Earth-based repair mortars: experimental analysis with different binders and natural fibers

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ABSTRACT: This work intends to contribute for a better knowledge of earth-based repair mortars. The studied mortars are made of a commercial earth (consisting mainly of clay), and other components namely: sand; powder hydrated air-lime; natural hydraulic lime; Portland cement; Roman cement and natural fibers. The experimental analysis of the mortars in the fresh state consisted in the determination of the consistence by flow table and bulk density. In the hardened state the tests conducted were: linear and volumetric shrinkage; water absorption capillary coefficient; drying test; dynamic modulus of elasticity by measuring the fundamental resonance frequency; flexural and compressive strengths.

1 INSTRUCTION

Rammed earth is one of the most important earth building techniques, both in traditional construction and modern earth architecture. In Portugal, the number of buildings being built with this technique or simply rehabilitated is increasing. However, it is common to find anomalies, often due to the use of incompatible materials, in both types of interventions.

Degradation of the exterior surface of rammed earth constructions is very common. It is also frequent to find rammed earth constructions repaired by applying cement-based mortars in the attempt to overcome the decay; but these mortars normally end up causing additional problems to the construction, especially when used in unstabilised earth constructions (Guelberth & Chiras 2008; Walker & Standards Australia 2001).

The surface repairs should be made of mortars with physical, mechanical and chemical properties similar to those of the walls. Indeed, the main requirement of repair mortars should be the protection of the original material of the walls. The durability of the repair mortar itself should come only as a second order requirement, but this is often not respected. Mortars have to ensure the long-term integrity of the bond to the earth substrate; this property is very important but also difficult to achieve.

This article intends to contribute for a better knowledge of earth-based repair mortars. An experimental campaign was conducted aimed at the development of earth-based mortars for the repair of rammed earth walls. It consisted of the following types of laboratory tests: (i) in the fresh state: determination of the consistence by flow table and bulk density; (ii) in the hardened state: linear and volumetric shrinkage; water absorption capillary coefficient; drying test; dynamic modulus of elasticity by measuring the fundamental resonance frequency; flexural and compressive strengths.

2 MATERIALS

A commercial earth, herewith designated “reference-earth”, with a large percentage of clay, was used as binder. Sand, mainly composed by quartz and with dimensions in the range of 0.6 to 2.0 mm, was also used in the mortars subjected to the present experimental campaign. Figure 1 shows the particle-size distribution of the reference-earth and the sand. The addition of sand had the main objective of reducing the shrinkage which otherwise would be very high because the reference-earth consists essentially of clay.

The basic volumetric composition of the mortars was 1:3 (reference-earth:sand).

The mortars included also the addition of 0%, 5%, 10% or 15% of binder, and 0% or 5% of hemp fibers (F) (percentages by weight in relation to the earth). Four types of binder were used: powder hydrated air-lime (AL) EN 459-1 CL 90-S; natural hydraulic lime (NHL) EN 459-1 NHL5; Portland cement (PC) CEM II/BL 32.5 N and Roman cement (RC).

The compositions of the ten distinct groups of earth-based mortars that resulted from these mixtures are presented in Table 1.

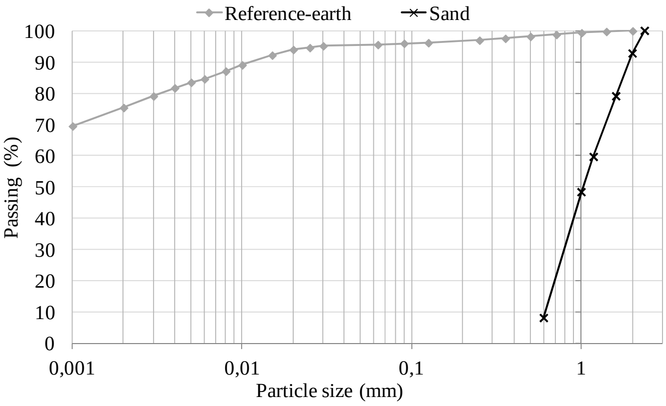

Figure 1. Particle size distribution nomograms for the reference-earth and sand.

Table 1. Composition of the ten groups of mortar.

Group of mortar reference-earth (MRE)	Designation	Binder (%)*				F
		AL	NHL	PC	RC	(%)*
Reference-earth	MRE	-	-	-	-	-
Reference-earth with fibers	MRE_F	-	-	-	-	5
Reference-earth with hydrated air-lime	MRE_AL5	5	-	-	-	-
	MRE_AL10	10	-	-	-	-
	MRE_AL15	15	-	-	-	-
Reference-earth with hydrated air-lime and fibers	MRE_AL5_F	5	-	-	-	5
	MRE_AL10_F	10	-	-	-	5
	MRE_AL15_F	15	-	-	-	5
Reference-earth with natural hydraulic lime	MRE_NHL5	-	5	-	-	-
	MRE_NHL10	-	10	-	-	-
	MRE_NHL15	-	15	-	-	-
Reference-earth with natural hydraulic lime and fibers	MRE_NHL5_F	-	5	-	-	5
	MRE_NHL10_F	-	10	-	-	5
	MRE_NHL15_F	-	15	-	-	5
Reference-earth with Portland cement	MRE_PC5	-	-	5	-	-
	MRE_PC10	-	-	10	-	-
	MRE_PC15	-	-	15	-	-
Reference-earth with Portland cement and fibers	MRE_PC5_F	-	-	5	-	5
	MRE_PC10_F	-	-	10	-	5
	MRE_PC15_F	-	-	15	-	5
Reference-earth with Roman cement	MRE_RC5	-	-	-	5	-
	MRE_RC10	-	-	-	10	-
	MRE_RC15	-	-	-	15	-
Reference-earth with Roman cement and fibers	MRE_RC5_F	-	-	-	5	5
	MRE_RC10_F	-	-	-	10	5
	MRE_RC15_F	-	-	-	15	5

*Percentages by weight in relation to the reference-earth.

3 EXPERIMENTAL METHODOLOGY

The experimental analysis of the mortars in the fresh state consisted in the determination of the consistence by flow table (CEN EN 1015-3 1999) and the bulk density (CEN EN 1015-6 1998). In the hardened state, the following tests were conducted: linear and volumetric shrinkage (Alcock's test); capillary water absorption (RILEM TC 25-PEM 1980b) and drying (RILEM TC 25-PEM 1980a) which were carried out sequentially using the same six cubic specimens (dimensions 50×50×50 mm) for each mortar; the dynamic modulus of elasticity by the fundamental resonance frequency (CEN EN 14146 2004), the flexural and compressive strength (CEN EN 1015-11 1999) were also performed sequentially on the same six prismatic specimens (dimensions 40×40×160 mm) of each mortar. These test methods are discussed in detail in Gomes *et* al. (2012a).

Figure 2 to Figure 5 shows the capillary absorption test, dynamic modulus of elasticity test, the flexural strength and the compressive strength tests, respectively.

Figure 2. Capillary absorption test on the MRE_RC10 specimens.

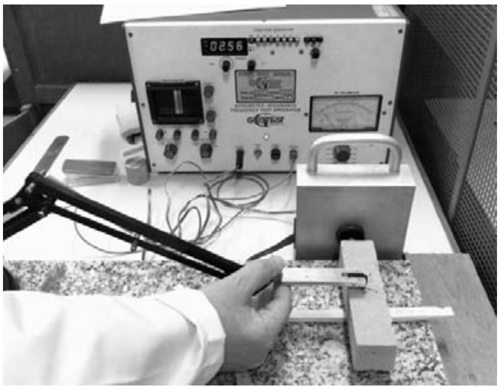

Figure 3. Dynamic modulus of elasticity test on the MRE_PC10 specimen.

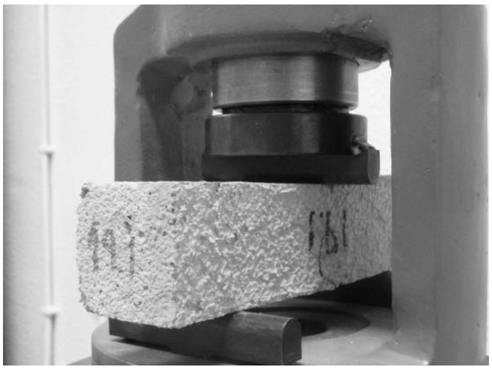

Figure 4. Flexural strength test on the MRE_AL15_F specimen.

Figure 5. Compressive strength test on the MRE_AL15_F specimen.

Note that several of the tests are not easily applicable to earth mortars due to the low mechanical strength and sensitivity to the action of water of earth materials. Therefore, numerous preliminary tests and the adaptation of existing testing protocols were often necessary.

3.1 *Preparation of the earth-based mortars*

In the mixing of the mortars, CEN EN 196-1 (2005) was followed as closely as possible. However, this standard is not specific either for repair mortars or for earth-based mortars, thus some adjustments had to be made.

A mechanical mixer was used, composed by a vat of stainless steel with a capacity of 3 l and a paddle mixer driven by an electric motor. It was necessary to increase the mixing time in relation to that specified in the standard because the mixtures have a large percentage of clay and, else, a good homogenization would be difficult to achieve.

The methodology was as follows: manual homogenization of the material; introduction of water into the vat, followed by introduction of the material; manual mixing for 2 minutes (to assure a uniform wetting of the mixture, otherwise, even in low speed, the mixture would splash); mixing at slow speed for 150 seconds; a 90 second halt (in the first 15 seconds, the adhering mortar was removed from the walls of the vat with a rubber spatula and added to the remainder mortar); finally, continued mixing at slow speed for an additional 60 second period.

3.2 *Curing conditions*

CEN EN 1015-11 (1999) specifies the curing conditions of various types of mortar (cement, lime) but not those of earth-based mortars. However, since there was no alternative, the method recommended for lime mortars was followed, albeit with some adjustments. The specimens were kept in the mould during 7 days, in a sealed polyethylene bag. After this period the bag was removed. The specimens remained in the mould for 7 additional days, in a conditioned room (20 ± 2 °C and 50 ± 5% RH). After this period the specimens were demoulded and remained in the same room until they reached the age of 90 days. When they reached the age of 28 days, the mortars with hydrated air-lime (AL) were placed for 7 days in a carbonation chamber (5% CO_2, 21 ± 2 °C and 71 ± 2% RH) to ensure complete carbonation.

4 RESULTS AND DISCUSSION

4.1 *Tests on fresh mortars*

The flow values were adjusted to the target 160-176 mm interval which, as previously shown (Gomes *et* al. 2012c), corresponds to earth-based mortars with excellent workability. Table 2 shows the flow values obtained for the earth-based mortars, which ranged from 159 to 180 mm. The bulk density of the fresh mortars and the water/dry material ratio are also reported in Table 2.

Table 2. Flow, bulk density and shrinkage of the earth-based mortars.

Designation	Water/dry material (%)	Flow (mm)	Bulk density (kg/m^3)	Shrinkage (%)	
				LS	VS
MRE	31	170	1872	1,15	4,06
MRE_F	34	170	1783	0,90	0,95
MRE_AL5	30	172	1873	1,59	7,83
MRE_AL10		172	1871	1,77	6,39
MRE_AL15		170	1854	1,36	6,21
MRE_AL5_F	33	165	1787	0,48	4,18
MRE_AL10_F		163	1776	0,23	6,03
MRE_AL15_F		163	1770	0,27	6,02
MRE_NHL5	29	171	1878	0,70	4,65
MRE_NHL10		172	1879	0,61	3,77
MRE_NHL15		172	1880	0,57	5,49
MRE_NHL5_F	32	169	1793	1,40	4,57
MRE_NHL10_F		166	1794	1,65	2,80
MRE_NHL15_F		166	1798	1,51	4,30
MRE_PC5	29	176	1893	0,86	2,52
MRE_PC10		176	1897	0,30	2,43
MRE_PC15		180	1902	0,37	3,19
MRE_PC5_F	33	169	1796	0,50	2,60
MRE_PC10_F		173	1798	0,22	1,84
MRE_PC15_F		173	1800	0,18	2,14
MRE_RC5	29	172	1889	1,37	4,88
MRE_RC10		173	1892	1,94	5,17
MRE_RC15		159	1876	1,72	4,07
MRE_RC5_F	32	168	1811	1,00	1,12
MRE_RC10_F		172	1807	1,21	2,01
MRE_RC15_F		163	1786	1,41	1,55

LS: Linear shrinkage; VS: volumetric Shrinkage

As seen in Table 2, the water/dry material ratio was systematically higher for the mortars with fibers. Thus, fibers appear to increase the amount of water needed to achieve good workability. This can be clearly observed for the MRE mortar which had a higher water/dry material ratio than the MRE_F mortar, while having equal flow. This is probably due to the fact that hemp fibers absorb part of the water used in the mixture. The variation of flow with binder content did not show a clear trend, which suggests that the slight differences in binder content do not significantly affect the workability of the mortars.

Fiber containing mortars have also lower density (Table 2) due to their higher water content and to the fact that hemp fibers exhibit very low density.

4.2 *Linear and volumetric shrinkage*

The results of the linear and volumetric shrinkage, summarized in Table 2, were quite variable. Interestingly, linear shrinkage does not appear to be representative of total shrinkage. Also, no clear relationship was observed between binder content and either linear or volumetric shrinkage. The use of fibers reduced the linear and volumetric shrinkage for all mortars, with the exception of the linear shrinkage of natural hydraulic lime mortars.

Figure 6 shows the total shrinkage of the MRE_PC15 material, following the Alcock´s test.

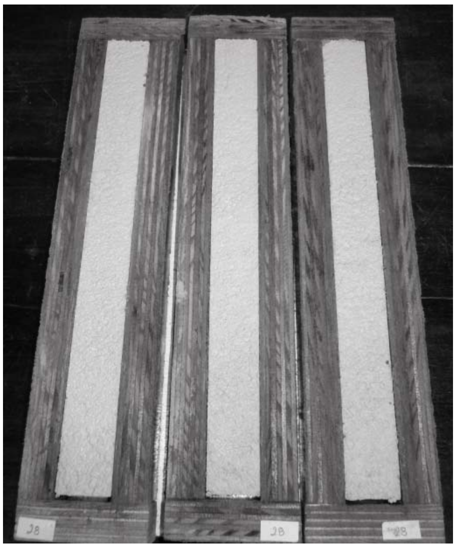

Figure 6. Alcock's test on the MRE_PC15 material.

The mortars of Portland cement and hydrated air-lime with fibers showed the lowest linear shrinkage, while Roman cement and Portland cement mortars with fibers showed the lowest volumetric shrinkage.

The linear shrinkage did not exceed 2% in any of the mortars. New Zealand Standard 4298 (1998) considers 3% as the limit for linear shrinkage of earth mortars, as obtained in the Alcock's test. Thus, it can be concluded that all tested mortars had acceptable shrinkage.

4.3 *Capillary water absorption*

Capillary water absorption curves express the amount of water absorbed per unit area (kg.m^{-2}) as a function of the square root of the elapsed time (s$^{1/2}$). The slope of the linear portion of these curves corresponds to the capillary absorption coefficient (CC), shown in Table 3.

It can be concluded that: (i) the water absorption coefficient increases with the percentage of binder; (ii) there is not a clear or significant influence of the fibers on the capillary absorption coefficient; (iii) the highest results of the water absorption coefficient were observed for the Portland cement binder, when compared to the mortars with the same content of other binders, both with and without fibers.

Table 3. Capillary absorption coefficient, drying index, dynamic modulus of elasticity, flexural and compressive strength of the tested mortars.

Designation	CC (kg/(m^2.s$^{1/2}$))	DI	E_{DM} (MPa)	FS (MPa)	CS (MPa)
MRE	0,138	0,122	1065	0,17	0,51
MRE_F	0,226	0,130	967	0,14	0,47
MRE_AL5	0,226	0,139	576	0,08	0,11
MRE_AL10	0,473	0,156	609	0,11	0,20
MRE_AL15	0,509	0,154	683	0,13	0,28
MRE_AL5_F	0,208	0,154	532	0,06	0,25
MRE_AL10_F	0,339	0,173	551	0,08	0,31
MRE_AL15_F	0,465	0,184	597	0,12	0,45
MRE_NHL5	0,102	0,121	1190	0,12	0,31
MRE_NHL10	0,120	0,128	821	0,09	0,26
MRE_NHL15	0,381	0,133	604	0,08	0,19
MRE_NHL5_F	0,050	0,131	1160	0,17	0,44
MRE_NHL10_F	0,114	0,151	954	0,15	0,36
MRE_NHL15_F	0,262	0,164	759	0,12	0,38
MRE_PC5	0,259	0,148	537	0,09	0,18
MRE_PC10	0,449	0,183	312	0,06	0,17
MRE_PC15	0,566	0,181	183	0,04	0,18
MRE_PC5_F	0,333	0,150	564	0,11	0,29
MRE_PC10_F	0,505	0,178	286	0,06	0,25
MRE_PC15_F	0,682	0,187	214	0,06	0,27
MRE_RC5	0,058	0,121	1129	0,20	0,39
MRE_RC10	0,147	0,130	1105	0,20	0,39
MRE_RC15	0,205	0,136	775	0,19	0,33
MRE_RC5_F	0,096	0,142	1239	0,20	0,48
MRE_RC10_F	0,238	0,150	1214	0,25	0,58
MRE_RC15_F	0,395	0,150	967	0,23	0,53

CC: capillary absorption coefficient; DI: drying index; E_{DM}: dynamic modulus of elasticity; FS: flexural strength; CS: compressive strength.

4.4 *Drying test*

The results of the drying test can be expressed by a single quantitative parameter, the Drying Index (Normal 29/88, 1991). The Drying Index (DI) values obtained for the tested mortars are listed in Table 3.

For the same type of binder and considering similar binder content, it can be conclude that drying was slower for the mortars with fibers (with the single exception of the MRE_PC10 mortar).

Generally, for the same binder content, drying was faster in the reference-earth mortars (MRE and MRE_F), natural hydraulic lime without fibers and Roman cement mortars without fibers. The slowest drying was observed for the Portland cement mortars, with or without fibers.

A general trend was found for drying to become slower as the binder content increased.

4.5 *Dynamic modulus of elasticity*

The test results for the dynamic modulus of elasticity are shown in Table 3.

The introduction of fibers did not appear to significantly affect in a clear way the modulus of elasticity. The highest modulus (lower deformability) was verified for the Roman cement mortars with fibers.

The dynamic modulus of elasticity decreases with the binder content for all mortars, with the exception of the hydrated air-lime mortar, whose values increased, for the mortars with and without fibers.

4.6 *Flexural and compressive strength*

The results for both the flexural and compressive strength tests are also given in Table 3.

For the same binder content, the introduction of fibers: (i) increased the flexural strength in all cases except for the hydrated air-lime and reference-earth mortars, where the values decreased; (ii) increased the compressive strength, except for the reference-earth mortars.

There was no clear relationship between binder content and flexural or compressive strength. The authors think that, because the binder content values are always small, they do not result in significant differences in terms of mechanical strength.

For the same binder content, the reference-earth mortars and Roman cement mortars presented the highest flexural and compressive strengths, with and without fibers.

4.7 *Biological growth*

In three out of the four groups of binders, fungi appeared in the mortars with hemp fibers. The hydrated air-lime mortars were the exception.

The highest amount of fungi appeared in the mortars with the lowest binder content, decreasing with increasing binder content.

Fungi appeared on the surface of the MRE_NHL5_F and MRE_RC5_F mortars (Figure 7) while the specimens were still in the respective moulds. For the following mortars, fungi appeared during the course of the tests: (i) in MRE_NHL15_F, MRE_PC10_F and MRE_RC15_F, biological growth had no great significance, as it was hardly noticeable; (ii) differently, MRE_NHL10, MRE_PC5_F and MRE_RC10_F showed a large amount of fungi.

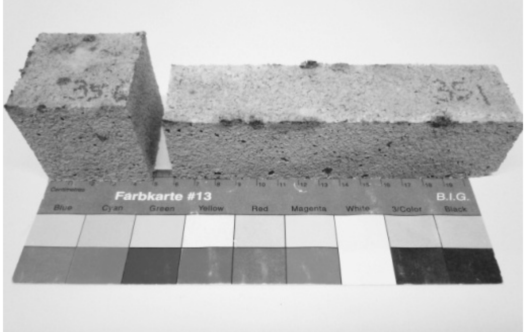

Figure 7. Fungus on the MRE_RC5_F specimens.

It is believed that such occurrences are linked to the presence of the hemp fibers. The fibers may enhance the biological growth, which is inhibited or hindered in some cases (in mortars with hydrated air-lime and mortars with the highest percentage of other binders), possibly due to pH changes. Traditionally, air-lime was used for health purposes, which is consistent with the fact that no fungi were found in the hydrated air-lime mortars.

5 WORK IN PROGRESS

To verify the compatibility, the applicability and effectiveness of the earth-based repair mortars on a rammed earth substrate, rammed earth blocks were manufactured.

The material used in these blocks was obtained from non deteriorated parts of walls of old rammed earth buildings in south Portugal (Alentejo region). Earth with three different compositions was collected, with each composition corresponding to a different building. The three earth materials were chosen to represent different grain size distributions and types of clay used in rammed earth walls, in the Alentejo. The characteristics of the collected material and the location of the respective buildings are described in Gomes *et* al. (2012b).

The rammed earth blocks had dimensions of 30×20×28 cm. Two types of anomalies commonly found in the exterior surfaces of rammed earth walls were recreated, in a typified manner, on the sides of the rammed earth blocks: (i) deep holes; (ii) superficial loss of material. The blocks are being kept at 20 ºC and 50% RH for two years. Their manufacturing procedure is described in Gomes & Faria (2011).

The earth-based mortars will be applied in both types of anomalies in order to verify their applicability and evaluate its behavior as repair mortars. These will then be subjected to artificial ageing tests.

6 CONCLUSIONS

Regarding the addition of fibers in the mortars, it was found that: (i) shrinkage, both linear and volumetric, decreases for all mortars with the exception of the linear shrinkage of natural hydraulic lime mortars; (ii) there is no clear influence on the capillary absorption coefficient; (iii) the drying index increases; (iv) there is no clear influence on the dynamic modulus of elasticity; (v) the flexural and compressive strength decrease in most cases (vi) biological growth appears recurrently associated to the hemp fibers, except in the case of the hydrated air-lime mortars which seem to hinder such development.

Regarding the binder type, it can be concluded that: (i) there is apparently no relationship between linear and volumetric shrinkage and binder content; (ii) the capillary water absorption coefficient increases with the percentage of binder; (iii) generally, drying becomes slower as binder content increases; (iv) the dynamic modulus of elasticity decreases with increasing binder content for all the mortars, except the hydrated air-lime mortars with and without fibers; (v) there is no clear relationship between the variation in binder content and the flexural and compressive strength.

The present work is part of an ongoing effort to assess the adequacy of earth-based mortars as repair mortars for rammed earth materials and further studies will define their most appropriate application conditions.

This work is an excerpt of the first author's PhD work. The mortars with the best results will, in a second phase of the work, be applied on rammed earth blocks manufactured for this purpose, and then subjected to artificial ageing tests.

7 ACKNOWLEDGEMENT

This work was carried out at the National Laboratory for Civil Engineering (LNEC), in Lisbon. M.I. Gomes was supported by a doctoral grant from the Portuguese Foundation for Science and Technology (FCT).

Authors are grateful to the people who collaborated in the experimental work, in particular, LNEC technicians José Costa, João Junior, Luis Nunes, and Bento Sabala. Thanks to Sorgila company for providing the reference earth and sand, to Lusical and Secil companies for providing hydrated air-lime powder, natural hydraulic lime and Portland cement and to Aubiose Company for the hemp fiber.

Thank also Georg Hilbert, Johannes Weber and Grzegorz Adamski who, within the scope of the ROCARE EU project, provided the roman cement used in this work.

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