlen and Ziegert (2011) refer that shrinkage can be 0.09%. In the present study, the cement-based pre-mixed mortar presents linear shrinkage of 0.19%, showing that the range can vary with the mortar formulation, which is unknown in the case of the pre-mixed mortar. The mortars based on lime ($CL\_{}_{f}S$), gypsum ($G\_{}_{f}S$ and G_m) and cement (C_m) also exhibit low linear shrinkage.

20.3.2 Mechanical Properties

Figure 20.2 shows the compressive (CStr) and flexural (FStr) strengths and dynamic modulus of elasticity (Ed) for all mortars (average and standard deviation).

Observing flexural and compressive strength and after analyzing the DIN 18947 (2018) standard, the minimum mechanical strength values defined in the class S-I (CStr $\geq$ 1.0 N/mm^2 and FStr $\geq$ 0.3 N/mm^2), for all the earth mortars (with and without the addition of binder), have not been reached; the exception was the mortar $E_{1\_m}S$ + G that achieved both conditions (CStr and FStr), and $E_{2\_f1c}S$, that reached class S-I in CStr. Nevertheless, it is possible to notice that two other mortars, $E_{3\_f}s\_F_{ib}$

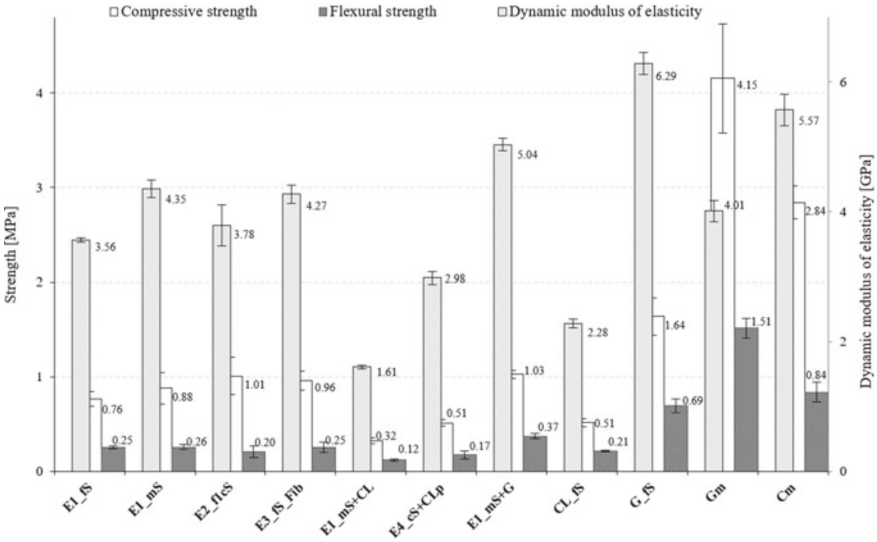

Fig. 20.2 Compressive and flexural strength and dynamic modulus of elasticity

and $E_{1\_m}S$, almost achieved the minimum values of mechanical resistance, CStr and FStr, defined for class S-I; and $E_{1\_f}S$ almost reached the minimum value for FStr.

Different classes for compressive strength at 28 days, for plastering mortars, are defined in the standard EN 998-1 (2010). These are: CS I values between 0.4 and 2.5 N/mm^2; CS II values between 1.5 and 5.0 N/mm^2; CS III values between 3.5 and 7.5 N/mm^2 and CS IV for values ≥6 N/mm^2. All earth mortars analyzed (with and without binder) are in the CSI class, except for $E_{1\_m}S + CL$ (0.32 N/mm^2). This earth mortar where powder hydrated air lime was added, did not reach the minimum limit to be classified. $G\_{}_{f}S$, Cm and Gm fit within the CS II class. According to this standard (EN 998-1 2010), these studied mortars meet the requirements for interior and exterior plasters and renders, respectively. However, it should be noted that these were not tested for 28 days. Röhlen and Ziegert (2011) refer that earth plasters must be made with earth mortars that have a compressive strength classified as CS II, namely values between 1 and 3 N/mm^2 for earth mortars ($E_{2\_f1c}S$ and $E_{1\_m}S + G$ fall into this condition) and 3 N/mm^2 for gypsum plaster mortars (just Gm fits in this condition).

EN 13279-1 (2008) defines a range of values for gypsum plasters, namely for CStr of 2–6 N/mm^2 and aFStr of 1–2 N/mm^2. Is possible to observe that Gm mortar is in these limits but $G\_{}_{f}S$ stays outside this range. The mortars that stand out from the others by the higher values in mechanical resistance are Gm, Cm and $G\_{}_{f}S$, both in CStr and FStr strengths, what could be expected in comparison to all the other non-hydraulic mortars.

According to Schroeder (2018), the compressive strength (according to EN 1015-11 (1999)) of earth mortars applied in secondary spaces must be greater than 0.5 MPa.

In the present study, all the earth mortars supersede the defined limit, exception made to $E_{1\_m}S + CL$ (Fig. 20.2).

Note should be made that the lowest values in mechanical resistance, CStr and FStr, are found in the earth mortars with lime addition and in the lime mortar, namely $E_{1\_m}S + CL$, $E_{4\_c}S + CLp$, $CL_{\_f}S$. The later presents the highest mechanical resistance in this mortar group and, as previously mentioned, its specimens' carbonation was confirmed through phenolphthalein test. Among the two earth mortars with lime addition the lowest mechanical resistance (CStr and FStr) is presented by mortar $E_{1\_m}S + CL$. This might be related to the shorter aging period of these mortar specimens or related to a higher lime addition content on mortar $E_{4\_c}S + CLp$. However, once the constituent proportions of the latter are unknown no further conclusions are possible.

Nevertheless, is possible to assess the effect over mechanical resistance (CStr and FStr) of the small addition of lime present in mortar $E_{1\_m}S + CL$ by comparison with mortar $E_{1\_m}S$, formulated exactly with the same constituent proportions (apart from the lime addition). In this comparison is clear that the small amount of lime addition reduced the mechanical resistance of the earth mortar by more than half. These results are not likely to be justifiable only by the shorter aging period of mortar $E_{1\_m}S +$ CL, furthermore, considering the low mechanical resistance presented by the lime mortar $CL_{\_f}S$, formulated with the same sand and volumetric proportions of the earth mortar $E_{1\_m}S$, and having its carbonation confirmed through phenolphthalein test, as previously mentioned. Therefore, a limited statement can be made pointing that the low addition of air lime tends to significantly decrease the mechanical strength of earth mortars.

Similar results were obtained by Santos et al. (2017) and Gomes et al. (2018) for contents from 5 to 15%: after 60 days, the addition of 5% of air lime in an illitic earth mortar decreased its mechanical strengths (Santos et al. 2017); after 90 days, the addition of 5–15% of air lime in a kaolinitic earth mortar, Gomes et al., (2018) obtained similar results. This should be justified by the weakness of the structure defined by the lime; interrupting the bonds between the clayish lamellas, in turn make the overall structure weaker in comparison with earth mortars without lime addition. However, considering that the carbonation of the lime may not be complete, some increase of strength can yet occur with aging.

Houben and Guillaud (1994) reported that the compressive strength of earth-air lime mortars tends to increase with the age of the mortar, easily reaching values of 2–5 N/mm^2. They also refer that additions of 2–6% of lime tend to increase compressive strength and, for larger additions, this strength tends to fall. As previously mentioned, that behavior was not observed for mortar$E_{1_m}S + CL$ with the addition of 5% of lime (CL) in volume (Table 20.1) which presented a CS of 0.32 N/mm^2 after an aging of 42 days (Fig. 20.2), value very low compared to those reported by the researchers. Also, the pre-mixed mortar $E_{4\_c}S + CLp$, obtained a value of 0.51 N/mm^2 (Fig. 20.2) for CStr, the value is also considerably lower when compared to the indicated by the authors, although, in this mortar the percentage of air lime is unknown, so it is not possible to effectively assess the effect of the lime addition.

Regarding the dynamic modulus of elasticity in earth mortars Röhlen and Ziegert (2011) refer that values lie, typically, within the range of 450–3000 N/mm^2. In this case, just $E_{1\_m}S + CL$, $E_{4\_c}S + CLp$ are within these limits (Fig. 20.2), the remaining mortars present higher values. These results may be due to the clay type or the mortar formulation, leading to a higher deformability of the mortars analyzed.

Low values of Ed in mortars may be advantageous if these mortars are applied in substrates with low mechanical properties. The mechanical characteristics of the mortars must not exceed those of the substrate on which they are applied, to guarantee compatibility between the mortar and the substrate in the long-term. Otherwise, premature anomalies and detachment of the mortar may occur due to this lack of compatibility between the substrate and the mortar. Veiga et al. (2010) defined general requirements for the application of plastering mortars on old buildings; one of the characteristics presented was Ed values, in a range between 2000 and 5000 N/mm^2. Observing these ranges, $E_{1\_m}S + G$ is at the upper limit and $E_{1\_m}S + CL$ does not fit in the limits presented by the authors (Fig. 20.2). All the remaining earth mortars are within the limits shown.

20.3.3 Hygroscopic Properties

Considering DIN 18947(2018), all earth plasters without the addition of binder, $E_{1\_f}S$, $E_{1\_m}S$, $E_{2\_f1c}S$, $E_{3\_f}s\_F_{ib}$ (Table 20.3), obtained adsorption values above the lower limit of the water adsorption class WS-III (adsorption water vapor adsorption greater than 60.0 g/m^2 after 12 h at a temperature of 23 °C and a relative humidity of 80%), the higher class defined in the standard. However, and although the classes are only for unstabilized plasters, $E_{1\_m}S + CL$ and $E_{1\_m}S + G$ plasters were very close to reach the WS-III class, with values of 57.7 g/m^2 and 56.3 g/m^2, respectively. Considering the standard, they meet the class WS-II with a water vapor $\geq$47.5 g/m^2.

The higher adsorption observed in the earth plasters group in comparison with the binder-based plasters group is clearly associated with the presence of the clayey material in the mortar's formulation as well as its mineralogy. Among the three main clay groups with significant available in the nature to allow being consider as plastering materials, namely, montmorillonitic, illitic and kaolinitic clays, the first is characterized by having very high hygroscopicity and shrinkage, while the latter is known for its low hygroscopicity and shrinkage. In turn, the illitic clays, the one prevalent in the earth mortars assessed in this study, present an average condition of hygroscopicity and shrinkage (Lima et al. 2020).

Comparing the adsorption among the four unstabilized earth plasters it is possible to conclude that plaster $E_{2\_f1c}S$, whose prevalent clay minerals are illite and kaolinite, presents the lowest adsorption. This result can be associated with the lower hygroscopicity of kaolinite minerals, as well as with the lower clayey material content of this mortar formulation (Table 20.1).

The higher water vapor adsorption capacity of unstabilized earth plasters is even more evident when looking at the behavior of mortar $E_{3\_f}s\_F_{ib}$: after 12 h, it reached a value higher than 78.3 g/m^2 of water vapor adsorption (31% higher than the 60 g/m^2 limit defined in class WS-III of the DIN 18947 (2018)). The behavior of this mortar becomes more surprising at 24 h, when water vapor adsorption is 103.9 g/m^2 with a tendency to continue the increase; therefore, this mortar could still increase its adsorption capacity for a significantly longer period of time. As this mortar contains fibers in its formulation, it may be necessary to have some attention, since the fibers provide an increase in adsorbed water (Ashour et al. 2011; Gomes et al. 2018) but can also provide an enhanced growth of mold. That will be most probable if the indoor environment is not well ventilated, or if it is in prolonged conditions of high relative humidity (Gomes et al. 2019).

The results obtained with the earth mortars are extremely important: the water vapor adsorption capacity allows the earth-based plasters to act as a moisture buffer, and thus positively contribute to balance the relative humidity of the indoor environment, reducing its peaks. Through this passive process the health and comfort of the buildings' occupants are promoted.

Surprisingly, $E_{4\_C}S + CLp$ plaster, despite being based on earth and with addition of lime putty lime, presents a weak adsorption; even after 24 h only absorbed about 24 g/m^2, value that does not reach the minimum classification by DIN 18947 (2018), that is class WS-I with a water vapor ≥35 g/m^2 after 12 h; nevertheless, the classification of this standard is applied only for unstabilized earth plasters, as previously mentioned. It is reported in the literature that the addition of air lime decreases hygroscopicity in earth plasters, as it appears that the airline network blocks the clay structure, creating a new structure between the clay lamellar structure and inhibiting the hygroscopic characteristics of the clay; the performance of this mixture becomes representative of the air lime and loses the dynamic behavior of the clay (Gomes et al. 2016; Santos et al. 2020). However, observing Fig. 20.3, it appears that $E1_{\_m}S + CL$ mortar, where lime was also added, but hydrated in powder form, presents quite high values for water adsorption; in this case the lime structure does not seem to interrupt the clay matrix's hygroscopic and dynamic behavior. The difference in behavior of these two plasters may be in the lime type (one was hydrated to become a powder and the other was hydrated with abundant water to turn into a putty) and particularly its content (the added percentage). However, the percentage of lime putty added in $E_{4\_C}S + CLp$ mortar is not known; therefore, it is impossible to be sure that the air lime content in $E_{4\_C}S + CLp$ mortar is higher than the one in $E1_{\_m}S + CL$ mortar. Another difference between these two plasters is the main material—the earth—as it may behave differently with lime.

The Gm, $G_{\_f}S$ and $CL_{\_f}S$ plasters present low adsorption capacity compared with the unstabilized earth plasters, being respectively 9 g/m^2, 12 g/m^2 and 21 g/m^2. However, the Cm plaster absorbed 39 g/m^2, higher than the $E_{4\_C}S + CLp$ plaster adsorption. This proves the good ability to regulate the relative humidity of the interior environments of earth mortars compared to mortars based on other types of binder mortars.

All plasters showed a good performance with respect to desorption since they desorbed almost the total water vapor they initially adsorbed. The mortars that, after 24 h desorption, still retained the highest values of moisture (although low) were

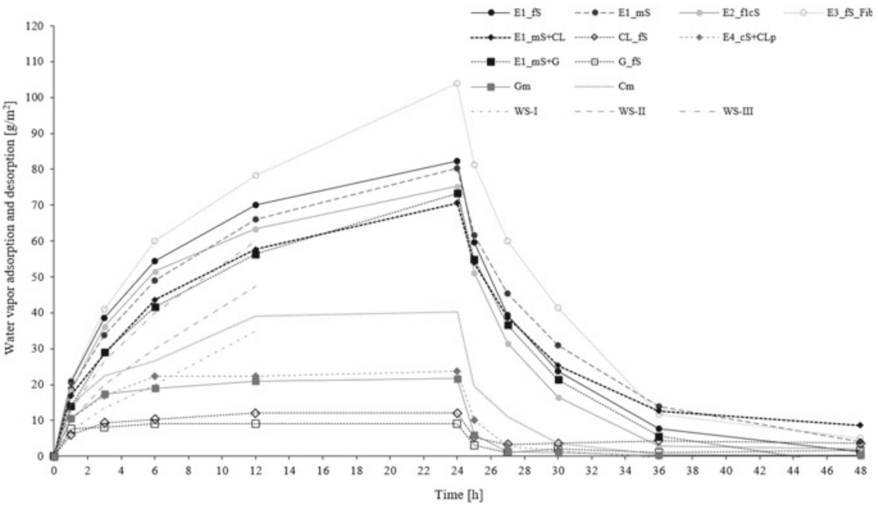

Fig. 20.3 Water vapor adsorption and desorption curves and class limits (WS-I, WS-II and WS-III) defined by DIN 18947 (2018)

E1_$_{m}$S + CL and E$_{3}$_$_{f}$S_F$_{ib}$, with 8.7 and 5.1 g/m^{2} of water vapor, respectively. However, if the test was carried out for a longer period of time, the plasters would probably reach a desorption value similar to the initial values, as they show a downward trend. But they would take a longer period to achieve it. The hysteresis presented by these mortars may be related to the addition of air lime and fibers: the air lime may have blocked the mortar matrix and the fibers may retain water vapor inside, making the desorption more difficult. The E$_{4}$_$_{C}$S + CLp, Cm and Gm plasters desorbed all the water vapor they had adsorbed for the same period: after performing the desorption, these plasters present a similar water vapor content, close to zero (similar to the one at 0 h).

The results observed in this study are quite similar to other studies carried out on adsorption and desorption in earth plasters (Minke 2006; Maddison et al. 2009; Maskell et al. 2018). Although slightly different values are observed in the results, the studies are unanimous in considering that earth plasters have a higher water vapor adsorption when compared with other plasters, namely air lime, gypsum and cement plaster.

The adsorption and desorption results obtained in the present study by the different plasters analyzed confirmed the capacity of clayey plasters to absorb and desorb water vapor more quickly and in greater quantities than other building products, such as lime, gypsum or cement plasters, as observed by other researchers (Minke 2006; Morton 2008). That shows that, although all the earths used for plasters can be different, with diverse types and different contents of clays, silts and sands, the results are now conclusive.

The capacity of earth plasters to absorb water vapor can strongly contribute to create healthy environments inside the buildings, through moderate regulation of the relative humidity of the indoor air, and it may even reduce the peak of high humidity that may be promoted by cooking food or water vapor from the baths or, in turn, the peak of low humidity associated with the continuous heating of buildings (Morton 2008).

By analysis of a psychrometric diagram (Moret-Rodrigues et al. 2009), it appears that the thermal comfort inside the buildings is favored by the regulation of relative humidity, since the temperature increases with the decrease in relative humidity. The perception of thermal comfort in indoor spaces can be improved through the regulation of relative humidity, taking into account that a high relative humidity leads to an increase of the thermal conductivity of the air and moderates the evaporation of the skin; consequently, it can increase the sensation of discomfort associated with the perception of cold or heat (Moret-Rodrigues et al. 2009).

The mineralogical, chemical and microstructural composition of the clayey materials may allow them to absorb pollutants from the indoor air, although this mechanism is not well known yet. According to Minke (2006) and Morton (2008), the clay soil can absorb and bind pollutants dissolved in water. This mechanism may be related to the hygroscopic capacity of mortars, due to the fact that pollutants may be dissolved in moisture and, in turn, be absorbed by the plaster as water vapor. Lamble et al. (2011) and Darling et al. (2012) also refer that earth plasters can contribute to improve the quality of the indoor air, since the clay can act as a passive removal material, decreasing the internal ozone concentrations and, therefore, reducing the likelihood of an ozone reaction with other building materials inside buildings. Earth plasters are known for not releasing toxins compounds to the indoor environment, at least if they have no additions in their formulation.

20.4 Conclusion

Currently, there is a growing concern with the environment and the indoor air quality in buildings. Around the world, researchers are looking for eco-efficient building materials and products that are not harmful to human health. The building materials used inside buildings can influence positively or negatively the health and comfort of the inhabitants. Since plasters can have a significant interior area coating walls and ceilings, they should contribute to a healthy indoor environment.

In the present study eleven plasters based on different mortars were produced and samples were tested: two earth plasters with the same earth and added sand, just varying the particle size of the sand; two earthen plasters with the same base formulation as one of the previous but with 5% volumetric addition of hydrated calcitic air lime and hemi hydrated gypsum, respectively; a ready-mixed earthen plaster with another type of earth, coarse sand, limestone powder and addition of calcitic air lime putty (characteristics and proportions of each constituent are not known); an earth plaster with another earth and a higher content of added sand; a premixed earth mortar known for including cut straw fibers and having earth from the same region as the first ones (proportions of each constituent are not known);

powder hydrated air lime and gypsum hemi-hydrated mortars with the same volume ratio of binder and sand, respectively; two premixed gypsum and cement mortars, respectively(the proportions of constituents and other components are not known).

It is important that plasters perform well, not only to contribute to indoor comfort and health but also to be durable and visually interesting, namely without cracks. The results from the present study have shown that all the mortars evaluated have a low linear drying shrinkage, including the earthen mortars. Regarding the mechanical strength, the study discussed more deeply earthen mortars because they are considered low strength mortars. For the tested earth mortars, the results of flexural and compressive strength indicated that they can be suitable to use in indoor spaces. However, an improvement in mechanical performance of earth plasters may be achieved by a reinforcement placed in corners within the mortar layer. Furthermore, an increase in mechanical strength can be achieved through the formulation of mortars with different earths, with diverse types of clays and different contents of the fractions of clays, silts and sands and a good particle size distribution of added sand, which predictably will also lead to changes in terms of the hygroscopic capacity.

Contrary to what is reported in some of the literature, the stabilization of earth mortars with low contents of binders does not always contribute to increasing their mechanical performance. It seems that the addition of low contents of air lime decreases the mechanical strength of the earthen mortars. On the contrary, the addition of low contents of gypsum seems to increase the mechanical strength of the earthen mortars.

Concerning hygroscopicity, unstabilized earth plasters present the highest water vapor absorption capacity, while air lime and gypsum plasters have the lowest. Therefore, this study shows the ability of earth plasters to contribute to the regulation and balance of indoor air humidity; thus, earth plasters can influence in a positive way the healthiness of the indoor environment, when compared to other plasters, such as based in lime, gypsum or cement. Earth as a building material acts as buffer protection against significant variations in humidity, contributing to balance the relative humidity of the indoor environments in buildings, promoting comfort and health of occupants. This capacity in an earth plaster comes from the exchange of water vapor with air, releasing moisture when the air is drier and adsorbing it when the air is more humid. It is important to note that this capacity for hygrothermal rebalancing depends on factors such as the clay type of the earth with which the plaster is produced, the clay proportion in the plaster, and possible stabilization with mineral binder or other added products. Another aspect that may influence the adsorption and desorption capacity are finish systems that can be applied on some plasters, such as paints. Furthermore, the effect of consecutive cycles of water vapor adsorption and desorption should also be studied because they can lead to a decrease of plasters hygroscopic capacity. Finally, as a contribution to indoor air quality, not only the plasters cannot release pollutants but, if possible, they should be optimized in order to capture pollutants present indoor.

The main conclusions regarding the eleven mortars and regarding the tests carried out are as follows:

- as it was expected, earth mortars have lower mechanical resistance when compared to gypsum and cement mortars, still these are appropriate to use in indoor spaces; the addition of lime in an earth mortar, although low, did not seem to be mechanically advantageous, unlike gypsum (in low quantities) seems to increase mechanical strength of the earthen mortars
- earth plaster exhibit greatest advantages when compared to the others studied plasters, validating their ability to regulate the relative humidity inside the buildings; they present excellent capacity for adsorption and desorption; when the absorption test was interrupted, at 24 h, all earth plasters (with the exception of the earth plaster stabilized with lime), would continue to absorb water
- When applied on ceilings and walls, the high capacity of earth plasters to capture water vapor contributes to indoor comfort in buildings, leading to very positive consequences on indoor air quality, namely a healthier environment while, at the same time, contributes to energy savings as a way of ensuring comfort.

Therefore, being an area of interest and due to the importance for the indoor air quality field, more research is still needed, namely for earth plasters. That research is justified by the fact that earth is a natural building material and earth plasters present low CO_2 emissions in its manufacture and application, and low incorporated energy. All these factors are important for the sustainability of the building and the planet, as well as for the health of building users.

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