Natural Fibre Reinforced Earth and Lime Based Mortars

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ABSTRACT: The present research work was developed with the main objective of enhancing the basic characteristics of earth and lime plastering mortars, in particular taking into account the shrinkage effect of clays in order to avoid cracking. For this purpose one has studied: a standard mortar made of earth and lime, without the addition of fibres; the incorporation of several types of fibres in the standard mortar. The addition of natural fibres (banana, coconut, sisal) was tested and, in order to compare its results, the incorporation of synthetic fibres (polypropylene) was also tested. Due to the large range of earth clay contents and types of clay, with distinct behaviours, one has performed expeditious tests in order to characterize the clays. To evaluate the performance of the incorporated fibres in the mortars one has developed laboratorial tests to achieve the most relevant properties: workability; mechanical behaviour; water behaviour; and susceptibility to cracking.

1 INTRODUCTION

As a result of the increasing demand for a sustainable architecture, the interest in earth building, as well as in earth and lime based mortars have recently grown. Therefore, these mortars have been studied regarding its use both in renovating old buildings and in new ones made with earthen walls (Gomes et al 2012 and Morton & Little 2007) or in straw bale walls (Taylor et al 2006).

The main advantages of using these mortars are: i) higher compatibility with old materials than cement based mortars (Gomes et al 2012); ii) less energy consumption during its manufacture (Taylor et al 2006); iii) and greater healthy building interiors similarly to what happens in earth building (Morton 2008).

An earthen mortar consists of a mixture of earth with fine grains and water. The cohesion of these mortars is essentially assured by the clay fraction present in the earth material but also due to additives, fibres and fillers eventually added to the mortar to improve their characteristics. It is recommended that earthen mortars should be produced with adequate additives, such as crushed straw or other fibrous plants. Other additives may be added as lime, gypsum, artificial or natural pozzolans, cement, resins, biopolymers, etc (Dachverband Lehm e.V. 2008). The added materials should be selected in such a way that the properties of the obtained mortar meet the requirements set out according to the *Lehmbau Regeln* (Rules governing building with earth) from German Association for Building with Earth (Dachverband Lehm e.V. 2008).

The properties of earthen mortars depend essentially on bonding strength of earth material, provided by the amount and type of the existing clay. It is recommended to use a soil which clay content will not be very poor and it must be free of stones and with grains dimensions lesser than 5 mm (Dachverband Lehm e.V. 2008). The variety of clay minerals present in the soil also influences directly the soil properties and consequently the obtained mortars. These minerals result in different levels of water retention, plasticity, water dispersion and expandability of soil.

The lime may be added to clay-rich soils, once it provides an increase of mechanical strengths and subsequently its durability (Houben 2008). However, it is not possible to advise a suitable mixture because the amount of reactive clay can differ considerably. Holmes and Wingate (Morton & Little 2007) have suggested an optimal content of 10% of clay and a lime proportion between 3% and 10%. However, these authors warn that for proportions inferior to 5% the compressive strength can be reduced instead of increased (Morton & Little 2007).

Regarding the use of lime either in paste or in powder, in a research study about in-situ applications of lime mortars, the respective laboratory tests do not differ significantly in the resistances or capillarity of mortars made with lime in paste or in powder form (Margalha, et Al 2006). However, the lime paste present some advantages compared to lime powder: do not lose quality with the storage, because the water reduces the carbonation process; improves the workability; and reduces the later cracking of the dry mortars (verified with the use of lime pastes of old hydration) (Margalha, et Al 2006).

The use of fibres in earthen mortars is mainly associated with the possibility of shrinkage cracking reduction**.** However, there are many types of fibres, with different physical properties, and this may affect how they interact within clay and lime materials (Morton & Little 2007).

The purpose of this research study was to propose a possible solution for earth walls rendering and evaluate the main properties of earth and lime based mortars with addition of natural fibres (sisal, banana and coconut) and synthetic fibres of polypropylene. To evaluate the performance of the incorporated fibres in the mortars one has developed laboratorial tests to achieve the most relevant properties: workability; mechanical behaviour; water behaviour; and susceptibility to cracking. The obtained results will be presented and analysed.

2 REQUIREMENTS FOR EARTH BASED PLASTERING/RENDERING MORTARS

A research about reference values for essential properties of earth based plastering/rendering mortars has been conducted and the following recommendations were found.

In Lehmbau Regeln it is mentioned that the minimum compressive strength for interior plastering should be ≥1,5 MPa, corresponding to Category CSII (compressive strength between 1,5 to 5,0 N/mm^2 according to EN 998-1) (Dachverband Lehm e.V. 2008). Minke & Ziegert (2008) cited other requirements for plastering mortars, these are listed in Table 1.

Table 1. Minimum requirements for the compressive strength of clay mortar in relation to their intended use (Minke & Ziegert 2008).

Type of use	Compressive strength (MPa)	Pull-out strength (MPa)
Secondary spaces	≥0,5	-
Clay plaster intended for subsequent surface stabilizing in rooms for general use, e.g. living and work rooms in single and multi-occupancy houses	≥1,0	≥0,03
Clay plaster as base for finishing plaster, coating, and wallpapers	≥1,5	≥0,03

Regarding the replacement or renewal plastering, Veiga (2003) mentions some values for properties of plastering for irregular masonry walls, based on the acquired experience (see table 2). In this case, the requirement for compressive strength is included in class CSI, as defined in the standard EN 998-1.

Table 2. Minimum requirements for different properties (Veiga 2003).

Mortar	Tensile strength (MPa)	Compressive strength (MPa)	Pull-out strength (MPa)	Capillarity coefficient, C ($kg/m^2.min^{0.5}$)
Rendering mortar	0,2–0,7	0,4–2,5	0,1–0,3 or cohesive	1≤C≤1,5
Plastering mortar	0,2–0,7	0,4–2,5	rupture by the plaster	1≤C≤1,5

3 SELECTED MATERIALS AND PERFORMED MIXTURES

3.1 *Selected materials*

The selected soil was collected in a region at the centre of Portugal (near Figueira da Foz) and before its use was submitted to manual crushing. For soil characterization sieve and sedimentation analysis were performed, as well as the checking of clay type present in the soil.
Commercial available natural river sand was added, whose particle size distribution is medium (0,063 mm - 4 mm in accordance with the standard EN 933-1). This sand addition has the purpose of reducing the high shrinkage, once the soil has a large amount of fine particles (clay and silt), around 39% by weight, as can be seen in Figure 1. Through the sedimentation analysis of the fine sample, it was verified that approximately 47% is clay and 53% is silt.

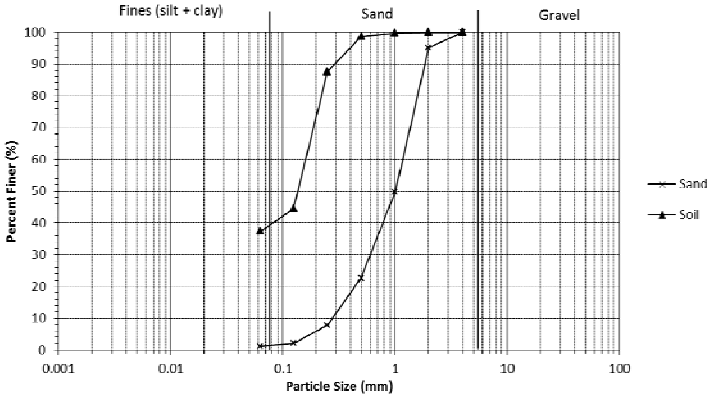

Figure 1. Particle size distribution of soil and sand used.

In order to confirm the clay type in the used soil the "*Emerson*" test described by Houben & Guillaud (1989) was performed. According to this test, the presence of kaolinite and montmorillonite in equal proportions was verified.

The used binder added was lime paste from a Portuguese company (Fradical) which may be classified as a CL90 one according to standard EN 459-1, and with a density of 1300 kg/m^3 (Fradical 2006).

The used fibres (sisal, banana and coconut or coir) are from Brazil, which are classified as natural, organic, of plant origin. Sisal fibres are originated from the sisal leaves, coconut fibres from the fruit of coconut palm and banana fibres from the stem of banana tree. The fibres were cut in pieces of 20 mm in length approximately. However, this length was more difficult to achieve with coconut fibres, because they were jumbled. The physical and mechanical properties can be seen in Tables 3 and 4.

Table 3. Physical properties (Carvalho 2012, Vimaplás 2009, Jalali & Torgal 2010).

Fibre	Diameter (μm)	Specific mass (kg/m^3)	Linear mass (Tex) (g/km)	Water absorption after 5 min (%)	Water absorption when saturated (%)
Sisal	100–300	1260	26–45	67–92	190–250
Banana	150	1500	10–30	-	407
Coconut (coir)	40–400	1390–1520	16–35	22–38	85–135
Polypropylene	38	-	-	-	-

Table 4. Mechanical properties of fibres (Carvalho 2012, Vimaplás 2009).

Fibre	Tensile strength (MPa)	Young's modulus (GPa)	Maximum force (N)	Elongation in maximum force (mm)
Sisal	324–329	19	12,4–18,1	3,0–3,5
Banana	700–800	-	2,2–4,7	2,3–2,5
Coconut (coir)	95–134	2,5–4,5	2,6–5,1	11,4–14,0
Polypropylene	340–400	3,5–4	-	-

3.2 *Performed mixtures*

The mortars were prepared in the proportion of 1:1,5:3 (lime: soil: sand) and with an addition of 0,24% of fibres (by weight of dry mixture). The amount of water added was determined through trial mixtures according to a required consistency of about 150 mm (flow test, see table 5). The mixtures were performed with the main objective of maintaining the water/binder ratio as low as possible in order to improve the performance of the plastering and considering that the average percentage of water contained in the lime paste (after drying at 100ºC) was 57%.

The process of mixing adopted was manual and it followed a specific methodology: i) homogenization of soil with sand; ii) introduction of lime; iii) manual mixing with water addition to attain required consistency (according to the result of the performed flow test); iv) and finally the addition and mixing of fibres in the paste.

The different mixtures performed are called as EM (earthen mortar) in the tables and graphics of this paper and each associated number corresponds to a mixture (e.g. EM0-Without fibres).

4 METHODOLOGY

The experimental research that has been carried out has involved the mortars characterization in the fresh state, through the consistency determination by flow test, as well as the characterization in dry state by evaluation of: i) susceptibility to cracking; ii) water absorption by capillarity; iii) drying; iv) mechanical resistance (flexural tensile strength and compressive strength); v) and adherence to the support by pull out tests. It should be noted that some tests are not easy applicable to earthen mortars due to the slow hardening, low mechanical resistance and susceptibility to water action, which forced to adapt the test procedures.

The flow test was performed according to European standard EN 1015-3 (1999). The consistency considered as adequate for the mortars was fixed in a flow of 150 ± 10 mm.

The flexural tensile strength and compressive strength tests were performed according to EN 1015-11 (1999). Concerning the specimen's manufacture, some difficulty in the use of compacting with pestle (prescribed by the standard) was verified because of the presence of the incorporated fibres. Therefore, mechanical compacting equipment prescribed by the standard EN 196-1, with 25 shocks by each layer was employed. The maturing conditions for mortars (of cement, lime and others) require a moist environment during 7 days, with the specimen 2 or 5 days inside the moulds. However, in this case, the specimens did not harden enough until 5 days and the specimens were kept in the moulds for 7 days. After, the specimens were removed from the moulds and were placed in a conditioned room (at 20 ± 2ºC and 65 ± 5% RH) until 21 days of age. In the compressive strength test, the halves of the specimens resulting from the flexural strength test were used.

The evaluation of the susceptibility to cracking consists of the application of a mortar sample on one side of a ceramic brick (dimensions of 30×20×15 cm^3), checking over time, through visual observation, the appearance, or not, of cracks. The mortar was applied in one layer with a maximum thickness of 1.5 cm and these bricks were kept in normal room conditions, with average temperature of 16,6 ºC and relative humidity of 62,3% for 28 days.

The water absorption by capillarity tests was performed according to EN 1015-18 (CEN, 2002). For this purpose, two specimens of each mixture were used, which were sideways waterproofed at 28 days of age and tested. The test was made subjecting the broken surfaces of the specimens on contact with water (10 mm above the specimen base).

The drying tests were performed using the specimens after the water absorption by capillarity test, with the underside sealed by a polyethylene film and placed in a conditioned room (at 20 ± 2ºC and 60 ± 5% RH).

The pull out tests were performed according to EN 1015-12 (2000) in five samples obtained from the mortar applied on the ceramic bricks for evaluation of cracking.

5 OBTAINED RESULTS AND DISCUSSION

5.1 *Consistency determination by flow test*

Table 5 shows the water added to the mixtures, the corresponding water/dry material ratio and the obtained flow. As it can be seen, the mixture made with sisal present a higher value of added water. This value can be explained due to the high water absorption of sisal, but also because of its high stiffness which makes the flow of the plaster more difficult. It is also important to notice that the incorporation of banana, coconut and polypropylene fibres didn't seem to increase significantly the water demand.

Table 5. Ratio of water/dry material and the respectively results of flow test.

Mixtures	Water added (ml)	Ratio of water*/dry material (%)	Flow (mm)
EM0 - Without fibres	350	19,91	160
EM1 - Sisal	465	23,04	150
EM2 - Banana	350	19,91	150
EM3 - Coconut	360	20,18	150
EM4 - Polypropylene	350	19,91	150

* including the water present in lime paste.

5.2 *Mechanical strength*

The results of flexural tensile strength and compressive strength are presented in Figure 2. It can be noted that the addition of natural and synthetic fibres have increased the resistances compared to the mixture without fibres, especially in compressive strength. The increase was higher for coconut fibres, about 70% and 44% in compressive and flexural strength respectively.

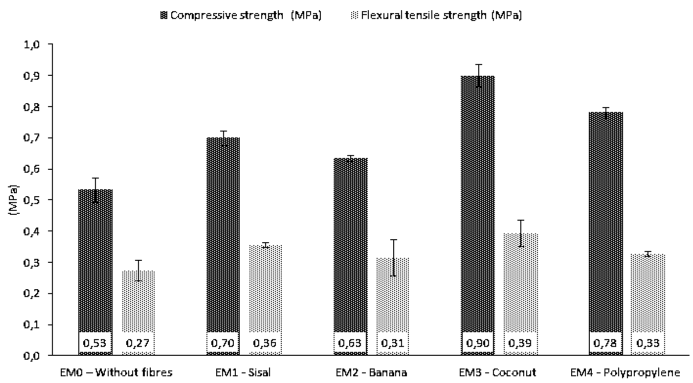

Figure 2. Flexural tensile and compressive strength with standard deviation.

5.3 *Susceptibility to cracking*

For the evaluation of susceptibility to cracking, one has applied the selected mixtures on ceramic bricks, with the purpose of its visual observation along time. One has only detected the appearance of cracks in the mortars made without fibres (EM0) and in the mortars with polypropylene fibres (EM4). In Figure 3 one can see some large cracks in the EM0 mixture and the highest number of cracks in the mixture EM4, although these are of much lesser length and thickness.

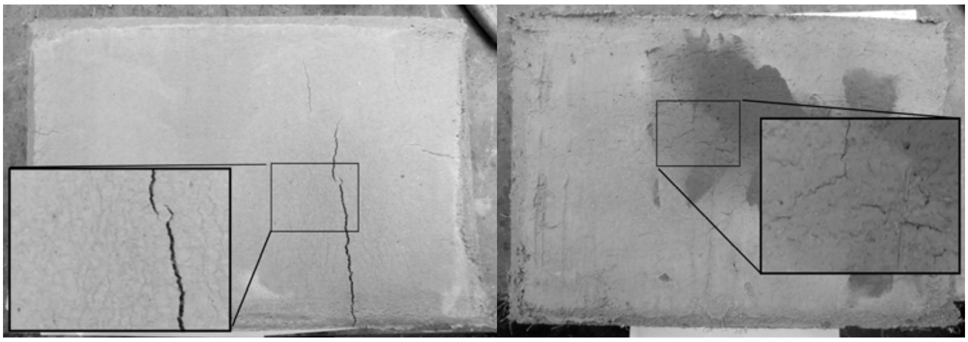

Figure 3. Mortars without fibres (EM0) (left) and mortars with polypropylene (EM4) (right).

5.4 *Water absorption by capillarity*

Figure 4 shows the obtained capillarity coefficients and the curves representing the kinetics of water absorption by capillarity. The slope of the first linear straight section of the water absorption curve corresponds to the capillarity coefficient.

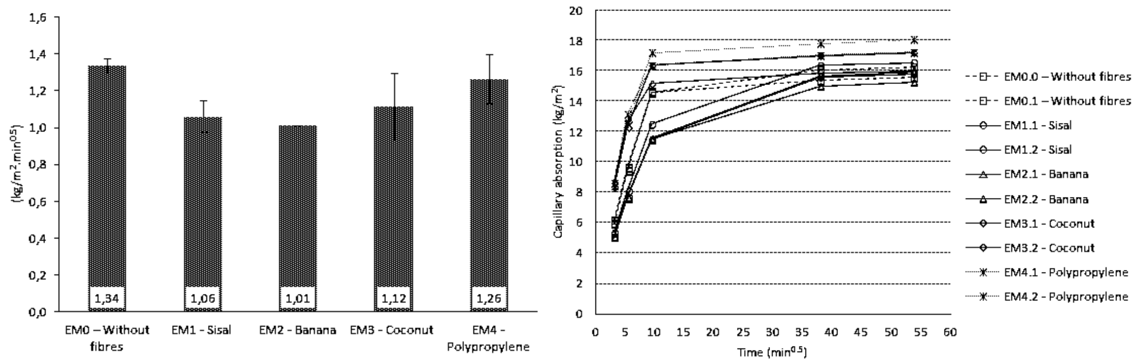

Figure 4. Capillarity coefficient and the respective curves of water absorption.

The obtained values of the capillarity coefficient reveal a slight decrease on the water absorbed in the mixtures made with fibres, mainly with natural fibres (EM1, EM2 and EM3).

Regarding the curves of water absorbed by capillarity, comparing it with the mixture without fibres (EM0), it can be observed that the mixture EM4 of polypropylene fibres absorbed more water and the mixtures EM1 and EM2 (fibres of sisal and banana) absorbed less water at the 90 minutes (≅ 10 min^{0,5}). However at 24 (≅ 38 min^{0,5}) and 48 hours (≅ 54 min^{0,5}) there are no significant differences among the tested mixtures.

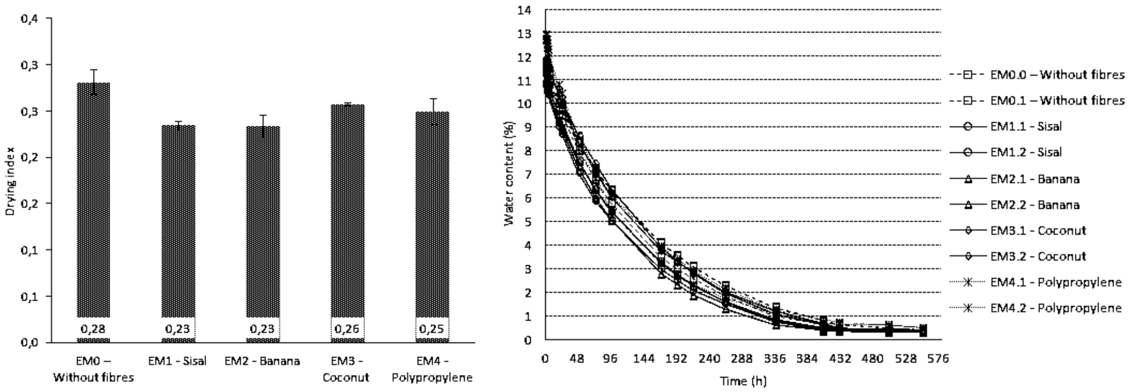

Figure 5. Drying index and curve of evaporation.

5.5 *Drying*

The behaviour of the different mixtures during the drying test is showed in Figure 5, through the drying index and curve of evaporation. This property is important for plastering mortars, once these are used in interiors, where it is expected that mortars dry faster in order not to increase the relative humidity in interior rooms.

The drying index was calculated according to the formula of Cultrone, G. et al (2007).

The results reveal that, although their similarity of magnitude, it seems that the incorporation of fibres (especially the sisal and banana fibres) contributed to a slight reduction of the time of evaporation. It was noted that the mixtures with an initial lower water content dried faster.

5.6 *Adherence to the support*

Table 7 shows the results of the pull out tests, presenting the values of tensile strength, its coefficient of variation and the prevailing typology of rupture.

It is noted a higher coefficient of variation in the standard mixture (EM0) what makes the evaluation more difficult. However, in general, the results reveal that the tensile strength values, comparing with the mixture made without fibres (EM0), the incorporation of fibres do not seem to affect significantly the adherence of mortars to the support.

Regarding the typology of rupture, it was noted that: i) the mixture without fibres (EM0) and the mixture with polypropylene fibres (EM4) had a rupture mostly adhesive (in the coating plane of the support); ii) the mixtures with banana and coconut fibres (EM2 and EM3) had a rupture mostly cohesive (within the coating plane); iii) and the mixture with sisal fibres had a mixed rupture. In general, these results show that the tensile strength of mortars should be close to the tensile of adherence between the mortars and the bricks.

Table 7. Results of pull out tests and typology of rupture.

Mixtures	Average tensile strength (MPa)	Coefficient of variation (%)	Prevailing typology of rupture
EM0 - Without fibres	0,13	20,74	Mostly A
EM1 - Sisal	0,09	9,47	Mixed AB
EM2 - Banana	0,12	9,50	Mostly B
EM3 - Coconut	0,10	5,57	Mostly B
EM4 - Polypropylene	0,10	4,83	A

A - Adhesive rupture (in the coating plane of the support); B – cohesive rupture (within the coating plane).

6 CONCLUSIONS

The incorporation of natural fibres, sustainable and inexpensive, can be a good solution to solve the general problem of earthen mortars, the cracking by shrinkage. The obtained results highlight that the cracking decrease and the properties in dry state (mechanical and water behaviour) practically have not been affected.

Concerning the mentioned requirements for plastering earthen mortars, one can conclude that these mortars in general comply with the recommended values. In flexural tensile strength, the obtained values were higher than 0,27 MPa (requirements between 0,2 and 0,7 MPa), but at compressive strength these mixtures only comply with the lower recommended values (≥0,5 MPa) for secondary spaces. However, a significant increase of resistances over time is expectable. In water absorption by capillarity, the obtained results in these mixtures complies the recommended values (between 1 and 1,5 $kg/m^2.min^{-0,5}$. In pull-out tests, most of the mixtures complies the minimum of 0,1 MPa of tensile strength recommended for earthen mortars. But, for replacement or renewal plastering the obtained values are, in general, between the suggested values (0,1 to 0,3 MPa or cohesive rupture by the plaster).

In addition, the studied mortars, also had a good behaviour concerning the drying after water absorption, revealing that these will not compromise the relative humidity in interior rooms, present a good workability and were very easy to apply in the used support (ceramic bricks).

Regarding the sustainability, comparing this type of mortar (with earth, lime and natural fibres) with conventional plastering mortars of lime, gypsum or cement, the clay content can reduce, partial or completely, the percentage of processed binder. The processed binders require a considerable energy consume in its manufacture, therefore, this reduction is a good contribute for sustainability. Comparing with simple earthen plasters, made without stabilizer, the sustainability of the manufacture is lower, but the mechanical resistance and durability could be higher. Thus, considering the long term performance, the addition of stabilizers will be beneficial.

However, the plastering mortars with earth and lime with natural fibres, being a reappearing material, deserves more research study to provide more guarantees in its application, due to the multiplicity of fibres and the variability of soils and limes used.

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CONTRIBUTION OF SUSTAINABLE BUILDING TO MEET EU 20-20-20 TARGETS

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