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Abstract

In rainy climates the external surfaces of earthen buildings suffer water erosion. In this paper the properties of earth plasters have been investigated considering the specific relationship with the underlying substrate. Ten typologies of earth plasters containing different admixtures and surface treatments, a cob wall and a rammed earth wall were produced in laboratory. The aim is to evaluate the effectiveness of the coatings in protecting the earthen walls against weathering. An in-situ procedure consisting of a shrinkage test followed by an adhesion strength test was performed in order to identify the earth-sand ratio optimal for the plaster manufacturing. Then, a series of tests was carried out both on the plasters and the two walls: compression, water vapor permeability, surface color, wettability, water absorption and erosion. The results demonstrate that all the plasters are physically and mechanically compatible with the earthen substrates and that the most important differences are in the specific relationship with water. The earth plaster treated with the silane-siloxane product was found to be the best one: it is fully compatible, water-repellent and highly resistant to water erosion. Hence there is a potential for the use of earth plasters for the protection of earthen buildings against weathering.

Keywords: earth plaster / rammed earth wall / cob wall / protection against weathering / admixture / surface treatment

1 - Introduction

Raw earth buildings represent an important, although difficult to quantify, part of the world building heritage. They can be found in very different climates, in the arid zones as well as in the tropical and temperate latitudes. At present about 15% of UNESCO Heritage Sites is represented by earthen architectures [1]. In the Marche region (Italy) a total of 245 earthen buildings are still present according to a recent official cataloguing [2]. They need to be preserved from ruin and deterioration, as they represent a cultural and architectural heritage.

The main drawback of raw earth is its affinity for water. In rainy climates the degradation of historic earthen buildings is mainly due to water in combination with other factors such as abandonment state, lack of roof maintenance and inadequate protective elements. It is important to identify plasters able to protect the external surfaces of such buildings against weathering. The plaster should have specific characteristics, such as: good workability, physical and mechanical compatibility with the substrate, hydrophobicity and high resistance to water erosion.

The earth plasters seem to be the most suitable [3-4]. The earth for plastering is taken from the natural soil under the arable layer and consists of grains of variable size. In particular, the clayey component acts as a binder for the sand grain skeleton (or gravel), and the particles of silt with intermediate diameter complete the grain size distribution curve. The clay binder provides the dry strength and causes the drying shrinkage of the soil material. To regulate the shrinkage and prevent the cracking of the plaster, the soil can be admixed with other materials such as: straw, coarse sand or other mineral aggregates [5].

These renders have several advantages. Unlike cement based coatings, they are compatible with the earthen walls in terms of material, esthetic appearance, water vapor permeability and mechanical behavior [3]. The continuity of the water vapor permeability throughout the wall is an important feature: when moisture inside an earthen wall is not free to evaporate outside because trapped by a waterproof coating, deleterious phenomena such as blown render, damp internal walls and mould may occur. The mechanical compatibility is a key factor too: when there is too much difference between the Young's modulus of the wall and that of the coating, the stress changes due to overloads, moisture and temperature variations could generate a differential strain high enough to damage the bond of the plaster with the underlying substrate.

The earth plasters have a main weak point: they are poorly resistant against weathering because of their sensibility to water [4,6]. However the addition of other materials (admixtures) in the plaster as well as the application of a protective treatment on its hardened surface could eliminate or reduce this lack.

In the international context many authors studied the properties of raw earth as a building material, sometimes testing new solutions based on the combination of soil with low percentages of stabilizers (cement, lime, fiber, natural additives, etc.). Several aspects such as sustainability, embodied energy and CO_2 emissions [7], building energy efficiency and thermo-hygrometric comfort [8-10], durability [11-13] and physical-mechanical behavior [13-17] were investigated. Some researchers deepened the effects of fiber contents on the mechanical properties [18-20] and on the shrinkage [19-20] of earthen materials. On the contrary, few studies have been carried out on the protection of earthen surfaces against atmospheric agents, both in the field of historic building preservation and that of new constructions. Concerning the earth plasters, Hamard et [3] al. found that: both the nature of the substrate and the clay content of the plaster significantly influence the adhesive strength; an increase in clay percentage strengthens the plaster until the effect of shrinkage becomes predominant and weakens the plaster-wall interface; the presence of fibers prevents the plaster from cracking during the drying shrinkage.

Delinière et al. [21] studied the physical, mineralogical and mechanical properties of ready-mixed clay plasters, demonstrating that: the linear shrinkage of fresh plasters as well as the flexural and compressive strengths of hardened plasters are correlated with the mass percentage of clay content whereas they are not linked with the nature of the clay minerals and with the initial water content; the adhesive strength depends significantly on the substrate preparation: an effective preparation should determine higher values with a lower dispersion for the adhesive strength.

According to Beas Guerrero de Luna [22] the mucilage admixture has no effect on the earth plaster; the acrylic additive improves the abrasion resistance, but significantly reduces the vapor transmission and increases the capillarity; the Ethyl-silicate additive behaves like the acrylic, but makes the plaster more resistant to water.

Concerning the earth-gypsum plasters, Mattone [4] demonstrated that the use of treatments such as aleurites oil and corn oil, unlike the potassium silicate, significantly enhance the behavior of the plaster in terms of water absorption and erosion resistance.

It is evident that some questions are still open: there are few studies in literature dealing with protective plasters for earthen walls; the latter rarely use a multidisciplinary approach for determining the performances of the plasters in relation with the underlying substrate; there is still a lack of effective solutions for the protection of the earthen surfaces of existing or new buildings against atmospheric agents.

This paper investigates the effectiveness of several earth plasters in protecting the earthen walls against weathering. A cob wall and a rammed earth wall were produced in laboratory to study the performances of the plasters in relation with the substrate. After the identification of the earth/sand ratio most suitable for the plaster manufacturing, to create the different typologies of plasters, which were made with the selected soil proportion, different additives (i.e. admixtures) and surface treatments, including nano-technological products, were exclusively added. A series of tests was carried out: compression, water vapor permeability, surface color, wettability, water absorption and erosion. Also, the shrinkage and the adhesive strength of the plasters were evaluated.

2 - Materials

Soil for construction was taken at a depth of about 50 cm below the ground level, in the Arcevia's countryside (Ancona, Italy), a few kilometers far from the archeological site of Suasa where adobe walls inside a Roman Republican domus were recently discovered [17].

Grain size distribution of soil by sieving and hydrometer analyses, Atterberg limits and natural water content were determined in accordance with the ASTM standards [23-25]. The soil was then compared with the soil constituting three historic cob buildings located in 'Villa Ficana' district of Macerata, recently studied by the Università Politecnica delle Marche DICEA department [26-27]. The soil geotechnical are reported and compared in Fig. 1. The earth taken near Arcevia was considered suitable because of its similarity to that of Villa Ficana. It was hence used to manufacture the two wall panels and the plasters. The coarse sand was used only in the plasters as a dimensional stabilizer to contrast the drying shrinkage. The sand was of 3 mm nominal diameter and was taken from a local quarry of alluvial sand.

Table 1 reports the detailed composition for the different typologies of plasters (Arabic numerals) and for the six recipes of plasters (Roman numerals) tested only in the preliminary phase. The first type of plaster, named as 'basic plaster', is made only with the earth, sand and water. The different typologies of plasters are obtained by adding, singularly and exclusively, three synthetic additives, one natural fiber and four surface treatments. In one case it was used 1mm sand instead of 2 mm sand (see Section 4).

The admixtures and the surface treatments were commercially available. The barley straw is known to have beneficial effects on the earthen materials [19]. The synthetic additives (silicon nano-particles, organic derivates of silicon, limestone aggregates admixed with fatty acids and synthetic polymers) are validated to hydrophobise concrete and cement mortars [28]. The surface treatments (silicon-nano-particles, titania and silica nano-particles, silane-siloxane, beeswax) are indicated to protect the surfaces of porous building materials against weathering. In particular, according to their product data sheet, the treatment with titania and silica nano-particles is to make the surfaces self-cleaning while the other treatments are to make the surfaces water-repellent.

3 - Construction process of the earthen wall panels

A rammed earth wall and a cob wall were produced in laboratory using the soil after being fragmented into small grains. The dimensions of each wall were 100 cm × 30 cm × 100 cm (height).

For the rammed earth manufacturing (Fig. 2a) the soil with its natural water content ($w_{initial}$ = 22%) was poured in layers about 20 cm thick and rammed through a metal pestle weighing 5 kg, equipped with a 8 × 8 cm^2 ramming plate. After compaction, the thickness of each layer was reduced more than a half.

For the cob manufacturing (Fig. 2b) it was adopted the cob construction technique developed over the centuries in the area of Macerata according to a recent historic analysis [27]. Each cob element was manually produced through the following steps: mixing 3 kg of soil ($w_{initial}$ = 22%) with the water amount considered necessary for its workability (water added 300 g, manufacture water content 34%); modeling the mixture until obtaining a cylindrical shape (diameter 10 cm, length 30 cm); rolling and pushing the clay cylinder on a wet straw-bed, so that the straw fibers, about 5-15 cm long, can adhere on its external surface. When the cob elements were still in a plastic state, they were laid and pressed with the longest side along the wall thickness, proceeding with staggered joints in successive layers.

The dry density ρ_d of each wall was determined using intact specimens sampled from a wall block, according to method B (direct measurement of the dimensions and mass of a specimen) of the standard ASTM D7263 [29]. For the rammed earth wall it is equal to 1.660 g/cm^3 and lower than the values found in the literature, which range from 1.800 g/cm^3 to 2.200 g/cm^3 [14]. This was expected since the water content and the clay content of the soil used in this study are higher than those normally adopted for rammed earth constructions [14-16]. For the cob wall ρ_d is 1.420 g/cm^3 and no reference value was found.

Also, the same parameter ρ_d was evaluated on dried specimens, observing that the rammed earth and the cob walls increase their dry density respectively up to 1.950 g/cm^3 and 1.870 g/cm^3.

The two wall panels were cured before testing for more than three months inside the laboratory at room humidity and temperature. Plastic covers and wooden planks were used to regulate the drying process and to limit the effect of shrinkage.

4 - Manufacturing of the specimens

The specimens for the plasters were of two typologies: 1) samples applied to the wall panels, according to a real on-site procedure; 2) small laboratory specimens.

The manufacturing process for both of the specimen typologies involved the following phases: firstly the earth and the sand were separately oven-dried to constant mass at T = 105 °C; then the earth was fragmented into 2 mm maximum diameter grains, and the sand was passed through a 2 mm sieve (in the case of the plaster made with sand of smaller size, the sand was passed through a 1 mm sieve); hence the two components were mixed together in the desired proportion, firstly in the dry state to a homogeneous distribution, then by adding water until obtaining a uniform consistency. The water amount, reported in Table 1, was that necessary to make the mixture workable.

The additives were introduced during the blending phase of the soil components. They were used in the percentage by mass of the binder component, following the product data sheet specifications and considering clay instead of cement. The treating products were applied superficially on the hardened plasters by three coats of paintbrush, using the highest consumption reported in the product data sheet.

The specimens belonging to the first typology consisted of a single 20 mm thick layer applied to the wall by spatulas. The earthen substrate to be rendered was previously prepared by a scratching followed by a wetting (Fig. 3). Scratching by metal brush was intended to clean the wall surface and to make it rough for a better adhesion of the plaster. Wetting with a clay slurry prepared by mixing dry earth and water in the ratio of 1/1.5 by mass was intended to improve the workability during the plastering operation and to allow the drying process of the coating to be regular.

The specimens belonging to the second typology were produced by the casting and compacting the mortar into PVC molds.

Similarly, the specific features of the two earthen substrates were studied, depending on the test, directly on the walls or on small specimens obtained by sampling operations.

After production, all the specimens were cured in laboratory for 15 days at room humidity and temperature, unless otherwise specified in the adopted test method (see Section 5), and then tested. In particular the surface treatments were applied on the fourteenth day because they take one day to become effective.

5 - Experimental method

The experimental method consisted of a preliminary phase and a main phase. The first one was aimed to find the most suitable earth/sand ratio that will be used to manufacture the plasters for the subsequent phase. Then, four physical-mechanical tests, a surface color test and four water resistance tests were carried out on in order to evaluate the effectiveness of the plasters in protecting the earthen walls. Also the two walls were tested to identify their specific contributions and features.

5.1 - Preliminary tests

A shrinkage test followed by adhesion strength test were conducted according to the procedure proposed by Hamard et al. [3].The samples for each earth/sand ratio (without additives and surface treatments) were applied to each of the wall panels. The substrate type was taken into account.

The shrinkage test required a 250 mm × 250 mm sample for each formulation of plaster. After drying, when the shrinkage was completed, the presence or the absence of cracks on the sample was noted through a visual inspection.

The adhesive strength (Fig. 4a) was studied in terms of shear resistance since, as highlighted by Delinière et al. [21], this type of stress could be more representative of the in-situ behavior than a procedure based on a pull-out test. The test required, for each formulation of plaster, four specimens of 45 × 45 mm^2 surface area to be tested in different points of the substrate. After drying, the samples were loaded until failure by increments of 0.125 kg applied for 15 sec. The loading device was the same of that used by Hamard et al [3]. The mass at which the sample breaks, which is called failure mass, was recorded. The average shear strength (τ_{max}, Nmm^{-2}) was calculated as follows:

$$\tau_{max} = m_f \times g / S \quad (1)$$

where:

m_f is the failure mass (kg);

g is the gravitational acceleration = 9.81 m s^{-2};

S is the surface area of the specimen (mm^2).

5.2 - Physical-mechanical tests

The physical-mechanical tests concerned the following features: shrinkage, adhesive strength, compression stiffness and water vapor permeability.

The ten typologies of plasters were tested by using the same procedure described in Subsection 5.1, even if, for the treated plasters no shear strength measurement was made because the effect of the surface treatment on this parameter was supposed to be negligible.

The unconfined compression test (Fig. 4b) was carried out according to ISO/TS 17892-7 [30] with some adaptation for sample production (Section 4). Two cylindrical specimens of 40 mm diameter and 80 mm height (diameter/height ratio = ½) were used for each of the walls and the plasters, except for the treated plasters, which were not tested because the surface treatments were not supposed to influence the mechanical behavior of the plasters. After curing, the specimens were measured to account for the size reduction due to shrinkage and then tested. The loading machine was equipped with a loading press with a capacity of 500 kg and two transducers respectively for the force and for the bottom plate vertical displacement. The test was run at a constant speed of 0.9144 mm/min and the readings were performed every 5 minutes. The secant modulus at 50% of unconfined compressive strength (E_{50}, MPa) was determined as graphically represented in Fig. 4b.

The water vapor permeability test (Fig. 4c) was carried out according to EN 15803 [31] using the wet cup system. Two cylindrical specimens of 100 mm diameter and 20 mm thickness were used for each of the walls and the plasters. Before testing, the specimens were stored in a climate-controlled test chamber for a period long enough for their weight to stabilize with the test climatic conditions. Then the specimens were sealed on top of the test cups, with the treated surfaces oriented upwards. The test cups contained an aqueous saturated salt solution of KNO_3, able to create an internal environment with RH = 93%. The cups were stored in the test chamber at T = 20 °C and RH = 50% for a week and weighed at daily intervals. Parameters such as water vapor diffusion resistance coefficient (μ, -) and water vapor diffusion-equivalent air layer thickness (S_d, m) were calculated.

5.3 - Surface color test

A simple digital imaging method, such as that proposed by some authors [32-33] for measuring and analyzing color of food surfaces, was used mainly to study the color change induced by the admixtures and the surface treatments on the earth plaster. The procedure consisted of two phases: color measurement, using a digital camera to take a picture of the sample and to obtain the color values of the pixels; color analyses, using the graphics software Adobe Photoshop [34] to obtain the color averages. The specimens were placed inside a dark room at controlled conditions of illumination, camera angle, distances between camera, specimen and light source. The image acquisition system consisted of a Natural Daylight source (6500 K) and a digital camera (Casio Exilim EX-Z65with 5.3 Mega Pixels). The images were taken at maximum resolution (2816 × 1872 pixels) and saved as JPEG files. The other camera settings were: white balance manually configured, no flash, zoom 1x, lens aperture at f/4.4, ISO sensitivity at 400, exposure time at 1/250. Three models were used for the color analysis: $L*a*b*$, RGB (red, green, and blue) and CMYK (cyan, magenta, yellow, black). The color values were analyzed in Photoshop by means of Info Palette and Color Sampler tool. The latter was set to sample the average color of 101 × 101 pixels around a selection point.

5.4 Water resistance tests

The water resistance tests concerned the following features: wettability, water absorption and erosion resistance.

The wettability was studied through a qualitative evaluation of the static contact angle ($\theta°$) that is the angle at which the liquid-vapor interface of a water drop meets the horizontal surface of the specimen. The measurement was conducted on pictures taken with a digital camera in four distinct times, respectively at 5 sec, 15 sec, 2 min, 10 min from the first contact between the drop and the specimen.

The water absorption (Fig. 4d) was determined using the Karsten pipe method according to the Rilem II.4 recommendations [35]. The tests were performed on 250 mm × 250 mm plasters applied to a wall panel (cob wall) and also on the bare surfaces of the two walls. The Karsten pipe is a tube graduated to the 10th of a millimeter provided, in the lower end, with an aperture of 500 mm^2 internal area. The pipe standing in a vertical position was sealed to the sample with mastic and then filled with water. The initial water column, 92 mm high, exerted a pressure of about 900 Pa in the contact area between the pipe and the earthen surface. The readings of the reduction in water level were taken every minute for 15 minutes and then the water absorption rate (C_{10min}, g $m^{-2}s^{-1}$) was calculated using the following formula:

$$C_{10min} = (m_{15min} - m_{5min}) / (A \times t_{10min}) \qquad (2)$$

where:

m_{15min} is the water absorption at 15 min (g);

m_{5min} is the water absorption at 5 min (g);

A is the contact area between the pipe and the earthen surface (m);

t_{10min} is equivalent to 10 minutes (s).

The erosion test was carried out according to New Zealand Standard NZS 4298 [36], with some adaptations for the criteria of evaluation. Both the Geelong method and the pressure spray method were used.

The Geelong test (Fig. 4e) involved the dripping of 100 ml of water onto the specimen for a duration going from 20 to 60 minutes and the measurement of the final erosion depth (D, mm). The drops fell from an established height of 400 mm and the specimen, placed with an inclination of 50%, was characterized by an area of 75 × 150 mm^2 and a thickness of 30 mm. In the specific case of the treated plasters, the surface treatment was applied on the entire surface of the specimen.

The pressure spray test (Fig. 4f) was performed on 250 mm × 250 mm plasters applied to the wall panel (rammed earth wall), and also on the bare surfaces of the two walls. It consisted of spraying the exposed section of the sample for a period of 1 hour or until the sample was eroded through, with interruptions at 15-minute intervals to record the erosion depth (*D*, mm). The water jet was projected from a distance of 470 mm with a pressure of about 50 kPa.

6 - Results and discussion

The following subsections report the results obtained for each of the experimental tests and the relative discussion with reference to other authors' findings.

6.1 - Preliminary tests

The results of the preliminary tests are shown in Fig. 5 and Fig. 6. An earth/sand ratio is validated if no crack appears on the plaster during the shrinkage test and if the shear adhesion strength is high enough. To have an adequate adhesive strength, the plaster should bear its own load with a safety coefficient of 10. Considering a thickness of 60 mm, which could be the maximum thickness for in-situ applications, and a density of 1.7×10^{-5} kg mm^{-3}, it is assumed a threshold adhesive strength of 10 kPa (10×60 mm $\times 1.7 \times 10^{-5}$ kg $mm^{-3} \times 10$ $kg^{-1}N = 0{,}0102$ $Nmm^2 \approx 10$ kPa). Among the validated earth/sand ratios, the one with the best workability was selected for manufacturing the plasters of the subsequent phase.

The results of the shrinkage test (Fig. 5) demonstrate that the behavior of each plaster is not dependent upon the substrate type. Instead, as also observed by Hamard et al. [3], the clay content has a great influence on shrinkage: 20% clay plasters fell down from the support; those with 16% and 13% clay cracked and/or partially detached from the substrate; 10% clay plasters cracked and those with 8% and 6% clay content remained flawless. Only the last two recipes of plasters are validated (their bond with the substrate is verified to be strong enough, as reported in the next paragraph) but among them, the recipe with 8% clay content (i.e. earth/sand ratio = 1/4) is more workable, presenting a better adhesion with the substrate during the plastering work. Therefore, the recipe with 8% clay was chosen to manufacture the plasters of the subsequent experimental phase.

The graphs reported in Fig. 6 represent, for each wall substrate, the relationship between the shear strength and the clay content of the plaster. Despite a certain scattering of the values, it can be observed a similar trend for the two substrates: as the clay content goes from 6% to 16% the shear strength values increase; then, beyond 16%, the values decrease. Therefore an increase in the clay percentage strengthens the plaster until the effect of shrinkage becomes predominant and decreases the shear strength. The scattering of the values is significantly influenced by the substrate preparation, as highlighted by Delinière et al. [21] for adhesive tensile strength of earth plasters, and this could be the starting point for further deepening studies. In all the cases, the average τ_{max} is greater than the 10 kPa threshold value (τ_{max} = 19 kPa in the case of 8% clay plaster) and, thus, the plasters are sufficiently secure to the substrate. The shear strengths on the two walls are similar up to 10% clay content: above this percentage the plasters applied on the rammed earth wall have higher performance than those on the cob wall. The adhesive bond depends on the type of wall as well as on the clay content of the plaster, and this is consistent with the findings of Hamard et al. [3] for earth plasters. However in the present study the clay content that maximizes the shear strength (about 16%) is higher than that found by Hamard et al. [3] (9% for Tassin earth and 6% for Rochechinard earth). Also, the clay content optimal for the shear strength and that most suitable for the plaster manufacturing are much closer in the experimentation of Hamard et al. [3]. These different results can be explained since there are many factors influencing the bond between the plaster and the wall: different type of clay mineral, proportion of soil components, water content, grain size of the sand fraction, type of wall and substrate preparation (in the present study the wall surface was scratched through a metal brush and wetted with a clay slurry while Hamard et al. used a lime-sand scratch coat). According to Minke [5] these factors, including the presence of additives, are crucial to determine the clay content most suitable for earth plasters, which is usually in the range of 5% to 12%.

6.2 - Physical-mechanical tests

The results of the shrinkage and shear tests for the ten typologies of plasters are presented below. No plaster cracked or detached during the shrinkage test. In the case of the plaster admixed with straw this was expected since Bouhicha et al. [19] demonstrated that the presence of barley straw in composite soil ensures a better control of shrinkage.

As shown in Table 2, all the average shear strengths are higher than the threshold value. Those of the plasters admixed with synthetic additives are similar to that of the basic plaster, regardless the type of substrate. The use of 1 mm sand instead of 2 mm sand, as well as the addition of straw inside the plaster, determines an enhancement in the shear strength on the rammed earth wall while having no meaningful effect on the cob wall. The similarity of the bond efficacy is related to the fact that the soil proportions are not significantly altered by the small quantity of admixtures. Instead the higher values of shear strength are probably due to higher amount of clayey material deposited at the plaster-wall interface.

The results of the unconfined compression test are shown in Fig. 7. The graphs represent the stress-strain curves until maximum strength of two specimens for each typology. The curve slope indicates the specimen stiffness. Values of deformation modulus E_{50}, unconfined compressive strength q_u, and axial deformation at failure ε_u are included. It was decided to report the whole curve, including the effect of local compression. The latter is related to the fact that the surface of the sample is not perfectly plane due to the presence of asperities, since the shrinkage that occurs during the drying process is not perfectly uniform. After an initial phase, approximately linear, the curve undergoes a sharp deviation, during which the rigid plates of the press crushed the asperities. Then, the curve resumes its linear proceeding. The secant modulus E_{50} calculated as graphically represented in Fig. 4b is a precautionary value, lower than that of the stress-strain curve without the phase of local compression. No threshold value for the secant modulus E_{50} of a plaster is fixed in literature but many authors [3,6,37] agree on the fact that the evaluation of the mechanical compatibility should be based on the comparison between the deformation modulus of the plaster and that of the underlying substrate. In the present work, as in that of Hamard et al. [3], it is assumed that the smaller the difference, the higher the mechanical compatibility, even if for other authors [6,37] the plasters should not be stiffer than the walls. The rammed earth wall ($E_{50, mean}$ = 164 MPa) was found to be stiffer than the cob wall ($E_{50, mean}$ = 90 MPa), and the two walls stiffer than the plasters. The basic plaster ($E_{50, mean}$ = 83 MPa) and that with 1 mm sand ($E_{50, mean}$ = 87 MPa) are the coatings most similar to the walls from a mechanical point of view, and the plaster admixed with silicon nano-particles ($E_{50, mean}$ = 44 MPa), the most different. Hence all the studied plasters are considered to be mechanically compatible with the two earthen walls.

The results of the water vapor permeability test are reported in detail in Table 3. It is commonly accepted that the breathing capability of the plaster should be lower than that of the bearing wall [37]. While the μ value is a unitless parameter and used to compare the materials regardless of their layer thicknesses, the S_d value is more suitable to define the breathing capability of a given thickness layer. Hence, a plaster and its wall substrate are considered to be compatible with each other in terms of the water vapor permeability if the S_d value of the plaster is the lower one. All the plasters (20 mm thick) are characterized by a medium permeability to water vapor, according to the EN 15824 classification [38], with the μ coefficient ranging from 8 to 10 and the S_d values from 0.16 m to 0.20 m. Due to their greater thickness (300 mm), the rammed earth wall and the cob wall are characterized by S_d values higher than those of the plasters, and respectively equal to 1.20 m and 2.40 m. These data highlight the compatibility between the plasters and the walls. Among the two walls, the rammed earth one (μ =4), despite its major density and porosity (see Section 3), is more permeable than the cob one (μ =8). In fact, micro-cracking occurred in the rammed earth samples during the drying process, but not in the cob ones because of the presence of straw. Moreover, it should be noted that the specimens for the cob wall were sampled in the middle of a cob element, not at the interface between multiple elements where there could be some empty pores.

6.3 - Surface color test

The results of the surface color test are shown in Fig. 8. For each typology of plaster and wall, the figure reports the following data: the image of the sample; the $L^*a^*b^*$, RGB and CMYK values of the color sampled. From an esthetic point of view, an admixture or a surface treatment should not significantly modify the appearance of the earthen material. Since the colors of a picture depend also on the lighting in the room and the camera settings, the color coordinates of each pixel can vary with these parameters. Therefore the evaluation of color change induced by the admixtures and the surface treatments is made with a comparative criterion. Since $L^*a^*b^*$ model is easier related to the perceived color than the other scales and it is device-independent, unlike the RGB and CMYK models, the comparison is done with reference to it. For all the typologies of plasters and for both walls, the values for a^* and b^* are in the range of -10 to +10, indicating colors with low saturation, and the lightness L^* value varies from 50 to 70. The two plasters made only with earth and sand are chromatically very similar to the two walls, even if the latter have smoother and glossier surfaces due to the higher clay content. All the admixed plasters and that treated with the silane-siloxane product are characterized by about the same L*a*b* values of the basic plaster: these are positive results and consistent with a subjective perception. Instead, the remaining treatments caused a small color change on the plaster surface according to the numerical analysis, but an evident alteration, although not excessive, to the human perception: this could not be a negligible factor in phase of choice for a colorless treatment for an earthen plaster.

6.4 Water resistance tests

The results of the wettability test are shown in Fig. 9. As conventional, when the contact angle is greater than 90° the surface is considered to be lowly wettable (i.e. hydrophobic, water repellent), otherwise highly wettable (i.e. hydrophilic). Only the silane-silixane treatment and that with silicon nano-particles are able to make the plaster water-repellent. In both cases the contact angle is about 110° and remains the same over time. On the plaster treated with beeswax, the drop forms an initial angle of about 90° that decreases gradually and in a few minutes it is completely absorbed by the plaster. Similar behavior can be observed for the plasters admixed with silicon nano-particles and those admixed with organic derivatives of silicon. About the other plasters and the two walls, as the drop is put on the surface of the specimen, it is quickly absorbed, and this made the measuring impossible.

The results of the water absorption test are shown in Fig. 10. The graphs show the absorption (g) as a function of the time (min), recorded on two samples for each typology. The greater the average slope of the curve, the greater the rate of absorption C_{10min}. The test was carried out not only to appreciate the C_{10min} values of the plasters and the walls but also to determine if their surfaces are water repellent: when the absorption of a plaster or a wall is zero, its surface is expressed to be water repellent. For the latter purpose the Karsten pipe method could be considered as an alternative to the previous test of wettability. However, the major interest towards this method comes from the fact that it simulates the pressure of driving rain, a pressure which could be able to 'break' the water repellent behavior of a treated material. As it can be seen in Fig. 10, the plaster treated with the silane-siloxane product and that treated with silicon nano-particles are water repellent (C_{10min} = 0.00 g m^{-2}s1), as also highlighted by the contact angle evaluation. The basic plaster has an average absorption rate of 1.58 g m^{-2}s^{-1} that decreases to 1.25 g m^{-2}s^{-1}, 1.17 g m^{-2}s^{-1} and 0.75 g m^{-2}s^{-1}

with the use respectively of the silicon nano-particles additive, the treatment with titania and silica nano-particles and the beeswax impregnator. On the other hand it increases up to 1.75 g $m^{-2}s^{-1}$, 2.08 g $m^{-2}s^{-1}$ and 2.33 g $m^{-2}s^{-}1$ with the use respectively of the organic derivatives of silicon, 1 mm sand and the straw fibers. The additived limestone aggregates does not substantially modify the absorption rate of the basic plaster. Lower values for the absorption rate, equal to 0.50 g $m^{-2}s^{-1}$ and 0.42 g $m^{-2}s^{-}1$, are assigned respectively to the rammed earth wall and the cob wall. This is due to the higher clay content that strongly reduces the permeability to liquid water.

The results of the water erosion tests are shown in Fig. 11. It should be noted that the results of the admixed plasters and those of the two walls cannot be compared with the results of the treated plasters since, in the latter case, the erosion resistance could vary significantly once the outer layer of the plaster, where the treatment acts, is eroded. For this reason the erosion resistance is not evaluated through the attribution of the NZS 4298 erodibility indices, which are valid only for untreated specimens. However, the values of erosion depth are reported and discussed below.

During the water dripping of Geelong erosion test, the specimens made only with earth and sand absorbed water and broke due to loss of cohesion. The same phenomenon occurred in the plaster admixed with straw, in that admixed with additived limestone aggregates, and in the plaster treated with titania and silica nano-particles. The erosion depths D of the abovementioned coatings were measured and found to be in the range of 7 to 11 mm. All the other plasters and the two walls were eroded for a depth lower than 5 mm, but under this threshold value the drip test is not suitable to characterize the erosion resistance. As a consequence, in these cases, to obtain more significant results it was resort to the pressure spray test.

The results of the latter test show that the two walls have a good resistance against water, as expected for the relatively high clay content. After 1 hour of water jet, both of them were eroded for a maximum depth of about 12 mm, and this is consistent with the findings of Bui et al. [11] demonstrating that rammed earth walls in France are highly durable against the erosion of weathering. The plaster admixed with organic derivatives of silicon and that admixed with silicon nano-particles were eroded for the full depth (20 mm) respectively within 30 and 15 minutes and their erosion was diffuse all over the plaster surface. In particular, the former plaster was found to have the highest performance among all the admixed plasters. In the cases of the plaster treated with beeswax and the plaster treated with silicon nano-particles, the pressure of the water spraying, simulating the driving rain, was able to break the efficacy of the treatment and to erode the body of the plaster during the first 15 minutes of the test; the erosion was concentrated in some areas of the plaster surface. Finally, the plaster treated with the silane-siloxane product is the only one, among all the studied typologies, that remained flawless after the test, thus demonstrating the best resistance to water erosion.

7 - Conclusions

The study identifies the soil proportion most suitable for manufacturing earth plasters and the treatment or additive most effective to make them durable against weathering.

The plaster formulated with the best soil proportion was found to be that with 8% clay, 9% silt and 83% sand, and to have the following properties:

- a good bond with the earthen substrates, being characterized by a shear strength of about 19 kPa on both the rammed earth wall and the cob wall. Also, this bond was observed to be significantly influenced by the clay content of plaster and the typology of underlying substrate;
- a good physical and mechanical compatibility with the earthen walls;
- on the other hand, a high vulnerability to the erosive action of water.

About the effects of the admixtures and the surface treatments, when used in the selected plaster, the following conclusions can be drawn:

- in all the cases the plaster remains physically and mechanically compatible with the earthen walls;
- unlike the admixtures, the surface treatments, except for the silane-siloxane one, determine an evident color change of the plaster;
- the addition of straw fibers inside the plaster, as well as the use of 1 mm instead of 2 mm sand, produces an increase in the absorption rate and an alteration in the shear adhesion strength that need to be investigated in further works; however, the straw fibers are recommended as they provide a better control of shrinkage;
- the water resistance of the plaster varies significantly depending on the additive or the surface treatment used. In particular, going from the worst to the best case: the admixture with additived limestone aggregates and the treatment with titania and silica nano-particles have no particular effect; the treatment with beeswax and that with silicon nano-particles significantly reduce the wettabilty of the plaster but the pressure of the driving rain is able to break their efficacy; the additive with silicon nano-particles slightly increases the

erosion resistance of the plaster, while reducing its water absorption; the additive with organic derivates of silicon determines for the plaster a decisively higher erosion resistance but a greater absorption rate; the silane-siloxane surface treatment is the only product able to make effectively the plaster water-repellent and highly protect from weathering.

Among all the typologies, the plaster that optimizes all the surveyed properties is the 8% clay plaster treated superficially with the silane-siloxane product. The treatment presents an active ingredient content of 8%; a current cost of 8-9 €/m^2 considering a consumption of 1 kg/m^2; it needs for an application by paintbrush or by low pressure spray gun and each successive coat should be applied when the previous one is still wet; being water-based its environmental impact is lower than a synthetic solvent-based treatment.

The soil is a sustainable building material with low embodied energy, very positive life circle, wide availability; it is cheap and harmless for human health. Certainly the addition of a synthetic treatment such as the silane-siloxane one determines a slight worsening in the ecological and economic qualities of the plaster, but this difference is not significant. Hence there is a potential for the use of the earth plaster treated with the silane-siloxane product for the protection of earthen buildings against weathering.

Future research should focus on determining, through using in-situ tests, the durability over the time for this product.

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Figure captions

Fig. 1. Geotechnical characterization of the soil.

Fig. 2. Production of the earthen walls.

Fig. 3. Plaster manufacturing: scratching (a) and wetting (b) of the substrate; plastering (c); shaping of the sample (d).

Fig. 4. Test method details.

Fig. 5. Shrinkage test results.

Fig. 6. Shear strength vs. clay content of the plasters.

Fig. 7. Unconfined compression test results.

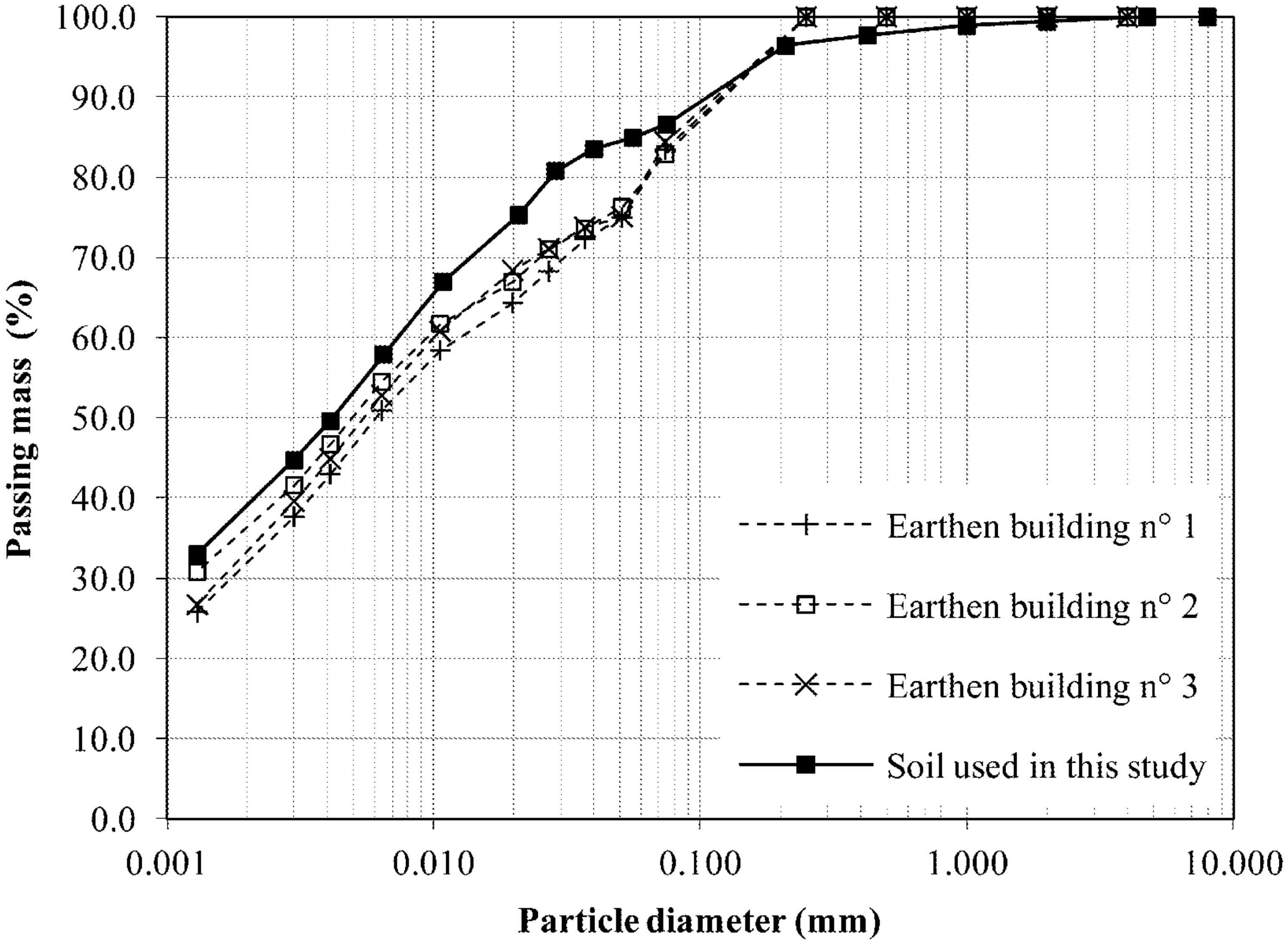
Fig. 8. Surface color test results.

Fig. 9. Wettability test results.

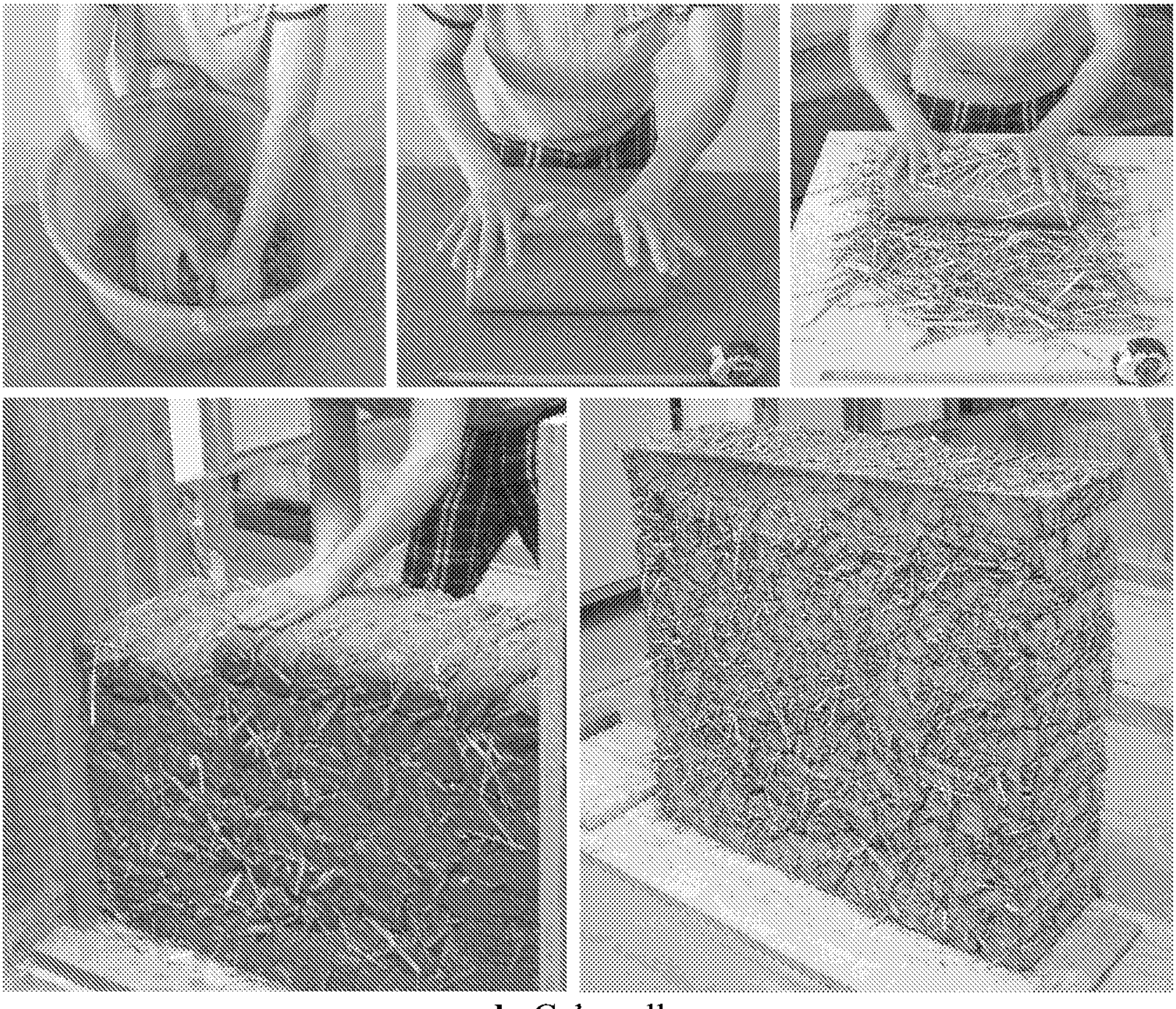
Fig. 10. Water absorption test results.

Fig. 11. Water erosion test results.

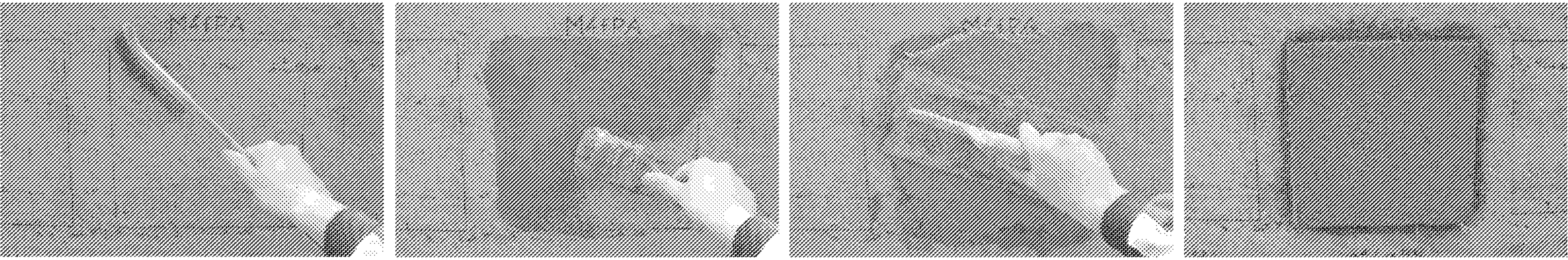
	Soil used in this study	Earthen build. n° 1	Earthen build. n° 2	Earthen build. n° 3
Gravel (> 4.750 mm) %	0	0	0	0
Sand (4.750 mm - 0.075 mm) %	13	17	17	16
Silt (0.075 mm - 0.002 mm) %	47	51	47	51
Clay (< 0.002 mm) %	39	32	36	33
Water natural content %	22	-	-	-
Liquid limit %	44	39	39	37
Plastic limit %	25	19	19	20
Plasticity index %	18	20	20	17
USCS Classification %	CL	CL	CL	CL



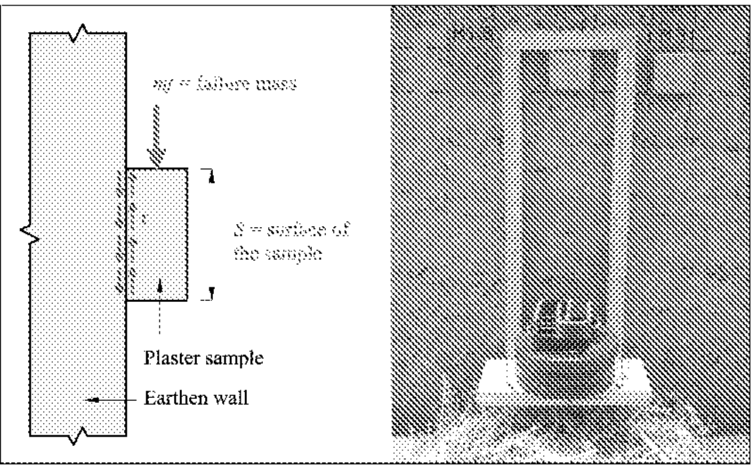
a. Rammed earth wall.



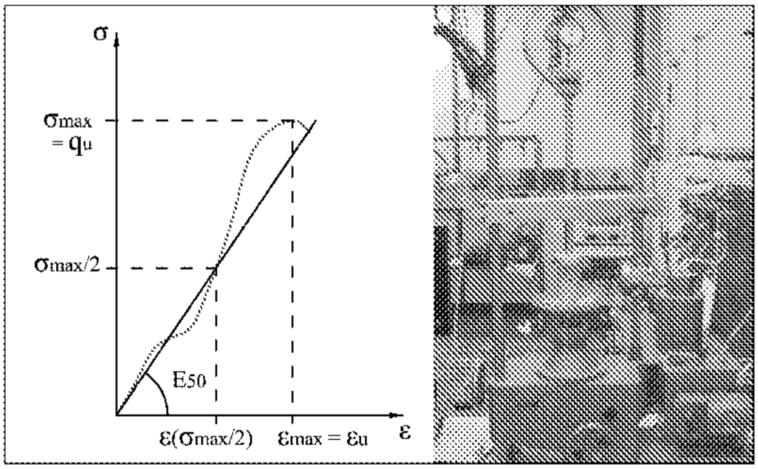
b. Cob wall.



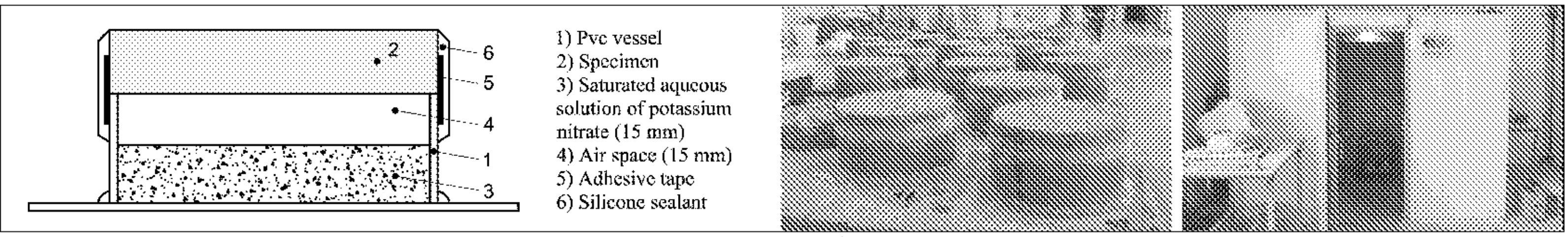
a b c d



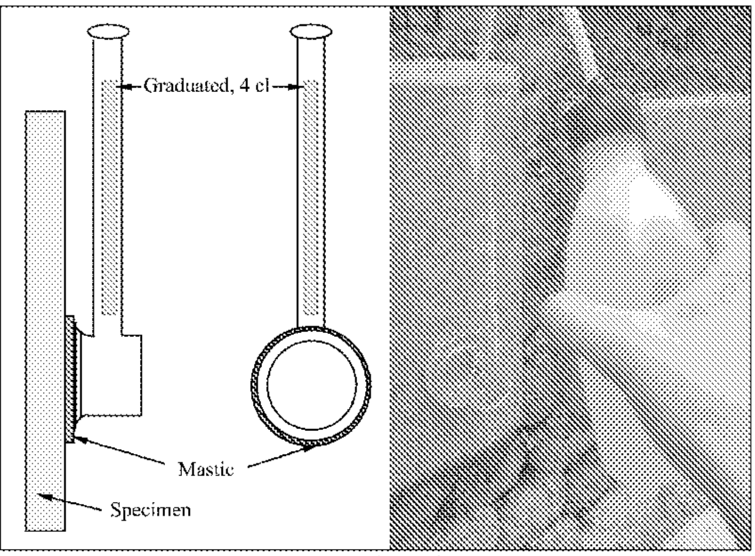
a. Shear adhesion test.



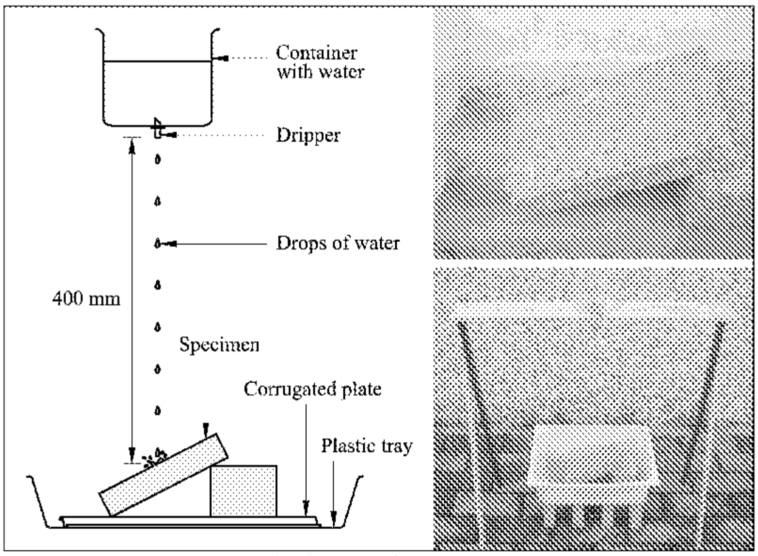
b. Unconfined compression test.



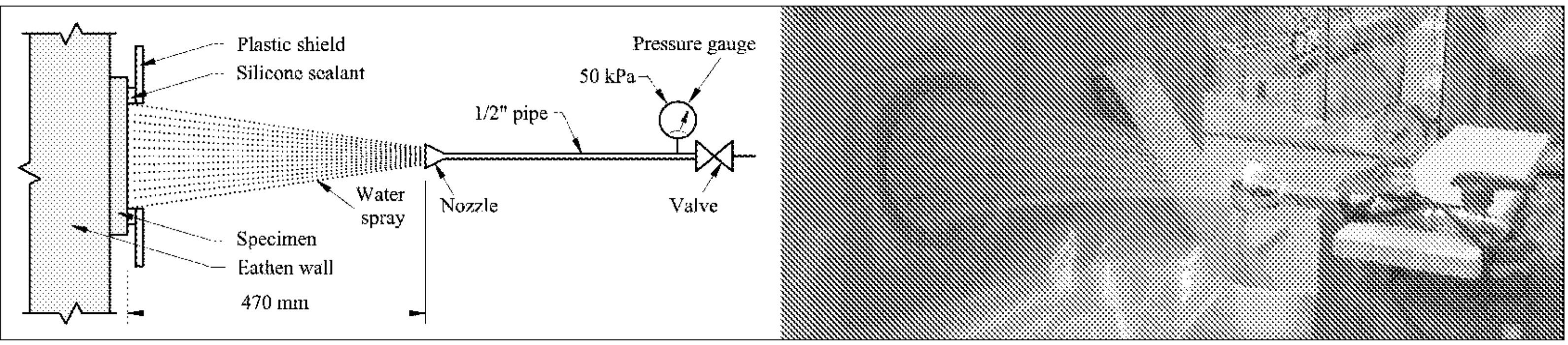
c. Water vapor permeability test.



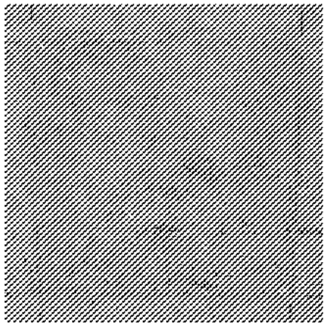
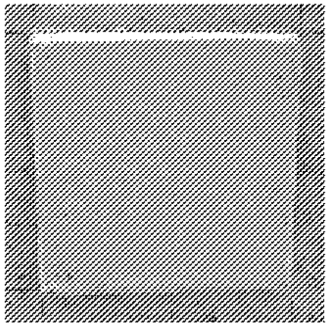
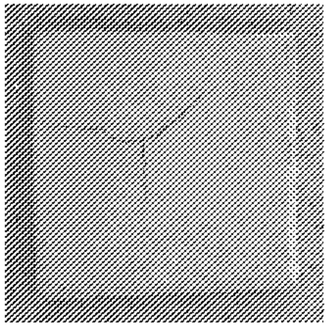
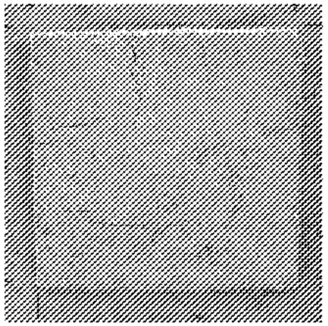
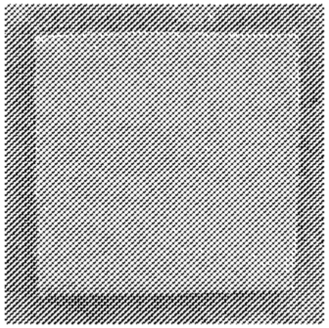
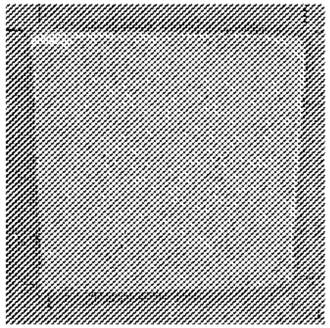
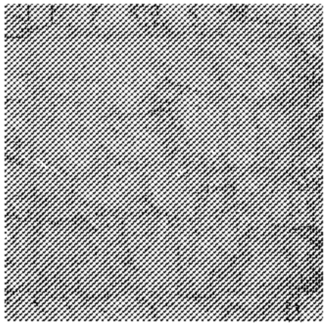
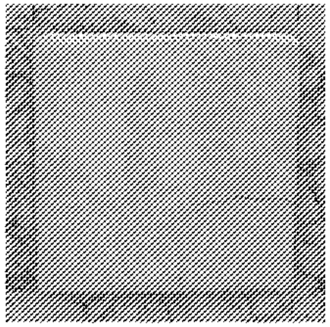
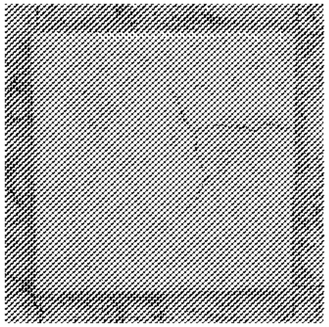
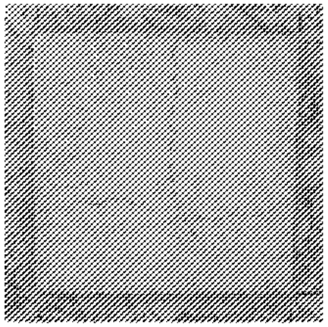
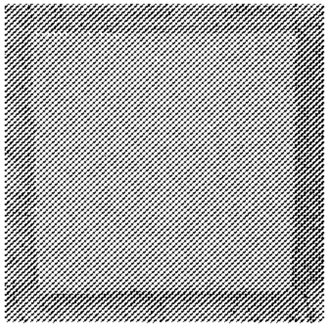
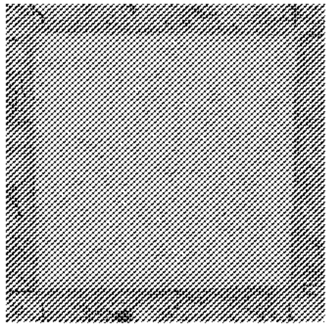
d. Water absorption test.

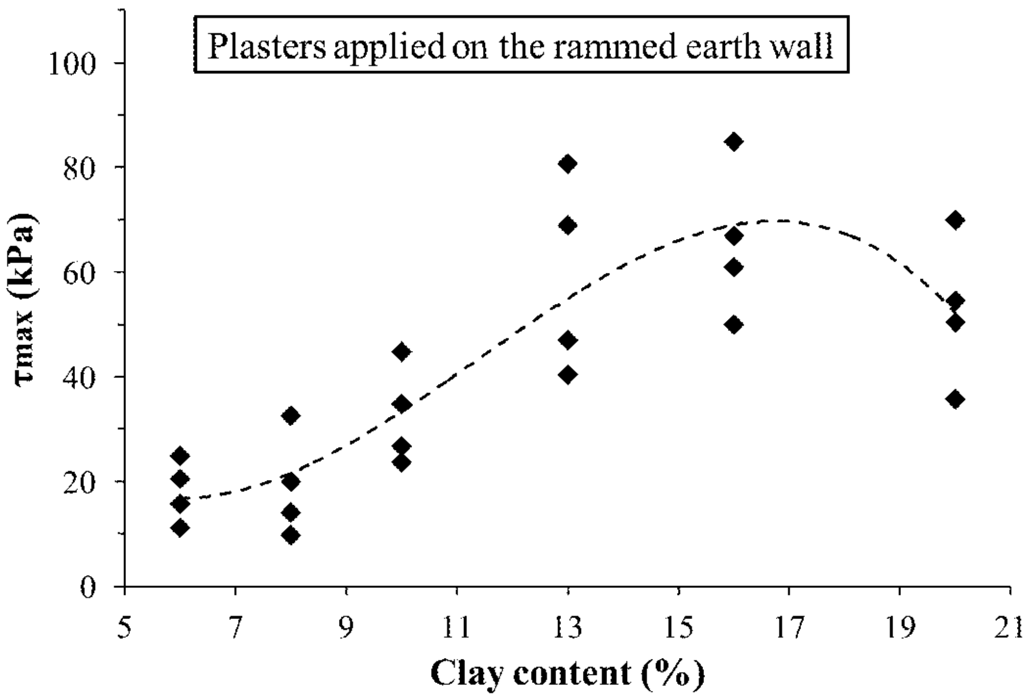


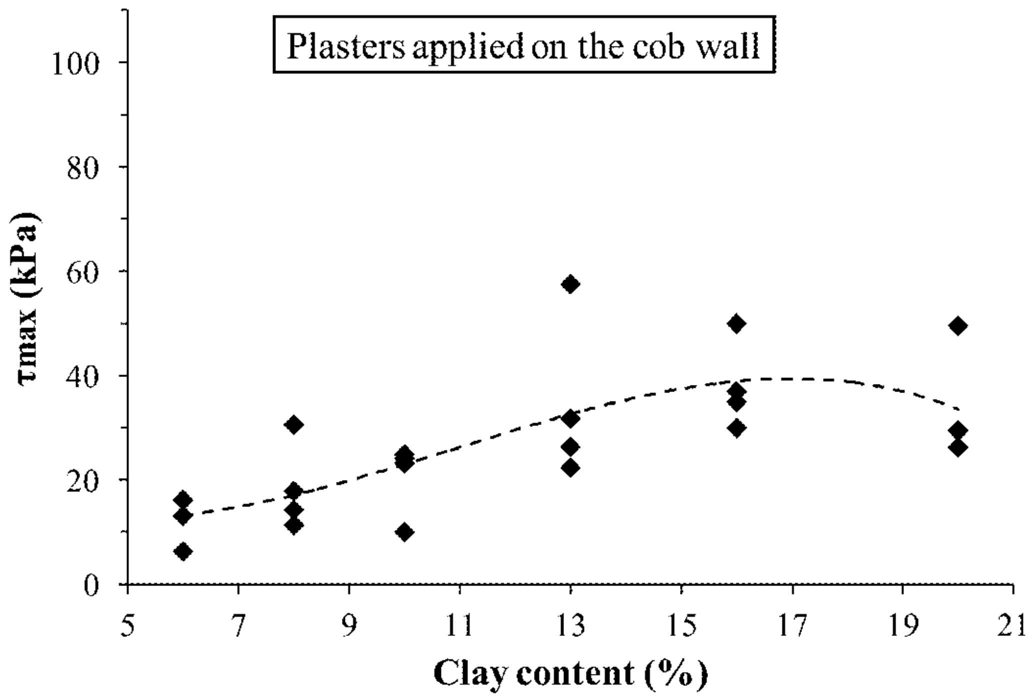
e. Geelong erosion test.

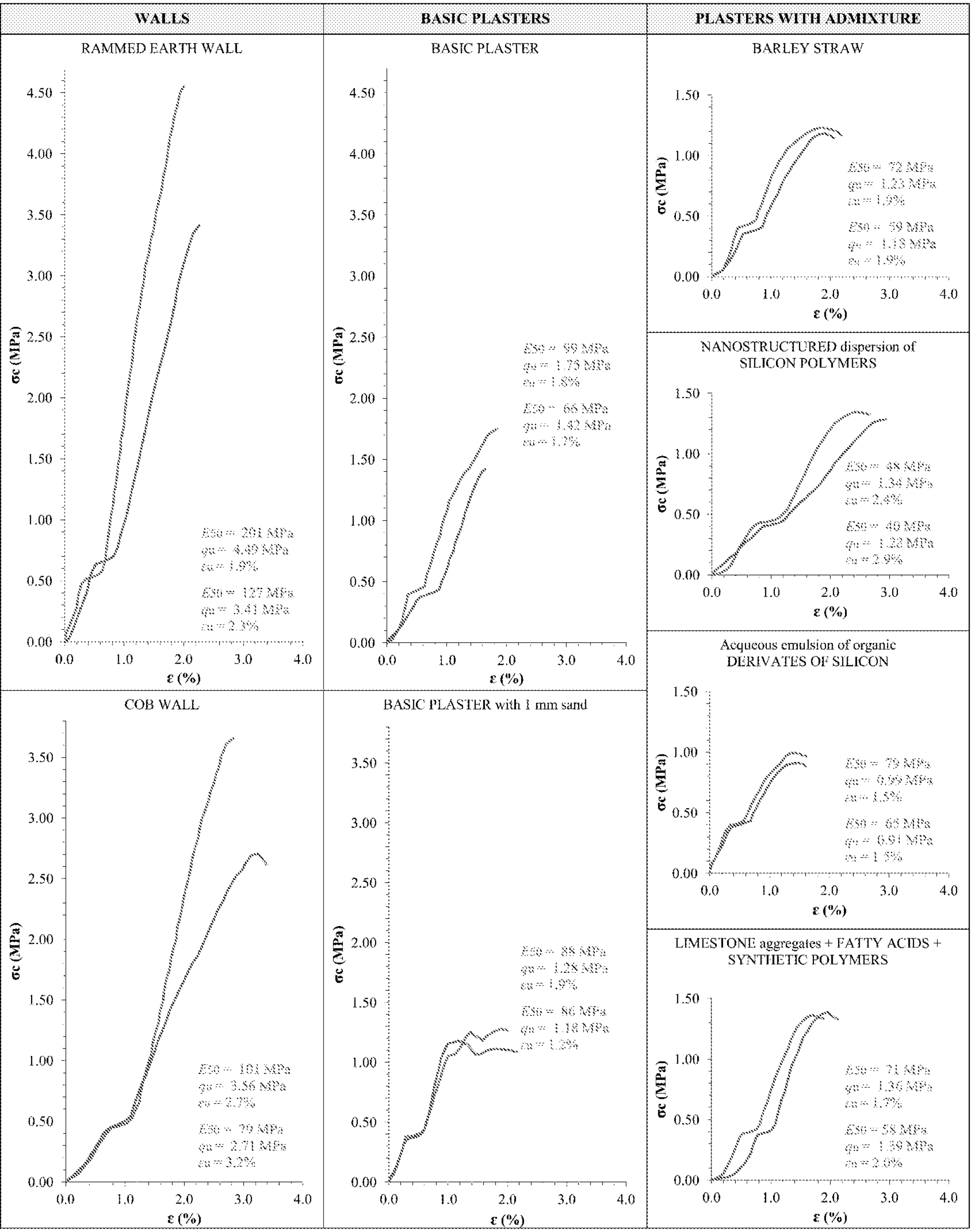


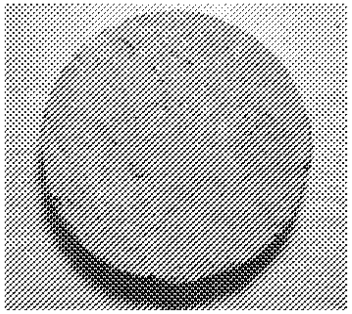
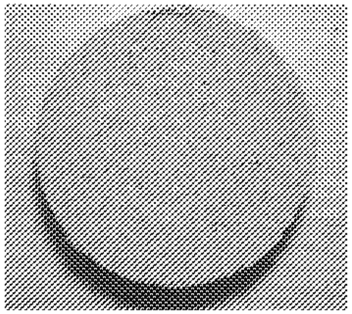
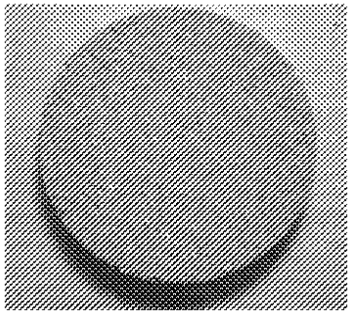
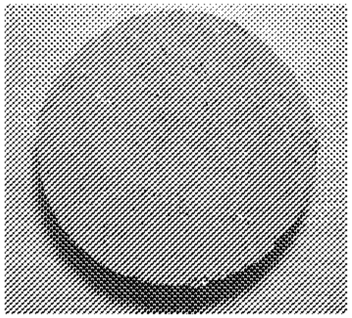
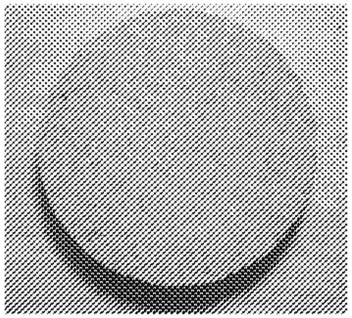
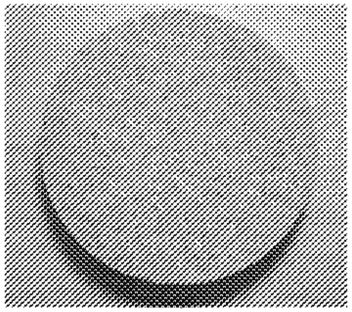
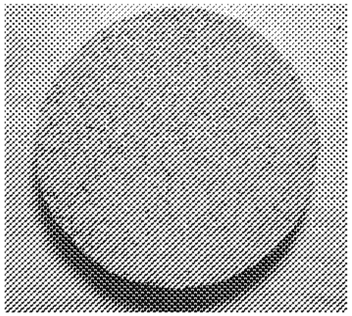
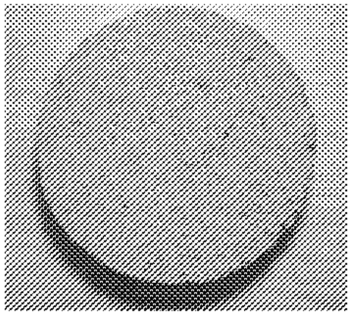
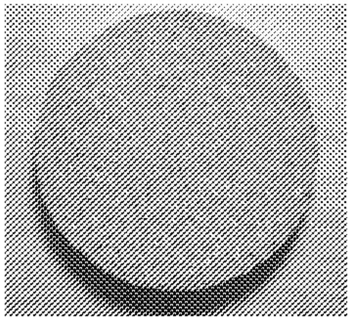
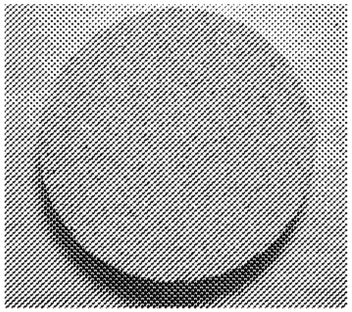
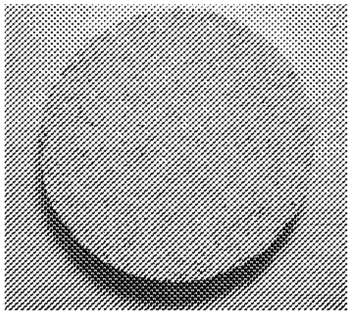
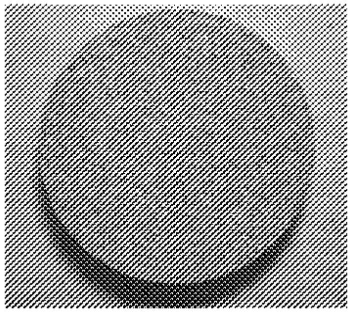
f. Pressure spray erosion test.

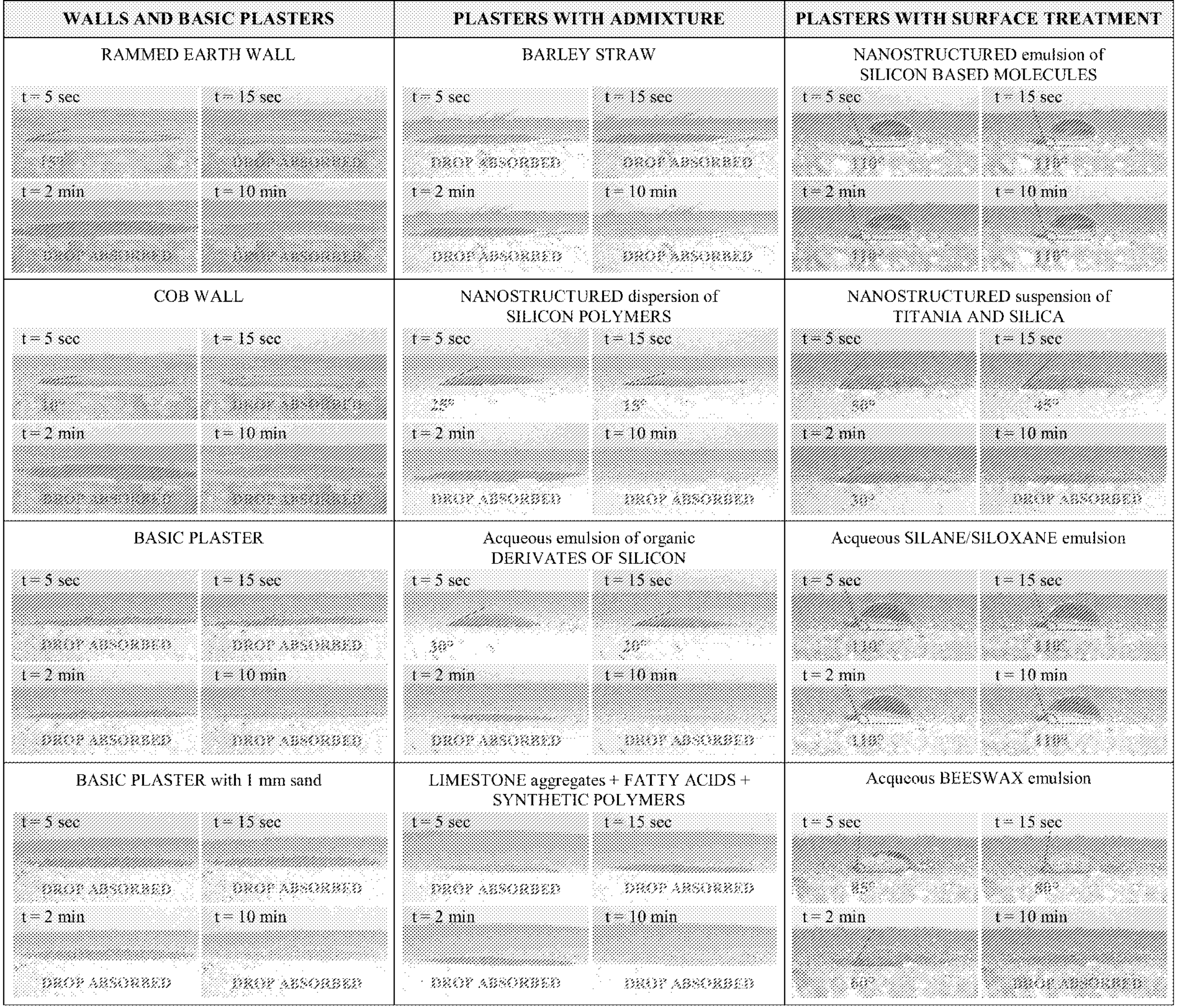
SUBSTRATES	PLASTER RECIPES: 1 EARTH + 1 SAND 20% Clay	1 EARTH + 1.5 SAND 16% Clay	1 EARTH + 2 SAND 13% Clay	1 EARTH + 3 SAND 10% Clay	1 EARTH + 4 SAND 8% Clay	1 EARTH + 5 SAND 6% Clay
RAMMED EARTH	 Cracked - Partially detached - Fallen Yes	 Cracked No Partially detached Yes Fallen No	 Cracked Yes Partially detached Yes Fallen No	 Cracked Yes Partially detached No Fallen No	 Cracked No Partially detached No Fallen No	 Cracked No Partially detached No Fallen No
COB WALL	 Cracked - Partially detached - Fallen Yes	 Cracked Yes Partially detached Yes Fallen No	 Cracked Yes Partially detached Yes Fallen No	 Cracked Yes Partially detached Yes Fallen No	 Cracked No Partially detached No Fallen No	 Cracked No Partially detached No Fallen No

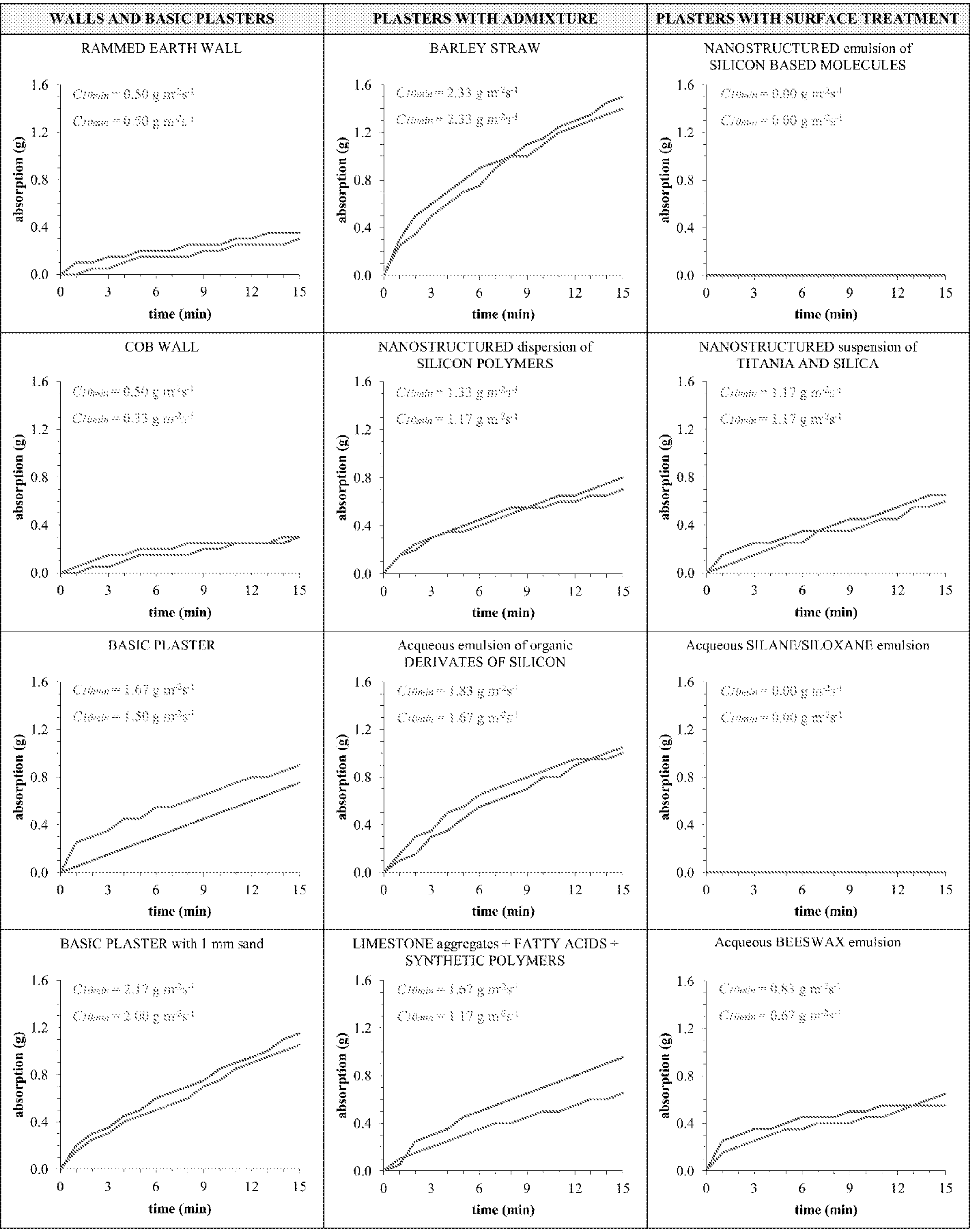

Plasters applied on the rammed earth wall
τmax (kPa)
Clay content (%)
0
20
40
60
80
100
5
7
9
11
13
15
17
19
21


Plasters applied on the cob wall
τmax (kPa)
Clay content (%)
0
20
40
60
80
100
5
7
9
11
13
15
17
19
21


WALLS
BASIC PLASTERS
PLASTERS WITH ADMIXTURE
RAMMED EARTH WALL
E50 = 201 MPa
qu = 4.49 MPa
εu = 1.9%
E50 = 127 MPa
qu = 3.41 MPa
εu = 2.3%
BASIC PLASTER
E50 = 99 MPa
qu = 1.75 MPa
εu = 1.8%
E50 = 66 MPa
qu = 1.42 MPa
εu = 1.7%
BARLEY STRAW
E50 = 72 MPa
qu = 1.23 MPa
εu = 1.9%
E50 = 59 MPa
qu = 1.18 MPa
εu = 1.9%
NANOSTRUCTURED dispersion of SILICON POLYMERS
E50 = 48 MPa
qu = 1.34 MPa
εu = 2.4%
E50 = 40 MPa
qu = 1.28 MPa
εu = 2.9%
Acqueous emulsion of organic DERIVATES OF SILICON
E50 = 79 MPa
qu = 0.99 MPa
εu = 1.5%
E50 = 65 MPa
qu = 0.91 MPa
εu = 1.5%
COB WALL
E50 = 101 MPa
qu = 3.56 MPa
εu = 2.7%
E50 = 79 MPa
qu = 2.71 MPa
εu = 3.2%
BASIC PLASTER with 1 mm sand
E50 = 88 MPa
qu = 1.28 MPa
εu = 1.9%
E50 = 86 MPa
qu = 1.18 MPa
εu = 1.2%
LIMESTONE aggregates + FATTY ACIDS + SYNTHETIC POLYMERS
E50 = 71 MPa
qu = 1.36 MPa
εu = 1.7%
E50 = 58 MPa
qu = 1.39 MPa
εu = 2.0%
σc (MPa)
ε (%)

WALLS AND BASIC PLASTERS	PLASTERS WITH ADMIXTURE	PLASTERS WITH SURFACE TREATMENT
RAMMED EARTH WALL  **L*: 63** **a*: -4** **b*: 4** R: 148 G: 153 B: 144 C: 49% M: 34% Y: 40% K: 1%	BARLEY STRAW  **L*: 67** **a*: -3** **b*: 3** R: 159 G: 163 B: 156 C: 44% M: 31% Y: 36% K: 1%	NANOSTRUCTURED emulsion of SILICON BASED MOLECULES  **L*: 58** **a*: -4** **b*: 9** R: 137 G: 140 B: 123 C: 52% M: 38% Y: 49% K: 5%
COB WALL  **L*: 60** **a*: -4** **b*: 7** R: 142 G: 145 B: 132 C: 51% M: 36% Y: 46% K: 3%	NANOSTRUCTURED dispersion of SILICON POLYMERS  **L*: 68** **a*: -3** **b*: 2** R: 162 G: 166 B: 161 C: 43% M: 30% Y: 33% K: 0%	NANOSTRUCTURED suspension of TITANIA AND SILICA  **L*: 66** **a*: -2** **b*: -3** R: 155 G: 160 B: 164 C: 46% M: 33% Y: 29% K: 0%
BASIC PLASTER  **L*: 65** **a*: -3** **b*: 6** R: 155 G: 158 B: 146 C: 45% M: 33% Y: 41% K: 1%	Acqueous emulsion of organic DERIVATES OF SILICON  **L*: 67** **a*: -3** **b*: 3** R: 159 G: 163 B: 156 C: 44% M: 31% Y: 36% K: 1%	Acqueous SILANE/SILOXANE emulsion  **L*: 64** **a*: -3** **b*: 6** R: 153 G: 155 B: 143 C: 46% M: 34% Y: 41% K: 1%
BASIC PLASTER with 1 mm sand  **L*: 64** **a*: -3** **b*: 4** R: 152 G: 155 B: 147 C: 47% M: 34% Y: 39% K: 1%	LIMESTONE aggregates + FATTY ACIDS + SYNTHETIC POLYMERS  **L*: 66** **a*: -3** **b*: 2** R: 156 G: 161 B: 155 C: 46% M: 32% Y: 35% K: 1%	Acqueous BEESWAX emulsion  **L*: 52** **a*: 3** **b*: 10** R: 130 G: 121 B: 107 C: 50% M: 47% Y: 53% K: 12%


WALLS AND BASIC PLASTERS
PLASTERS WITH ADMIXTURE
PLASTERS WITH SURFACE TREATMENT
RAMMED EARTH WALL
t = 5 sec
t = 15 sec
DROP ABSORBED
t = 2 min
t = 10 min
DROP ABSORBED
DROP ABSORBED
BARLEY STRAW
t = 5 sec
DROP ABSORBED
t = 15 sec
DROP ABSORBED
t = 2 min
DROP ABSORBED
t = 10 min
DROP ABSORBED
NANOSTRUCTURED emulsion of SILICON BASED MOLECULES
t = 5 sec
110°
t = 15 sec
110°
t = 2 min
110°
t = 10 min
110°
COB WALL
t = 5 sec
t = 15 sec
t = 2 min
t = 10 min
NANOSTRUCTURED dispersion of SILICON POLYMERS
t = 5 sec
25°
t = 15 sec
15°
t = 2 min
DROP ABSORBED
t = 10 min
DROP ABSORBED
NANOSTRUCTURED suspension of TITANIA AND SILICA
t = 5 sec
50°
t = 15 sec
45°
t = 2 min
30°
t = 10 min
DROP ABSORBED
BASIC PLASTER
t = 5 sec
DROP ABSORBED
t = 15 sec
DROP ABSORBED
t = 2 min
DROP ABSORBED
t = 10 min
DROP ABSORBED
Acqueous emulsion of organic DERIVATES OF SILICON
t = 5 sec
30°
t = 15 sec
20°
t = 2 min
DROP ABSORBED
t = 10 min
DROP ABSORBED
Acqueous SILANE/SILOXANE emulsion
t = 5 sec
110°
t = 15 sec
110°
t = 2 min
110°
t = 10 min
110°
BASIC PLASTER with 1 mm sand
t = 5 sec
DROP ABSORBED
t = 15 sec
DROP ABSORBED
t = 2 min
DROP ABSORBED
t = 10 min
DROP ABSORBED
LIMESTONE aggregates + FATTY ACIDS + SYNTHETIC POLYMERS
t = 5 sec
DROP ABSORBED
t = 15 sec
DROP ABSORBED
t = 2 min
DROP ABSORBED
t = 10 min
DROP ABSORBED
Acqueous BEESWAX emulsion
t = 5 sec
85°
t = 15 sec
80°
t = 2 min
60°
t = 10 min
DROP ABSORBED


WALLS AND BASIC PLASTERS
PLASTERS WITH ADMIXTURE
PLASTERS WITH SURFACE TREATMENT
RAMMED EARTH WALL
C10min = 0.50 g m-2s-1
C10min = 0.50 g m-2s-1
BARLEY STRAW
C10min = 2.33 g m-2s-1
C10min = 2.33 g m-2s-1
NANOSTRUCTURED emulsion of SILICON BASED MOLECULES
C10min = 0.00 g m-2s-1
C10min = 0.00 g m-2s-1
COB WALL
C10min = 0.50 g m-2s-1
C10min = 0.33 g m-2s-1
NANOSTRUCTURED dispersion of SILICON POLYMERS
C10min = 1.33 g m-2s-1
C10min = 1.17 g m-2s-1
NANOSTRUCTURED suspension of TITANIA AND SILICA
C10min = 1.17 g m-2s-1
C10min = 1.17 g m-2s-1
BASIC PLASTER
C10min = 1.67 g m-2s-1
C10min = 1.50 g m-2s-1
Acqueous emulsion of organic DERIVATES OF SILICON
C10min = 1.83 g m-2s-1
C10min = 1.67 g m-2s-1
Acqueous SILANE/SILOXANE emulsion
C10min = 0.00 g m-2s-1
C10min = 0.00 g m-2s-1
BASIC PLASTER with 1 mm sand
C10min = 2.17 g m-2s-1
C10min = 2.00 g m-2s-1
LIMESTONE aggregates + FATTY ACIDS + SYNTHETIC POLYMERS
C10min = 1.67 g m-2s-1
C10min = 1.17 g m-2s-1
Acqueous BEESWAX emulsion
C10min = 0.83 g m-2s-1
C10min = 0.67 g m-2s-1
absorption (g)
time (min)

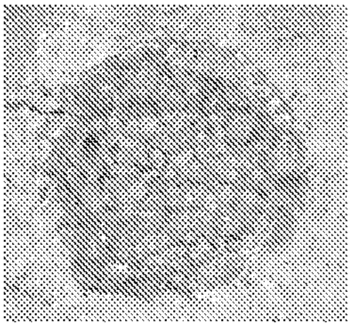
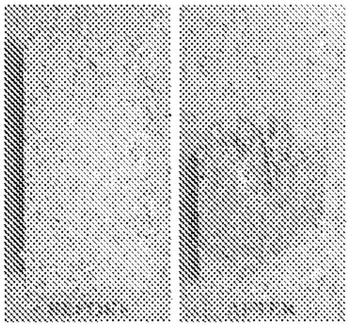
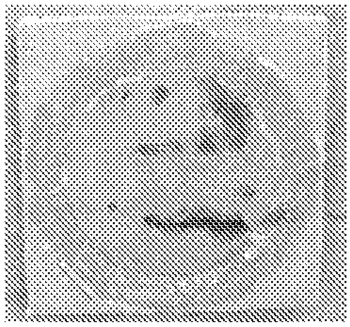
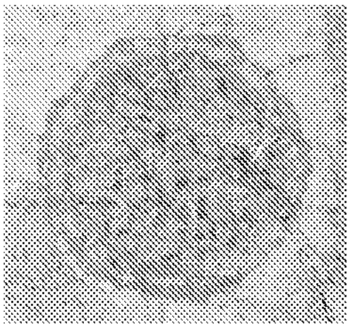
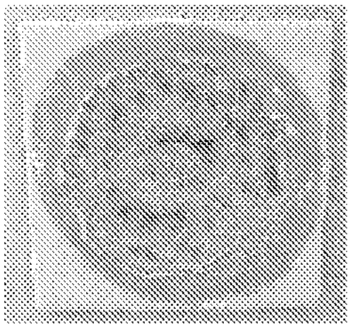
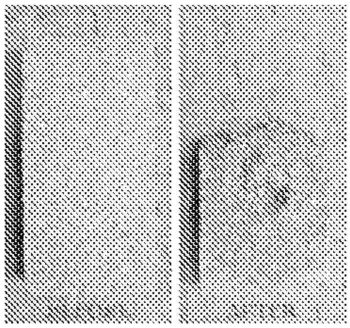
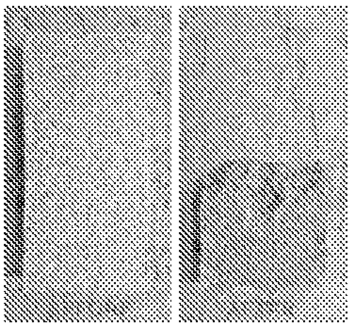
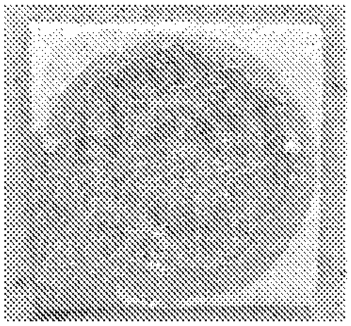
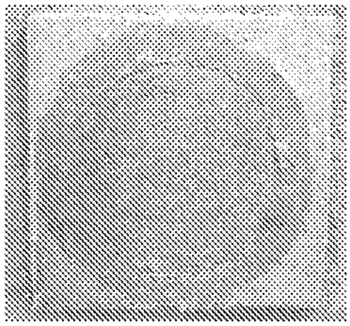
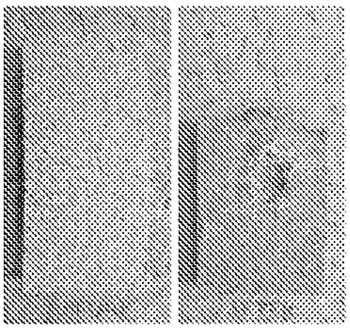
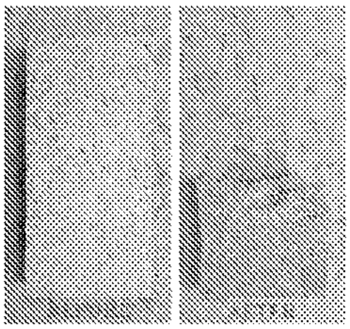
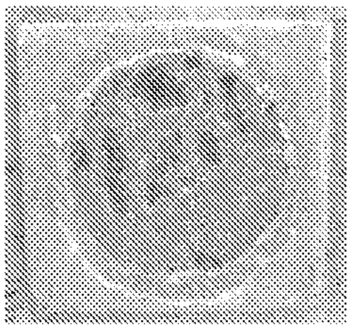
WALLS AND BASIC PLASTERS	PLASTERS WITH ADMIXTURE	PLASTERS WITH SURFACE TREATMENT
RAMMED EARTH WALL GEELONG METHOD Not eroded PRESSURE SPRAY METHOD Eroded for about 12 mm after 1 hour  PRESSURE SPRAYED WALL AREA	BARLEY STRAW GEELONG METHOD Erosion depth: 7 mm PRESSURE SPRAY METHOD -  GEELONG TEST SPECIMEN	NANOSTRUCTURED emulsion of SILICON BASED MOLECULES GEELONG METHOD Not eroded PRESSURE SPRAY METHOD Eroded for the full depth within 15 min  PRESSURE SPRAYED SPECIMEN
COB WALL GEELONG METHOD Not eroded PRESSURE SPRAY METHOD Eroded for about 12 mm after 1hour  PRESSURE SPRAYED WALL AREA	NANOSTRUCTURED dispersion of SILICON POLYMERS GEELONG METHOD Not eroded PRESSURE SPRAY METHOD Eroded for the full depth within 15 min  PRESSURE SPRAYED SPECIMEN	NANOSTRUCTURED suspension of TITANIA AND SILICA GEELONG METHOD Erosion depth: 9 mm PRESSURE SPRAY METHOD -  GEELONG TEST SPECIMEN
BASIC PLASTER GEELONG METHOD Erosion depth: 9 mm PRESSURE SPRAY METHOD -  GEELONG TEST SPECIMEN	Acqueous emulsion of organic DERIVATES OF SILICON GEELONG METHOD Not eroded PRESSURE SPRAY METHOD Eroded for the full depth within 30 min  PRESSURE SPRAYED SPECIMEN	Acqueous SILANE/SILOXANE emulsion GEELONG METHOD Not eroded PRESSURE SPRAY METHOD Not eroded  PRESSURE SPRAYED SPECIMEN
BASIC PLASTER with 1 mm sand GEELONG METHOD Erosion depth: 8 mm PRESSURE SPRAY METHOD -  GEELONG TEST SPECIMEN	LIMESTONE aggregates + FATTY ACIDS + SYNTHETIC POLYMERS GEELONG METHOD Erosion depth: 11 mm PRESSURE SPRAY METHOD -  GEELONG TEST SPECIMEN	Acqueous BEESWAX emulsion GEELONG METHOD Erosion depth: 3 mm PRESSURE SPRAY METHOD Eroded for the full depth within 15 min  PRESSURE SPRAYED SPECIMEN

Table 1

Typologies and detailed composition of the plasters.

N.	Composition	Earth (g)*	Sand added (g)*	Clay content (%)**	Silt content (%)**	Sand content (%)**	Water added (g)	Water added (%)**	Additive (%)***	Surface treatment (g/dm^2)
1	**BASIC PLASTER: (1 earth + 4 sand + water)**	1000	4000	8	9	83	850	17	-	-
2	Basic plaster with 1 mm maximum diameter sand	1000	4000	8	9	83	900	18	-	-
	Basic plasters + ADMIXTURE:									
3	Barley straw	1000	4000	8	9	83	915	18	7	-
4	Nanostructured polymeric dispersion of silicon	1000	4000	8	9	83	850	17	7	-
5	Acqueous emulsion of organic derivates of silicon	1000	4000	8	9	83	850	17	1	-
6	Premix of limestone aggregates admixed with fatty acids and synthetic polymers	1000	4000	8	9	83	850	17	2	-
	Basic plasters + SURFACE TREATMENT:									
7	Nanostructured emulsion of silicon based molecules	1000	4000	8	9	83	850	17	-	4
8	Nanostructured suspension of titania and silica	1000	4000	8	9	83	850	17	-	4
9	Acqueous silane-siloxane emulsion	1000	4000	8	9	83	850	17	-	10
10	Acqueous beeswax emulsion	1000	4000	8	9	83	850	17	-	8
	Plaster recipes tested in the preliminary phase:									
I	1 earth + 1 sand + water	2500	2500	20	24	57	1070	21	-	
II	1 earth + 1.5 sand + water	2000	3000	16	19	65	980	19	-	
III	1 earth + 2 sand + water	1667	3333	13	16	71	900	18	-	
IV	1 earth + 3 sand + water	1250	3750	10	12	78	880	17	-	
V	= N. 1									
VI	1 earth + 5 sand + water	833	4167	7	8	83	810	16	-	

*dry mass; ** percentage by mass of earth and sand; *** percentage by mass of clayey component.

Table 2

Average shear strengths of the plasters (mean values).

	τ_{max} (kPa)	
	Rammed earth wall	Cob wall
BASIC PLASTER: (1 earth + 4 sand + water)	19	19
Basic plaster with 1 mm maximum diameter sand	42	12
Basic plasters + ADMIXTURE:		
Barley straw	44	19
Nanostructured polymeric dispersion of silicon	24	24
Acqueous emulsion of organic derivates of silicon	24	17
Premix of limestone aggregates admixed with fatty acids and synthetic polymers	24	23
Basic plasters + SURFACE TREATMENT:		
Nanostructured emulsion of silicon based molecules	-	-
Nanostructured suspension of titania and silica	-	-
Acqueous silane-siloxane emulsion	-	-
Acqueous beeswax emulsion	-	-

Table 3

Water vapor permeability test results (mean values).

	Water vapor flow rate G ($kg\,s^{-1}$)	Vapor transmission rate g ($kg\,m^{-2}s^{-1}$)	Water vapor permeance W_p ($kg\,m^{-2}s^{-1}Pa^{-1}$)	Water vapor permeability δ_p ($kg\,m^{-1}s^{-1}Pa^{-1}$)	μ (-)	Thickness D* (m)	Sd * (m)
Walls							
Rammed earth wall	1.71E-08	2.44E-06	2.41E-09	5.16E-11	4	0.30	1.20
Cob wall	8.61E-09	1.29E-06	1.28E-09	2.33E-11	8	0.30	2.40
BASIC PLASTER: (1 earth + 4 sand + water)	9.23E-09	1.23E-06	1.22E-09	2.42E-11	8	0.02	0.16
Basic plaster with 1 mm maximum diameter sand	9.30E-09	1.24E-06	1.23E-09	2.42E-11	8	0.02	0.16
Basic plasters + ADMIXTURE:							
Barley straw	8.89E-09	1.19E-06	1.17E-09	2.34E-11	8	0.02	0.16
Nanostructured polymeric dispersion of silicon	8.13E-09	1.10E-06	1.09E-09	2.13E-11	9	0.02	0.18
Acqueous emulsion of organic derivates of silicon	7.57E-09	1.01E-06	1.00E-09	1.98E-11	10	0.02	0.20
Premix of limestone aggregates admixed with fatty acids and synthetic polymers	8.10E-09	1.09E-06	1.08E-09	2.08E-11	9	0.02	0.18
Basic plasters + SURFACE TREATMENT:							
Nanostructured emulsion of silicon based molecules	8.09E-09	1.08E-06	1.07E-09	2.11E-11	9	0.02	0.18
Nanostructured suspension of titania and silica	8.33E-09	1.12E-06	1.11E-09	2.19E-11	9	0.02	0.18
Acqueous silane-siloxane emulsion	7.65E-09	1.03E-06	1.02E-09	2.01E-11	10	0.02	0.20
Acqueous beeswax emulsion	8.27E-09	1.11E-06	1.10E-09	2.16E-11	9	0.02	0.18

* $Sd = \mu \times D$, where D is the thickness of the plaster (or wall), which is different from the thickness of the specimen used in the test.