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Effectiveness of the repair of unstabilised rammed earth with injection of mud grouts

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HIGHLIGHTS

- The repair effectiveness of mud grouts is tested.
- The shear behaviour of rammed earth depends on binding, friction and interlocking.
- Mud grouts incorporating the same soil of the rammed earth perform better.
- Grout injection provides satisfactory strength recovery.
- Grout injection is incapable of recovering the initial shear stiffness.

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ABSTRACT

The presence of cracks debilitates the structural performance of rammed earth. Grout injection is a repair solution put forward recently, where compatibility issues demand using mud grouts. Little is known on this topic, whereby an experimental program on the mechanical effectiveness of grout injection for repairing cracks in rammed earth was performed. Specimens tested under bending and diagonal compression were retested after repair with injection of mud grouts. Mud grouts incorporating the original soil of the rammed earth are shown to perform better and their injection achieves satisfactory shear strength recovery, but is less effective in recovering initial shear stiffness.

1. Introduction

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. This type of construction is also associated to the concept of vernacular architecture, meaning that several variations exist, namely regarding the geometry, materials and fabric of the rammed earth [1]. For example, in Alentejo (Portugal) the length of rammed earth blocks from typical dwellings may vary

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from 1.40 m to 2.50 m, the height from 0.40 m to 0.55 m and the thickness from 0.40 m to 0.57 m [2].

Despite the recent age of rammed earth construction relative to other earth construction techniques [3], its use is reported to be thousands of years old [4,5]. This type of construction is present in countries of all inhabited continents, which include the USA, Brazil, Morocco, Portugal, Spain, Germany, India, China, Australia and New Zealand. Rammed earth has been mainly used for building dwellings. Nevertheless, the use of rammed earth also resulted in several monumental and military constructions with important cultural, historical and architectonic value. The Great Wall of China is a good example of such important heritage, where many of its sections were built in rammed earth [5].

In Portugal, there is also an important rammed earth built stock, concentrated in the southern region of the country, namely in the regions of Alentejo, Algarve and Ribatejo. However, it appears more often in southern Alentejo, where there is less rain and other building materials, such as stone and timber, are scarce [1]. In general, the Portuguese rammed earth built stock can be classified according to its use, as civil and military [6]. The first group includes most of the built stock and is associated to the construction of dwellings, windmills, farm storehouses and religious constructions. The second group is mainly constituted by fortifications built during the Islamic presence in Portugal, between the 8th and 13th centuries [7].

Many of the aforementioned constructions are found, nowadays, in poor conservation condition, resulting from lack of maintenance and continuous abandon during the past half-century. This situation contributes for increasing the vulnerability of these constructions [8]. Rammed earth constructions are particularly vulnerable to rainfall and earthquakes [9]. The presence of cracks is a type of damage often present in these constructions, which has particular influence on the structural performance. Cracks constitute preferential paths for rainfall infiltration, moistening directly the rammed earth, substantially reducing its mechanical properties [10]. The presence of structural cracks in rammed earth walls decreases their bearing capacity and stiffness, and disrupts the overall monolithic behaviour of the structure.

Nowadays, the rehabilitation of the rammed earth heritage assumes great interest, namely in what concerns its housing and touristic valorisation [11]. Furthermore, Alentejo and Algarve are regions with an important seismic hazard, meaning that lack of proper intervention solutions puts at risk the rammed earth built heritage and the life of eventual inhabitants. Cracks can be repaired using different techniques, but the repair efficiency greatly varies from case to case [9]. The most basic solution consists in simply filling the crack with earth mortar [12]. However, within this procedure it is difficult to re-establish the continuity of the material, since earth mortars tend to loose bond due to shrinkage cracking. Furthermore, in the cases where the crack is thin (less than ~30 mm), the wall needs to be cut back [13], making the procedure more complex. These problems can be overcome by injecting a grout sufficiently fluid to completely fill the crack. The grout also needs to be compatible with the rammed earth, meaning that earth should be included in its composition, as suggested by the technical committee of the Getty Conservation Institute for earth construction [14]. Such grouts are known as mud grouts and were used in few reported cases with apparent successful results [15,16]. Very recently, Müller et al. [17] used a binary grout (composed by hydrated lime and pozzolanas) for repairing cracks in cob wallets. This type of grouts is claimed to be also capable of achieving compatibility requirements with earthen materials, while providing lower shrinkage and better control on the strength development than mud grouts. However, the mechanical repair effectiveness of the proposed grout was shown to be very low.

Despite the few research available on mud grouts [18–20], Vargas et al. [18] has shown that unmodified mud grouts (without incorporation of additional binders like cement and lime) are capable of providing better adhesion in adobe walls than modified ones (with incorporation of binders like cement and lime). More recently, Silva et al. [20] analysed the influence of the composition of unmodified mud grouts on their fresh-state rheology, hardened-state strength, as well as on the adhesion capacity based on three-point bending tests of small-scale unstabilised rammed earth (URE) specimens. The results of these last tests seem to show that the mud grouts employed present good efficiency in terms of strength recover after repair. Nevertheless, the small scale of the specimens did not allow to conclude on the reliability of the repair effectiveness observed.

This paper tries to answer the above referred limitation with basis on an experimental program, which includes the testing of large scale URE specimens. The case of the URE from the region of Alentejo was selected as case study. In addition to the assessment of the mechanical repair effectiveness of different mud grouts, this experimental program also aimed at characterizing the mechanical properties of the rammed earth by including axial compression, three-point bending and diagonal compression tests on representative specimens.

2. Experimental program

The experimental program involved the testing of several URE specimens, which were prepared using a soil from Alentejo with corrected particle size distribution (PSD). This section describes the characterization of the soil used, the manufacturing of the URE specimens and the testing procedures used for the axial compression, three-point bending and diagonal compression tests.

2.1. Soil

The soil was collected from Amoreiras-Gare, Odemira (Alentejo) and its suitability for URE construction was assessed with basis on expeditious (sedimentation test, ribbon test, drop test and dry strength test) and laboratory (PSD analysis, Atterberg limits and standard Proctor) tests [21]. In general, the expeditious tests revealed that the clay content of the soil was excessively high for being considered suitable for URE construction. This observation was confirmed by the PSD analysis [22], whose PSD curve is presented in Fig. 1a. This curve is compared with the envelope of suitable soils for rammed earth construction, recommended by Houben and Guillaud [4]. The clay percentage of the soil (about 28%) is shown to exceed noticeably the maximum recommended value (about 16%). Table 1 presents the liquid limit (LL), plastic limit (PL) and plastic index (PI) [23], as well as the standard Proctor maximum dry density (ρ_{dmax}) and optimum water content (OWC) of the soil [24]. Houben and Guillaud [4] also proposed an envelope for consistency parameters of soils recommended for rammed earth construction, as depicted in Fig. 1b. Here is shown that this soil fits within recommend values, deeming it as suitable. However, Ciancio et al. (2013) [25] argues that the determination of consistency limits is inaccurate to assess the suitability of a soil for rammed earth construction, since the test is performed on the fraction of particles with size below 0.425 mm, which may not be representative of the behaviour of the full soil. The value obtained for ρ_{dmax} (1830 kg/m^3) seems to be too low for the soil being used in rammed earth construction, which may mean that the correspondent mechanical performance may be insufficient. In general, the characterisation of the soil showed that it is unsuitable for URE. Its high clay content is the main reason leading to this