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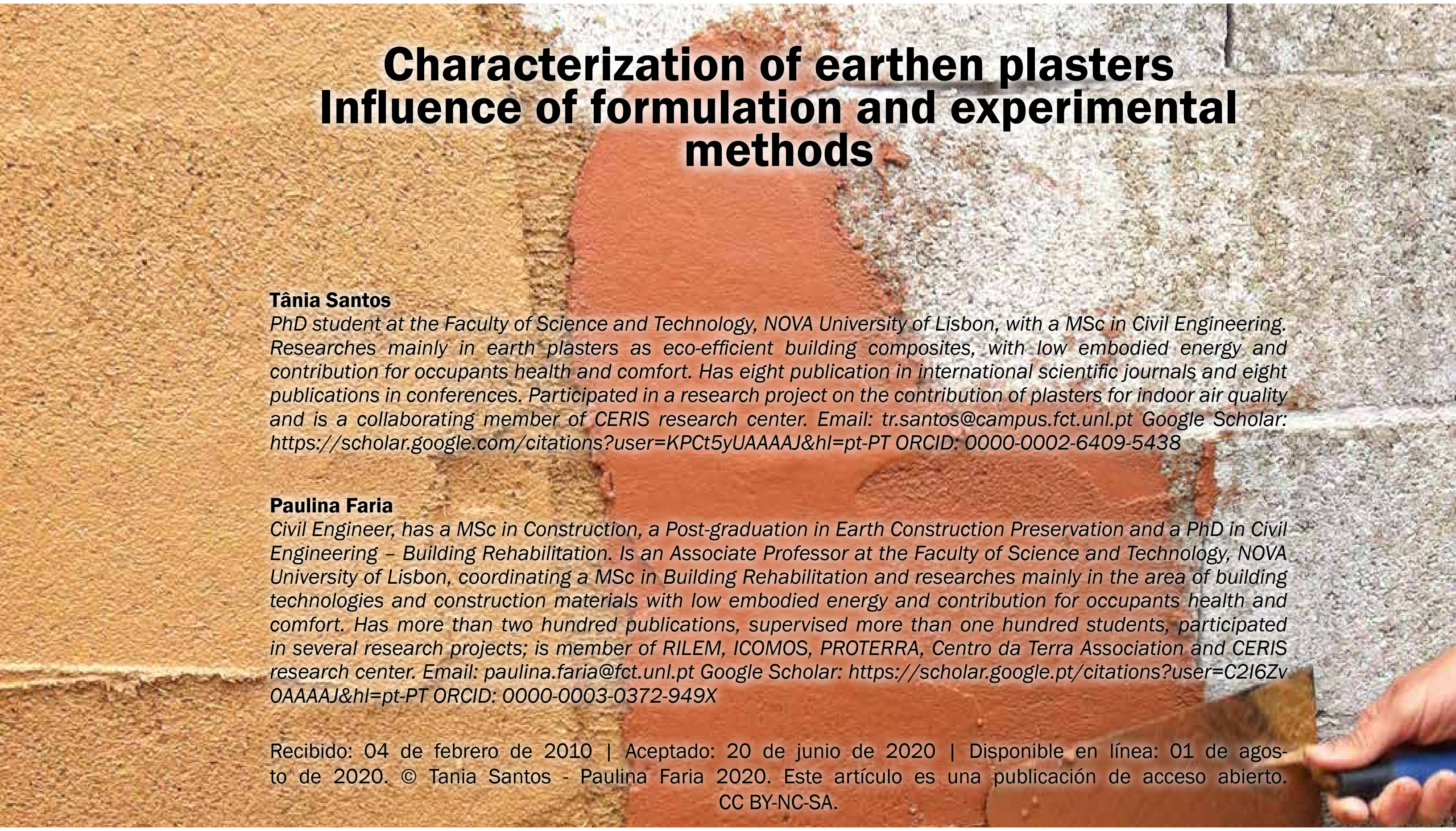

Characterization of earthen plasters Influence of formulation and experimental methods

Tânia Santos
PhD student at the Faculty of Science and Technology, NOVA University of Lisbon, with a MSc in Civil Engineering. Researches mainly in earth plasters as eco-efficient building composites, with low embodied energy and contribution for occupants health and comfort. Has eight publication in international scientific journals and eight publications in conferences. Participated in a research project on the contribution of plasters for indoor air quality and is a collaborating member of CERIS research center. Email: tr.santos@campus.fct.unl.pt Google Scholar: https://scholar.google.com/citations?user=KPCt5yUAAAAJ&hl=pt-PT ORCID: 0000-0002-6409-5438

Paulina Faria
Civil Engineer, has a MSc in Construction, a Post-graduation in Earth Construction Preservation and a PhD in Civil Engineering – Building Rehabilitation. Is an Associate Professor at the Faculty of Science and Technology, NOVA University of Lisbon, coordinating a MSc in Building Rehabilitation and researches mainly in the area of building technologies and construction materials with low embodied energy and contribution for occupants health and comfort. Has more than two hundred publications, supervised more than one hundred students, participated in several research projects; is member of RILEM, ICOMOS, PROTERRA, Centro da Terra Association and CERIS research center. Email: paulina.faria@fct.unl.pt Google Scholar: https://scholar.google.pt/citations?user=C2I6Zv0AAAAJ&hl=pt-PT ORCID: 0000-0003-0372-949X

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Abstract

All over the world there is a vast heritage of earth construction where earth plasters were applied. Nowadays, due to environmental but also technical reasons, new earth plasters are also applied on common new masonries. That is why its characterization, in the laboratory but also in situ, is very important. In the present study, a pre-mixed earth plastering mortar (as control) and nine earth-based plastering mortars formulated in laboratory with different compositions were characterized. These mortars were formulated with 1:3 (illitic clayish earth:aggregate) volumetric ratio. The aggregate comprises a variation of fine and coarse sand and the partial replacement of the fine sand by a phase change material (PCM). The influence of the addition of a low amount of oat fibers is also evaluated. The mortars were characterized by different methods in laboratory and on an experimental wall exposed outdoors by destructive and nondestructive methods: dry bulk density, dynamic modulus of elasticity, flexural and compressive strengths, adhesive and shear strengths, dry abrasion resistance, surface cohesion, ultrasonic pulse velocity and hardness. Results were discussed and some were correlated. Most mortars present good mechanical strengths. However, the addition of PCM significantly decrease the mechanical strength of mortars. In terms of mechanical properties, the addition of oat fibers only promotes an improvement on adhesive strength. The simple surface hardness by durometer presents laboratory and in situ results well correlated for earth mortars without PCM.

Keywords: clayish earth; phase change material; sand

1. Introduction

Clayish earth has been used for thousands of years as a building material and was the first used to produce mortars (Emiroğlu et al., 2015; Niroumand et al., 2017). With the production of chemical binders, as gypsum, air lime, limes with hydraulic properties and cement, the use of clayish earth has fallen into disuse in some countries and is often seen as a building material used by people with lower economic capacity.

However, in recent decades, with energetic problems and environmental conscience, earth re-began to be considered as a building material all over the world. The production of highly eco-efficient mortars for plastering indoor masonry is an example, and earth plasters are nowadays being attracting the attention of the scientific community, with regular studies, such as the ones of Ashour & Wu (2010), Darling et al. (2012), Delinière et al. (2014), Gomes et al. (2016, 2019), Santos et al. (2019), Santos, Faria, et al. (2017), Santos, Nunes, et al. (2017) and Stazi et al. (2016), all published in the last decade. Earthen plasters present several ecologic and environmental advantages: low embodied energy due the very low energy required for extracting, transportation and preparation of the raw materials (earth and, eventually, sand), as local materials may be used. In comparison to cement and lime plasters, earth plasters are totally reusable and easily recyclable (when chemically unstabilized) (Gomes et al., 2018). They also present lower environmental impact, by life cycle assessment (LCA) methodology, in comparison to conventional plasters based on chemical inorganic binders that need thermal treatment for production (Melià et al., 2014). In addition, earth plastering mortars may significantly contribute to improve indoor comfort for buildings inhabitants, due to the hygroscopic capacity of clays, helping to regulate relative humidity of the indoor environment of buildings and, therefore, indoor air quality (Ashour et al., 2011; Bruno et al., 2017; Cagnon et al., 2014; Emiroğlu et al., 2015; Liuzzi & Stefanizzi, 2016; Maddison et al., 2009; Maskell et al., 2018; Randazzo et al., 2016). However, these are aspects that the European standard EN 998-1 (2016) for common mineral plasters does not consider yet.

When added to earth plasters, vegetal fibers can promote a decrease of dry bulk density, thermal conductivity and shrinkage (Faria & Lima, 2018; Laborel-Préneron et al., 2016) and, eventually, an increase of adhesive strength of the plaster to the support (Faria & Lima, 2018; Lima & Faria, 2016) and compressive strength (Palumbo et al., 2016). That may depend on the fibers type and content.

Phase change materials (PCM) are materials that can absorb and release heat while changing between the solid and liquid states, though their latent heat capacity (Rao et al., 2018; Wang et al., 2016). Thus, the PCM may increase the thermal efficiency of plasters (Baetens et al., 2010). However, it must be ensured that the introduction of PCM into a plaster formulation does not compromise their mechanical characteristics.

The codes and standards for earth building materials are very scarce. Currently, there is only one German standard specific for the laboratory characterization of earth plasters: the DIN 18947 (2013). However, in situ nondestructive or slightly destructive characterization is also important and knowledge of the differences that can occur in comparison to a characterization in controlled laboratory conditions can be important. It is therefore necessary to define and eventually adapt some tests. An example of a test needing further detailed methodology is adhesive strength where the substrate to specimens preparation (hollow brick or other), the type of application (with or without previous water spray or application of a clayish grout, different energy on the application), the samples to perform the test preparation (prepared in fresh state or cut after hardening) may all have influence on results (Faria et al., 2019).

The experimental study presented in this paper intends to evaluate some physical and mechanical characteristics of different mortar formulations though conventional tests, such as dry bulk density, dynamic modulus of elasticity, flexural, compressive and adhesive strengths, as well as through other simple tests such as surface cohesion, surface hardness, dry abrasion resistance and ultrasonic pulse velocity. Some of these tests are nondestructive and can be applied in situ.

A pre-mixed earth mortar and nine other earth-based mortars formulated in laboratory, using the same clayish earth, were analyzed. The formulated mortars were prepared with variation of particle size distribution of siliceous sands (fine and coarse sand), with partial replacement of the fine sand by a PCM and with addition of low amount of oat fibers. The mortars were characterized in laboratory and on a hollow brick masonry test wall, in outdoors protected from rain conditions. The use of oat fibers and PCM on the analyzed earth mortars allows the comparison of the use of vernacular and contemporaneous additions, respectively. In the present study the influence of PCM on the thermal behavior of the plasters has not been evaluated. However, the influence of a PCM as replacement of sand or as an addition may increase the thermal performance of plasters due to the high thermal inertia of PCMs (Baetens et al., 2010; Rao et al., 2018), being advisable to take it into account for future research.

2. Materials, mortars and methods

2.1. Materials

A pre-mixed earth plastering mortar based on a natural illitic clayish earth from Algarve region (South of Portugal), siliceous sand with 0–2 mm and cut oat fibers 1–2 cm long, but with unknown exactly formulation, was tested. This mortar was commercialized by Embarro company and some of its characteristics (loose bulk density, particle size distribution, X-ray diffraction, flow table consistency and bulk density in the fresh state, dry bulk density, microstructure, thermal conductivity, dynamic modulus of elasticity, flexural and compressive strength, capillary absorption and drying, biological susceptibility to molds and surface roughness) have already been analyzed previously (Santos, Nunes, et al., 2017).

The formulated earth mortars were prepared with a clayish earth (E) collected in the same clay pit used by Embarro company, in Algarve region, South Portugal. The earth was previously disaggregated and sieved at 2 mm to eliminate big clods. The aggregate fraction was composed by two types of siliceous sands: a coarse (CS) and a fine (FS) sand, respectively. The content of each sand varies in the formulation of mortars to assess the influence of different grain size.

A phase change material (PCM), Micronal DS 5040 X, from BASF company, “microencapsulated purified paraffin” with melting point at 23ºC (BASF, 2020), was incorporated in some mortar formulations partially replacing the sand. Oat fibers (F), an agriculture waste, were cut with 1–2 cm long and added to one mortar. The incorporation of PCM and vegetable fibers in mortars may promote improvements in the plasters thermal behavior but can also promote drawbacks in other characteristics, namely changing the mortars workability and increasing its bio-susceptibility (Santos, Nunes, et al., 2017). In the present study, the aim of the partial replacement of fine sand by PCM and the addition of oat fibers in the tested earthen mortars is to evaluate the influence of these materials on mechanical characteristics, by tests that can be applied in laboratory and others that can be also applied in situ. All mortars were analysed by Santos, Faria, et al. (2021) for dry bulk density, dynamic modulus of elasticity, flexural, compressive and adhesive strengths and dry abrasion resistance.

The materials (dry pre-mixed mortar, clayish earth, siliceous sands, PCM and fibers) were visually observed and characterized in terms of loose bulk density, based on EN 1097-3 (1998), and dry particle size distribution, based on EN 1015-1 (1998/2006), and results were presented elsewhere (Santos, Nunes, et al., 2017). In short, loose bulk density were: 1.54 kg/dm^3 for pre-mixed product (P), 1.46 kg/dm^3 for clayish earth (E), 1.50 kg/dm^3 for fine and coarse sands (FS and CS), 1.02 kg/dm^3 for PCM and 0.07 kg/dm^3 for fibers (F).

Illite is the main crystalline constituent of the clayish earth, but some quartz and dolomite are also present, with traces of kaolinite, calcite, k-feldspar and hematite. The pre-mixed earth mortar presents illite, kaolinite and dolomite minerals and higher proportion of k-feldspar and quartz (Santos, Nunes, et al., 2017).

2.2. Mortars and specimens´ preparation

The composition of the mortars (volumetric and mass proportions, and water content) are presented in Table 1.

The pre-mixed mortar (P) was produced by addition of 20% volume of water (as indicated by the manufacturer). The mortars formulated in laboratory were produced with a 1:3 (clayish earth:aggregate) volumetric ratio, i.e. 25% of earth and 75% aggregate. The aggregate part was composed by different proportions of coarse (CS) and fine (FS) siliceous sands. In CS60_PCM15 mortar, 15% of PCM replaced the same amount of CS sand. It means the mortar is composed by 60% of CS and 15% of PCM. In some other mortars, the PCM was used to partially replace the FS sand, in percentages of 20 or 30% (CS30FS25_PCM20 and CS30FS15_PCM30). For example, the CS30FS15_PCM30 mortar is composed by 30% of CS, 15% of FS and 30% of PCM. In mortar CS30FS45+F5, 5% of the oat fibers were added to the total volume of mortar (earth and sands). Therefore, this mortar is composed by 30% of CS, 15% of FS and the addition of 5% of fibers. The water content of the formulated mortars was adjusted according to the workability presented by each mortar during the mixing, trying to achieve good and similar workability between all the mortars. The workability was assessed by an experimented technician.

The mortars were prepared by the following procedure: the dry components were homogenized and the water was added during the first 30 s of mechanical mixing; after additional 30 s of mixing the mortar rested for 5 min and a last period of 30

Table 1. Volumetric and mass proportions and water content of the mortars from Santos, Faria, et al. (2021).

Mortars notation	Volumetric proportions					Mass proportions					Water [vol, %]
	Earth	Sand		Fiber	PCM	Earth	Sand		Fiber	PCM	
		CS	FS				CS	FS			
P	Unknown proportions of earth, sand and fiber				-	Unknown proportions of earth, sand and fiber				-	20
FS75	1	-	3	-	-	1	-	3.08	-	-	20
FS60_PCM15	1	-	2.4	-	0.6	1	-	2.47	-	0.42	20
CS75	1	3	-	-	-	1	3.08	-	-	-	17
CS60_PCM15	1	2.4	-	-	0.6	1	2.47	-	-	0.42	17
CS45FS30	1	1.8	1.2	-	-	1	1.85	1.23	-	-	20
CS30FS45	1	1.2	1.8	-	-	1	1.23	1.85	-	-	20
CS30FS25_PCM20	1	1.2	1	-	0.8	1	1.23	1.03	-	0.56	20
CS30FS15_PCM30	1	1.2	0.6	-	1.2	1	1.23	0.62	-	0.84	20
CS30FS45+F5	1	1.2	1.8	0.2	-	1	1.23	1.85	0.01	-	25

Notation: mortars P, CS30FS45, CS30FS15_PCM30 and CS30FS45+F5 (four out of nine) were analyzed by Santos, Nunes, et al. (2017) for flow, wet density, dynamic modulus of elasticity, flexural and compressive strength, as well as for mineralogy, microstructure, capillary absorption and drying, thermal conductivity and biological colonization s mixing completed the mortars' production.

Different mortar specimens and experimental plasters were prepared for each mortar:

- prismatic specimens with 40 mm x 40 mm x 160 mm cast in metallic molds, filled in two layers mechanically compacted with 20 stokes each, manually leveled and demolded after 2 weeks;

- a mortar layer of 2 cm thickness applied manually on hollow bricks with 295 mm x 195 mm, simulating a plaster and not demolded; reproducing a method held in practice, the bricks were sprayed with water previously to the plasters´ application;

- a plaster with 80 mm x 500 mm with 20 mm thickness applied on a hollow brick masonry wall exposed outdoors but protected from the rain; the masonry wall was also sprayed with water previously to the plasters' application.

The specimens casted in laboratory were maintained in controlled environmental conditions at a temperature of 20±2°C and 65±5% relative humidity (RH). The plaster was exposed in a semi-urban environment, 3 km far from the Atlantic coast and the Tagus river mouth, in Caparica campus of NOVA University of Lisbon, in outdoors semi-protected conditions of 8.2–27.8ºC and 65–80% of RH.

2.3. Mortars test methods

For some tests, smaller specimens with defined dimensions were prepared on the mortar specimens on brick and the experimental plasters. The summary of the tests performed and test specimens used are presented in Table 2.

Tests were not performed for all mortars because, during the preparation of the mortar specimens on bricks, simulating a plaster, it was noticed that some mortars presented such high shrinkage that they could not be used as efficient plasters. Furthermore, indications of problems on the in situ tests are also provided when not performed.

2.3.1. Dry bulk density

Dry bulk density was geometrically determined with the prismatic specimens according to DIN 18947 (2013) and based on EN 1015-10/A1 (1999/2006), by the ratio between the dry mass and the volume of each specimen. The volume was obtained with a digital caliper and the dry mass was determined with a 0.001 g precision digital scale. This test was performed only in laboratory conditions. However, this test can be adapted and performed with samples removed from renders and plasters.

2.3.2. Dynamic modulus of elasticity and flexural and compressive strengths

Dynamic modulus of elasticity (Ed) was determined based on EN 14146 (2006) defined for natural stone, using a Zeus Resonance Meter ZMR 001 equipment. The flexural (FStr) and compressive (CStr) strengths were determined based on DIN 18947 (2013) and EN 1015-11 (1999/2006)

Table 2. Tests performed and number of mortar specimens used.

Dry bulk density, Ed, FStr, CStr	AStr	τ	Abrasion and surface cohesion	US velocity and durometer
3 prismatic specimens	3 specimens 50 mm diameter of the mortar on brick specimens	5 specimens 50 mm x 40 mm x 20 mm of mortar on experimental wall	3 specimens 65 mm diameter of the mortar on brick specimens	Specimens of the mortar on brick and on experimental wall

Notation: Ed – dynamic modulus of elasticity; FStr – flexural strength; CStr – compressive strength; AStr – adhesive strength; τ – shear strength; US velocity – ultrasonic pulse velocity with a Zwick Rowell Z050 equipment, with load cells of 2 kN and velocity of 0.2 mm/min for flexural strength and 50 kN and 0.7 mm/min for compressive strength. These tests were performed only in laboratory conditions.

2.3.3. Adhesive and shear strengths

Adhesive strength (AStr) were determined based on DIN 18947 (2013) and EN 1015-12 (2000), with a pull-off PosiTest AT-M equipment and pull-head plates with 50 mm diameter, on the mortar layer applied on brick in laboratory conditions. However, this portable equipment can also be applied in situ.

A different method, defined by Hamard et al. (2013), was also used to assess adhesion of the mortar plasters applied on brick masonry. The test presents the advantage of being easily applied in situ. As mentioned in Table 2, this test used five specimens of 50 mm x 40 mm x 20 mm, cut on the plasters of the experimental wall. The specimens are loaded through a simple charging device, with multiple weights of 250 g (Figure 1a), until rupture. With the mass that leads to the specimen failure is possible to determine the shear strength (τ) of mortars. The test was performed at an outdoor temperature of 18ºC and 78% of RH, approximately.

2.3.4. Dry abrasion resistance and surface cohesion

Dry abrasion resistance was determined, based on DIN 18947 (2013), by the mass loss of the mortar layer applied on hollow brick, with an equipment presented elsewhere (Faria et al., 2016; Santos et al., 2018), with a medium hardness circular polyethylene brush with 65 mm diameter and a pressure imposed by a mass of 2 kg. After 20 rotations with the brush the weight loss of each mortar is obtained by the average of 3 measurements in different areas of each specimen surface. This test was performed only in laboratory conditions.

The cohesion is the binding force between the

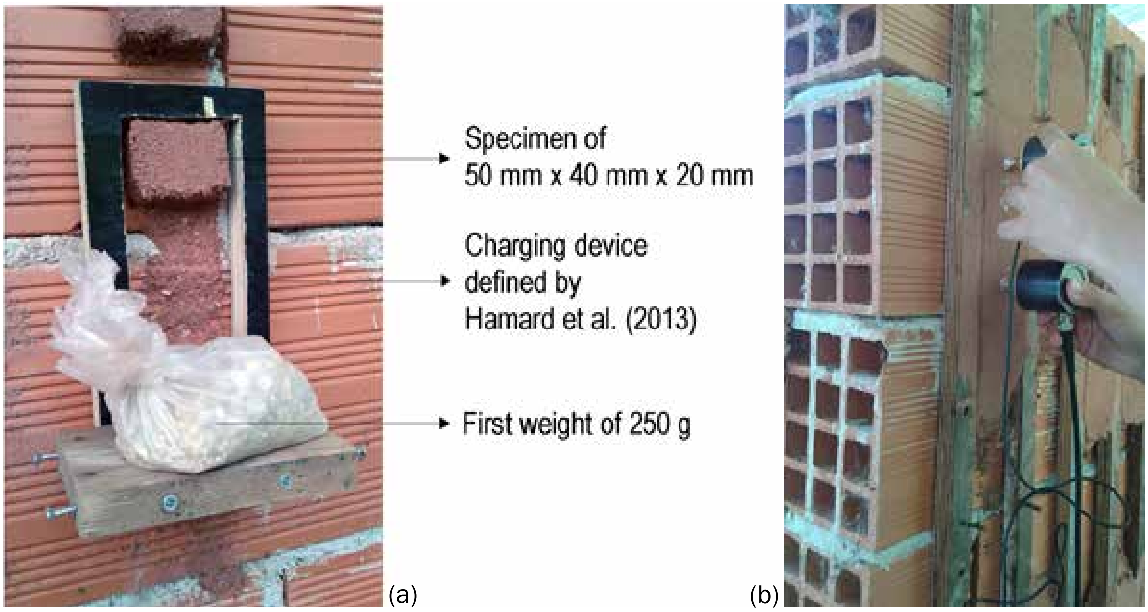

Figure 1. Adhesive shear strength (a) and US velocity (b) test of a plastering mortar specimen on outdoors brick masonry.

particles that constitute the material. Surface cohesion was determined by the weight increase of adhesive tapes with 50 mm x 70 mm pressed on the mortar surface on the brick specimens. The adhesive tape is pressed with a constant intensity produced by a 4 kg weight applied on top of a resilient material with the dimensions of the tape during 1 min (Parracha et al., 2019). The resilient material and weight were removed, and the adhesive tape was withdrawn from the surface of the mortar. The increase of mass of the adhesive tape define the surface lack of cohesion of each mortar and is determined by the average of 3 measurements in different areas of each specimen surface. This test was also performed only in laboratory conditions. However, it is possible to apply it in situ on a render or plaster, replacing the weight by manual pressure.

2.3.5. Ultrasonic pulse velocity and surface hardness

Ultrasonic pulse velocity (US velocity) allows evaluating the homogeneity, the compactness, presence of cracking and other defects of the mortar layers, as detachments. The specimens on bricks (in laboratory conditions) and on the experimental wall (in situ conditions) was determined with a Proceq Pundit Lab equipment, that emits waves and records the transmission time with two conic transducers (emitter and receiver) that are positioned at different distances, with a frequency of 54 Hz, based on EN 12504-4 (2004), using an indirect transmission method: the transducer-emitter and transducer-receiver are placed on the same surface (Figure 1b). On the experimental wall, the final results of US velocity are obtained by the average of these linear measurements in three different areas of the plaster. For mortars applied on hollow bricks in laboratory, the same method was used with 6 different points. The US velocity is the average of the three measurements in each point.

Surface hardness was determined by a PCE durometer Shore A, based on ASTM D2240 (2000), using a method that can both be applied in laboratory specimens and in situ (Santos et al., 2019; Santos, Faria, et al., 2017). The durometer is an equipment having a pin at the extremity which, when pressed against the plaster, indicates its resistance to penetration, as measured by the movement of the pointer to the length of a scale from 0 to 100. Results were obtained from 12 measurements by plaster and specimen, both in situ and in laboratory conditions.

3. Results and discussion

3.1. Dry bulk density

Dry bulk density of mortars (average and standard deviation) are presented in Figure 2. According to DIN 18947 (2013) the P, FS45, CS75, CS45FS30, CS30FS45 and CS30FS45+F5 mortars can be classified as class 1.8, the CS60_PCM15 mortar as class 1.6, the CS30FS45_PCM20 and CS30FS15_PCM30 mortars as class 1.4 and the FS60_PCM15 mortar as class 1.2.

All the mortars without PCM and fibers present very similar bulk density. The mortars with PCM show the lowest bulk densities and, therefore, they are classified in lower classes of DIN 18947 (2013). The lowest bulk density presented by these mortars can be justified by the lower loose bulk density of the PCM in comparison to the sands it replaces and a possible increase of the porosity of these mortars produced by the organic formulation of the PCM.

The formulated mortars with fibers also slightly decreased the bulk density; however, maintain the same class as the other mortars. Laborel-Préneron et al. (2016) refer that during the mixing of mortars the fibers increase their volume when wetted and return to the initial volume after drying. Apart from the volume occupied by the fibers that have less bulk density in comparison to the

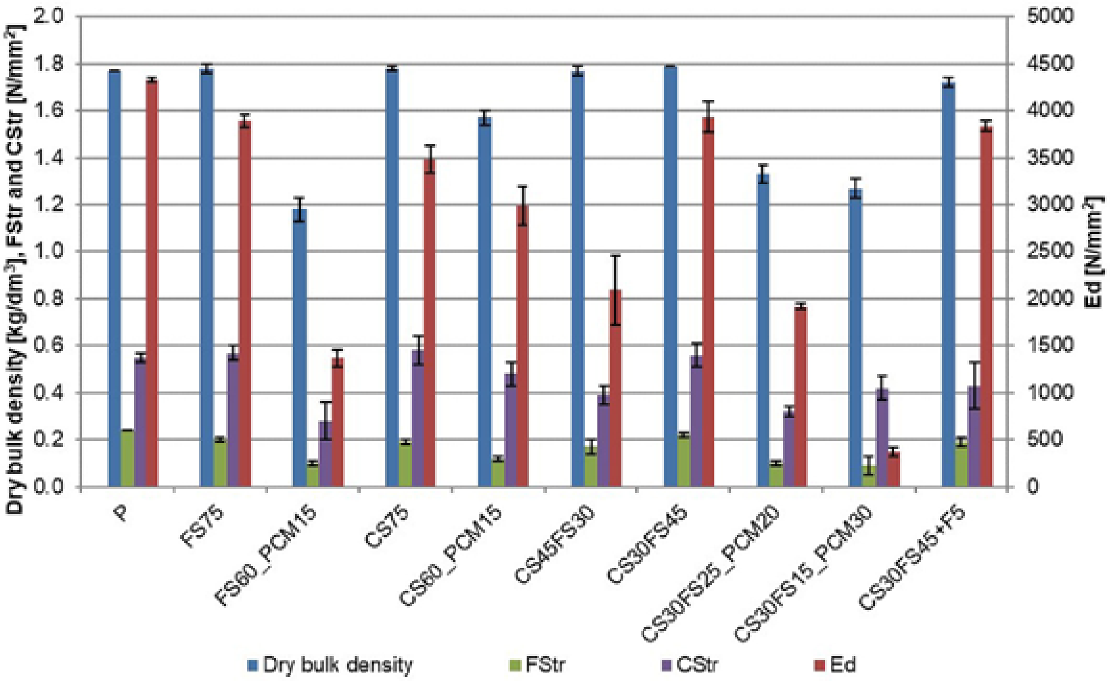

Figure 2. Dry bulk density, flexural (FStr) and compressive (CStr) strength and dynamic modulus of elasticity (Ed) of mortars from Santos, Faria, et al. (2021) - supplementary data.

mortars´ matrix, the variation of the fibers volume can increase the porosity of the mortars and this can justify the decrease of dry bulk density.

The bulk density does not show significant variation caused by different proportions of CS and FS sands. The similar loose bulk density of the two sands can justified this fact.

3.2. Dynamic modulus of elasticity and flexural and compressive strengths

The dynamic modulus of elasticity (Ed), flexural (FStr) and compressive (CStr) strengths (average and standard variation) of mortars are presented in Figure 2.

The requirements defined by EN 998-1 (2016) for the mechanical characteristics of rendering and plastering mortars (minimum of 0.4 N/mm^2 for compressive strength) were fulfilled by all the mortars, except mortars FS60_PCM15 and CS30FS25_PCM20. This confirms the mechanical feasibility of applying earth plasters.

The CS30FS15_PCM30 mortar showed some cracking (Figure 3a), higher than the ones shown by other mortars with 20% PCM. This can be justified by the effect that the PCM had on the fresh mortar, like if an air entrained has been used.

The FS75, CS30FS45 and CS30FS45+F5 mortars present mechanical properties similar to the P mortar, although lower. In general, the mortars with PCM have the lowest mechanical strengths for Ed, FStr and CStr. Comparing CS45FS30 and CS30FS45 mortars, it seems that the increase in fine sand content promotes an increase of Ed, FStr and CStr. Comparing CS30FS45 and CS30FS45+F5 mortars, it seems that the fibers addition does not have a significant effect on Ed and FStr but contributes to a decrease on CStr.

3.3. Adhesive and shear strengths

Adhesive (AStr) and shear (τ) strengths (average and standard deviation) of the plasters are presented in Table 3. Adhesive and shear strengths were not possible to determine for some mortars due to the fragility of some specimens, which

Table 3. Adhesive (AStr) and shear (τ) strengths of mortars, classes of DIN 18947 (2013) and results from previous studies.

Mortar	AStr [N/mm^2]	τ [kPa]
P	0.04±0.06	42.9±3.8
FS75	0.03±0.04	39.7±7.4
FS60_PCM15	(>0.03±0.02*)	27.0±13.8
CS75	x	x
CS60_PCM15	x	x
CS45FS30	x	56.9±1.6
CS30FS45	0.00±0.00**	x
CS30FS25_PCM20	0.01±0.03	40.2±3.8
CS30FS15_PCM30	0.03±0.05	x
CS30FS45+F5	(>0.10±0.00*)	38.5±5.0
SI	≥0.05	-
SII	≥0.1	-
Lima et al. (2016)	0.07$^{(a)}$	-
Faria et al. (2016)	0.15$^{(b)}$	-
Hamard et al. (2013)$^{(c)}$	-	0-47$^{(a)}$ 16-29$^{(b)}$
Lima & Faria (2016)	0.07-0.11$^{(b)}$	-
Delinière et al. (2014)	0.006-0.084$^{(b)}$ 0.11-0.14$^{(d)}$	-
Faria et al. (2019)	0.09-0.15$^{(b)}$ 0.12-0.15$^{(d)}$	10-50$^{(b)}$ 30-50$^{(d)}$
Sevilla Ávila et al. (2015)	0.10-0.12$^{(e)}$	-
Stazi et al. (2016)$^{(f)}$	-	19-44 (in rammed earth wall) 12-24 (in cob wall)

Notation: FS – fine sand; CS – coarse sand; F – oat fibers; 25% clayish earth mortars: FS60_PCM15 – 60% of FS and 15% of PCM; CS45FS30 –45% of CS and 30% of FS; CS30FS15_PCM30 – 30% of CS, 15% of FS and 30% of PCM; CS30FS45+F5 – 30% of CS, 45% of CS and 5% of F; * – cohesive failure on the mortar layer; ** – failure between mortar and support; x – not tested mortar; $^{(a)}$mortars without fibers; $^{(b)}$mortars with fibers; $^{(c)}$applied in rammed earth and cob walls; $^{(d)}$application of clayish grout; $^{(e)}$mortars with fibers and PCM; $^{(f)}$without and with additions and application of surface treatments; - – not applicable/ not determined in this study.

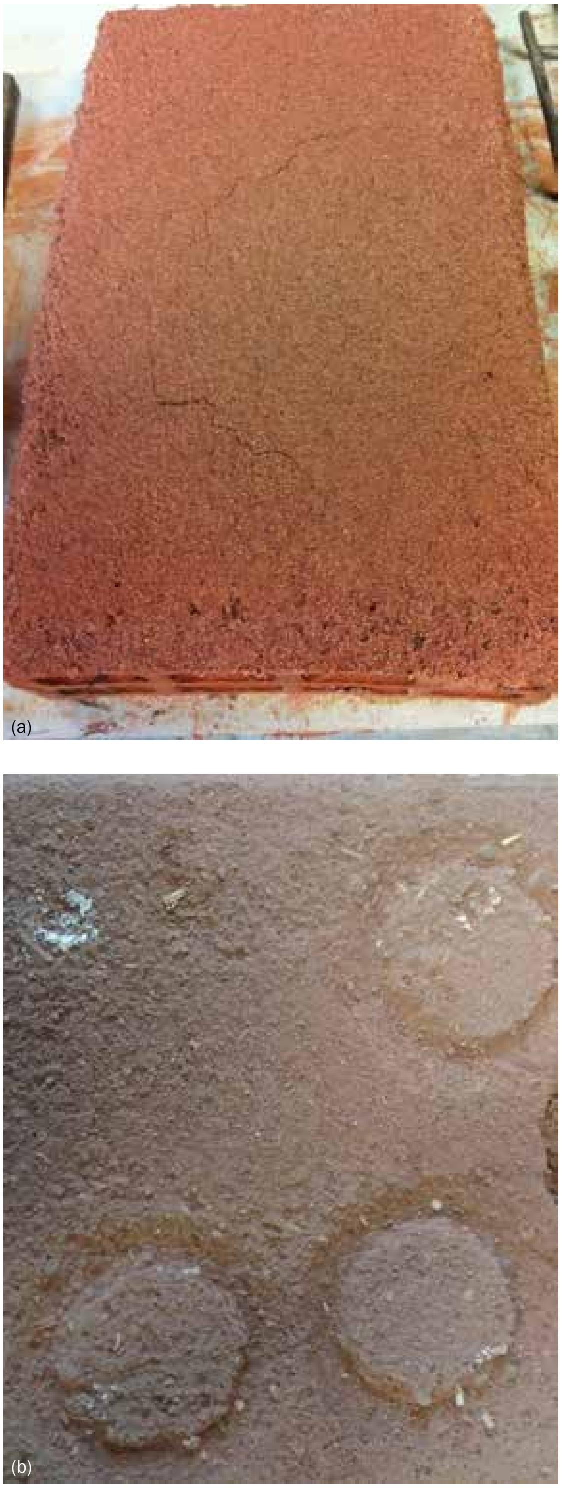

Figure 3. Specimens on brick of (a) CS30FS15_PCM30 mortar with cracking and (b) CS30FS45+F5 mortar after dry abrasion test.

detached from the support or degraded during the cutting of the test specimens, as mentioned in chapter 2.3.

The adhesive strength of the CS75, CS60_PCM15 and CS45FS30 mortars and the shear strength of the CS75, CS60_PCM15, CS30FS45 and CS30FS15_PCM30 mortars were not assessed due to the high shrinkage presented during the preparation of the mortar specimens on bricks simulating plasters and/or due to specimen degradation. For this reason, results for these mortars were considered negative.

In general, the fracture pattern obtained was an adhesive rupture at the interface between plaster and brick. Nevertheless, the FS60_PCM15 and CS30FS45+F5 mortars exhibited a cohesive failure, since it occurred within the plaster layer. Thus, the effective values of AStr are in fact higher than the values registered, as shown in Table 3. However, it is important to refer that some degradation of the specimen occurred. The higher AStr presented by the CS30FS45+F5 mortar confirms that the addition of oat fibers increase the AStr of earth plasters, as described by Faria & Lima (2018) and Lima & Faria (2016).The AStr of the CS30FS45 mortar was not considered because this mortar presented a failure between the mortar and the equipment (in the glue layer). The CS30FS15_PCM30 mortar presents adhesive strength similar to the P and FS75 mortars. This value was not expected considering that this is the mortar that presents lower values of mechanical strength. An effect of the organic PCM may justify the results.

From Table 3 it can be concluded that the mortar with fine sand and PCM (FS60_PCM15) is the one with lower shear strength. The CS45FS30 mortar presents the higher shear strength. This may be related to the high content of coarse sand in relation to the other mortars.

Table 3 presents also some adhesive and shear strengths of earth mortars obtained by different researchers. Comparing those results with the ones of the present study it is possible to conclude that:

- Previously tested earth mortars obtained AStr higher than the ones of the present study; the exception is the CS30FS45+F5 mortar that presents a failure in the mortar layer and, therefore, an AStr higher than 0.10 N/mm^2 and higher than the mortars analyzed by Lima et al. (2016) and Delinière et al. (2014), when analyzing plasters with a previous application of water spray on the substrate. Therefore, the low fibers content may have a positive effect on adhesive strength.

- For a pre-mixed earth mortar with and without addition of PCM, Sevilla Ávila et al. (2015) obtained higher AStr in comparison to results obtained in the present study. The different formulation of the mortars with PCM and amount of water added may justify the difference in the values obtained.

- The mortars analyzed in the present study show shear strengths in the same range obtained by Hamard et al. (2013), using the same test procedure; the exception is the CS45FS30 mortar that presents higher shear strength. Hamard et al. (2013) analyzed earth plasters applied in rammed earth and cob walls, while in the present study the earth-based plasters were applied on hollow brick masonry and in smaller plastered areas. The support preparation was not the same: Hamard et al. (2013) applied a clay grout primary on the substrate, prior to the application of the plastering mortar, while in the present study the earth mortar was applied just after the brick being water sprayed. These factors, as well as different mortars composition, may justify some of the differences obtained.

- The earth-based mortars tested in the present study exhibit higher shear strengths when comparing to results of Stazi et al. (2016) for plasters applied on cob walls and in the same range for plasters applied on rammed earth. The exception is the CS45FS30 mortar that presents higher shear strength, that may be justified by the use of a higher coarse sand content.

- The shear strengths obtained in the present study are in the same range of the results obtained by Faria et al. (2019), except the CS45FS30 mortar that presents higher shear strength. The results of Faria et al. (2019) confirm what had already been reported by Delinière et al. (2014): generally there is an adhesion improvement when a clay grout is used as a primary previous to the plaster application, and when the test sample is prepared when the mortar specimen is still in fresh state, so that cut vibration does not damage the sample.

3.4. Dry abrasion resistance and surface cohesion

Table 4 presents the mass loss of the surface by dry abrasion and by surface cohesion test, in terms of average and standard deviation. Figure 3b presents the abrasion pattern that occurred in the CS30FS45+F5 mortar.

Table 4 – Results of dry abrasion and surface cohesion tests of mortars and limits of DIN 18947 (2013) for abrasion classes SI and SII.

Mortar	Mass loss		Mass loss per unit of area of adhesive tape [x 10^{-3} g/cm^2]
	By dry abrasion [g]	By surface cohesion test [g]	
P	2.8±1.2	0.05±0.04	1.4
FS75	1.4±0.6	0.09±0.02	2.6
FS60_PCM15	1.2±0.1	0.08±0.04	2.3
CS75	x	x	x
CS60_PCM15	x	x	x
CS45FS30	x	x	x
CS30FS45	2.6±0.5	0.08±0.01	2.3
CS30FS25_PCM20	1.8±0.2	0.09±0.02	2.6
CS30FS15_PCM30	0.2±0.2	0.07±0.03	2
CS30FS45+F5	5.2±0.5	0.14±0.07	4
SI	≤1.5	-	-
SII	≤0.7	-	-

Notation: x – not tested mortar; FS – fine sand; CS – coarse sand; F – oat fibers; 25% clayish earth mortars: FS60_PCM15 – 60% of FS and 15% of PCM; CS45FS30 – 45% of CS and 30% of FS; CS30FS15_PCM30 – 30% of CS, 15% of FS and 30% of PCM; CS30FS45+F5 – 30% of CS, 45% of CS and 5% of F.

As mentioned for adhesive and shear strengths, the CS75, CS30_PCM15 and CS45FS30 mortars were also not evaluated for dry abrasion and surface cohesion due to the high shrinkage of the specimens. Results were considered negative for these mortars.

Analyzing the dry abrasion resistance of the plasters, the FS75 and FS60_PCM15 mortars can be classified as SI according to DIN 18947 (2013), while the CS30FS15_PCM30 mortar is classified as SII. The remaining mortars do not fulfil the DIN 18947 (2013) requirements because the obtained mass loss by dry abrasion are higher than the defined limits per test (1.5 g for SI class and 0.7 g for class SII). There is less mass loss by dry abrasion in mortars with PCM addition, what may be due to the lower bulk density of PCM mortars. From Table 4 it can be noticed that the P, CS30FS45 and CS30FS45+F5 mortars present the higher mass loss by dry abrasion, i.e. lower dry abrasion resistance. These results can be due to the presence of fibers and largest size of superficial aggregates that cause greater loss of particles.

Faria et al. (2016) evaluated the mass loss by dry abrasion on a pre-mixed earth plastering mortar by the same method and obtained a higher value (3.9±0.5 g), with exception of the CS30FS45+F5 mortar.

The same CS30FS45+F5 mortar shows the higher mass loss by surface cohesion test, and consequently, the lowest surface cohesion, while the P mortar, with the lower mass loss by the same test, has the highest surface cohesion. The difference between these two mortars can be justified by different composition, eventually in terms of particle size distribution.

Santos, Faria et al. (2017) analyzed earth-based plasters with low addition of air lime and natural hydraulic lime and obtained mass loss by surface cohesion test of 0.2 – 0.5 g (5.7 – 14.3 x 10^{-3} g/cm^2 – mass loss per unit of area of adhesive tape).

In the present study, only the CS30FS15_PCM30 mortar have results in the same range, while all other mortars show lower surface cohesion. It is important to mention that the plasters characterized by Santos, Faria et al. (2017) were studied when exposed outdoors, showing some erosion on the plaster surface. This weathering conditions may justify the higher mass loss by surface cohesion test, even though some plasters contain air lime and natural hydraulic lime.

Drdácký et al. (2015) analyzed the surface cohesion of air lime mortars by the same method but using a plastic tape with 25 mm x 160 mm and obtained loss of surface mass of 0.017–0.020 g (0.4 – 0.5 x 10^{-3} g/cm^2). The earth-based mortars analyzed in the present study present higher surface cohesion, except the CS30FS45+F5 mortar. These results were expected because air lime mortar, theoretically, has greater surface cohesion compared to earth mortars, due to the chemical binding capacity of air lime.

3.5. Ultrasonic pulse velocity and surface hardness

The US velocity and surface hardness by durometer results are presented on Table 5, in terms of average and standard deviation.

Table 5 – US velocity and surface hardness of mortars applied on bricks and on experimental wall masonry.

	US velocity [m/s]		Hardness [Shore A]	
Mortars	Brick	Masonry	Brick	Masonry
P	1479±91	758±88	80±7	76±10
FS75	618±66	664±50	80±7	77±15
FS60_PCM15	910±186	555±80	77±4	65±7
CS75	x	704±72	x	63±19
CS60_PCM15	x	595±67	x	56±19
CS45FS30	x	748±107	x	77±9
CS30FS45	1228±167	x	76±4	x
CS30FS25_PCM20	729±176	551±271	66±11	66±15
CS30FS15_PCM30	584±185	654±115	71±7	45±17
CS30FS45+F5	1023±121	797±199	68±13	67±8

Notation: x – not tested mortar; FS – fine sand; CS – coarse sand; F – oat fibers; 25% clayish earth mortars: FS60_PCM15 – 60% of FS and 15% of PCM; CS45FS30 – 45% of CS and 30% of FS; CS30FS15_PCM30 – 30% of CS, 15% of FS and 30% of PCM; CS30FS45+F5 – 30% of CS, 45% of CS and 5% of F.

The CS75, CS60_PCM15 and CS45FS30 mortars, in laboratory conditions, and CS30FS45 mortars, in outdoor exposure, were not evaluated due to its high shrinkage and degradation presented by some mortar specimens. The results were considered negative for these mortars.

The use of PCM has negatively affected the US velocity, being the P and CS30FS45+F5 mortars the ones with highest values. Also, the US velocities are different from laboratory to outdoors conditions, except in case of the FS75 and CS30FS15_PCM30 mortars. In general, higher US velocities are obtained in laboratory, which is in agreement with the results obtained by Santos et al. (2019) when analyzing a pre-mixed earth mortar by the same US velocity method. The lower value of US velocity of the CS30FS15_PCM30 mortar confirms the presence of microcracking that justifies the lower value of dynamic modulus of elasticity of this mortar (Figure 3a).

Durometer results are similar in the laboratory and outdoors (Table 5), albeit with a slight tendency to decrease outdoors.

In comparison to Santos et al. (2019), the results obtained in the present study are generally lower. Santos et al. (2019) evaluated the surface hardness by durometer on a plaster surface larger than that used in the present test, which allowed these researchers to obtain values that are more diffused.

Santos, Faria, et al. (2017) analyzed earth-based mortars and obtained 50–80 Shore A by durometer. In the present study, only the CS30FS15_PCM30 mortar presents lower surface hardness, that agrees to the low mechanical strength of this mortar.

When relating the US velocity (Figure 4a) and surface hardness (Figure 4b) determined both in the laboratory and in situ it is possible to conclude that there is no direct correlation between the

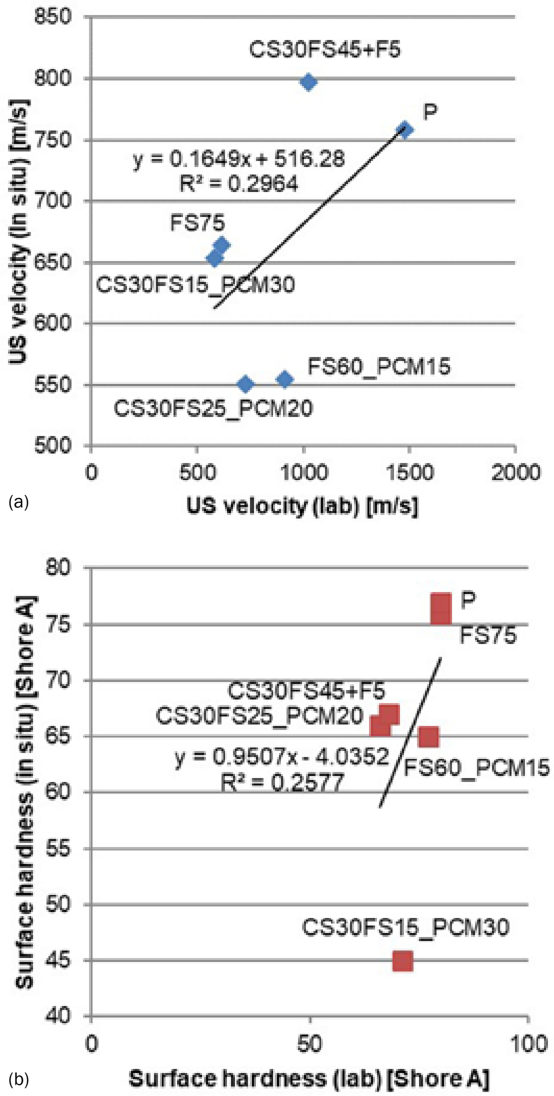

Figure 4. Coefficient of determination (R^2) between laboratory and in situ conditions of (a) US velocity and (b) surface hardness of all mortars.

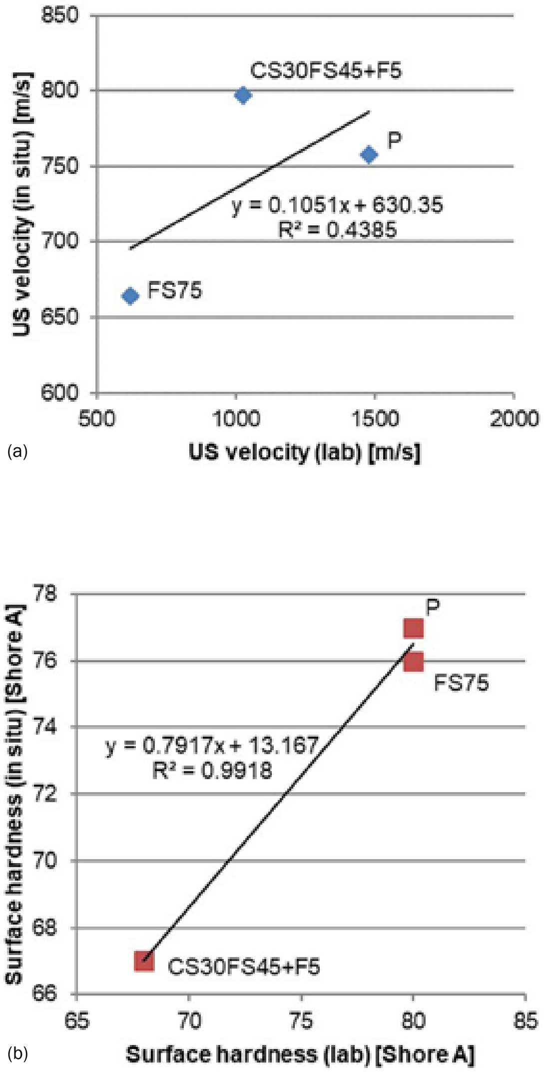

Figure 5. Coefficient of determination (R^2) between laboratory and in situ conditions of (a) US velocity and (b) surface hardness of mortars without PCM.

values obtained (coefficient of determination of 29.6% and 25.8%, respectively). That may be due to different aspects: the tests, although possible to apply both in laboratory and in situ, are not reproductible; the degradation occuring in situ may justify some loss of characteristics of the mortars (although not for all the cases); the different compositions of the mortars and the low number of mortars tested. When analyzing separately the earth-based mortars without (Figure 5) and with (Figure 6) PCM, an improvement in the correlation of results is observed on the mortars without PCM, presenting a coefficient of determination of 43.8% and 99.2% for US velocity and surface hardness, respectively. For mortars with PCM, the same is observed for US velocity with a coefficient of determination of 66.1%, but a significant decrease of the same coefficient is observed for surface hardness (0.0%).

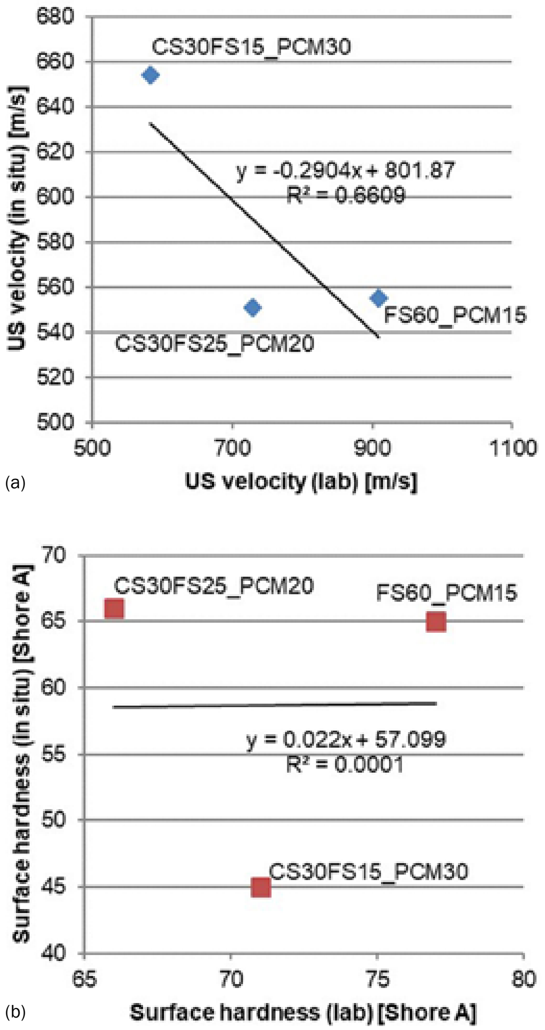

Figure 6. Coefficient of determination (R^2) between laboratory and in situ conditions of (a) US velocity and (b) surface hardness of mortars with PCM.

4. Conclusions

With the vast heritage of earth plasters and the contemporaneous interest by this type of eco-efficient plasters, its characterization in both laboratory and in situ conditions is considered extremely important. The aim of the present study was to analyze different characteristics through laboratory tests, but also through tests that can be carried in situ and to analyze the relationship between the results obtained. For that, ten mortars with different formulations were analyzed and evaluated, including the vernacular additions such as vegetable fibers and contemporaneous such as a phase change material (PCM).

The addition of PCM promotes a decrease of dry bulk density and mechanical characteristics (dynamic modulus of elasticity – Ed; flexural and compressive strengths – FStr and CStr) of earth-based mortars. However, the addition of this material did not have a significant influence on the adhesive, AStr, and shear, τ, strengths, since the addition of 30% of PCM presents AStr similar to the tested pre-mixed mortar and the mortar with only fine sand added to the clayish earth. However, this was not expected due to the low mechanical strengths demonstrated by the mortars with PCM. On the other hand, the replacement of 20% of fine sand by PCM decreases the shear strength of the mortar. The mass loss by dry abrasion and ultrasonic pulse (US) velocity of earth mortars both decrease with the replacement of sand by PCM.

The variation in the percentage of the fine and coarse sand in the earth-based mortars has no influence on the dry bulk density. However, the increase in the fine sand content promotes an increase in Ed, FStr and CStr, while the increase in the coarse sand content promotes an increase in shear strength.

The addition of oat fibers has no influence on the Ed and FStr but decreases CStr of the analyzed plasters.

Analyzing the US velocity and surface hardness of all mortars determined in laboratory and in situ conditions, it is possible to conclude that, in general, there is no direct correlation between the results obtained. This may be due to the different climatic conditions that alter the characteristics of the mortars. However, when analyzing separately the earth mortars with or without PCM, it is possible to conclude that there is a correlation between laboratory and in situ results for US velocity. Nevertheless, for surface hardness, the mortars without PCM present a direct correlation of results in laboratory and in situ.

The fact that it was not possible to test some mortars (CS75, CS55_PCM20, CS45FS30, CS30FS45 and CS30FS15_PCM30) due to their high shrinkage or to specimen degradation, demonstrates a negative behavior, allowing to conclude that these mortars are not suitable for application as plasters, despite their Ed, FStr and CStr.

The mechanical behavior of most mortars allows to conclude they should perform correctly when applied to plaster both vernacular buildings and contemporary ones.

It is important to define simple tests that can assess the characteristics of earth plasters both in laboratory and in situ. Therefore, there is a great interest on continuing this research.

The application of a clay grout before the plasters´ application on brick was not evaluated in the present study. In future researches that should be considered.

In the present study only a single clayish earth and one type of PCM and vegetable fibers were analyzed. Future works should analyze the influence of other types of clayish earth, PCM and vegetable fibers on mechanical characteristics of earthen mortars. The thermal effect of PCM should be evaluated in earth mortars formulations that are not compromised by high shrinkage and low mechanical properties.

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