Development of a high clay content earth plaster

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Abstract. Earth, as a building material, offers many advantages: on an ecological point of view, it is a natural, abundant, recyclable material with low energy used for production and transportation. Moreover, earth is known to be a natural humidity regulator and to improve comfort inside buildings, making it a good choice for indoor plastering. The clayey phase gives the global cohesion of the material by acting as a binder for the sand grain skeleton. The finest grain soil fraction is responsible for the dry strength, the water vapour permeability and the sorption capacity of earthen plasters. However, clay also induces the drying shrinkage of the mortar leading to the cracking of the plaster. The objective of this work is to improve the moisture buffer capacity of earthen plaster by increasing its clay content without jeopardizing the general behaviour of plasters. Based on consistency, shrinkage and shear tests, the characteristics of mortars in fresh and hardened states were evaluated. The hygric regulator potential of earthen materials were measured through the Moisture Buffer Value (MBV) test. As expected, results have shown that, to maintain a standard level of consistency, an increase in the clay content leads to a greater amount of mixing water. Moreover, to enhance the MBV, the highest possible earth content must be used. Addition of organic admixtures can be considered to improve the high-clay content plaster behaviour without jeopardizing the aesthetic and mechanical aspects of plaster.

1. Introduction
The building sector is a major contributor to resources’ consumption, such as energy and raw materials, as well as greenhouse gas and pollutant emissions. This industry is the largest consumer of energy (with about 40% of the total energy consumption), of non-renewable raw materials and is responsible for approximately 36% of greenhouse gas emissions in European Union [1]. Hence, building industry has to drive efforts to reduce its environmental footprint. This situation has contributed to the growing interest in locally available resources for the development of sustainable building materials.

Earthen materials fit in with this perspective. Earth, as a building material, offers many advantages as underlined by the Life Cycle Methodology implemented by Melià et al. [2]: although not renewable, earth is natural, non-toxic, reusable and recyclable (when used without chemical stabilization with binders). This raw material does not need energy for calcination like current binders, it can be found almost everywhere thus reducing costs and energy for transportation and production; it only requires a limited energy for milling.

Moreover, earth is known to present a good capacity to absorb and give off moisture [3]. Thus, building products based on raw clay have a high capacity to regulate the relative humidity of the indoor air [4], improving perceived indoor air quality [5] and inhabitants comfort and health, making it a good choice for indoor plastering [6], [7]. The clayey phase also contributes to the dry strength of plasters.
However, clay induces the drying shrinkage of the soil material, leading to the cracking of the mortar. So, to prevent this phenomenon, earth is admixed with sand.

Natural and innovative materials may be added to mortars to enhance their properties at fresh and hardened states: improving the workability of the mortar [8], reducing the bulk density and porosity to increase the thermal conductivity [6], [9], promoting the adhesion strength of plasters to the walls.

The objective of this work is to improve the moisture buffer capacity of earthen plaster. To do so, this study first aims to assess how clayish earth and sand ratio of mortars formulation can influence the fresh and hardened properties of plasters. The hygric regulator potential is evaluated through the Moisture Buffer Value (MBV) test. Finally, addition of organic admixtures is considered to prevent plaster from cracking without compromising the properties of the material.

2. Materials and Methods

2.1. Raw materials

The studied earth plasters are composed by local materials: a clayish earth, a siliceous river sand (0-2 mm) and water. The grain size distributions of the soil and sand used are presented in Figure 1.

![Grain size distribution of studied materials.](image)

In the soil material, the proportions of each constituent (sand, silt and clay) were determined. The liquid limit (LL) and plasticity index (PI) of the soil were also measured. The geotechnical characteristics are given in Table 1.

| % Clay (≤ 2 µm) | % Silt (0.002-0.063 mm) | % Sand (0.063-2 mm) | LL (%) | PI (%) | Normal proctor optimal water content (%) | Normal proctor optimal dry bulk density (kg/m³) |
|----------------|------------------------|---------------------|--------|--------|----------------------------------------|-----------------------------------------------|
| 22.5           | 38.5                   | 37.0                | 46     | 15     | 14.1                                   | 1880                                          |

On a geological point of view, clay is distinguished from other fine-grained soils by differences in size: clay fraction refers to a class of materials whose particles are smaller than 2 µm in equivalent sphere diameter. By virtue of its extremely small particle size and high surface-to-volume ratio, clay exhibits glue-like properties in the presence of water [10]. Thus, the clayey phase plays the role of binder while silts and sands form the granular skeleton. The clay minerals contained in the soil are montmorillonite, chlorite and illite.
By drying, the clayey phase shrinks, causing cracks in the plaster. To prevent this phenomenon, earth is admixed with sand.

A commercial fibrewood rigid panel is used as substrate. This material is intended for a facade/wall/roof insulation use. It is described as a fire-resistant (class E), thermal and acoustic insulation board ($\lambda = 0.044\ \text{W/(m.K)}$). The board is 35 mm thick and has a density of 180 kg/m$^3$.

2.2. Procedures

As no European standard exists for the characterization of clay plasters, the procedures used are adapted from the German standard for the characterization of ready-mixed clay plaster [11] and inspired by the methodology developed by Hamard et al. [8], Delinière et al. [12] and Stazi et al. [13].

2.2.1. Design and manufacturing of earth plasters. To assess how clayish earth and sand ratio can influence physical and mechanical properties of plasters, six mortars were formulated with different mass ratios of clayish earth and sand: 1:1, 1:1.5, 1:2, 1:2.5, 1:3, 1:4.

Mortars were prepared following the mixing procedure:
- the solid phase is mixed at low speed over 30 s;
- water is added and the amount adjusted to ensure a flow table value of 175 ± 5 mm;
- the mortar is mixed at low speed for 30 s and then switched to high speed for an additional 30 s;
- the mixer is stopped and the mixture left to rest for 5 min;
- 30 additional seconds of mixing is completed at high speed.

For the preparation of the test specimens, the mortar was directly applied on the substrate (fibrewood panel), which was previously soiled and sprayed with water. The plaster was easily levelled thanks to a wooden frame. The thickness of all plasters was around 1 cm.

2.2.2. Characteristics of fresh state plasters. For each formulation, the water content is defined to ensure similar consistency between the materials, ensuring a good workability. The flow value test consists in characterizing the consistency by measuring the mean diameter of a test specimen of fresh plaster that had been given 15 vertical impacts, allowing it to fall freely through a given height. A truncated conical mold (60 mm in height with internal diameter of 100 mm at the bottom and 70 mm at the top) is used to give form to the specimen and placed at the centre of a flow table disc. The German standard [11] proposes fixing the consistence at 175 ± 5 mm. The water content of the fresh clay plaster was then measured by drying at 60 °C.

2.2.3. Characteristics of hardened state plasters. Mechanical tests are conducted to validate the composition of plasters by means of a shrinkage test followed by a shear test. The shrinkage test requires two 250 x 250 mm$^2$ specimens of each formulation applied on the commercial fibrewood panels. After drying, the shrinkage evaluation is carried out: the presence or absence of cracks in the specimens was noted. An earth plaster is of acceptable mechanical quality if, after shrinkage, there are no cracks through which water can penetrate into the wall and if the plaster is not detached (even partially) from the substrate.

The shear test aims to evaluate the bond of the earth formulation with the wall. Five circular specimens of 7 cm diameter are tested for each formulation. The loading device is suspended to the specimens by a string, ensuring a good contact with the upper part of the specimen without any contact with the wall (Figure 2). Specimens were loaded until failure and the mass at which the specimen breaks was recorded.
2.2.4. **Moisture buffer value.** The moisture buffering performance of a material is a hygroscopic property by which hygroscopic materials in contact with the surrounding air adsorb and desorb moisture to create equilibrium with the relative humidity of the surrounding space. The methodology applied is based on the NORDTEST protocol [14].

Measurements were conducted on three 2 x 12 x 12 cm specimens of plaster applied on a 3.5 cm-thick substrate for each composition. Before testing, the test specimens were sealed on all but one side with aluminium tape. Then, they were stored in equilibrium with the air at 23 ± 5 °C and 50 ± 5 % RH. The test consists in exposing specimens to a daily relative humidity cycle (8 hours at 75 % RH - 16 hours at 33 % RH). Because of the change in relative humidity, the specimens gain or lose weight and their weight changes were tracked with an accuracy of 0.001 g. The MBV is determined at steady state defined by the NORDTEST Project. When the moisture exchange during one cycle (Δm) is reported per open surface area (A) and per % RH variation (RH_{high} - RH_{low}), the result is the practical MBV (kg/(m². % RH)):

\[
MBV = \frac{\Delta m}{A \cdot (RH_{high} - RH_{low})}
\]

### 3. Results

#### 3.1. Characteristics of fresh plasters

All mortars were characterized in the fresh state for flow table consistency. Table 2 presents the fresh state characteristics of plasters depending on the earth to sand ratio.

| Earth to sand ratio | Earth content (% of dry mass) | Water content (% of dry mass) | Flow table consistency (cm) |
|---------------------|-----------------------------|-----------------------------|----------------------------|
| 1:1                 | 50                          | 30.6                        | 17.4                       |
| 1:1.5               | 40                          | 27.8                        | 17.5                       |
| 1:2                 | 33                          | 26.2                        | 17.5                       |
| 1:2.5               | 29                          | 24.4                        | 18.0                       |
| 1:3                 | 25                          | 24.6                        | 17.7                       |
| 1:4                 | 20                          | 23.2                        | 17.3                       |
The water content necessary to obtain the right consistence for all mixtures ranges from 23.2 to 30.6%. Those values are slightly higher than water requirements of plaster found in previous studies [6], [12]. This can be explained by the nature of the clay minerals and the fact that not all mortars fulfil the flow table consistency defined in the DIN 18947 [11]. The results show that, as expected, to maintain a standard level of consistency, an increase in the clay content leads to a greater amount of mixing water.

3.2. Impact of clay content on hardened state plaster

The results of shrinkage test are presented in Table 3. The six mortars show distinguished facies after drying. No specimen fell off the wall but several cracked (1:1, 1:1.5, 1:2, 1:2.5) or bowed out (1:1, 1:1.5, 1:2). Only two mixtures did not display signs of shrinkage (1:3 and 1:4).

Table 3. Shrinkage test results.

| E/S | 1:1 | 1:1.5 | 1:2 | 1:2.5 | 1:3 | 1:4 |
|-----|-----|-------|-----|-------|-----|-----|
| Cracked | Yes | Yes | Yes | Yes | No | No |
| Bowed out | Yes | Yes | Yes | No | No | No |
| Fallen | No | No | No | No | No | No |

Clay content has a clear influence on earth plaster cracking, as underlined by Hamard et al. [8]. An increase in clay content leads to a greater amount of mixing water. The plaster shrinkage is hence more important and the cracks induced by the restrained shrinkage are more extensive. Mortar with the greater water content shows visible signs of a poorer plaster/wall bond than other mixtures as they take off the panel.

Outcomes also provide information about the maximum earth content with the soil used to prevent shrinkage cracks: below 25% of earth (1:3 formulation), the plaster surface area remains smooth and does not lift away from the wall.

Concerning the adhesive strength, the results of the carried out tests are gathered in Figure 3.

![Figure 3. Shear stress of plasters depending on the earth content.](image-url)
As anticipated by the shrinkage test, the clay content affects the plaster/wall bonds, resulting in lower breaking strength for highest amount of clay. The shear stress does not evolve as described by Stazi et al. [13]. The bond between earth plaster and the wall is controlled by antagonistic phenomenon: an increase in the plaster clay content leads to increased bonding strength which strengthens the plaster, and increased shrinkage, which weakens the plaster-wall interface [8], [13]. Here, the effect of shrinkage predominates and decreases the shear strength.

In all the cases, the average shear strength is greater than 20 kPa. This stress corresponds to the load caused by a virtual earth plaster which would have a 1.13 m thickness. The plaster is able to bear its own load with a minimum safety coefficient of 113. To have an adequate adhesive strength, a minimum safety coefficient of 10 was aimed [13], [15]. Thus, the plasters are sufficiently secure to the substrate. Shear tests highlight the high mechanical resistance of the studied plaster as all mixes are sufficiently secure to the substrate.

However, a quite significant dispersion of values is observed, as it has also been noted by several authors [8], [12], [13]. The scattering of the values is strongly influenced by the support type and preparation. It should also be pointed out that the bonding strength of earthen plasters cannot be dissociated from the type of substrate. In this way, the 1:2 formulation was applied to three other types of walls (chipboard, aerated concrete and another wood fibre board): all specimens fell off the substrates.

Consequently, as an earth to sand ratio is validated if no crack appears on the plaster during the shrinkage test and if the shear adhesion strength is high enough, both 1:3 and 1:4 mixtures are validated.

3.3. Moisture buffer value
The moisture buffer value is determined for two types of mortars: one invalidated by the shrinkage test (1:2), the other one validated by the whole procedure (1:3). Figure 4 gives the moisture buffer values of the two plasters calculated from the last three cycles.

![Figure 4. Moisture buffer values of two earthen plasters.](image)

Earthen plasters show a good hygric regulator potential that improve indoor comfort. A difference of about 2 % of clay content between the two mixtures leads to an increase of 21 % of the MBV value. Therefore, clay strongly contributes to regulate the relative humidity of the indoor air by its good capacity to absorb and give off moisture.

To enhance the MBV, the highest possible earth content must be used without jeopardizing the aesthetic and mechanical aspects of plaster. In the last part of this study, organic admixtures are considered to prevent higher content of clayish earth plasters from cracking.

3.4. Organic admixtures
This work finally focuses on the potential of organic admixtures to prevent cracking due to shrinkage for high clay content mortars, without altering their fresh state and bonding strength. This part reports
the preliminary investigations made in that direction. Inspired by the French national research project PaTerre+ [16] which aims to compile traditional recipes of stabilized earth materials, six organic admixtures were tested to improve the behaviour of plasters. On the one hand, according to the builders interviewed in the PaTerre+ project, the organic molecules such as alginic acid, casein, gluten, starch and ovalbumin, strengthen the soil by holding the clay particles together; they are long enough to adhere to several clay platelets at once and connect them. Hence, those molecules are supposed to contribute to the tensile strength improvement. On the other hand, tannic acid is listed as plasticizer.

The 1:2 formulation is used as a reference cracking plaster to assess the admixture impact. Shrinkage test are realized for the six admixed mortars. All organic admixtures were introduced up to 1 % of the solid dry mass and activated, when required, by 0.1 % of lime (case of casein and alginic acid). The results of the shrinkage test are presented in Table 4.

| Reference | Tensile strength improvement | Thinner |
|-----------|-----------------------------|---------|
| 1:2       | Alginic acid                | Casein  |
|           |                             | Gluten  |
|           |                             | Starch  |
|           |                             | Ovalbumin | Tannic acid |

Considering the present results, the organic admixtures do not limit the cracking of plaster. On the contrary, the shrinkage cracks are more extensive. The water content required to fulfil the flow table consistence standard for the tannin-based mortar is of 24 %. The tannic acid does not play any significant thinner role in the earthen material. To maintain the level of consistency of the reference plaster, the five other admixed plasters required a greater amount of water.

The nature of the clay or the amount of admixture may contribute to the failure of shrinkage limitation. Thereafter, those two parameters should be studied.

4. Conclusion
This work aims to improve the moisture buffer capacity of a montmorillonite-based plaster. To do so, the impact of two design parameters was studied: the sand to earth ratio and the addition of organic admixtures. For each formulation, the water content is defined to ensure similar consistency between the materials. Tests are conducted to validate the composition of plasters by means of a shrinkage test followed by a shear test. An earth plaster is of acceptable mechanical quality if, after shrinkage, there are no cracks through which water can penetrate into the wall, and the plaster has a sufficient bond with its wall. Then, its hygric regulator potential is evaluated through the Moisture Buffer Value (MBV) test.

As expected, results have shown that, to maintain a standard level of consistency, an increase in the clay content leads to a greater amount of mixing water. Consequently, the plaster shrinkage is more important and the cracks induced by the restrained shrinkage are more extensive. Furthermore, it affects the plaster/wall bonds, resulting in lower breaking strength for the shear test.

Outcomes also provide information about the maximum earth content with the soil used to prevent shrinkage cracks: below 25 % of earth, the plaster surface area remains smooth and does not lift away from the wall. Shear tests highlight the high mechanical resistance of the studied plaster as all mixes meet the requirements set for indoor application. Earthen plasters can be considered, based on the MBV test, as high potential hygric regulators. To enhance the MBV, the highest possible earth content must be used without jeopardizing the aesthetic and mechanical aspects of the plaster. This first campaign finally evidenced the impact of organic admixtures on the shrinkage of earth plaster: neither the tensile strength nor the water requirement are improved by a 1 % addition. This study is part of an ongoing
research which will focus on the impact of the nature of the clay and of the organic admixture content on the shrinkage behaviour of earthen plasters.

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