International RILEM Conference on Materials, Systems and Structures in Civil Engineering
Conference segment on Historical Masonry
22-24 August 2016, Technical University of Denmark, Lyngby, Denmark

ASSESSMENT OF THE INJECTION OF GROUTS TO REPAIR CRACKS IN RAMMED EARTH

Rui A. Silva (1), Oriol Domínguez Martínez (2), Daniel V. Oliveira (1), Eduardo Pereira (1), Edgar Soares (1)

(1) ISISE – University of Minho, Guimarães, Portugal
(2) The Getty Conservation Institute, Los Angeles, United States of America

Abstract

Rammed earth constructions are known for their high seismic vulnerability, which menaces their preservation and puts in risk the life of millions of people living in regions with important seismic hazard. The poor conservation condition of many of these constructions largely contributes for the aforementioned situation. The presence of cracks is one common type of damage occurring in the walls, which debilitates their structural behaviour both for in-plane and out-of-plane loading. The injection of grouts has been studied recently as a solution to repair this type of damage. However, the repair effectiveness of this technique needs further research. This paper presents an experimental program, where the effectiveness of the injection of a mud and a commercial grout base on hydraulic lime for repairing cracks in rammed earth is compared. Diagonal compression test were carried out on wallets before and after repair, where the response was monitored with Digital Image Correlation (DIC). Furthermore, sonic tests were used as a technique to assess the repair efficiency by non-destructive means. In general, both types of grouts presented similar performance.

1. Introduction

Even nowadays, building with raw earth is a popular solution to build shelter in developing countries. On the other hand, earth construction represents an almost negligible percentage of the new construction in developed countries. Despite that, an important earth built stock exists spread around the World [1], where it was estimated that in 1983 one third of the World's population was living in [2]. Among this built stock, exists several buildings and sites with important heritage value, such as Chan-Chan (Peru), the Great Wall of China (China), the Alhambra (Spain), the old town of Ghadames (Libya), the Ksar of Ait-Ben-Haddou (Morocco) and the Old Walled City of Shibam (Yemen), classified as World Heritage [3].

The concept of earth construction involves several techniques, since it is also related with the concept of vernacular architecture [4], where the local construction of the populations is shaped according to local factors. These factors include available building materials, local weather, as well as cultural, social and economic aspects of the population. Among the earth construction techniques, rammed earth constitutes one of the most popular, along with adobe masonry [5]. Building in rammed earth consists in compacting moist earth by layers inside a removable formwork to build monolithic walls. The use of a formwork and the ramming process constitute key features that differentiate this technique from other earth construction techniques. The construction process is carried out by courses (like masonry), where the formwork runs horizontally along the perimeter of the construction and then is lifted to build the next course [6].

Rammed earth constructions, like other earth construction techniques, are known for presenting high seismic vulnerability. This is a consequence of several factors, namely the low mechanical properties (especially the very low tensile strength), high dead-weight and poor connection between elements [7]. Taking into attention the fact that most of the earth constructions are built on regions with important seismic hazard, it becomes evident the urgent need in promoting the seismic retrofitting of the existing rammed earth built heritage.

In Southern Portugal, namely in Alentejo and Algarve, exists a significant rammed earth built stock, where are included military and civil constructions [8]. The first ones are mainly constituted by, still existing, millenary fortifications built during the Islamic presence in the Iberian Peninsula between the 8th and 13th centuries, such as Paderne's Castle [9]. The second ones are mainly constituted by dwellings built before the nineteen fifties, where a significant part of the population still lives in. However, Alentejo and Algarve are regions that present unneglectable seismic hazard, which combined with the seismic vulnerability of these constructions, puts in risks the preservation of this heritage and the life of their inhabitants. Furthermore, many of the rammed earth constructions in the region are found in poor conservation condition, which contributes for increasing the seismic vulnerability of these constructions [10]. The presence of cracks is among the most common types of damage often found in rammed earth walls, which has particular influence on the global structural performance. Cracks constitute preferential paths for rainfall infiltration, which are responsible for moistening directly the rammed earth, which reduces substantially its mechanical properties [11]. Structural cracks in rammed earth walls decrease their bearing capacity and stiffness, and disrupts the overall monolithic behaviour of the structure.

The adequate repair of rammed earth walls is required to re-establish the original structural behaviour of the whole structure, which needs to be complemented further with strengthening measures to improve the seismic safety. Cracks can be repaired using different techniques, but whose efficiency greatly varies from case to case [12]. For instance, the most basic solution consists in simply filling the crack with earth mortar, but the limited space and consistency of the mortar are major limitations to guarantee complete filling. Furthermore, earth mortars tend to crack due to exaggerated drying shrinkage, which limits the establishment of the bond disrupted by the filled crack.

The injection of grouts has been recently studied for repairing cracks [13], where the grout consists of a sufficiently fluid mortar capable of filling completely the crack. One of the premises of the research carried out by Silva [13] consists in the development of compatible grouts, which included earth in their composition and therefore are called mud grouts. The development and use of these grouts has been based on recommendations of a technical committee designated by the Getty Conservation Institute on earth construction [14]. Diagonal compression tests carried out on rammed earth wallets repaired with the developed mud grouts have shown that the injection repair promoted satisfactory shear strength recovery of the specimens, but was ineffective in recovering the initial shear stiffness.

On the other hand, the preparation of a mud grout is not an easy task, since it requires sieving the fine particles of the soil, which make the whole process very expensive. Despite being assumed that the compatibility of hydraulic lime based grouts is inferior to that of mud grouts, the first grouts are easily found in the market with affordable cost. Taking this into account, this paper aims at comparing the effectiveness of a mud grout with that of a commercial hydraulic lime based grout for repairing cracks in rammed earth. An experimental program was prepared with this respect, where rammed earth wallets were tested under diagonal compression, and then retested after injection repair. The tests took advantage of the digital image correlation (DIC) technique, which constitutes a valid procedure to the derivation of the full field surface displacements and strains of objects under load. The technique is based on the comparison of two digital images of the object, before and after deformation [15]. In addition, the experimental program also aimed at evaluating the used of sonic tests for assessing the effectiveness of the injection repair by non-destructive means.

2. Experimental program

The repair effectiveness of the injection repair of cracks in rammed earth walls was assessed by means of diagonal compression tests carried out on wallets representative of unstabilised rammed earth from Alentejo. First, the wallets were built in laboratory and were tested after drying. After testing, they were repaired with grout injection and retested. Sonic tests were also used before the first and second tests in order to evaluate the capacity of this method for assessing the repair effectiveness by non-destructive means.

2.1 Rammed earth specimens

Six wallets were built using soil collected from Amoreiras-Gare (Alentejo, Portugal), whose particle size distribution was corrected in advance, in the proportions 50% of soil, 28% of river sand and 22% of gravel. The corrected soil presented percentages of clay, silt, sand and gravel of about 14%, 16%, 32% and 37%, respectively. The wallets presented as dimensions 550x550x200 mm^3 and were compacted in nine layers with similar thickness. The density of the layers was controlled taking into account the maximum density obtained from the standard Proctor test, while the water content for compaction was controlled by means of the drop ball test [16]. In addition, six cylindrical specimens were also compacted with 100 mm diameter and 200 mm height. These cylinders were used to evaluate the compressive strength and Young's modulus of the rammed earth, whose average values were of about 1.5 N/mm^2 and 536 N/mm^2, respectively. Further information on the construction of the specimens is detailed elsewhere [17].

2.2 Testing procedure

The diagonal compression tests of the wallets were carried out according to the procedure of ASTM E 519 [18]. The test setup is depicted in Figure 1, where is illustrated that the deformations of the specimens were measured by means of LVDTs attached to the middle third of each diagonal in one of the faces. The other face was used for DIC photographs, and was painted white for then creating a random black spot pattern to facilitate the DIC analysis. The shoes used to support the wallets and applying the load were made of steel, with a width of about 100 mm. The contact with the specimens was rectified by means of neoprene rubbers introduced between specimens and shoes. The load was applied under monotonic displacement control at rate of 2 μm/s. This procedure was used in first and second tests of each wallet, where the second test was carried out about 28 days after the repair.

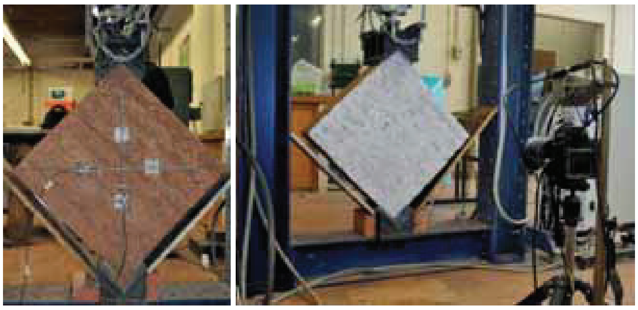

(a) (b)

Figure 1. Setup of the diagonal compression tests: (a) face with deformations measured with LVDTs; (b) face used for DIC analysis.

2.3 Repair procedure

The failure of the wallets resulted in the division of the specimens in some parts, which were removed from the testing apparatus and remounted together. The cracks were sealed using an earth mortar prepared with soil used to build the walls, sieved to remove the particles larger than 4.75 mm (see Figure 2a). Simultaneously, injection tubes with 6 mm diameter and made of flexible plastic were installed in one of the sides of the specimens. The tubes were positioned in such way that they would penetrate about 4 cm in the wallets, and that the maximum space between injection tubes would be of about 10 cm. The injection was carried out after letting the sealing mortar harden completely. With this respect, a syringe with 100 ml capacity was used to inject water in all injection tubes, 1 hour before injecting the grouts. This procedure aimed at mitigating the water sorption of the grouts, promoted by the rammed earth. The injection started from the bottom tubes up to the top ones, using the same syringe aforementioned (see Figure 2b). The injection of each tube stopped when the grout leaked from the next tube. Then, the injection tube was sealed and the injection was continued from the leaking tube, and so on.

As referred previously, two grouts were used to repair three wallets each, namely grout NMG40-60 and FB 790. NMG40-60 constitutes a mud grout composed by the same soil used to build the rammed earth wallets (S#80). The soil was wet sieved to remove the particles larger than 0.180 mm, which was defined as the maximum particle size of the mud grout. Limestone powder (200-OU) was also included in the composition as filler material, aiming at leaning the clay content of the sieved soil. The clay content of the mud grout is estimated to be of about 21%. Sodium hexametaphosphate (HMP) was also used with the objective of providing adequate fluidity to the grout, while keeping the water/solids ratio (W/S) low. FB 790 is a commercial grout based on hydraulic lime and is provided by Fassa Bortolo. This grout is specially indicated, by the manufacturer, for consolidation of historical masonry. The composition of the grouts is summarized in Table 1, where it should be noted that tap water was used for both cases.


(a) (b)

Figure 2. Repair of the wallets: (a) sealing of the cracks and installation of the injection tubes; (b) injection of the mud grout.

Table 1: Composition of the grouts.

Grout	S#80 (wt.%)	200-OU (wt.%)	HMP (wt.%)	FB 790 (wt.%)	W/S
NMG40-60	40	60	0.46	-	0.30
FB 790	-	-	-	100	0.33

Table 2 presents the properties of the grouts in terms of flow time of 1 dm^3 (according to ASTM C 939 [19]), average flexural strength (f_b) and average compressive strength (f_c) (according to EN 1015-11 [20]). The low W/S ratios of both grouts are similar and resulted in very similar flow time values. This seems to mean that a mud grout can achieve similar fluidity to that of a commercial one, while keeping similar W/S ratios. With respect to the strength values, the mud grout is 60% weaker than FB 790. This difference can be even higher at long-term with the hardening of the binder, since FB 790 was tested with 28 days of age. Despite of the Young's modulus of the grout FB 790 not being measured, such high values of strength, with respect to the rammed earth, indicate that the mechanical compatibility between both materials might be compromised.

Table 2: Properties of the grouts.

Grout	Flow time (s)	f_b (N/mm^2)	f_c (N/mm^2)
NMG40-60	42.3	1.4	2.1
FB 790	43.9	3.4	5.3

2.4 Sonic tests

Sonic tests were used to evaluate the effectiveness of the repair procedure of the tested rammed earth wallets, by measuring the homogeneity of the material before and after the injection of the grout. Sonic tests are Non Destructive Tests (NDT) that consist in transmitting stress waves within the frequency range of acoustic waves (20 Hz to 20 kHz), generated by an instrumented hammer, and in measuring their travel time through a section of the material by means of accelerometers. The set of instruments used to measure and analyse the signal consists of an instrumented hammer for the initial pulse; a piezoelectric accelerometer that measures the generated signal; an acquisition unit from National Instruments; and a computer with the software for acquisition, visualization and analysis of the results (Figure 3a). Direct tests were performed along the length of the wallets, from edge to edge, in 3 points of measurement with a distance of 55 cm. Indirect tests were performed in both sides using a grid of 3 by 3 points with a distance between points of measurement of about 35 cm (Figure 3b). The total number of points was 15 for each panel, with 15 measurements per point. From each point, the 6 most representative signals were evaluated, and only those with a coefficient of variation lower than 20% were considered for the analysis of the results.

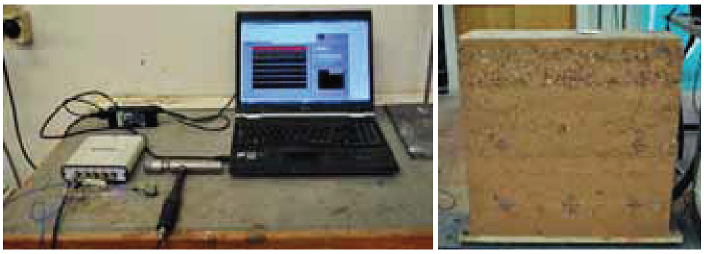

(a) (b)

Figure 3. Sonic tests: (a) testing apparatus; (b) grid of points used for indirect sonic tests.

3. Results and discussion

The results of the diagonal compression tests and sonic tests performed on the rammed earth wallets before and after repair are here presented and discussed.

3.1 Diagonal compression tests

Table 3 and Table 4 summarize the results of the diagonal compression tests carried out on the wallets repaired with grout NMG40-60 and FB 790, respectively. These tables include the dry density of the wallets (ρ_d), shear strength (f_{si}) and shear modulus (G_{0i}) before injection, shear strength (f_{sg}) and shear modulus (G_{0g}) after injection. The shear moduli were computed between 5% and 30% of the shear strength of the respective specimen. Figure 4 presents the shear stress – shear strain curves of the specimens before and after repair. In general terms, the curves of the first test are characterized by an early peak shear stress, which is followed by a marked stiffness loss. This early peak shear stress is thought to be related with the loss of cohesion (i.e. to the binding capacity) promoted by the clay fraction, as reported previously by Silva [13]. The shear behaviour of the wallets up to this peak seems to result from the contribution of the clay fraction to cohesion, and friction and interlocking capacity of the gravel-size (or larger) aggregates. Hereafter, the behaviour relies only on the friction and interlocking. The wallets also presented a large shear deformation capacity, which seems to be a feature that is expected to contribute to energy dissipation during a seismic event.

Table 3: Results of the diagonal compression tests carried on the specimens repaired with grout NMG40-60.

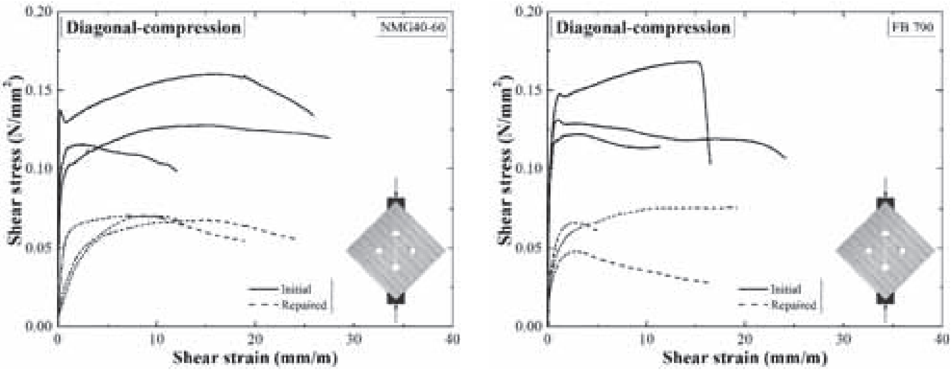
Specimen	ρ_d **(g/cm^3)**	f_{si} **(N/mm^2)**	f_{sg} **(N/mm^2)**	G_{0i} **(N/mm^2)**	G_{0g} **(N/mm^2)**
IIWURE_1	2.05	0.12	0.05	1056	14
IIWURE_3	2.04	0.17	0.08	632	20
IIWURE_4	2.04	0.13	0.07	1068	8
Average (CoV)	2.04 (1%)	0.14 (14%)	0.06 (18%)	919 (22%)	14 (36%)

Table 4: Results of the diagonal compression tests carried on the specimens repaired with grout FB 790.

Specimen	ρ_d **(g/cm^3)**	f_{si} **(N/mm^2)**	f_{sg} **(N/mm^2)**	G_{0i} **(N/mm^2)**	G_{0g} **(N/mm^2)**
IIWURE_2	2.04	0.16	0.07	1356	99
IIWURE_5	2.05	0.13	0.07	460	22
IIWURE_6	2.05	0.12	0.07	-	33
Average (CoV)	2.05 (1%)	0.14 (14%)	0.07 (2%)	908 (-)	51 (66%)

The wallets injected with the grout NMG40-60 showed shear strength values in the range of 0.05 and 0.08 N/mm^2 with an average value of 0.06 N/mm^2, while the wallets injected with FB 790 showed values of about 0.07 N/mm^2. In average, it was possible to recover about 44% and 51% of the initial shear bearing capacity for grout NMG40-60 and FB790, respectively. Both rates of repair effectiveness are similar, which seems to show that a commercial grout may have similar performance to that of a mud grout. It should be noted that, similar values of repair effectiveness were reported by Silva [13]. Furthermore, it was again observed the incapability of the grout injection in recovering the initial shear stiffness, confirming the inefficiency of this technique in recovering the friction and interlocking effect of the coarse particles, even that a stiffer grout (FB 790) is used. In fact, grout FB 970 presented higher shear stiffness recovery (about 3 times) than that of grout NMG40-60. Still, the values of the shear stiffness after repair are marginal when compared with the initial shear stiffness.

Figure 5 presents the maximum principal strains obtained from DIC analysis for wallets IIWURE_4 (grout NMG40-60) and IIWURE_2 (grout FB 790) in the first and second tests. These images were obtained, for each test, in a near collapse stage of the wallets. Despite the DIC analysis being resumed to this stage, it allowed to follow the development of the strain field of the specimens during the tests. In general, the failure of the wallets in the first test is characterized by the formation of a main crack or set of cracks with diagonal orientation that cross the entire specimen. The formation of these cracks occurs suddenly at the middle of specimens just before the peak load, and then progresses towards the supports. Cracks at the interfaces between layers are also formed, where the interfaces of IIWURE_4 seem to be weaker than those of IIWURE_2. With respect to the second test, the development of the diagonal crack was progressive since the beginning of the test. For all repaired wallets, the development of the main crack seems to occur in some regions coincident with the original crack. This situation occurs do to the fact that the rammed earth is damaged in the region adjacent to the crack and not because any of the grouts present little adhesion capacity. In fact, the inspection of the wallets after testing as shown a good adhesion of both grouts, since failure occurred mostly by the rammed earth.



(a) (b)

Figure 4. Shear stress-strain curves of the wallets in the first and second tests: (a) grout NMG40-60; (b) grout FB 790.

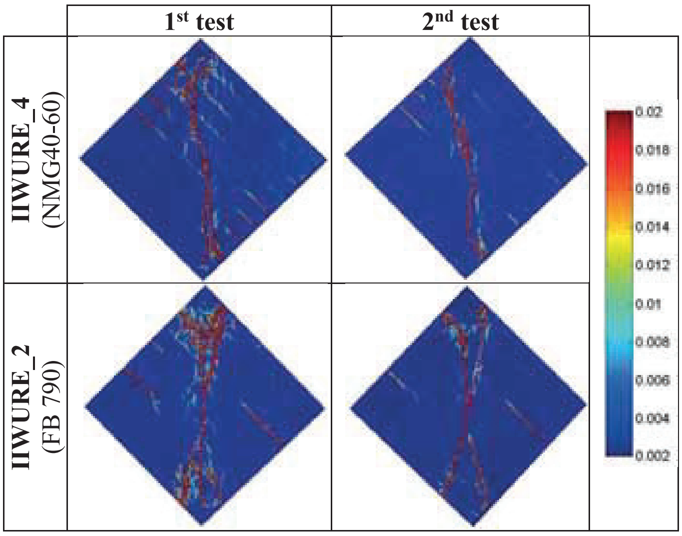
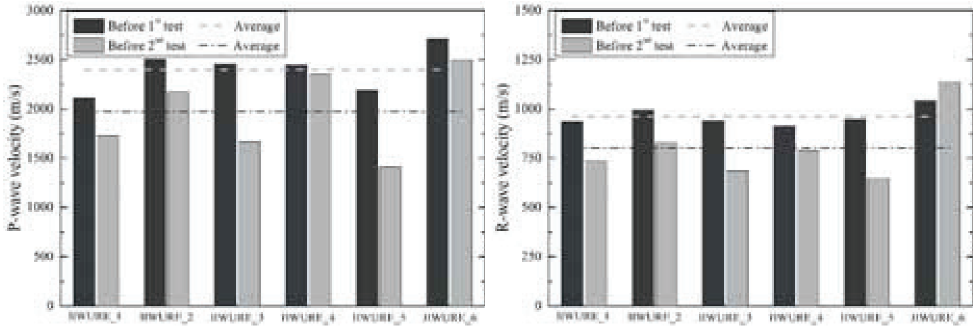


Figure 5. Maximum principal strains (near collapse stage) obtained from DIC analysis for IIWURE_4 and IIWURE_2 in the first and second tests.

3.2 Sonic tests

The results of the direct and indirect sonic tests carried out on the wallets are presented in Figure 6. The direct tests before the first test of the wallets resulted on average P-wave velocity values of about 2469 m/s, which is comparable to those of a mid-good quality masonry. This value was reduced in about 18% in the repaired wallets, which confirms the loss of homogeneity of the material. This situation can be explained by the presence of damage in the rammed earth, which could not be repaired. The use of different types of grouts seems not to affect the results, as they were very similar for both grouts used. Similar observations can be drawn from the indirect tests, where the average value of the R-wave velocity before the first test was of about 963 m/s, which decrease about 17% with respect to the repaired wallets. It should be noted that the measurements of the sonic tests are expected to be affected by the sealing mortar on the faces of the wallets, which can penetrate up to 2 cm inside. This material has obviously lower properties than the rammed earth and grout and therefore it tends to slow down the propagation of the sonic waves. In this way, it is difficulty to conclude about the reliability of sonic tests in assessing the repair effectiveness of grout injection to repair cracks in rammed earth.



(a) (b)

Figure 6. Results of the sonic tests: (a) direct tests; (b) indirect test.

4. Conclusions

The experimental program presented in in this paper allowed to confirm some aspects regarding the shear behaviour of rammed earth and the repair effectiveness of mud grouts, as reported by Silva [13]. In addition, it was observed that the repair effectiveness of a commercial grout based on hydraulic lime seems to have a similar repair effectiveness to that of a mud grout. Despite the good performance of this grout, its use should always take into account other compatibility issues, not discussed here. Finally, sonic tests seem not to be a reliable method to assess the repair effectiveness of injection by non-destructive means.

Acknowledgments

This work is financed by FEDER funds through the Competitivity Factors Operational Programme - COMPETE and by national funds through FCT – Foundation for Science and Technology within the scope of the project POCI-01-0145-FEDER-007633, project PTDC/ECM-EST/2777/2014 and Post-doc grant SFRH/BPD/97082/2013.

References

[1] Jaquin, P. A. et al, Chronological Description of the Spatial Development of Rammed Earth Techniques. International Journal of Architectural Heritage, 2(4) (2008), 377-400

[2] Houben, H. and Guillaud H., Earth Construction: A Comprehensive Guide. 3rd Edition, CRATerre - EAG, Intermediate Technology Publication, London, UK (2008)

[3] http://www.centrodaterra.org/pt/ferramentas/patrimonio_mundial/index.html (accessed on 15/03/2016)

[4] Rocha, M., Rammed earth in traditional architecture: construction techniques. In Earth architecture in Portugal. Argumentum, Lisbon, Portugal (2005), 21-26

[5] Minke, G., Building with earth: Design and technology of a sustainable architecture. Birkhäuse-Publishers for Architecture, Basel-Berlin-Boston (2006)

[6] Jaquin, P. A. Analysis of Historic Rammed Earth Construction. PhD Thesis, Durham University, Durham, UK (2008).

[7] Lacouture, L. et al, Estudios de vulnerabilidad sísmica, rehabilitación y refuerzo de casas en adobe y tapia pisada. Apuntes, 20(2) (2007), 286-303

[8] Braga, A. M. and Estêvão, J. M. C., Difficulties associated with the rehabilitation the rammed earth built heritage in Algarve. In proc. of Congresso da Construção 2012, 18-20 December, Coimbra, Portugal (2012). (in Portuguese)

[9] Correia, M., Islamic fortresses in military rammed earth, Pedra & Cal, 24 (2004), 16. (in Portuguese)

[10] Oliveira, D. V. et al, The rammed earth constructions and the earthquakes. In proc. of Congresso Nacional de Sismologia e Engenharia. SÍSMICA 2010, 20-23 October; Aveiro, Portugal (2010). (in Portuguese)

[11] Warren, J., Conservation of Earth Structures. Butterworth Heinemann, Bath, UK (1999).

[12] Silva et al., Conservation and new construction solutions in rammed earth. Structural Rehabilitation of Ancient Buildings, A. Costa; J. Miranda; H. Varum (Eds), Springer (2014), 77-108. ISBN 978-3-642-39685-4

[13] Silva, R. A., Repair of earth constructions by means of grout injection. PhD thesis, University of Minho / KULeuven, Guimarães, Portugal (2013)

[14] Getty, Interdisciplinary Experts Meeting on Grouting Repairs for Large-scale Structural Cracks in Historic Earthen Buildings in Seismic Areas. The Getty Conservation Institute (2007)

[15] Chu, T. C. et al, Applications of digital-image-correlation techniques to experimental mechanics, Exp Mech ,25(3) (1985), 232-244

[16] NZS 4298, Materials and workmanship for earth building, Standards New Zealand, Wellington (1998)

[17] Domínguez Martínez, O., Preservation and repair of rammed earth constructions. MSc Thesis, University of Minho, Guimarães, Portugal (2015)

[18] ASTM E 519, Standard Test Method for Diagonal Tension (Shear) in Masonry Assemblages, American Society for Testing and Materials, USA (2002)

[19] ASTM C 939, Standard test method for flow of grout for preplaced-aggregate concrete (flow cone method), American Society for Testing and Materials, USA (1994).

[20] EN 1015-11, Methods of test for mortar for masonry – Part 11: Determination of flexural and compressive strength of hardened mortar, European Committee for Standardization, Brussels (1999)