



earth construction & tradition

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Characterization of earth-based mortars for rammed earth repair

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Figs. 1a and 1b, source: M. Idália Gomes

Left (a): Boavista dos Pinheiros, Odemira, Portugal (2013), new construction in rammed earth kindergarten

Right (b): São Teotónio, Odemira, Portugal (2008), rehabilitation of a rammed earth dwelling

All over the world, many earth buildings are deteriorating due to lack of maintenance and repair. Repairs on rammed earth walls are mainly done with mortars, by rendering application; however, often the repair is inadequate, resorting to the use of incompatible materials, including cement-based mortars. It has been observed that such interventions, in walls that until that day only had presented natural ageing issues, created new problems, much more dangerous for the building than the previous ones, causing serious deficiencies in this type of construction. One of the problems is that the detachment of the new cement-based mortar rendering only occurs after some time but, until that occurrence, degradations develop in the wall itself. When the render detaches, instead of needing only a new render, the surface has to be repaired in depth, with a repair mortar. Consequently, it has been established that the renders, and particularly repair mortars, should have physical, mechanical and chemical properties similar to those of the rammed earth walls.

This article intends to contribute to a better knowledge of earth-based mortars used to repair the surface of rammed earth walls. The studied mortars are based on four types of earth: three of them were collected from non-deteriorated parts of walls of unstabilized rammed earth buildings located in Alentejo region, south of Portugal; the fourth is a commercial earth, consisting mainly of clay. Other components were also used, particularly: sand to control shrinkage; binders stabilizers such as dry hydrated air-lime, natural hydraulic lime, Portland cement and natural cement; as well as natural vegetal fibers (hemp fibers).

The experimental analysis of the mortars in the fresh state consisted in determining the consistency by flow table and the bulk density. In the hardened state, the tests made it possible to evaluate the following properties: linear and volumetric shrinkage; capillary water absorption; drying capacity; dynamic modulus of elasticity; flexural and compressive strength.

Introduction

Worldwide, earth as a construction material is one of the oldest traditional methods and it has been one of the preferred choices to build dwellings. In Portugal, for example, there is quite a significant rammed earth built heritage. Parts of this heritage have been abandoned for several decades and need conservation. In recent decades, new constructions and rehabilitation works in rammed earth have begun to emerge (see Figs. 1a and 1b), due to the environmental advantages of this type of construction and to its good contribution to thermal and acoustic characteristics.

To build with earth and to intervene in earth wall buildings it is necessary to understand the main construction methods, the characteristics of materials used and the causes of their degradation, so as to assure durability. However, it appears that, especially in rehabilitation and maintenance works, the requirements of compatibility between materials or building systems are not often taken into account, which unfortunately, quite frequently, leads to mistakes, inefficient interventions and to the premature appearance of anomalies in the constructions. One of the reasons is that there has been an increasing loss in know-how about earth construction, both in terms of construction and maintenance practices.

It is quite common to encounter unstabilized rammed earth buildings, either rehabilitated or even new ones, which have been recovered by applying cement-based mortars, as can be seen in the example of Fig. 2. In rehabilitation, such mortars are often used to fill more or less deep gaps in the walls, which have resulted from previous degradation. This practice has proven to be disastrous, especially when used in unstabilized earth constructions (Walker and Australia 2001, p. 58; Guelberth and Chiras 2003, p. 30). These interventions frequently lead to further deterioration or to the appearance of new problems. It is difficult to attribute the anomalies only to one reason. Usually, they are caused by a number of factors. One current anomaly is mortar detachment, which creates problems because if the mortar does not adhere to the wall, the water may easily penetrate and travel freely within the wall, creating points susceptible to further anomalies. That detachment is mainly due to the vapor barrier that the cement mortar layer constitutes, or to the deposition of salts that are transported by moisture in the wall and cannot

transpose the interface due to the poor hydric compatibility between the two types of material.

In the past, earth mortars were typically used, but today the experience of its use is almost lost. The development of studies on earth mortars is thus an interesting means to help overcome current problems. It will hopefully enable the use of sustainable materials that, because they are similar to the original ones, have a good compatibility with the substrate, with the advantage of having known and proven behavior and durability.

The purpose of this article is to disseminate the results obtained in the context of a research work aimed at the development of earth-based mortars to repair rammed earth walls. These mortars are based on four types of earth: three of them were collected from non-deteriorated parts of walls of unstabilized rammed earth buildings located in Alentejo region, south of Portugal; the fourth is a commercial earth, consisting mainly of clay. Other constituents were also used: sand to control shrinkage; stabilizers such as dry hydrated air-lime, natural hydraulic lime, Portland cement and natural cement, used in low contents (5%, 10% and 15%); as well as 5% of natural fibers (hemp fibers). The experimental analysis of the mortars in the fresh state consisted in the determination of the consistency by flow table and bulk density. The tests conducted in the hardened state were as follows: linear and volumetric shrinkage; capillary water absorption; drying capacity; dynamic modulus of elasticity by the fundamental resonance frequency; flexural and compressive strength. The behavior of the stabilized mortars is compared to that of the unstabilized mortars.

Materials

Four types of earth were collected in situ (Av, PD, VC and RE) to prepare the earth-based repair mortars which are named accordingly as MAv, MPD, MVC and MRE:

- three types of earth (Av, PD, VC) were taken from three old buildings made of rammed earth, but with different types of clay; the characteristics of the collected material and the location of the respective buildings are described in Gomes et al. (2014): only the material that, by wet sieve, passed through a 2 mm sieve (nº. 10 ASTM), was used; after that, the material had to be decanted, dried in a ventilated oven at 40°C, as well as ground and homogenized;
- a commercial earth was also used, henceforward designated as reference-earth (RE), with a large percentage of clay; it was subsequently ground to disaggregate the material and then homogenized.

The sand used in the mortars consisted mainly of quartz and its dimensions ranged from 0.6 mm to 2.0 mm. The sand was mainly intended to reduce shrinkage, which otherwise would be very high due to the high proportion of clay present in some of the types of earth. Sand was added in different proportions, by taking into account the different percentages and the type of clay present in the various types of earth.

Fig. 3 shows the particle-size distribution for the four types of earth used for the formulation of the repair mortars. The loose bulk density of each type of earth and the basic volumetric and weight proportion of repair mortars are shown in Table 1.

Four types of mineral binders were used as stabilizers and were also added to the reference earth: dry hydrated air-lime, CL 90-S, EN 459-1 (CEN 2001); natural hydraulic lime, NHL5, EN 459-1 (CEN 2001); Portland cement, PC, CEM II/BL 32.5 N, EN 197-1 (CEN 2001) and natural cement, NC, ROCARE EU-Project (2012); hemp fibers were also added. These fibers have a maximum length of about 2.5 cm and a maximum diameter of approximately 0.4 cm.

The tested mortars contained proportions of 0%, 5%, 10% or 15% of the binder stabilizers and of 0% or 5% of the hemp fibers (F), these being percentages by weight in relation to the earth. These compositions can be seen in Table 2.



Figs. 2a, b and c Rammed earth market house in S. Luís, Odemira, Portugal, source: M. Idália Gomes (a) market house in 2004, (b) and (c) market house in 2013 with detail of the repair

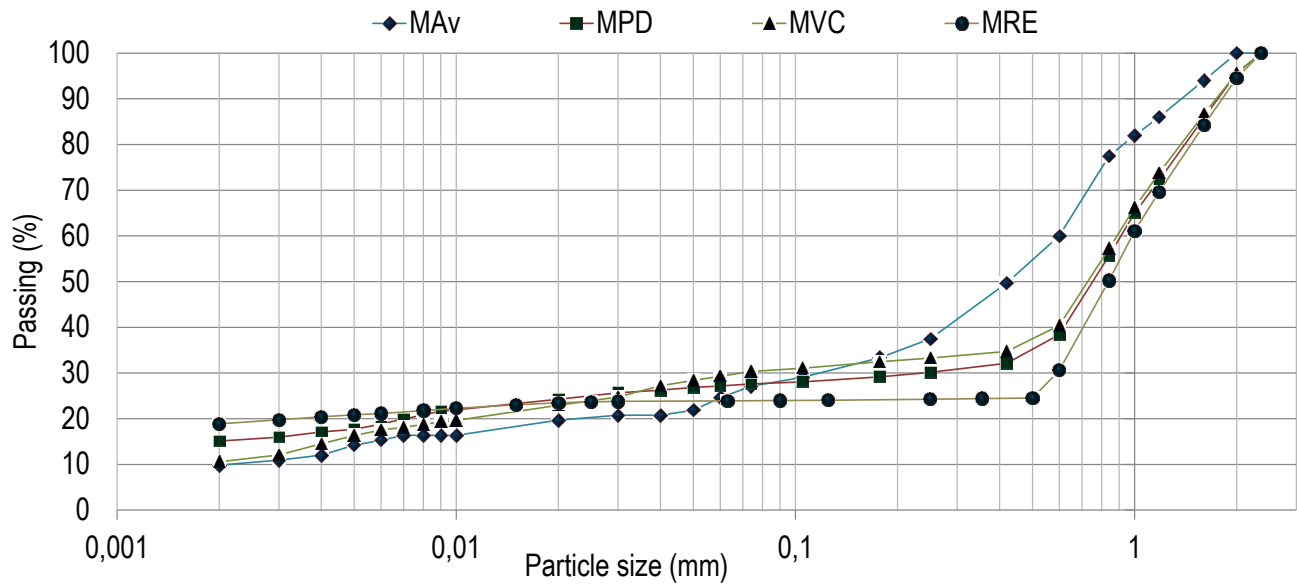


Fig. 3 Particle size distribution nomograms for the four types of earth for repair mortars, source: M. Idália Gomes

Types of earth	Designation of the mortar	Loose bulk density (kg/m ³)	Volumetric proportion (earth:sand)	Weight proportions (earth:sand)
Local earth Av	MAv	1461	1:0	1:0
Local earth PD	MPD	1105	1:1.5	1:1.9
Local earth VC	MVC	1002		1:2.4
Reference-earth	MRE	1136	1:3	1:3.8

Table 1 Loose bulk density of each type of earth, volumetric and weight proportion of repair mortars

Experimental methodology

The experimental analysis of the mortars in the fresh state consisted in the determination of the consistency by flow table (CEN 1999a) and of the bulk density (CEN 1998). The linear and volumetric shrinkage test (Alcock-test) was conducted during hardening and the remaining tests were performed at 90 days of age, respectively: (i) the capillary water absorption (RILEM 1980b) and drying (RILEM 1980a), which were performed sequentially using six cubic specimens (dimensions 50 mm x 50 mm x 50 mm) for each mortar; (ii) the dynamic modulus of elasticity by the fundamental resonance frequency

(CEN 2006a) and the flexural and compressive strength (CEN 1999b) being also performed sequentially on six prismatic specimens (dimensions 40 mm x 40 mm x 160 mm) of each mortar.

Of note is the fact that several of these tests are not readily applicable to earth mortars due to the low mechanical strength and sensitivity to the action of water of these mortars. For this reason, it was necessary to perform numerous preliminary tests and to adjust the test protocols accordingly.

Preparation of the earth-based mortars

Standard EN 196-1 (CEN 2006b) was followed as closely as possible for the preparation of the mortars. Because this standard is not specific either for earth-based mortars or for repair mortars, some adjustments had to be made. One of the major differences was the increase in mixing time in relation to that specified in the standard, which was necessary because the mixtures had a large percentage of clay. The mixing was done by a mechanical mixer, composed by a vat of stainless steel (with a 3-litre capacity) with a paddle mixer driven by an electric motor.

The methodology used for the earth-based mortars, MAv, MPD and MVC, was as follows:

- manual homogenization of the earth;
- introducing water into the vat, followed by introduction of the material;
- mixing at slow speed for 90 seconds (a);
- stopping mixer for 90 seconds; in the first 15 seconds, the adhering mortar was removed from the walls of the vat with a rubber spatula and was added to the remainder mortar;
- continuing mixing at slow speed for further 60 seconds.

For mortars MRE, it was necessary to increase the mixing time because of the type of clay, or else it would be difficult to achieve a good homogenization. Thus, after introduction of the material in the vat, a manual mixing for 2 minutes was done. This step was necessary to assure a uniform wetting of the mixture, because otherwise, even in low speed, the mixture would splash. The

step referred in (a) was also extended to 150 seconds in order to make the mixture more homogeneous.

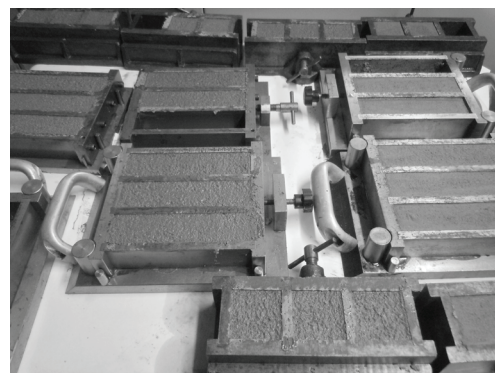
Curing conditions

Standard EN 1015-11 (CEN 1999b) focuses on the curing conditions of various types of mortar (i.e. cement, lime) but does not cover those where clay is the binder (earth mortars).

The standard indicates in all cases a wet curing ($95\pm 5\%$ relative humidity RH or sealed inside polyethylene bags) for 7 days, with the specimen kept for 2 or 5 days in the mould, depending on the type of mortar. Since there was no alternative, the method recommended for lime mortars was followed, albeit with some adjustments.

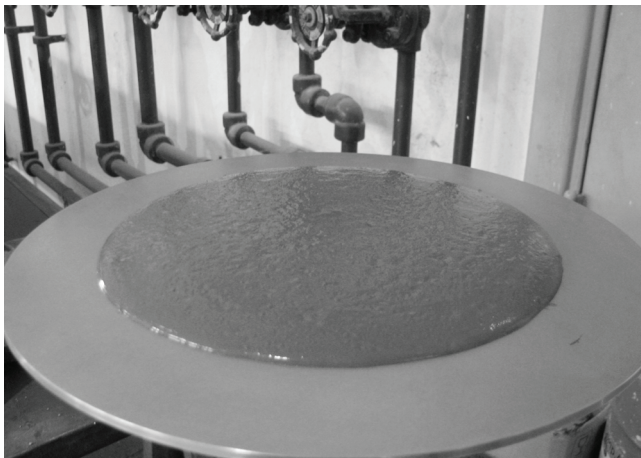
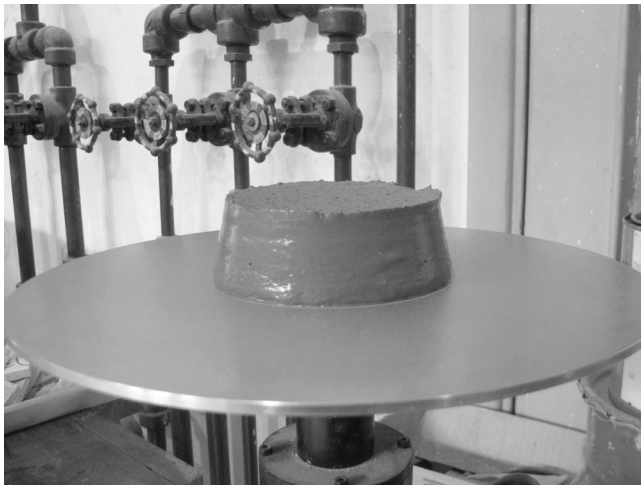
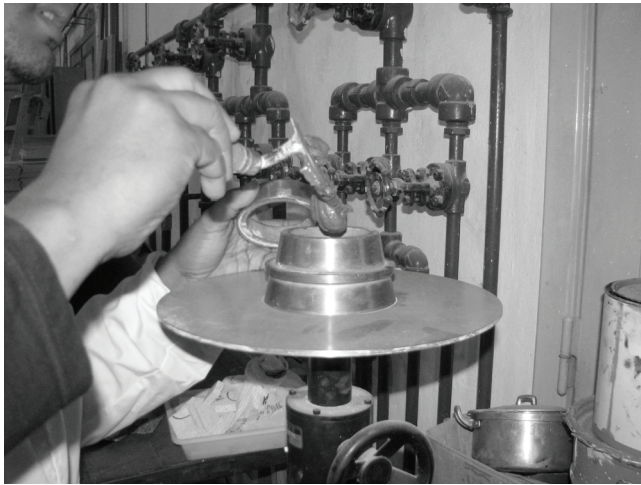
The specimens were kept in wet curing and at the end of the fifth day it was observed that samples were not yet hardened enough to be able to be demoulded. Thus, the specimens were kept for two more days in wet curing, in a sealed polyethylene bag (Fig. 4, left). After that, the specimens remained in the mould for 7 additional days in a conditioned room ($20\pm 2^\circ\text{C}$ and $50\pm 5\% \text{RH}$) without the polyethylene bag (Fig. 4, right). Afterwards they were demoulded and remained in the same room until they reached the age of 90 days.

At the end of the 28th day the specimens with dry hydrated air-lime (CL) were further subjected, for 7 days, to accelerated carbonation ($5\% \text{CO}_2$, $21\pm 2^\circ\text{C}$ and $71\pm 2\% \text{RH}$), a procedure considered necessary to ensure high level of carbonation of the lime, knowing in advance that the cure of these specimens with this type of binder is slow.



Figs. 4a and 4b Curing conditions for the specimens, source: M. Idália Gomes

Left (a): wet cure, specimens in a sealed polyethylene bag; right (b): specimens in the mould in a conditioned room



Methods and procedures

Consistency by flow table

Consistency by flow table is one of the tests most widely used to determine the workability of fresh mortars and was carried out by the procedure described in standard EN 1015-3 (CEN 1999a).

The test consists in placing a truncated conical mould – made of stainless steel – centrally on the disc of the flow table and filling it with mortar applied in two layers (Fig. 5), each layer being compacted by at least 10 sort strokes with pestle plastic to eliminate voids. Excess of material is to be removed by a palette knife at the top of the mould. After removing the mould, the mortar is subjected to the action of 15 blows in 15 seconds (1 blow/sec, constant frequency), obtained by successive drops of the table. As a result, the mortar spread on the disc (Fig. 5). Two orthogonal diameters are to be measured with the help of a caliper, the result of each test corresponding to the average of the two diameters. Two tests are performed for each mortar and the final result is given by averaging the two values.

Bulk density

The bulk density of a fresh mortar is determined by the ratio of its mass and the volume it occupies. This property was determined by the procedure described in standard EN 1015-6 (CEN 1998). The measuring vessel – with known volume and mass – should be filled with the mortar until about half the height.

The vessel-mortar assembly is dropped 10 times on a hard surface, on alternate sides. Then the vessel is filled and the process is repeated. The surplus mortar should be skimmed off with a palette knife. The bulk density of a fresh mortar is determined by the weight difference between the vessel filled and its own weight divided by its own volume. The final result is given by the arithmetic mean of two determinations.

Figs. 5 Consistency by flow table, source: M. Idália Gomes

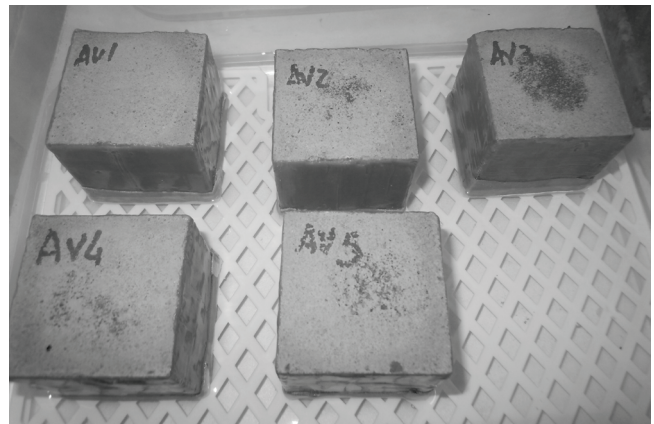


Figs. 6a to 6c Capillary water absorption, source: M. Idália Gomes

(a) covered with a cotton cloth, waterproofed along the four lateral sides

(b) weighing of the specimen

(c) specimens subjected to capillary water absorption, with the capillary fringe reaching the top



Linear and volumetric shrinkage test

The linear shrinkage was measured following the procedure proposed by Keable (1996, p. 30) and Walker & Australia (2001, p. 133), with some adjustments.

Boxes made of film-faced plywood were used in the tests, with the internal dimensions of 300 mm x 30 mm x 30 mm. The internal surfaces of the box were lubricated with oil release agents to prevent adhesion. The mortar was placed in the box and pressed to release the entrained air. Using a palette knife, any excess of mortar was skimmed off so as to render the mortar surface plane.

The box with the mortar was placed in a ventilated oven at a temperature of 30°C until the complete drying of the mortar, that is until reaching constant weight. To measure the linear shrinkage the soil must be pushed to one end of the box.

It was observed that the shrinkage of the samples was significant, not only throughout its length (linear shrinkage) but also in the other two dimensions (volumetric shrinkage). Thus, four measurements were performed on the specimen: height and width. The final height of the sample is the average of the four measurements and the final width is also the average of the four measurements.

The linear shrinkage (LS) and volumetric shrinkage (VS) are obtained as a percentage of the shrinkage of the average of three samples.

Capillary water absorption

The test was performed according to RILEM procedure *water absorption coefficient* (RILEM 1980a). The result of this type of capillary suction test is given as a curve, known as capillary absorption curve, that expresses the amount of water absorbed per unit area ($\text{kg}\cdot\text{m}^{-2}$) as a function of the square root of the elapsed time ($\text{s}^{1/2}$). The slope of the linear portion of this curve corresponds to the capillary absorption coefficient (CC).

Since this test is not suitable for earth mortars, it was necessary to adapt the procedure to prevent mass loss from the specimens.

In the test, the specimens were dried at 40°C to constant weight, and their dry mass was registered. Four of the six surfaces were waterproofed using a mixture with the mass proportion of 50% pitch blond and 50% beeswax. The bottom face was covered with a cotton cloth to prevent loss of material during the absorption phase or even during handling of the specimens (Fig. 6a). Then, they were placed over an open grid, in partial immersion, leaving the free water surface about 2 to 4 mm above the base of the specimens. At time intervals, shorter at the beginning and then longer, the samples were lightly wiped off with a dampened shammy cloth and weighed, and then put again in the water (Figs. 6b and 6c). The increase in the mass over time was determined.

Drying test

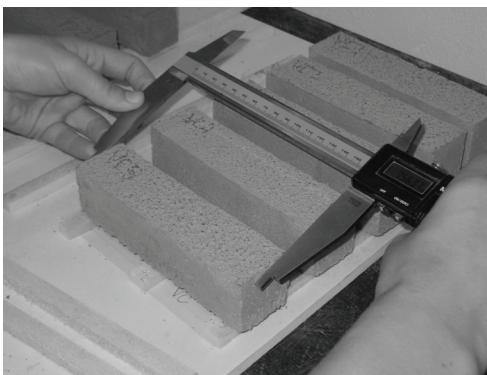
The drying test was performed according to RILEM procedures *evaporation curve* (RILEM 1980b) which began immediately after the capillary water absorption test. The result of the drying test was expressed by a single quantitative parameter, Drying Index, calculated by Normal (1991).

The bottom face of the specimens was sealed with polyethylene sheet. Then, the specimens were placed in a conditioned room at $20\pm 2^\circ\text{C}$ and $50\pm 5\%$ RH, away from walls and other obstacles that could influence the circulation of air and thus the drying process.

The amount of evaporated water is measured by periodical weighings. The result of the drying test is given as a curve, known as the drying curve, which expresses the percentual amount of moisture that remains in the mortar as a function of the elapsed time (s). The drying curve can then be translated into a single quantitative parameter, the drying index (Normal 1991).

Dynamic modulus of elasticity

To determine the dynamic modulus of elasticity, the procedure of standard EN 14146 (CEN 2006a) was followed, which is based on measuring the fundamental resonance frequency. This standard applies to natural stone and the fundamental resonance frequency (first natural frequency) concerns a vibration induced



Figs. 7a and b Dynamic modulus of elasticity test, source: M. Idália Gomes

Left (a): measurement of the specimens

Right (b): measuring the fundamental resonance frequency with the equipment Sonometer

in the longitudinal direction. The test was performed before the prismatic specimens were subjected to the tests of flexural and compressive strength, which are destructive. The specimens were weighed, measured and properly installed in the equipment *Sonometer* – frequency resonance test apparatus (Fig. 7). Liquid glue had been previously placed in the zone of contact of the specimens with the transducer (vibration transmitter), to avoid the effect of puncturing needle (by the pickup) and the subsequent breakdown in the material.

Flexural and compressive strength

The flexural and compressive strength followed the procedure of standard EN 1015-11 (CEN 1999b). However, due to the low resistance of the specimens, it was necessary to make some adjustments. First, it was necessary to make a manual adjustment in order that the equipment entered in contact with the specimen without impact. The load is applied at constant speed between 10 to 50 kN/s. According to the standard, the rupture of the specimen must occur between 30 and 90 seconds. However, even by using the lowest speed, 10 kN/s, it was not possible to comply with the 30 seconds required by the standard. The flexural strength, determined by a three points bending test, corresponds to the maximum force recorded during the test.

The compressive strength test uses the two halves of the specimens resulting from the flexural test. A manual adjustment of the equipment was also performed and the load was applied without shock at constant velocity. However, also in this test it was not possible to obtain the breakage of the specimen in the period of time required by the standard, between 30 to 90 seconds, although the minimum speed, 50 N/s, has been used. The compressive strength corresponds to the maximum force recorded, divided by the contact area of the sample.

Results and discussion

Tests on fresh mortars: consistency and bulk density

A study previously carried out by the same authors (Gomes et al. 2012, p. 273) showed that earth-based mortars with flow values between 152–177 mm present a good workability. When the flow value is between 160

and 176 mm the workability can be considered excellent. Hence, the flow values of the tested mortars were adjusted to the first interval. Table 2 shows the obtained flow values which were between 159 and 177 mm. The bulk density of the fresh mortars is also reported in Table 2. As can be seen, mortars containing fibers have a lower density; this is because hemp fibers exhibit a very low density.

Linear and volumetric shrinkage

The results of the linear and volumetric shrinkage are quite variable, as shown in Fig. 8. Linear shrinkage does not appear to be representative of total shrinkage; volumetric shrinkage is much higher than linear shrinkage and seems a more sensitive parameter. However, normative documents only mention linear shrinkage; for these reasons, it is considered that the differences between these two parameters are important to be correlated in future studies.

New Zealand Standard 4298 (1998, p. 24) and Lehmbau Regeln (2009, p. 80) are unique among the various documents consulted. This indicates a quantitative threshold for the (linear) shrinkage of earth mortars, being respectively: 3% the limit for linear shrinkage in earth mortars without cement and 1% in mortars with earth and cement, values obtained through Alcock's test; and 2% in prismatic specimens with the dimensions 40 mm x 40 mm x 160 mm in accordance with a free shrinkage. Nevertheless, earth mortars with addition of Portland cement have a linear shrinkage less than 1%. Thus, it can be concluded that all tested mortars had acceptable values for linear shrinkage; as can be seen, the linear shrinkage did not exceed 2% in any of the mortars.

No clear relationship was observed between binder content and either linear or volumetric shrinkage. The use of fibers had a positive influence, reducing both the linear and the volumetric shrinkage for all mortars (the only exception were the natural hydraulic lime mortars where the fibers did not reduce the linear shrinkage).

The lowest value, both for the linear and the volumetric shrinkage, is observed on MAV, with lower percentage of clay materials (Fig. 8). Mortars with the addition of fibers and the binder stabilizers Portland cement and hydrated air-lime showed the lowest linear shrinkage, while natural cement and Portland cement mortars with fibers showed the lowest volumetric shrinkage.

Designation	Group of mortar	Binder (%)*				F (%)*	Flow (mm)	Bulk density (kg/m ³)	CC (kg/(m ² .s ^{1/2}))	DI (-)
		CL	NHL	PC	NC					
MAv	Local_Avis	-	-	-	-	-	174	2000	0,0	0,2
MPD	Local_Pá Danado	-	-	-	-	-	177	2001	0,0	0,1
MVC	Local_Val Chaim	-	-	-	-	-	177	1976	0,1	0,1
MRE	Reference-earth	-	-	-	-	-	170	1872	0,1	0,1
MRE_F	Reference-earth with fibers	-	-	-	-	5	170	1783	0,2	0,1
MRE_CL5	Reference-earth with hydrated air-lime	5	-	-	-	-	172	1873	0,2	0,1
MRE_CL10		10	-	-	-	-	172	1871	0,5	0,2
MRE_CL15		15	-	-	-	-	170	1854	0,5	0,2
MRE_CL5_F	Reference-earth with hydrated air-lime and fibers	5	-	-	-	5	165	1787	0,2	0,2
MRE_CL10_F		10	-	-	-	5	163	1776	0,3	0,2
MRE_CL15_F		15	-	-	-	5	163	1770	0,5	0,2
MRE_NHL5	Reference-earth with natural hydraulic lime	-	5	-	-	-	171	1878	0,1	0,1
MRE_NHL10		-	10	-	-	-	172	1879	0,1	0,1
MRE_NHL15		-	15	-	-	-	172	1880	0,4	0,1
MRE_NHL5_F	Reference-earth with natural hydraulic lime and fibers	-	5	-	-	5	169	1793	0,1	0,1
MRE_NHL10_F		-	10	-	-	5	166	1794	0,1	0,2
MRE_NHL15_F		-	15	-	-	5	166	1798	0,3	0,2
MRE_PC5	Reference-earth with Portland cement	-	-	5	-	-	176	1893	0,3	0,2
MRE_PC10		-	-	10	-	-	176	1897	0,5	0,2
MRE_PC15		-	-	15	-	-	177	1902	0,6	0,2
MRE_PC5_F	Reference-earth with Portland cement and fibers	-	-	5	-	5	169	1796	0,3	0,2
MRE_PC10_F		-	-	10	-	5	173	1798	0,5	0,2
MRE_PC15_F		-	-	15	-	5	173	1800	0,7	0,2
MRE_NC5	Reference-earth with natural cement	-	-	-	5	-	172	1889	0,1	0,1
MRE_NC10		-	-	-	10	-	173	1892	0,2	0,1
MRE_NC15		-	-	-	15	-	159	1876	0,2	0,1
MRE_NC5_F	Reference-earth with natural cement and fibers	-	-	-	5	5	168	1811	0,1	0,1
MRE_NC10_F		-	-	-	10	5	172	1807	0,2	0,2
MRE_NC15_F		-	-	-	15	5	163	1786	0,4	0,2

*Percentages by weight in relation to the reference-earth; CL – powder hydrated air-lime; NHL – natural hydraulic lime; PC – Portland cement; NC – natural cement and F – fibers; CC – capillary absorption coefficient and DI – drying index

Table 2 Composition of the earth-based repair mortars and values for flow table consistency, bulk density, capillary absorption coefficient and drying index of tested mortars.

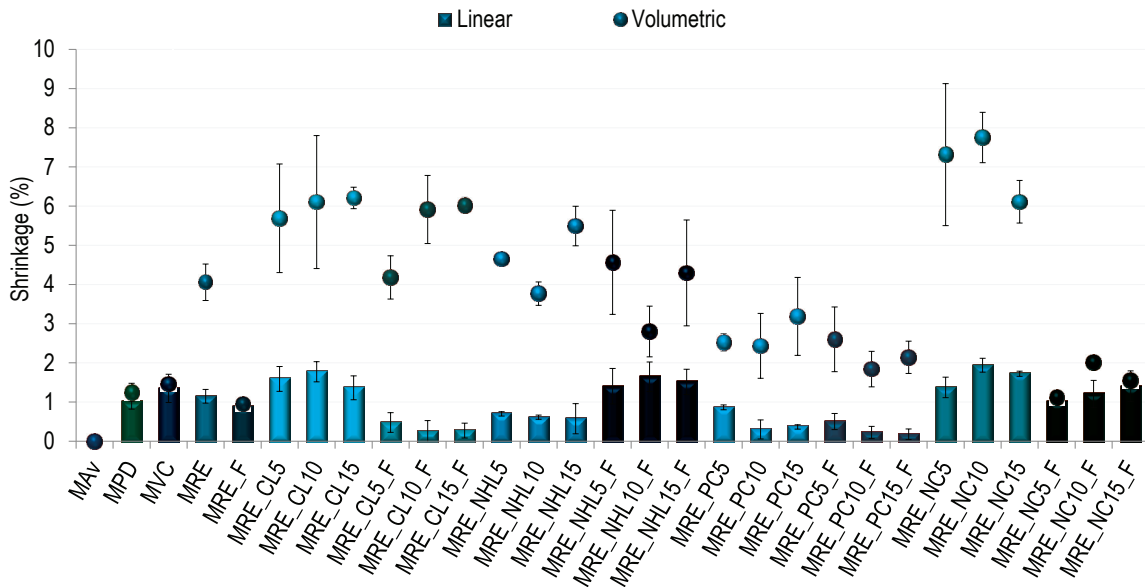
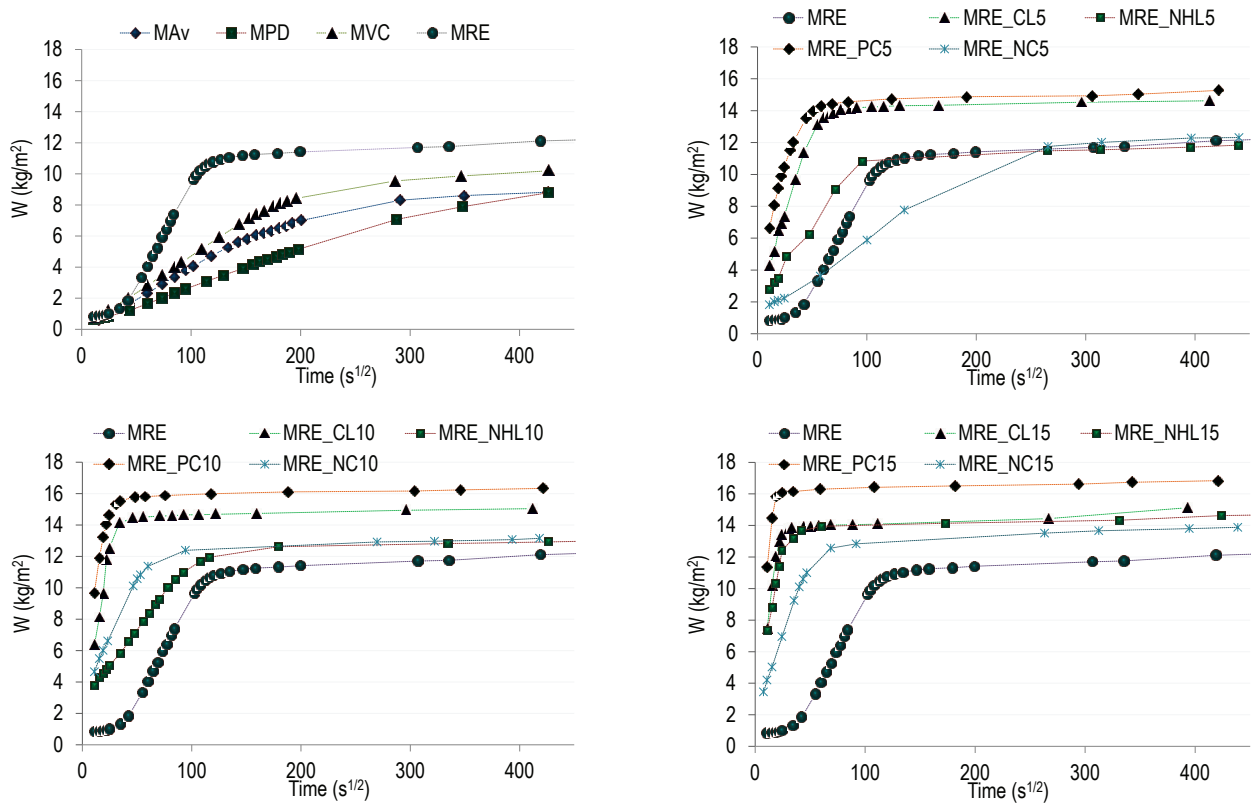


Fig. 8 Linear and volumetric shrinkage on the earth-based repair mortars, source: M. Idália Gomes



Figs. 9a to 9d Absorption curves showing the anomalous capillary suction behaviour on earth-based repair mortars without fibers at 90 days, source: M. Idália Gomes
 Top left (a) unstabilized materials; Top right (b) MRE materials with 5% of CL, NHL, PC and NC; Bottom left (c) MRE materials with 10% of CL, NHL, PC and NC; Bottom right (d) MRE materials with 15% of CL, NHL, PC and NC

Capillary water absorption

The absorption curves obtained in this study can be seen in Fig. 9 and the corresponding capillary absorption coefficient (CC) values are shown in Table 2.

Analyzing Table 2 and Fig. 9, it can be concluded that: (i) mortars with local earths (MAv, MPD and MVC) have the lowest capillary absorption coefficient; (ii) the *water absorption coefficient* increases with the percentage of binder, for all the four types of binders; (iii) there is not a clear trend in the influence of the fibers on the capillary absorption coefficient; (iv) the mortars with Portland cement have the highest water absorption coefficient, with and without fibers, when compared to the mortars with the same content of other binder stabilizers.

The absorption curves are shown in Fig. 9 (the unstabilized MRE earth is repeated in the four plots). As seen, the unstabilized materials present nonlinear (exponential) $t^{1/2}$ dependence during the first minutes, but afterwards the amount of water absorbed per unit area becomes directly proportional to the square root of the elapsed time. The anomalous suction behavior of the first minutes disappears with the addition of even the smallest amounts of binder.

Anomalous suction behavior has been reported (Hall et al., 1995, p. 1178; Lockington & Parlange, 2003, p. 761), for example, for cement-based materials, in which case it has been attributed to the triggering of hydration reactions of non-hydrated cement that remained in the material. For the present earth-based mortars, the anomaly is probably related to the occurrence of clay swelling. This swelling is halted by the binder stabilizers.

The anomalous behavior is particularly relevant for the MRE earth, which, according to Fig. 8, is also the one with the higher drying shrinkage (4.1% volumetric shrinkage in the Alcock's tests, against 0.0%, 1.2% and 1.5% for the MAv, MPD and MVC, respectively). The use of binder stabilizers eliminates swelling, enabling perfect $t^{1/2}$ dependence.

As seen in Fig. 9, the use of binder stabilizers can increase significantly the amount of water absorbed per unit area ($\text{kg}\cdot\text{m}^{-2}$). Their use can also increase the maximum amount of water absorbed, i.e., the capillary porosity of the material. This statement is also corroborated by Hall & Djerbib (2006, p. 388) and Hall & Allinson (2009, p. 692).

These effects are more relevant for Portland cement (PC), though they are also clear for the remaining binder

stabilizers. Present results show that both hydraulic stabilizers and also air lime can increase significantly the capillary porosity of the earth material, which is an undesirable effect.

Drying

The results of the drying test are expressed by the drying curve (Fig. 10) and a single quantitative parameter, the Drying Index listed in Table 2.

The highest value for the drying index was observed on mortars with the local earth, MAv, followed almost simultaneously by mortars MRE_CL15_F and MRE_PC15_F.

Mortars with fibers have slower drying than those without fibers, considering the same type of binder stabilizer with the same percentage (with the single exception of MRE_PC10 mortar), Table 2. This may be due to the fibers release apparently moisture more slowly than the other constituents.

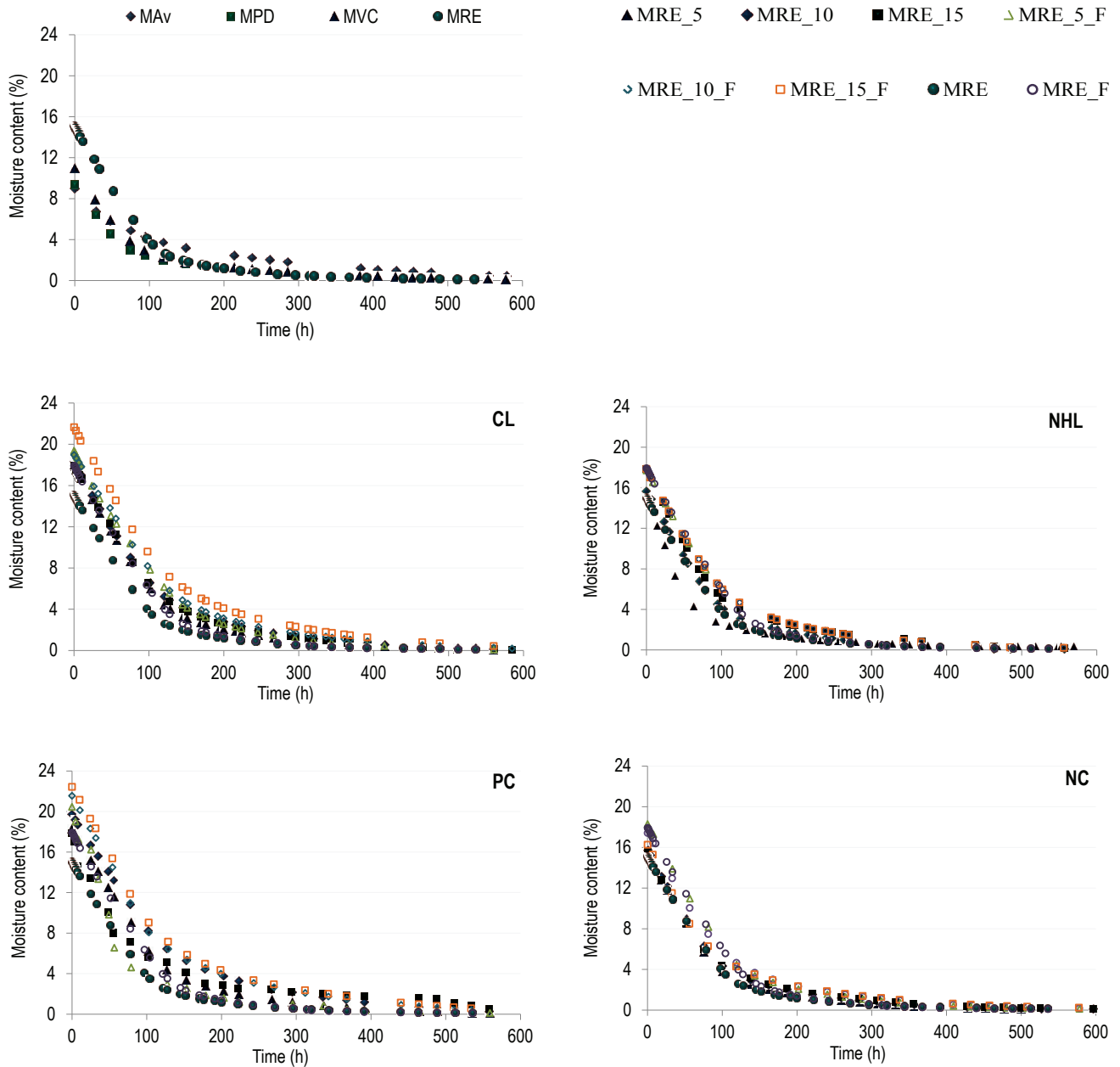
A general trend was observed for drying to become slower as the binder stabilizer content increased. The slowest drying was observed on MAv and on mortars with Portland cement, with or without fibers (Table 2).

Generally, for the same percentage of binder, drying was faster in the reference-earth mortars with and without fibers, in the natural hydraulic lime mortars without fibers and in the natural cement mortars without fibers.

Dynamic modulus of elasticity

According to RILEM (2008, p. 860), mortars with a low modulus of elasticity can be required for very weak substrates, such as some earth walls.

The test results for the dynamic modulus of elasticity by measuring the fundamental resonance frequency are shown in Fig. 11. The introduction of fibers did not appear to affect significantly and in a clear way the modulus of elasticity. The highest modulus (lower deformability) was verified for the local earths (MAv, MPD and MVC); for the mortars using the reference-earth, the highest value was verified for the natural cement mortars with fibers. The dynamic modulus of elasticity decreases as the percentage of binder stabilizers increases for all mortars, with the exception of the hydrated air-lime mortar, of which the values increased, both with and without fibers.



Figs. 10a to 10e Drying curves of the earth-based repair mortars at 90 days, source: M. Idália Gomes

Top (a) unstabilized materials

Middle left (b) MRE materials with 0%, 5%, 10% and 15% CL

Middle right (c) MRE materials with 0%, 5%, 10% and 15% NHL

Bottom left (d) MRE materials with 0%, 5%, 10% and 15% PC

Bottom right (e) MRE materials with 0%, 5%, 10% and 15% NC

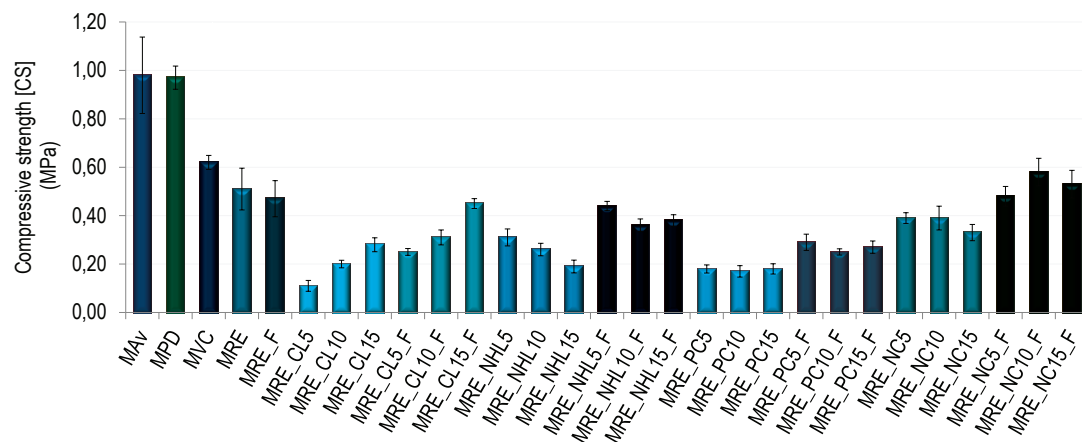
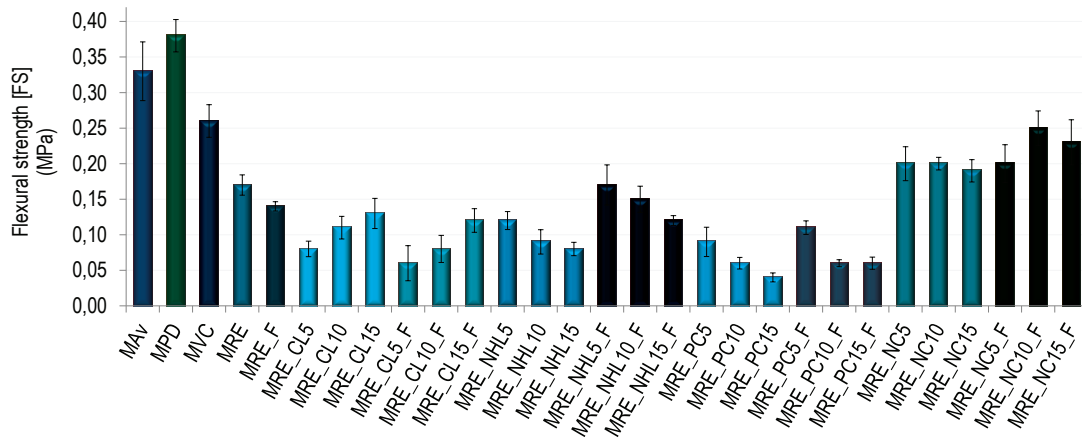
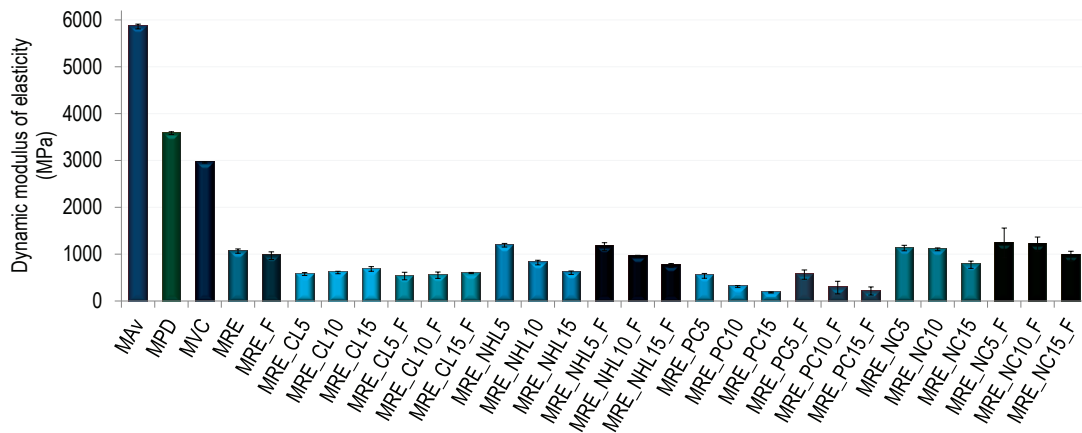


Fig. 11 Dynamic modulus of elasticity of the earth-based repair mortars at 90 days, source: M. Idália Gomes

Fig. 12 Flexural strength of the earth-based repair mortars at 90 days, source: M. Idália Gomes

Fig. 13 Compressive strength of the earth-based repair mortars at 90 days, source: M. Idália Gomes

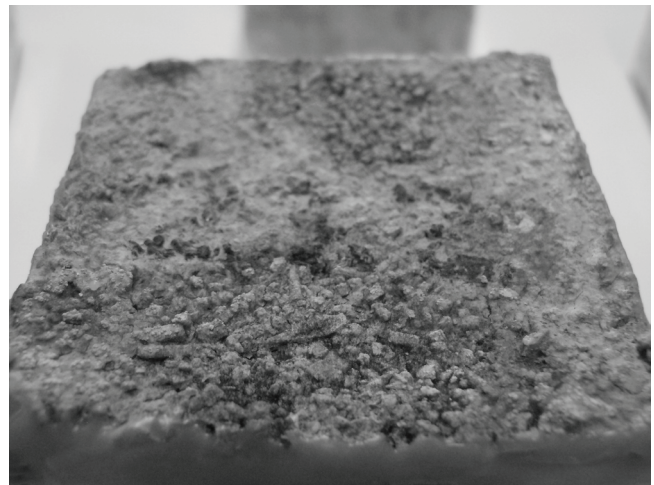
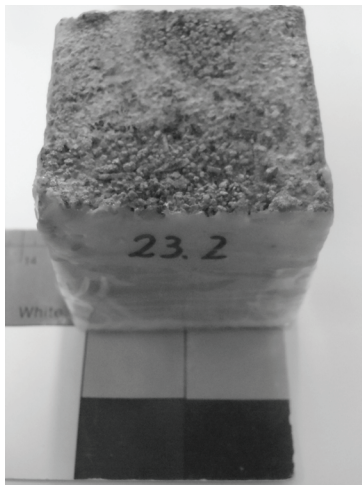


Fig. 14 Fungi in the specimen with fibers and natural hydraulic lime binder stabilizer, after the specimen had been subjected to the capillary water absorption test, source: M. Idália Gomes.

Flexural and compressive strength

The results for both the flexural and compressive strength tests can be seen in Fig. 12 and Fig. 13, respectively.

It can be concluded that:

- the mortars with the local earth MAv, MPD and MVC (material from the buildings), have the highest values both for the flexural and the compressive strength, in agreement with results of dynamic modulus of elasticity; the results are different than the expected – large differences in the results between stabilized and non-stabilized mortars; such may occur because the material is inconsistent and heterogeneous and, another cause may be due to the fact that the testing methodology do not translate the characteristics of these materials, it can be noted that, either in the determination of flexural and compressive strength, was not possible to complete the period of time (in the test) required by the standard; it may be necessary (in future studies) to adapt tests for these materials;
- the introduction of fibers increased the flexural strength, except for the unstabilized reference-earth mortars and with hydrated air-lime; the compressive strength also increased, except for the reference-earth mortars;
- there is no clear relationship between percentage of binder and the flexural or compressive strength; contrary to what would be expected, the addition of binder

did not provide significant differences in this characteristic; this might be due to the fact that the low percentage of binder stabilizer does not result in significant differences in terms of mechanical strength; it is necessary to conduct further research in order to answer what is the ideal percentage to gain mechanical strength without compromising the compatibility with the support;

- for the same percentage of binder stabilizer, mortars with natural cement have a higher flexural and compressive strength.

Biological growth

The susceptibility of the mortars to biological growth was evaluated by visual observation, throughout the period that elapsed between the beginning of curing until the end of the drying test. Fungi appeared in the mortars with hemp fibers, air-lime mortars being the only exception.

It was observed that the highest amount of fungi appeared in the mortars with the lowest percentage of binder stabilizer, decreasing with the increase in the percentage of binder stabilizer. Among the mortars with natural hydraulic lime, Portland cement and natural cement, mold fungi did not appear only in the specimen with the higher percentage of Portland cement. The presence of hemp fibers also enhanced biological growth.

By observing the results, these occurrences can be related to four different factors: the organic nature of the hemp fibers; the presence of organic materials in the earth; the humid environment during the initial wet curing; and the specimens being subjected to tests with water, i.e. capillary water absorption (Fig. 6).

As previously referred, it was also observed that fungi were inhibited or obstructed in some cases, which is attributed to changes in the pH value. In fact the presence of fungi was not observed in the mortars with air lime or the higher percentage of Portland cement, even with the addition of fibers. Traditionally, air-lime was used for health purposes, which is consistent with the fact that no fungi were found here in this kind of mortars.

Indeed, strongly alkaline materials such as air lime or cement have fungicidal properties, due to their high pH value (Straube & DeGraauw 2001, p. 3; Röhlen 2012, p. 113), but when contaminated they may also be subject to the formation of mold fungi. The high level of alkalinity hampers the fungal growth.

Conclusions

The main conclusions of the study regarding the addition of the four stabilizers (dry hydrated air-lime, natural hydraulic lime, Portland cement and natural cement) are that:

- the four unstabilized earth materials depicted non-linear (exponential) $t^{1/2}$ dependence during the first minutes of capillary suction; this anomalous behavior was probably due to clay swelling; any of the four tested binder stabilizers enabled linear $t^{1/2}$ dependence, probably because clay swelling did not take place in this case;
- in general, increasing the percentage of binder stabilizer increases the capillarity coefficient of the mortar, which is undesirable; the worst behavior was observed for the mortars with Portland cement;
- increasing the percentage of binder stabilizers results in a slower drying in mortars;
- for the three hydraulic binders, the elastic modulus of elasticity (E modulus) decreases with the percentage of binder stabilizer; this effect was not observed for air lime, which did not compromise the deformability of the earth mortars;
- the addition of the present low percentages of binder stabilizers did not improve the mechanical behavior.

Regarding the addition of fibers in the mortar, the main conclusions are:

- shrinkage decreased in general, both in linear and volumetric terms, with the only exception of the natural hydraulic lime mortars where the linear shrinkage increases;
- drying became slower; this may be due to the apparent fact that fibers release moisture more slowly than the other constituents;
- there is no clear influence on the dynamic modulus of elasticity; contrarily to the expected, fibers did not improve this feature;
- the flexural and compressive strength increases in most cases;
- it may give rise to undesirable biological growth; this effect was observed in all the tested mortars except those with air lime.

Another interesting conclusion of this work concerns the drying shrinkage test. As observed, the values for the linear and volumetric shrinkage (shrinkage analysis on the three directions) are quite different. Linear shrinkage does not seem enough to indicate the total shrinkage. It is advisable to consider also the volumetric shrinkage for this type of materials. The compatibility, applicability and effectiveness of the present earth-based repair mortars has also been evaluated after application on rammed earth substrates; part of such results are presented in Gomes et al. (2013).

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