Repair of Rammed Earth by Injection of Mud Grouts: a Case Study from Portugal

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ABSTRACT: The region of Alentejo, in southern Portugal, holds an important heritage built in rammed earth. However, little is known about this heritage, which is often found in a relative advanced level of decay. The presence of cracks is a common damage and is responsible for debilitating the structural performance of these constructions, putting in risk their existence and the life of thousand of people. However, the preservation and conservations of this rammed earth heritage requires adopting compatible intervention solutions. With this respect, the repair of cracks by means of the injection of mud grouts is a technique that has been showing great potential. Thus, this paper aims at contributing for the development of the knowledge on the rammed earth heritage from Alentejo and of the injection of mud grouts. With this purpose, an experimental program was carried out where the suitability of soils from Alentejo for unsubstabilised rammed earth was assessed, as well as the repair effectiveness of the injection of mud grouts.

Keywords: Rammed earth, mud grouts, adhesion

1 INTRODUCTION

Raw earth is used as building material since ancient times, as is confirmed by archaeological evidences of millenarian cities built entirely with earth, such as Jericho (Israel), Çatal Huyuk (Turkey), Harappa (Pakistan), Akhmet-Aton (Egypt), Chan-Chan (Peru), Babylonia (Iraq) and Duero (Spain) (Lacouture et al., 2007). Nowadays, a large housing stock built from earth is found widely distributed around the world (Houben & Guillaud, 2008). This heritage resulted from the intensive use of this material as low cost housing solution. Furthermore, some sites and buildings among this heritage feature an important historical, cultural and architectural value, which is important to preserve. The Great Wall of China is a great example of such important heritage, where many of its sections were built in rammed earth (Jaquin et al., 2008).

Building in rammed earth consists in compacting layers of moist earth inside a removable formwork to erect walls, which constitute part of dwellings or even fortresses. Because of this particular building process, carried out fully on site, these constructions are considered as monolithic structures.

Alentejo is a region located in southern Portugal, where rammed earth construction remarks an important presence in the built heritage. However, little is known about these constructions and a significant part of them presents a relative advanced level of decay or in the worst scenario, are completely abandoned. The presence of cracks is one of the most common types of structural damage found in these constructions, and is a consequence of several agents, namely foundation settlements, concentrated loads and horizontal thrusts. The strength and stiffness of the rammed earth walls is decreased by the presence of structural cracks, which debilitates the structural performance. This constitutes an even more serious problem, since the non-negligible seismic hazard of Alentejo menaces the existence of these constructions and the life of thousands of people. Moreover, the presence of cracks creates paths for further decay, such as by promoting rainfall infiltration.
The successful conservation of this type of heritage requires employing adequate intervention techniques, meaning that the repair materials must be compatible with the original ones. Having this in mind, the injection of mud grouts (incorporating earth in their constitution) is being studied as a technique to repair cracks in rammed earth walls (Silva et al., 2012), which aims at recovering part of their initial structural performance and preventing further decay.

This paper presents an experimental program featuring two different objectives. First, several soils collected from Alentejo were analysed by means expeditious and laboratory tests. These tests aimed at assessing the suitability of these soils for unstabilised rammed earth (URE) construction. This process ended with the selection of a soil, which was used to continue the experimental program. Second, the selected soil was used to manufacture URE beam-specimens tested under three-point bending. The aim of these tests was to assess the repair effectiveness of two unmodified mud grouts (without the addition of current binders, such as cement, lime or gypsum), using specimens of larger scale than those tested by Silva et al. (2012). The grouts used include an “artificial” mud grout composed by kaolin and limestone powder, and one “natural” mud grout composed by sieved soil and limestone powder.

2 SUITABILITY OF SOILS FROM ALENTEJO FOR URE

2.1 Methodology

The suitability of soil for URE is defined with basis on the assessment of its properties or/and on the performance of rammed earth specimens manufactured with such soil. In general, documents on earth construction (Houben & Guillaud, 2008; Standards Australia, 2002; LNEC, 1953; NZS, 1998; Doat et al., 1991) outline limit properties of the soil, such as those regarding the texture, consistency, binding force and compactness. Thus, if the soil properties fit within limit values, it is assumed that the respective rammed earth will present the required performance. However, the correlation existing between the soil properties and the performance of the respective rammed is not clear. This may result in misleading suitability assessments, whose reliability would require testing the performance of manufactured rammed earth specimens. In this case, the compressive strength and the water erosion resistance of rammed earth are frequently adopted as performance indicators (Ciancio et al. 2013). Then, the suitability of the soil is defined by comparing the performance of the specimens with that required by the project or by regulating documents (Standards Australia, 2002; NZS, 1998; NMAC, 2006).

The suitability for URE of four soils from Alentejo (here termed as S1, S2, S3 and S4) was assessed by taking into account the aforementioned methodology. The natural soils S1, S2 and S3 were collected from Serpa, Odemira and S. Luis, respectively. Soil S1 was used in the construction of a rammed earth wall for a commercial exhibition; soil S2 was going to be used in the construction of a new rammed earth house; and soil S3 was used to build two houses (in stabilised rammed earth) from a rural tourism place. Soil S4 is a soil with corrected particle size distribution (PSD) by addition of coarse aggregates, and was used in the construction of a new rammed earth house in Odemira.

2.2 Soil assessment

The soils were first analysed by means of expeditious tests, which included the sedimentation test, ribbon test (Standards Australia, 2002) and dry strength test (Houben & Guillaud, 2008). Then, the soils were analysed by means of geotechnical tests, namely PSD analysis (LNEC, 1966) and Proctor test (LNEC, 1967).

The results of the sedimentation test are presented in Figure 1. Soils S2 and S3 are those presenting the highest percentages of clay plus silt. According to Houben & Guillaud (2008) the clay plus silt percentage is recommended to be between 21% and 37%, whereby the percentages of soil S2 and S3 are considered to be excessive. Soil S1 complies with this requirement, while the clay plus silt percentage of soil S4 is slightly below the minimum value.

![Figure 2. Results from the sedimentation test.](image_url)

The ribbon test also allows assessing qualitatively the proportions between the different size-fractions composing the soil. The ribbon length of each soil is

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given in Table 1, where all soils seem to be adequate for rammed earth construction. Moreover, the soil S1 and S3 seem to be those presenting higher clay content due to their higher ribbon length.

The dry strength test was carried out on dry soil pats (fraction below 0.425 mm) with 4 cm diameter and 1 cm thickness. The test was carried out by breaking the specimens and crushing them between the thumb and forefinger, and the results were interpreted according to Houben & Guillaud (2008). Soils S2 and S3 have moderate dry strength, while soils S1 and S4 have high dry strength.

Table 1. Results of the ribbon tests.

<table>
<thead>
<tr>
<th>Soil</th>
<th>Length (mm)</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>55</td>
<td>Suitable for URE</td>
</tr>
<tr>
<td>S2</td>
<td>41</td>
<td>Suitable for URE</td>
</tr>
<tr>
<td>S3</td>
<td>65</td>
<td>Suitable for URE</td>
</tr>
<tr>
<td>S4</td>
<td>37</td>
<td>Probably suitable for rammed earth</td>
</tr>
</tbody>
</table>

The PSD of the soils was obtained by means of sieving and sedimentation analyses. The PSD curves of the soils were then compared with the recommended envelope defined by Houben & Guillaud (2008), as depicted in Figure 2. Soils S1, S2 and S4 have very similar PSD curves and follow the lower limit of the envelope, within or slightly below it. On the other hand, the PSD curve of soil S3 is within or slightly above the envelope. Soils S2 and S3 are those presenting higher percentages of clay content, which goes against the results obtained for the dry strength, but agrees with the results from the sedimentation test, from a comparative perspective. This unexpected result can be explained by the type of clay minerals composing the clay fraction of each soil and by its respective submicron PSD. By comparison with the results from the sedimentation test, it is shown that this expeditious test fails in giving the exact proportion between the size fractions composing each soil. However, it constitutes a simple and fast method to compare qualitatively the fine fraction percentage among the soils.

The results of the Proctor test (standard) are summarised in Table 2 in terms of maximum dry density (ρ_{max}) and optimum water contents (OWC). In addition, the water content obtained from the drop test (DTWC) is also presented. The drop test (NZS, 1998) is used on site to determine if the soil presents adequate moisture in order to be compacted. This test is shown to provide a good estimation of the OWC. Soils S1, S2 and S4 are those presenting higher maximum dry densities, with similar values among them. On the other hand, soil S3 presents a substantially lower value for this parameter.

According to Doat et al. (1991), soils S1, S2 and S3 are expected to result in earthen materials with very satisfactory performance (1.76 g/cm³ < ρ_{max} < 2.10 g/cm³), while soil S4 is expected to result in a material with excellent performance (2.10 g/cm³ < ρ_{max} < 2.20 g/cm³). The lowest OWC of soil S4 means that it is less prone to suffer from shrinkage problems. Another important observation is with respect to DTWC, which is very similar to the OWC of each soil, and whose difference varies between 0.3% and 1.2%. Therefore, the drop test seems to be an adequate method to obtain compaction water content similar to OWC, at least for these four soils.

![PSD curves of the soils compared against the envelope recommended by Houben & Guillaud (2008).](image)

Figure 2. PSD curves of the soils compared against the envelope recommended by Houben & Guillaud (2008).

Table 2. Compaction properties of the four soils.

<table>
<thead>
<tr>
<th>Soil</th>
<th>ρ_{max} (g/cm³)</th>
<th>OWC (%)</th>
<th>DTWC (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>2.06</td>
<td>10.6</td>
<td>11.7</td>
</tr>
<tr>
<td>S2</td>
<td>2.07</td>
<td>9.8</td>
<td>9.5</td>
</tr>
<tr>
<td>S3</td>
<td>1.84</td>
<td>16.4</td>
<td>17.7</td>
</tr>
<tr>
<td>S4</td>
<td>2.12</td>
<td>8.7</td>
<td>7.5</td>
</tr>
</tbody>
</table>

### 2.3 URE performance assessment

The performance of the URE manufactured with the soils was assessed by means of compression test and the Geelong test (NZS, 1998).

With respect to the compression tests, it was also aimed at assessing the influence of the compaction conditions on the compression behaviour of the rammed earth manufactured with the soils. A set of six specimens per soil were prepared, representing each a point of the respective compaction curve (standard Proctor), in terms of dry density and water content. The specimens consisted of three-layered cylinders with dimensions of 100 mm diameter and 200 mm height, compacted in a metallic mould by means of an electrical hammer. The specimens were demoulded immediately after compaction. The tests were carried out after the specimens achieving the equilibrium water content at 20°C of temperature and 57.5% of relative humidity (drying period between 27 and 35 days). The vertical deformations
at the middle third of each specimen were measured by means of three LVDT’s radially-disposed. The tests were carried out under displacement control at a rate of 3 µm/s. The specimens were rectified with gypsum capping in the day before testing. Figure 3 presents the stress-strain curves of the specimens manufactured with soil S1, as an example (see Silva (2013) for the remaining soils). In general, the different compaction conditions resulted in substantial differences in terms of compressive strength and deformability. The difference between the minimum and maximum values of the compressive strength obtained among the specimens of each soil varied between 19% and 59%.

Figure 3. Stress-strain curves of the specimens manufactured with soil S1 (the compaction water content increases from CURIESI_1 to CURIESI_6).

Regarding the maximum compressive strength, soil S4 presents the highest value (1.02 N/mm²), which seems to result from its higher maximum dry density. In opposition, soil S3 presents the lowest maximum compressive strength (0.43 N/mm²), despite its higher clay content. Nevertheless, none of the soils deems with the minimum requirements of documents regulating rammed earth construction (eg: NZS, 1998; Standards Australia, 2002). For example, the less demanding standard NZS 4298 (NZS, 1998) requires a minimum compressive strength of about 1.14 N/mm². This fact deems the soils as unsuitable for URE.

The Geelong test was carried out on cubic specimens (one per soil), with dimensions 150x150x150 mm³, compacted in three layers with the maximum dry density and OWC obtained from the Proctor test. The specimens dried in a room with controlled temperature (20°C) and relative humidity (57.5%) and were tested with 21 days of age. The pitting depth and depth of moisture penetration were measured in each test and are presented in Table 3, as well as the respective erodibility index according to NZS (1998). The moisture penetration depth of all soils is less than 120 mm, as is required by the standard. All soils have similar results in terms of pitting depth, but soil S4 is that presenting the lowest value, while soil S3 presents the highest. The use of these soils in unplastered URE walls is limited to situations/locals that require erodibility indexes equal or higher than 3. According to Standards Australia (2002), this erodibility index allows the use of these soils in protected URE walls. This is the case of the dwellings typically found in Alentejo, where the walls are protected by a plaster of lime/earth mortar.

Table 3. Results of the Geelong test.

<table>
<thead>
<tr>
<th>Soil</th>
<th>Pit. depth (mm)</th>
<th>Erod. index</th>
<th>Penetr. Depth (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>6</td>
<td>3</td>
<td>15</td>
</tr>
<tr>
<td>S2</td>
<td>6</td>
<td>3</td>
<td>28</td>
</tr>
<tr>
<td>S3</td>
<td>8</td>
<td>3</td>
<td>30</td>
</tr>
<tr>
<td>S4</td>
<td>5</td>
<td>3</td>
<td>16</td>
</tr>
</tbody>
</table>

3 EFFECTIVENESS OF THE REPAIR BY INJECTION OF MUD GROUTS

3.1 Methodology

The adhesion capacity unmodified mud grouts in the repair of URE was assessed by means of tests carried out on medium-scale specimens. These specimens consisted of beams tested under three-point bending. The specimens were first tested and then were repaired resorting to two unmodified mud grouts, namely an “artificial” mud grout composed by kaolin and limestone powder and one “natural” mud grout composed by sieved soil and limestone powder. The adhesion capacity was then assessed by testing again the repaired specimens. The injectability of the tested mud grouts was also assessed during the repair works.

3.2 Selected soil

The original soil (S5) used to compose soil S4 was selected to manufacture the specimens. However, its PSD analysis revealed that its clay content was too high, deeming it as unsuitable for URE (see Figure 4). Therefore it was decided to correct the PSD of the soil in order to adjust the PSD curve to a Fuller curve with maximum diameter (D) of 19.1 mm and parameter n equal to 0.25, as recommended by Houben & Guillaud (2008). The PSD correction was carried out by means of the addition of river sand and gravel. The resulting soil S6 is composed by 50% of soil S5, 28% of river sand and 22% of gravel (in wt.). The behaviour in compression of the URE manufactured with soil S6 was assessed by means of compression test carried on six specimens compacted with \( P_{\text{max}} \) (2.10 g/cm³)
and OWC (10.1%). The preparation of the specimens and testing was similar to those presented in Section 2.3. The average compressive strength was of about 1.26 N/mm², which respects the requirements of NZS 4298 (NZS, 1998).

![PSD correction of soil S5.](image)

### 3.3 Preparation of the specimens

The beam-specimens presented as dimensions 150x150x600 mm³, and were manufactured by compacting three layers of similar thickness, within a metallic mould. The compaction water content of the soil was controlled by means of the drop test and all the specimens were demoulded immediately after compaction. A total of twelve specimens were prepared.

### 3.4 Testing and repair procedures

The specimens were first tested under three-point bending after drying for 6 weeks under a room temperature of about 22±2°C. The load was applied at middle span and the distance between supports was of about 500 mm (Figure 5a). The application of the load was carried out under monotonic displacement control at a rate of 1 μm/s. The testing procedure of the specimens after injection was similar, but the tests were carried out 3 weeks after the repair.

![Testing (a) and repair (b) of the beam-specimens.](image)

### Table 4. Composition of the mud grouts.

<table>
<thead>
<tr>
<th>Mud Grout</th>
<th>Mibal-A (wt.%)</th>
<th>$#80$ (wt.%)</th>
<th>200-OU (wt.%)</th>
<th>HMP (wt.%)</th>
<th>W/S</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>20</td>
<td>-</td>
<td>80</td>
<td>0.40</td>
<td>0.30</td>
</tr>
<tr>
<td>B</td>
<td>60</td>
<td>40</td>
<td>60</td>
<td>0.46</td>
<td>0.30</td>
</tr>
</tbody>
</table>

### Table 5. Properties of the mud grouts.

<table>
<thead>
<tr>
<th>Mud Grout</th>
<th>Flow time (s)</th>
<th>$f_i$ (N/mm²)</th>
<th>$f_c$ (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>85.9</td>
<td>0.62</td>
<td>1.48</td>
</tr>
<tr>
<td>B</td>
<td>36.5</td>
<td>0.92</td>
<td>2.44</td>
</tr>
</tbody>
</table>

![PSD curves of the materials composing the grouts.](image)

### 3.5 Results and discussion

Regarding the injectability of the mud grouts, none of the grouts showed difficulty in penetrating through the two types of cracks. Table 6 summarizes the results of the three-point bending tests in terms of average initial flexural strength ($f_i$), flexural strength after grout injection ($f_c$), and the recovery...
rate $f_{bg}/f_{bi}$. Grout A showed poor recovery rate for both tested gap widths, where for $d_{w}= 2$ mm the average recovery rate was of about 26%, while that for $d_{w}= 8$ mm was of about 17%. Grout B, on the other hand, showed very satisfactory adhesion capacity by presenting an average recovery rate of about 55% for $d_{w}= 2$ mm and of about 74% for $d_{w}= 8$ mm. Even though grout B is stronger than grout A, this fact does not justify the unsatisfactory results obtained for grout A. Probably this difference is explained by differences in their clay fraction, where that of grout B is similar to that of the beam-specimens, since it is composed by the respective soil. Therefore, this result seems to encourage using the same soil used in the construction to compose a mud grout in a repair intervention.

Table 4. Results of the three-point bending tests.

<table>
<thead>
<tr>
<th>Grout</th>
<th>$d_{w}$ (mm)</th>
<th>$f_{bg}$ (N/mm$^2$)</th>
<th>$f_{bi}$ (N/mm$^2$)</th>
<th>$f_{bg}/f_{bi}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2</td>
<td>0.22</td>
<td>0.06</td>
<td>26</td>
</tr>
<tr>
<td>A</td>
<td>8</td>
<td>0.21</td>
<td>0.04</td>
<td>17</td>
</tr>
<tr>
<td>B</td>
<td>2</td>
<td>0.20</td>
<td>0.11</td>
<td>55</td>
</tr>
<tr>
<td>B</td>
<td>8</td>
<td>0.26</td>
<td>0.20</td>
<td>74</td>
</tr>
</tbody>
</table>

4 CONCLUSIONS

In general, the properties of the soils from Alentejo tested showed them to be suitable for URE. However, the performance of the respective URE revealed that these soils are unsuitable, especially with respect to the required compressive strength. This situation emphasizes that the suitability assessment of a soil only based on its properties might be unreliable and that testing the performance of the rammed earth should be always required. On the other hand, this does not mean that the URE constructions from Alentejo are unsafe for normal loading conditions. Bui et al. (2009) highlight that a traditional rammed earth wall (about 50 cm thick) bears stresses between 0.1 N/mm$^2$ and 0.3 N/mm$^2$. In practical terms, this means that an URE dwelling built with any of the soils tested would not collapse under normal conditions (e.g. in the absence of moisture problems and important seismic events).

Regarding the effectiveness of the repair of URE by means of grout injection, the results obtained seem to show that the same soil used in the construction should be incorporated in the mud. The effectiveness of the "natural" mud grout was much superior to that of the "artificial" grout. Furthermore, the incorporation of the original soil is expected to promote compatibility between the grout and the original URE.

ACKNOWLEDGEMENTS

The authors wish to express their gratitude to Catarina Martins and Júlio Machado for their support in the experimental work. The financial support provided by the Portuguese Science and Technology Foundation through the project FCOMP-01-0124-FEDER-028864 (FCT-PTDC/ECM-EST/2396/2012) is also gratefully acknowledged.

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