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Validation of the repair effectiveness of clay-based grout injections by lateral load testing of an adobe model building

Rogiros Illampas [a], Rui A. Silva [b], Dimos C. Charmpis [a], Paulo B. Lourenço [b], Ioannis Ioannou [a,*]

[a] Department of Civil and Environmental Engineering, University of Cyprus, 75, Kallipoleos Str., P.O. Box 20537, 1678 Nicosia, Cyprus[1]
[b] Department of Civil Engineering, ISISE, University of Minho, Campus of Azurém, 4800-058 Guimarães, Portugal[2]

HIGHLIGHTS

- Clay-based grout used to repair cracks on an unreinforced adobe model building.
- Repaired model subjected to static lateral loading tests.
- Grouting resulted to almost full recovery of initial stiffness and strength.
- Grouting precluded damage development at the injected cracked sections.

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ABSTRACT

This study investigates the use of clay-based grout injections for the repair of adobe masonry constructions. Relevant data from the literature is reviewed, whilst the effectiveness of a laboratory-prepared clay-based grout is assessed through an experimental program. A 1:2 scaled adobe model building, previously subjected to a series of lateral loading cycles resulting in significant cracking damage, was injected with the clay-based grout and re-tested. The mix design of the aforementioned grout was based on the use of the same soil composing the earth masonry materials, hence ensuring compatibility between repairing and original materials. Although the grouting repair did not significantly alter the observed damage pattern after re-testing, it generally succeeded in preventing failure propagation through the injected crack paths. Furthermore, the injection of clay-based grout proved to be a repair technique capable of partly restoring the initial stiffness and load-bearing capacity of adobe masonry. The high strength recovery ratios recorded under the tests using static monotonic horizontal loading are particularly encouraging.

1. Introduction

Adobe bricks composed of unfired earth and, often, natural fibers have been used for the construction of masonry since the Neolithic era [1,2]. Nowadays, the use of adobe bricks for building contemporary structures is limited, although efforts are currently in progress to develop sustainable earth-based construction materials (in some cases not load-bearing) that fulfill modern-day requirements (e.g. [3]). Nevertheless, a large stock of earthen buildings still exists in many parts of the world and constitutes an important part of the international built cultural heritage. Historic and vernacular adobe buildings are, in fact, also encountered in regions of moderate to high seismic hazard such as the East Mediterranean, Southern Europe, North Africa, Middle East, South Asia and Central and South America.

Cyprus is among the countries of the Mediterranean basin with strong tradition of building with adobe masonry. Local adobes have a characteristic slab-like shape with typical dimensions of about (height × length × width) $5 \times 45 \times 30\,cm^3$. Their mechanical properties are rather variable due to the non-industrialized production methods used [4], while the response of adobe assemblages exhibits high deformability [5].

Adobe bricks were extensively used in the lowland regions, urban centers and coastal areas of Cyprus until the mid-20th century [6]. Surviving earthen structures range from simple single-roomed dwellings to elaborate urban houses featuring stone supporting members (i.e. arches and buttresses) and timber

* Corresponding author.
E-mail addresses: rilamp01@ucy.ac.cy (R. Illampas), ruisilva@civil.uminho.pt (R. A. Silva), charmpis@ucy.ac.cy (D.C. Charmpis), pbl@civil.uminho.pt (P.B. Lourenço), ioannis@ucy.ac.cy (I. Ioannou).
[1] URL: http://www.ucy.ac.cy/cee/en/.
[2] URL: http://www.isise.net/.

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elements. Many of these constructions have been declared listed buildings or monuments, and their protection is subsidized by governmental rehabilitation programs. Aiming at the preservation of their specific character, focus is being given on the adoption of non-invasive intervention techniques that can efficiently restore structural strength and stability.

Despite the wide use and historic value of adobe masonry, experience has shown its high vulnerability to cracking damage, due to its low tensile strength and the quasi-brittle nature of its constituents (Fig. 1). As a result, adobe structures may develop diagonal and/or vertical cracks even at relatively low levels of seismic action. Foundation settlements and concentrated static loads can also induce cracking. The presence of cracks poses a negative effect on the static and seismic behavior of adobe masonry elements as they disrupt structural continuity, reduce the overall stiffness and provide a path for damage propagation. Moreover, cracks promote moisture penetration, which leads to water-mediated decay of the earthen materials, further reducing their load-bearing capacity.

Up to date, methods commonly used for repairing cracks in adobe masonry structures included filling the gap with mortar, partial reconstruction of damaged areas and stitching with timber/steel elements [7,8]. Questions are raised regarding the effectiveness of these techniques because certain interventions fail to reinstate monolithic behavior of the element, while others are considered excessively intrusive and costly as they involve considerable loss of fabric. Furthermore, installing materials much stiffer than adobe (e.g. steel or cement-based composites) into cracked sections can result in adverse effects, since such interventions cause abnormal stress concentrations. Research has shown that grout injection is an alternative repair solution with the capacity to provide adequate stiffness and strength recovery [9]. However, the development and validation of grouts incorporating earth in their composition, in order to be compatible with adobe, remains a challenge.

In light of the above, this paper aims at investigating the effectiveness of the injection of clay-based grouts on the recovery of the load-bearing and deformation capacity of damaged adobe masonry constructions. For this purpose, a 1:2 scaled model of an existing adobe building from Cyprus was constructed and tested at the laboratory under monotonic static lateral loading. After subjecting the model building to a number of loading cycles that caused depletion of its overall stiffness and bearing capacity, the resulting masonry cracks were injected with a laboratory-prepared clay-based grout and a new series of tests was undertaken. The structural behavior of the model before and after repair is hereby compared in terms of the recorded force-displacement response, damage distribution and failure mode. It is worth noting that this is one of the few studies that assess the effectiveness of clay-based grout injection through laboratory tests on a large scale specimen, namely a full model of an adobe building.

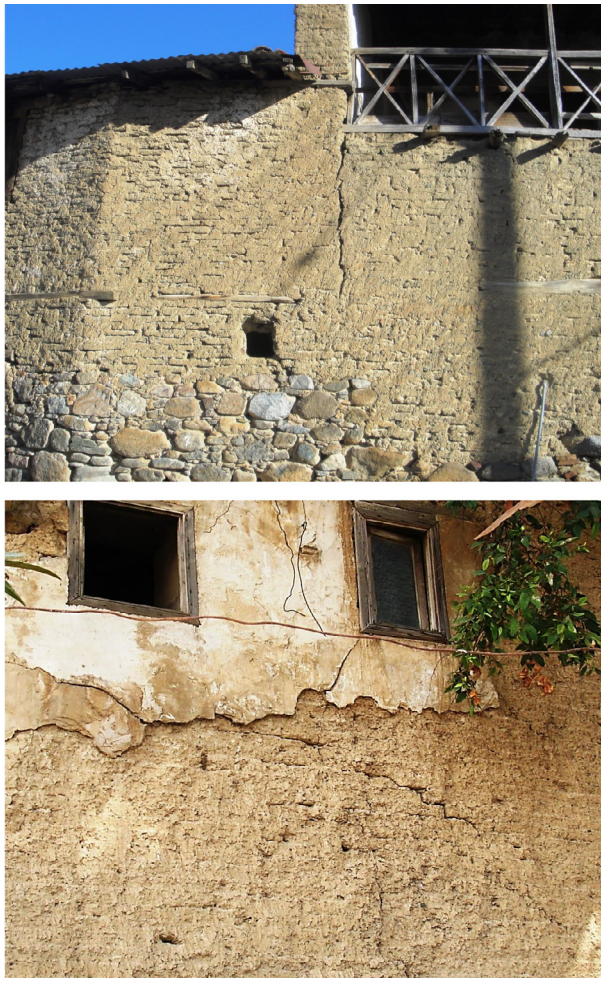

Fig. 1. Cracks on adobe masonry walls in the mountainous village of Kakopetria (a) and in the coastal city of Limassol (b) in Cyprus.

2. Repair of earth constructions with grout injection

Grouts are essentially fluid mixtures that can be injected into cracks, fissures or gaps using gravity flow or pressure-assisted pumping. As the grout fills these voids and hardens, it provides adhesion between the masonry materials, re-enabling stress transfer; this contributes greatly to the enhancement of the monolithic behavior of the structural parts. Grout injection is considered a practical and effective repair technique that can be used without altering the architectural aesthetics of historic constructions [10]. In fact, the injection of lime- and cement-based binary and ternary grouts have been shown to be highly effective in strengthening unreinforced stone and brick masonry structures [11–18].

It is worth noting that different commercial grouts might exhibit variable properties [19]. The suitability of a repair grout depends on whether the fresh mix possesses adequate fluidity and stability against sedimentation [20,21]. It also relies on the strength, stiffness, bond, chemical stability and microstructure of the hardened mix. Although the grouts developed for conventional masonry present good rheological properties, in many cases their physico-mechanical properties render them inappropriate for the repair of adobe structures, especially when bearing in mind that their use constitutes an irreversible intervention. Many lime- and cement-based grouts are substantially stronger and stiffer than adobe bricks and bedding earth mortars. Hence, they are unable to follow the levels of deformation of the adobe masonry generated by recurrent static, seismic and thermal loads, thus causing undesirable damage [22]. Moreover, due to the comparatively low porosity of some of the aforementioned grouts, they tend to act as moisture barriers affecting water vapor transport [23]. Finally, cementitious grouts can introduce sulfates and other salts that may enhance the decay of adobe masonry. Therefore, efforts are currently in progress for the design of grout mixtures compatible with earthen materials.

The use of adobe's basic constituent material (i.e. unfired earth) in the composition of repair grouts seems to be an obvious solution to ensure compatibility. Hence, emphasis has been given on the development of either unstabilized or stabilized clay-based grouts. Unstabilized clay-based grouts are suspensions constituting of earth and other aggregates, whose hardening relies solely on the