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In situ mechanical investigation of rammed earth: Calibration of minor destructive testing

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ABSTRACT

This paper was written with the awareness that no literature was available on the mechanical investigation of earthen buildings through minor destructive testing. The different aspects of the research were analysed through specific methods: a rammed earth test wall was built and minor destructive techniques such as flat jack, hole-drilling, and mini-pressuremeter were employed for evaluating its mechanical characteristics. Simple compressive testing was performed on cylindrical samples. The main purpose of the paper is to be used as a reference for future research, but also to be employed in practical terms in conservation work.

1. Introduction

Earth has been used as construction material since ancient times, whilst at present, an important part of the world population lives or works in earthen buildings [1]. As a reference, 96 (17%) of the 563 cultural sites that are included by UNESCO in its World Cultural Heritage List are fully or partially built with earth [2].

The discipline of earthen structures conservation is still under development because of its shorter history if compared for instance to stone or fired brick conservation. The aim of this section is to make an overview of the recent developments in this field.

1.1. Traditional repair methods

An approach to earthen structures is that of traditional repair methods as explained by elderly craftsmen [3]. For instance, in the UK, the Devon Earth Building Association has produced several useful leaflets for the conservation of cob buildings, and the book by Keefe [4] combines traditional repair methods with more recent ones. One of the advantages in using such methods is that '…most of the traditional techniques conform to accepted current-day conservation philosophy and ethics: minimum interference with the historic fabric, the recycling of materials, and repairing like with like' [3].

1.2. Visual analysis of earthen structures deterioration

At present there is no internationally accepted glossary that can be employed by practitioners and academics working in the field of earthen structures conservation. In the past, local earthen materials glossaries were developed in English, French and Spanish. However, not all international practitioners and scholars can access these scarce studies because in some cases they are unpublished or available as grey literature. As for other building materials, two international glossaries were published for fired brick and stone and they have led to wide adoption in building conservation and maintenance [5,6].

The most recent glossary on earthen materials deterioration patterns is that of Cooke et al. [7], a preliminary attempt made by the ICOMOS Scientific Committee on Earthen Architectural Heritage (ISCEAH). Similarly to what explained by Franke and Shumann [5] for the fired brick atlas, the Earthen Materials Glossary is not meant to be adopted by private owners. This is crucial because a wrong interpretation could lead to improper conservation interventions if a professional is not involved.

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[1] Since the completion of this paper, Dr. Enrico Fodde sadly passed away after a long illness. A full tribute to Enrico can be found on the University of Bath web page: http://www.bath.ac.uk/ace/news/news-items/news_0085.html.

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1.3. Experimental diagnosis of earthen construction in the laboratory

In recent years, several investigations have been conducted in the laboratory, leading to developments in materials characterization, possible additions (stabilizers and fibers) to optimize its mechanical behaviour, and mechanical performance of medium to large scale specimens. In Table 1 some of the most common laboratory tests are listed.

More specifically, with regards to materials characterization, studies have been devoted to the physical–mechanical and mineralogical characterization of earth material [8]. Other studies focused on possible stabilizers [9,10], with or without fibers [11,12], and on mechanical performance at different scales [13,14]. In terms of possible reinforcements applicable, several experimental campaigns, covering a wide type of reinforcement systems, have been conducted [15].

Furthermore, earthen construction is strongly vulnerable to earthquakes, such as for instance that of Bam (2003, Iran) of magnitude 6.3 [16]. Because of similar disasters in other areas of the world, several experimental campaigns have been undertaken in the last decade. They were devoted to evaluate the effectiveness against earthquake of several reinforcements applied to earthen structures [17–20].

1.4. Other approaches

It is important to stress the extent to which experimental analysis and the information provided by the craftsmen are complementary [21]. Just as the information provided by the craftsmen is often incomplete, laboratory analysis does not provide the necessary data on the craftsmanship involved in traditional construction [22–24]. An interdisciplinary approach is therefore clearly necessary.

The issue of lack of standardised methods for rammed earth testing is recognised by some authors [25] who explain that physical tests employ modified standards for soil cement and that at present very few countries have developed standard tests specifically suited to rammed earth. Use is thus often made of tests originating in other disciplines such as concrete construction and road construction. Digital photogrammetry and total station recording were employed to reconstruct digital terrain models and to record rate of deterioration/erosion of mud brick and rammed earth walls [26]. Similarly, stereo-photogrammetry was employed by other authors to measure the erosion of rammed earth test walls exposed for 20 years to natural weathering [27]. Earth material characterization and the ageing of earthen materials has been studied by several authors [21,28]. Recent research showed also that damage to earthen structures can be analysed with another approach which is based on the application of unsaturated soil mechanics principles [29].

The inevitable conclusion is that of all the authors who have looked at earthen architecture, no one has yet initiated any work on in situ estimation.

1.5. A new approach: In situ estimation of earthen construction through non/minor destructive diagnostic techniques (N-MDT)

Earthen materials are vulnerable to atmospheric degradation. Furthermore, earthen buildings are often depicted as being weak and structurally unsound: they present a very low tensile strength, a low compressive strength and a fragile behaviour. Moreover, literature concerning the conservation of earthen structures often lacks any scientific knowledge of the material. These considerations point at the necessity of taking in account non/minor destructive diagnosis techniques (N-MDT) with the objective to evaluate, onsite, the state of conservation of earthen heritage. This could provide useful information on adequate conservation methods. Table 2 lists some N-MDT techniques which may be used for the in situ estimation of earthen materials.

The scope of this paper is to study some effective and minor destructive methods for understanding the structural soundness of rammed earth buildings. The methods explained here (flat jack, hole-drilling, and mini-pressuremeter) have the advantage of being adequate from the scientific point of view, but also of being repeatable in other contexts.

Flat jack technique was tuned in the 1980s [30] specifically for masonry of fired brick or stone. No use of this technique on rammed earth structures has been found in the literature review. In addition, the first reference of stress estimation using the hole-drilling technique is that of Barla and Rossi who studied stress levels in a concrete tunnel [31]. However, Sánchez-Beitia developed and optimized a methodology for masonry. There are studies on the application of the hole-drilling technique to masonry both in the laboratory [32] and on site [33,34]. However, there are no examples of the application of the technique to rammed earth structures.

The first model of pressuremeter was developed by Kogler in 1933 in Germany and Menard significantly improved the initial design [35] in the 1960s. Since then, significant advances have been made in terms of equipment, interpretation methodology and in the practice and application of the pressuremeter test. The dilatometer appeared in the 1970s as an adaptation of Menard's rock pressuremeter for use in rocks. Although such methods were developed for geo-techniques application, they have been used also for the mechanical characterization of masonry such as that of the Tower of Pisa [36,37], the Bell Tower of San Marco in Venice [38] and the church of the Monastery of Serra do Pilar in Porto [39]. Based on the above literature review, no reference was found on the mechanical evaluation of rammed-earth structures with pressuremetre techniques.

The research significance of the present study relates to the application of N-MDT to rammed earth walls. This is an original contribution to the topic as it was never carried out before. The scope of the research is to be taken as a reference for implementing conservation activities and interventions on earthen buildings.

Table 1
Some of the laboratory tests most commonly used for the characterization of earthen materials.

Characterization	Technique	
Chemical	Soluble salts content; carbonates content; measurement of pH elemental microanalysis with energy dispersive X-ray spectroscopy (EDAX); X-ray fluorescence (XRF); mineralogical analysis by X-ray diffraction (XRD) microscopy	
Physical	Density; porosity; capillary absorption particle size distribution curve; soil color Atterberg limits (plastic limit, liquid limit, and plasticity index) Proctor test	
Mechanical	Small scale specimens	Compressive strength (σ_r, E and v)
	Medium and large scale specimens	Compression/shear/bending tests combined compression and shear tests Earthquake shaking table tests
Durability	Freeze and thaw test; wetting and drying test abrasion test; erosion test; shrinkage test	