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Mechanical behaviour of earthen materials: A comparison between earth block masonry, rammed earth and cob

Lorenzo Miccoli [a,*], Urs Müller [b], Patrick Fontana [a]

[a] BAM Federal Institute for Materials Research and Testing, Division 7.1 – Building Materials, Unter den Eichen 87, 12205 Berlin, Germany
[b] CBI Swedish Cement and Concrete Research Institute, c/o SP, Box 857, Brinellgatan 4, 50462 Borås, Sweden

HIGHLIGHTS

- Compression and diagonal compression tests of earthen wallettes were performed.
- Manufacturing practice is one of the key factors affecting performances of earth block masonry.
- Earth block masonry and rammed earth show a brittle mechanical behaviour under compression.
- Cob shows relatively ductile post peak behaviour under compression due to fibres content.
- Cob presents a relatively good performance as far as shear behaviour is concerned.

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ABSTRACT

Earth represents one of the oldest construction materials, which is still utilised both in developed and in developing countries. In this paper a comparison of the mechanical performance of structural elements built in three basic techniques, earth block (adobe) masonry, rammed earth and cob, is presented. In order to gain better knowledge on the structural behaviour under static loads an extensive compression and diagonal compression (shear) test campaign was performed. First compression results showed brittle mechanical behaviour in the case of earth block masonry and rammed earth elements, whereas cob exhibited a very different stress–strain pattern: cob can deform beyond the elastic range with a gradual drop in capacity. Despite its low compressive strength, cob thus presents a relatively good performance within the earthen material range as far as shear behaviour is concerned.

The data here reported represents a base for a further investigation on the dynamic behaviour of the three materials considered. The study was carried out within the framework of the project NIKER funded by the European Commission dealing with improving immovable Cultural Heritage assets against the risk of earthquakes.

1. Introduction

It is estimated that 30–40% of the world population currently live or work in structures built from earth. Earthen structures require high maintenance as they are prone to erosion under rainfall, spalling and cross-sectional reduction when salts are transported by capillary action. They are also susceptible to cracking both under low tensile and low compressive stresses. When these dwellings are located in regions with high earthquake risk, their intrinsically low resistance to dynamic actions is further worsened by such durability issues.

A number of construction and repair practices negatively affect earthen buildings and make them susceptible to high damage even under low seismic forces [1]. A few typical recurring examples are lack of continuity at corners and at wall junctions, the presence of heavy roofs that are not supported by ring beams, and also roofs often not connected to walls. Some countries where the population, particularly the rural one, still inhabits earthen buildings have been affected by highly destructive earthquakes, for instance Turkey (Erzinkan 1992), Iran (Bam 2003), Peru (Pisco 2007), and Chile (Concepción 2010). Although damage to dwellings and their collapse is usually the cause of human losses, earthquakes are as well devastating to the built cultural heritage in these regions. As a matter of fact, it is often overlooked that a considerable amount of heritage sites, of which many are endangered, are built from earth. Some vernacular earthen building techniques are no longer

* Corresponding author. Tel.: +49 30 8104 3371; fax: +49 30 8104 1717.
E-mail address: lorenzo.miccoli@bam.de (L. Miccoli).

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in practice, and the knowledge of how to build in such materials has been lost. Earthen building techniques considerably differ as far as material composition and construction methods are concerned. While some guidelines and standards for building with earthen materials do exist, e.g. ASTM E2392/E2393 M [2], IS13827 [3] and NTE E.080 Adobe [4], these often lack design charts. Moreover, values specified do not take the high variability of earthen materials in terms of mechanical properties into consideration, which is dependent on a number of parameters affecting physical and chemical bonds at microstructural level, e.g. granulometry or fibre content [5], compaction and moisture content.

Newly introduced seismic regulations for countries where earthen buildings are still present within the built environment (e.g. Morocco [6], Pakistan [7]) are often based on those of developed countries and exclude earth as a building material. When seismic regulations for earthen buildings do exist (e.g. in New Zealand [8]), these tend to group all earthen materials into one category.

In comparison to recent advances in research on stone and fired brick masonry, knowledge on the material properties and failure mechanisms of earthen materials is limited and scattered [9]. Most of the assembled results have been obtained for earth block masonry [10–12].

The scatter of mechanical property values in the literature as shown in Table 1 can be large. This clearly is not only due to factors such as workmanship and weathering, but also to different testing procedures, for instance in the derivation of Young's modulus.

This paper focuses on the determination of material parameters and the behaviour of earthen wallettes and other test specimens under different loading conditions. The study provides an overview of mechanical behaviour of the three basic techniques, earth block masonry, rammed earth and cob. Up today a scientific study comparing mechanical and mineralogical properties of these earthen building techniques is still missing.

Walls made of cob can be regarded as fibre-reinforced monolithic structural elements. With rammed earth, monolithic elements are built as well. But, in general, rammed earth is not reinforced with fibres. In contrast, earth block masonry is considered as a modular construction technique, not as monolithic. In some cases earth blocks are reinforced with fibres to enhance their heat insulation properties and in [13–15] the positive influence of natural fibres on the mechanical properties of earth blocks is reported. However, fibre-reinforcement of the earth blocks does not change the modular nature of earth block masonry and its general failure mechanisms when subjected to compression and shear loads.

The entire experimental programme was performed in the laboratories of BAM. The types of wall specimens considered in the experiments consisted of one-leaf earth block masonry with earth mortar and of monolithic rammed earth and cob wallettes (Table 2). Investigations were carried out at micro and macro structural levels to acquire the mechanical behaviour of constituent materials as well as that of the structural elements (wallettes). The goal of the experiments was to acquire a basic knowledge of the mechanical properties of the different building techniques and to compare the general failure mechanisms.

The results of the presented study represent an important development of the data partially reported in previous papers [16,17]: Investigations of damage mechanisms via a photogrammetric method and investigation of the influence of pre-wetting of earth blocks on the shear resistance of earth block masonry.

1.1. Earth block masonry

The terms 'adobe' and 'earth block' will only be used here for the description of building blocks made from air dried earthen materials. Other synonymous terms, such as 'mud brick', 'sun baked brick' or 'unfired brick' often mentioned in literature will not be used.

Earth block masonry consists of earth blocks and mortar, usually an earth mortar. Sometimes stabilising additives, such as lime, cement or gypsum have been/are being used for mortars and blocks. Nowadays earth blocks can have various forms and sizes with or without perforations. In the past, blocks without perforation were usually used in various sizes. These blocks were produced by throwing a handful of a malleable mass of earth into a mould. Due to the higher water content, the plastic earth cannot be compacted. In the last century more and more compressed earth blocks (CEB) were produced, which were mostly stabilised by cement or lime. For CEB a fairly dry earth is used which is mechanically compacted in a mould with a higher pressure producing a material with a higher strength.

Although earth block is a widely utilised building material since prehistoric times, it also represents a type of masonry block that yields the lowest strength values. Typical values for compressive strength of historical unstabilised earth blocks are in a range from 1.0 MPa up to 5.0 MPa [18]. The modulus of elasticity measured on modern earth blocks with similar compressive strength and particle size distribution as historical earth blocks is in the range of 400–2000 MPa. Compared to some building stones or fired bricks, earth blocks show a rather moderate to low anisotropic effects towards their mechanical and physical properties.

Within the frame of a programme focusing on strengthening adobe houses, adobe wall specimens in simple compression, diagonal tension and flexure on both, the vertical and horizontal axes of the walls were tested by Hernandez et al. [19]. The same tests were

Table 1
Summary of material properties for earthen materials in the literature.

Material	Bulk density (kg/m^3)	Compressive strength (MPa)	Tensile strength (MPa)	Young's modulus (MPa)	Reference
Earth block masonry	1870	2.15	0.021	315	[18]
Rammed earth	2100–2300	2.40–3.00	nd	650	[36]
	1800	1.00	nd	90–105	[28]
	1700–2400	1.50–4.00	nd	750	[18]
	2020–2160	0.75–1.46[a]	nd	nd	[31]
	1870–2170	1–80–2.00	nd	nd	[32]
	nd	0.60–0.70	nd	60	[9]
	1850	3.88	nd	205	[33]
	1850	2.46	nd	160	[34][b]
	1763–2027	0.62–0.97	nd	60–70	[34][c]
Cob	1400–1700	0.45–1.40	0.09–0.34	170–335	[35]

nd = not determined.
[a] Value corrected because the very low slenderness.
[b] Specimen dimensions: $d = 10$ cm, $h = 20$ cm.
[c] Specimen dimensions: $30 \times 30 \times 60$ cm^3.