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Effect of moisture content on the mechanical characteristics of rammed earth

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HIGHLIGHTS

- Compressive strength, elastic modulus and Poisson's ratio were determined.
- Influence of water on the mechanical characteristics of earthen material.
- Variations of mechanical characteristics following suction.
- A slight increase in water content (<4% by weight) is not followed by sudden drop in strength.
- Interpretations at the microscopic level are presented for sandy, clayey and stabilised soil.

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ABSTRACT

In this paper, influence of moisture content on the mechanical characteristics of rammed-earth has been studied. Samples from different soils (sandy, clayey, stabilised) were manufactured and tested in unconfined compression at several moisture contents. Compressive strength, elastic modulus and Poisson's ratio were determined. A simplified method to measure the suction within rammed earth samples has been developed and validated. The variation of mechanical characteristics related to moisture content and suction are presented. This paper shows that a slight increase in the moisture content of dry rammed-earth is not followed by sudden drop in wall strength. Qualitative explanations at the nano-scale are presented.

1. Introduction

In the context of sustainable building, modern interest in earth as a building material is largely derived from its low embodied energy [19] and also because the material has good natural moisture buffering of indoor environments [1]. On one hand, to act as a RH buffer, the material must be capable of adsorbing and desorbing moisture. However, if the moisture content of unstabilised earthen materials increases excessively, the material loses its strength. Therefore the question is remains: what is the moisture buffering limit for a material without detrimental loss of mechanical strength?.

On the other hand, the greatest difficulty for the application of earthen material in practice is the variability of soil characteristics. Indeed, because earth is not an industrial material, its mechanical characteristics vary from one site to another. The questions before every earth construction are: is it necessary to use a stabiliser, which type of stabiliser and how much to use? Although some empirical techniques exist [21,5], to our knowledge, there are not yet scientific base for a fundamental understanding.

To answer these questions, it is necessary to study the source of the cohesion in rammed earth, to understand why earthen material is sensitive to water. The knowledge about fundamental phenomena will be useful to formulate material's composition. This paper deals with the quantification of suction inside rammed earth samples and a study of the limiting moisture values to maintain mechanical strength. The role of clay and hydraulic binder are also discussed. The experiments were carried out on rammed earth materials, but the analysis presented can be extended to other earthen materials such as adobe and cob for example.

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2. Rammed earth material

Rammed earth materials are ideally sandy–clayey gravels. The materials are prepared to their optimum moisture content and compacted inside temporary formwork to form walls. The earth composition varies greatly and always contains clay but should not include any organic components. Clay acts as the binder between the grains, a mixture of silt, sand, gravel up to a few centimetres diameter. Compaction is undertaken on material prepared to its optimum moisture that provides the highest dry density for the given compactive energy [18]. The rammed earth wall is composed of several layers of earth. The earth is poured loose in layers about 10–15 cm thick into a timber or metal formwork, which is then rammed with a rammer (manual or pneumatic). After compaction, the thickness of each layer is typically 6–10 cm. The procedure is repeated until completion of the wall. Detailed presentation of rammed earth construction can be found in Walker et al. [21].

For traditional rammed earth construction, referred to as "rammed earth" or "unstabilised rammed earth," the only binder is clay. Other binders can also be added such as cement, hydraulic or calcium lime. This is often called "stabilised rammed earth" (SRE). The main advantage of stabilization is the increase in durability and mechanical performance. However, stabilization increases the construction cost and environmental impact.

Unstabilised rammed-earth is the focus of scientific research for two main reasons. Firstly, the heritage of rammed-earth buildings in Europe and the world is still important [11]. The maintenance of this heritage needs scientific knowledge on the material to assess appropriate renovations. Secondly, the use of unstabilised rammed-earth in new constructions is possible in several countries, particularly in the current context of sustainable development [3]. The question "which conditions (soil suitability, weather) are suitable for the use of unstabilised rammed-earth?" awaits scientific answers. This question has a relation to the influence of moisture on rammed-earth wall behaviour, because moisture plays a role in the cohesion of earthen material, but it can also decrease the strength of the last one.

Concerning the influence of moisture content on characteristics of rammed-earth, Olivier and Mesbah [20] first initiated the idea to use the suction concept to study the role of moisture in the compacted earth material. They showed that increasing the moisture content accompanied a decrease in the suction of compacted soil material. In a more recent study, Jaquin et al. [16] studied the influence of suction on mechanical characteristics of rammed-earth material. This study found that suction was a source of strength in unstabilised rammed-earth, and that the strength increased as moisture content reduced. However, in that study, the moisture content only varied between 5.5% and 10.2% (by mass), while the moisture content of an unstabilised rammed-earth wall in normal conditions is around 1–2% [4]. In addition, in that study, only one soil was tested and the mechanical strengths obtained were relatively low ($f_c \sim 0.5$ MPa) compared to current values 1–2 MPa, [21]. Hence, in this paper, the influence of moisture on the mechanical characteristics of rammed-earth material was studied, on several different soils and with a greater range of moisture contents: from the wet state just after manufacturing (11%) to "dry" state in normal atmospheric conditions (1–2%). Samples in this study were manufactured and tested in unconfined compression at different moisture contents which correspond to different values of suction. A simplified method to measure suction was also developed and validated.

3. Influence of moisture content on the mechanical characteristics of rammed-earth material

3.1. Laboratory manufacturing process

3.1.1. Soils

Five different soils were used in this study which were taken from sites of rammed earth construction. Table 1 presents the composition of these soils that were obtained by sieving (for elements >80 μm) and the sedimentometric (for elements <80 μm). The clay contents of these soils were close to the interval proposed by Walker et al. [21], 5–10%. The methylene blue tests were carried out following French Standard (NF P 94-068 [12]) to obtain methylene blue values. The clay activity index A_{CB} was calculated from the methylene blue values. That index enables to identify the soil's mineralogical composition (Table 2) following an abaqus given by Lautrine [17] which was reused by Chiappone et al. [7].

In order to investigate the role of hydraulic binder, soils B and E were stabilised at 2% and 8% of natural hydraulic lime (NHL 3.5) by weight, respectively. Natural hydraulic lime is produced by heating calcining limestone which contains clay without adding. Number 3.5 indicates the minimum compressive strength at 28 days (which can vary from 3.5 to 10 MPa). Calcium reacts in the kiln with the clay minerals to produce silicates that enable the lime to set without exposure to air. Any unreacted calcium is slaked to calcium hydroxide. Hydraulic lime is used for providing a faster initial set than ordinary lime (calcium lime). Eight percent of lime was chosen because it was the maximum quantity observed in practice for stabilised rammed earth; beyond this limit, stabilised rammed earth lost its interest of "green material".

3.1.2. Sample manufacturing

In the present study, to investigate the influence of moisture on the characteristics of rammed-earth material, reproducing the dynamic compaction and the layer superposition of rammed-earth technique was essential without regard the sample size effect. To achieve this, an automatic Proctor machine was adopted. The standard mold of the Proctor test was replaced by a mold 16 cm in diameter and 32 cm high. To obtain the dry density of *in situ* rammed earth material (~1920 kg/m^3; [4]), a series of preliminary tests were conducted to determine the manufacturing moisture content and the amount of soil to be poured into the mold for each layer. An 11% moisture content was chosen as the compaction moisture content and 2.2 kg of moist soil was weighed out for each layer. Each layer received the Proctor energy ($E = 0.6$ kJ/dm^3). There were six compaction layers in each specimen prepared. The final height of the cylinder after the release was 30 cm giving to the sample an aspect ratio of 2. It is very important to avoid smaller aspect ratio [2]. Prior to mixing, the soil was sieved through a 2-cm screen.

The compacted layer thickness in *in situ* rammed earth walls is around 10 cm. Due to nature of compaction there is a density gradient in each layer, as the upper part of each layer is more compacted and therefore denser than the bottom [4]. The layer

Table 1
Soils used in this study.

Soil	Clay content (by weight) (%)	Silt (%)	Sand (%)	Gravel (%)
Soil A	5	30	49	16
Soil B	4	35	59	2
Soil C	9	38	50	3
Soil D	10	30	12	48
Soil E	10	22	43	25