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Unsaturated characteristics of rammed earth

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ABSTRACT: Rammed earth is both an ancient construction technique and the name for the material produced by the technique. Rammed earth is gaining in popularity around the world due to its ecological and sustainable attributes. Walls of rammed earth are formed by taking a graded mixture of (usually) locally-won soil and compacting the mixture between formwork in a similar manner to concrete. The formwork is then removed leaving a solid earth wall. There is little scientific understanding of the source of strength in rammed earth and design to date has used empirical approaches. In this paper we consider rammed earth as an unsaturated soil thus explaining one source of strength to be from suction. Laboratory tests have been carried out on rammed earth samples including unconfined compression and Brazilian tests (to measure strength) and filter paper tests (to determine the water retention properties). The tests all indicate that a source of strength in rammed earth derives from suction and conclusions are drawn as to their levels in ancient rammed earth structures.

1 INTRODUCTION

Rammed earth is both a material (a compacted mixture of sand, gravel and clay) and the name for the construction procedure whereby walls are built using this material rammed in layers between formwork. The technique has been used by man for thousands of years and many historic structures containing rammed earth features remain standing to this day. Examples include the Potala Palace in Lhasa, Tibet and the Alhambra in Granada, Spain (Guillaud et al. 2004). Historic rammed earth structures have been studied by engineers and archaeologists at Durham for a number of years (e.g. Jaquin et al. 2006).

The use of rammed earth for building has to date relied on empirical rules developed from experience, and often linked to a particular location in the world. A large number of heritage rammed earth structures exist, some of considerable antiquity. They are most commonly located in a belt around the equator reaching as far north as the UK (Jaquin et al. 2007). The nature of the material is such that arid conditions are favourable for long term durability and there are now concerns for the future of some of these structures under the effects of climate change.

Increased interest in rammed earth for new buildings is being seen in countries away from this traditional zone of past use. The reason for this is the inherent sustainability of the material (it can be re-used), the often local sourcing and the avoidance of the use of cement. An exception to the last of these is the material termed "stabilised" rammed earth, where cement or another stabiliser is added to improve durability. In the tests described later in this paper we will be concerned only with unstabilised rammed earth.

Rammed earth mix design is somewhat of a black art with advice varying according to location, soil type and occasionally cultural constraints. A typical mix is well-graded, containing particles in each of the four soil fractions: gravel, sand, silt and clay. Walker et al. (2005) indicate that the majority of modern rammed earth mixes lie in the following ranges of percentages by mass: sand and gravel, 45–80%; silt 10–30% and clay, 5–20%. The large size of these ranges provides further evidence of the empirical nature of rammed earth design.

It is clear that a material which can be formed into vertical walls which stand for hundreds of years has some cohesive strength. The source for this could be cementation between particles; however, walls can also be built from plain unstabilised rammed earth where no cementation is present. The source of strength must then lie elsewhere and suction appears to be a prime candidate, although to our knowledge this has not been highlighted before.

Few studies exist where rammed earth is characterized as an engineering material using rigorous testing procedures. One example is Lilley and Robinson (1995) who describe tests on rammed earth walls built at near full-size studying the effects of making (or forming) various openings. In this work the authors undertook rudimentary materials testing including cube tests (as for concrete) finding compressive strengths of 1.8–2.3 MPa. Another example can be found in a series of papers by Hall (e.g. Hall and Djerbib, 2004) where the hydraulic behaviour is linked to particle size distribution through experimental and analytical work. However neither of these or the few other published studies make the link between suction and strength in rammed earth.

Our contention is that rammed earth can be regarded as a compacted unsaturated soil. Modern rammed earth is usually prepared and compacted into place at optimum moisture content. With further drying, made easy by the large surface area of the walls, the material must reach a very low degree of saturation. This is likely to be even lower than the degree of saturation found in compacted soils with which geotechnical engineers are familiar. Therefore high suctions must be generated within the walls, hence providing some apparent cohesion. The purpose of the research described below is to begin to verify this theory. If rammed earth can be regarded as a manufactured unsaturated soil it is then possible to bring a greater degree of scientific rigour to the study of the material and to the development of economic design codes.

Clearly this suction-induced increase of apparent cohesion with drying cannot be unlimited. A completely dry rammed earth mix would have no apparent cohesion due to suction as no water would be present. However this is both unrealistic (as rammed earth in a structure will never completely dry) and in the laboratory as, even at oven dry conditions (i.e. zero water content), adsorbed water will still be present on clay particles and will be available to generate suctions. Other studies (e.g. Toll and Ong, 2003) have shown that in soils similar to rammed earth the contribution to strength from suction reduces as the degree of saturation reduces, so although suction increases as the soil dries out, the contribution to strength reaches a peak and then drops away (Toll, 1990). The apparent cohesion in rammed earth is therefore expected to peak between the two limits of zero water content and saturation.

1.1 *Suction and relative humidity*

Rammed earth includes particles with a much greater range of sizes than in the unsaturated soils that are commonly studied. However, there is no reason why the presence of water in liquid bridges should not provide strength through established mechanisms. A liquid bridge exists in a soil pore where both air and water are present in the pore space. The surface tension acting at the interface of the water and air, combined with tension in the water, act to provide an attractive force across the pore, which provides an unsaturated soil with an apparent cohesion. This liquid bridge force between the soil particles was first idealised by considering the soil particles to be spherical (Fisher 1926) assuming a wetting angle of zero. Developments of this theory towards realistic soils has progressed via the works of Gillespie and Settineri (1967) who extended to a finite liquid-solid contact angle, and Pietsch (1968) who took account of surface roughness of the particles by assuming a separation distance between idealised smooth spheres. Lian et al. (1993) provided a mathematical basis for the interactions between a liquid bridge and rough rigid spheres which were applied more recently by Molenkamp and Nazemi (2003). It is clear that further developments could begin to approach the pore structures likely to be present in rammed earth, with large particle size ranges, angularity and surface roughness. In addition, at the continuum level double-structure models for unsaturated soils (as reviewed recently in Gens et al. (2006)) could provide suitable frameworks for constitutive modelling of rammed earth materials.

The effect of relative humidity (*RH*) is particularly important for rammed earth due to the large exposed surface areas. Total suction s (the sum of matric and osmotic suctions) is linked to the relative humidity of the pore air through Kelvin's equation, which can be expressed as

$$s = -\frac{\rho_w RT}{w_v} \ln(RH) \tag{1}$$

where $R =$ the universal gas constant, $T =$ absolute temperature, $\rho_w =$ density of water and $w_v =$ the molecular mass of water vapour (Likos and Lu 2004). Equation 1 is plotted in Figure 1 for $T = 20°\mathrm{C}$. The figure shows that small variations in *RH* between 100% and 95% lead to large changes in total suction up to around 1MPa. Small variations in *RH* below 95% then lead to relatively small changes in suction (although the actual values of suction are large). Such low values of *RH* are likely to be present in the arid parts of the world where heritage structures containing rammed earth can be found and thus supports the hypothesis that suction is the significant provider of strength in rammed earth. Structures existing in

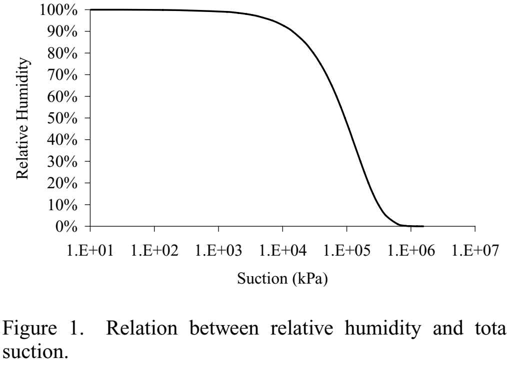

Figure 1. Relation between relative humidity and total suction.

regions in which *RH* is in the descending part of the curve of Figure 1 will experience relatively small changes in suction, thus leading to stability over time. Evaporation of pore water is affected by the relative humidity (*RH*) of the pore air compared to that of the adjacent air outside the wall. In practice drying of the walls will continue until the pore air humidity equals the humidity of the surrounding air.

2 LABORATORY TESTING

The aim of the laboratory testing described below was to confirm a link between suction and strength in rammed earth and also to study the changes in water retention behaviour as changes are made to the mix constituents. Laboratory testing consisted of unconfined compression tests, Brazilian tests and filter paper tests. The basic rammed earth mixture used in this study was taken from a development site at Aykley Heads, Durham, which included a large rammed earth wall completed in 2006. The mixture used on site was blended from material dug from the site (alluvial sand), coarse aggregate and a powdered clay/silt mixed in proportions (0.25:0.60:0.15; aggregate:sand:clay) using a horizontal axis mixer. In the laboratory tests described here, this mixture was first sieved to remove material retained on a 14 mm sieve. This was necessary to enable testing on standard sized samples. The sieved basic mix constituents are given in Table 1.

The basic mix was altered for the Brazilian and filter paper tests to include a 10% increase in sand (mix A) and a 10% increase in clay (mix B). The dry density/water content relationship for the basic mix was obtained using the vibrating hammer compaction test (BS1377:2, 1990) and showed an optimum water content of approximately 8–10%. The vibrating-hammer was used as it was thought closer to the field compaction that would be used during wall construction and the method of sample preparation for the compression tests (in comparison to the standard Proctor test).

2.1 *Unconfined compression tests*

Seven unconfined compression tests at constant water content were carried out on the basic rammed earth mix at variable water contents achieved through air-drying of the samples. A tensiometer was used in each test to measure suction during shearing. These instruments have been developed at Durham University for the measurement of high suctions up to the air entry value of the ceramic incorporated into these devices, in this case 1500 kPa (Lourenço et al. 2006).

Table 1. Constituents for basic rammed earth mix.

Constituent	% by mass	Passing	Size
Sand	21.5	D10	2.1 μm
Silt	52.3	D30	85.9 μm
Clay	26.2	D60	345.0 μm

Cylindrical samples (200 × 100 mm dia.) were prepared using a Proctor split compaction mould, as outlined in Walker et al. (2005), with modifications following Horncastle (2006). Samples were compacted in 5 layers following which a screed of particles passing a 425 μm sieve was placed on the top surface of the cylinder. This screed served a dual purpose of producing both a flat loading surface and a fine particle paste on which to place the tensiometer. Immediately following application of this screed, the Proctor split mould was removed and the mass and height of the sample recorded. Dry densities of between 2017 and 2061 kg/m^3 were achieved using the same compactive effort each time. Once samples had air dried to the required water content for testing they were wrapped in an impermeable sheath secured with rubber O-rings placed against steel loading plates at the top and bottom of the sample. The samples were then left for at least 7 days to allow suctions to equilibrate throughout the sample. When it was considered that the samples were ready for testing, the top plate was replaced with a loading plate drilled to accommodate a tensiometer. The samples were sheared under constant water content conditions in a triaxial testing rig. Displacement was controlled at a constant 0.1 mm/min and measurements of suction, load and axial displacement taken every 10 seconds using the logging software *Triax* (Toll 1999).

Figure 2 shows plots of deviator stress against suction measured for the seven tests.

The figure provides strong evidence of a link between starting water content and strength as indicated by the dotted envelope to the results. However, this can also be stated as a link between suction present in the sample at the start of testing and strength.

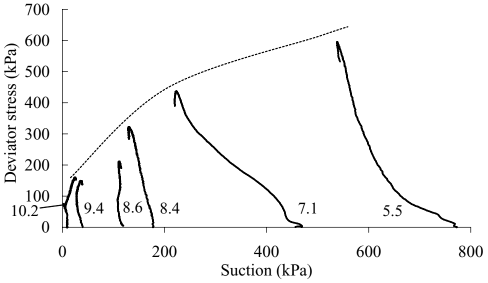

Figure 2. Plots of deviator stress against suction for unconfined compression tests. Test water contents indicated against each test.

Another feature evident from this figure is the difference in the change in suction during shearing. In samples with initially high water contents, suction rises during the test. For the low water content samples the opposite is seen to happen. This is consistent with the concept of a unique water content to suction relationship at the Critical State as proposed by Toll (1990). It also complies with the framework including a Continuously Disturbed Line (CDL) for unsaturated soils proposed by Croney and Coleman (1954) and revisited recently by Tarantino (2007).

Figure 3 shows plots of axial total stress against axial strain for the seven tests. Here it is notable that there is brittle behaviour for the low starting water content samples and ductile for high water content samples. Linking Figures 2 and 3 it is possible also to conclude that stiffness of a rammed earth sample is linked to suction. Further aspects of these tests are explored in more detail in Jaquin et al. (2007a).

2.2 *Brazilian and filter paper tests*

Following the unconfined compression tests described above the basic rammed earth mix was remixed to increase the coarse (sand) fraction (termed mix A) or to increase the fine (clay) fraction (termed mix B). What limited advice there is at present for the design of rammed earth mixes is based on mix proportions of the fractions. In this part of the study the aim therefore was to investigate the effects of changing the particle size distribution in a controlled way on the strength (and additionally) on the water retention properties.

The filter paper test is an indirect method of measuring both matric and osmotic suction where filter papers are arranged adjacent to or sandwiched between, soil samples which are then left to equilibrate. The final water content of the filter paper provides the suction present in the soil sample via a calibration curve. In these tests the procedure described by Leong et al. (2002) was used. The advantage of the filter paper method over the tensiometers used in the unconfined compression tests is that much higher suctions can be measured with the former.

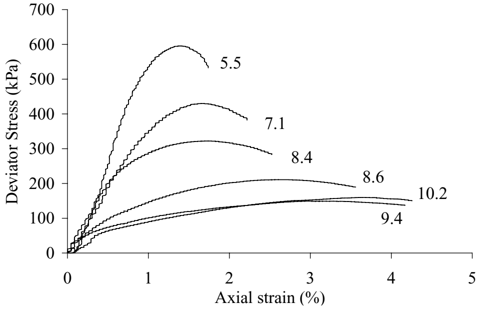

Figure 3. Plots of axial total stress against axial strain for the unconfined compression tests. Test water contents indicated against each test.

The filter paper specimens were prepared at 55 mm diameter with a height of 22 ± 2 mm from each of mixes A and B at a starting water content of 10%. Dynamic compaction of these specimens in an adapted Proctor apparatus proved difficult to control so these specimens were instead statically compacted in a triaxial rig to the required thickness maintaining the same target dry density of 2.05 $\mathrm{Mg/m^3}$. Then a sandwich of three filter papers was inserted between two compacted samples and the joint wrapped with electrical tape. An additional filter paper was suspended above the soil sample and the whole system placed inside a closed sealed jar and left to equilibrate for two weeks inside a constant temperature container at 25 ± 1°C.

By preparing a batch of samples and leaving them to dry to different moisture contents before filter paper testing it was possible to determine portions of the drying part of the soil water retention curve.

Following the filter paper tests the same samples were then quickly tested using a modified Brazilian test. This test is widely employed to determine tensile strengths in rocks and involves compressive loading of a circular disc sample across a diameter to failure. An analytical solution exists (assuming elasticity) linking the tensile strength of the sample σ_t with the applied load P as follows:

$$\sigma_t = \frac{2P}{\pi dt} \tag{2}$$

Where d = sample diameter and t = sample thickness. Clearly most soils are unsuitable for this type of test having little or no tensile strength and also often being too friable to withstand these conditions. For the rammed earth samples at low water contents no problems of this nature were experienced. The reuse of samples from the filter paper test for the subsequent Brazilian test proved successful although it was important to minimize the time between completing the filter paper test and starting the Brazilian test.

Figure 4 shows the change in water content over time as samples air-dried. Note the scatter in the initial water contents. Although the mixes were prepared as a whole to uniform water content, the actual water content of each individual disc varied about this value. It is noticeable that mix B (clay added) dries to approximately the same water content in the first day as mix A (sand added) despite starting from a generally higher initial water content although the mechanism for this difference is not clear. The process of drying in rammed earth is complex. Knowledge of the particle size distribution does not provide sufficient information on the soil microstructure in the

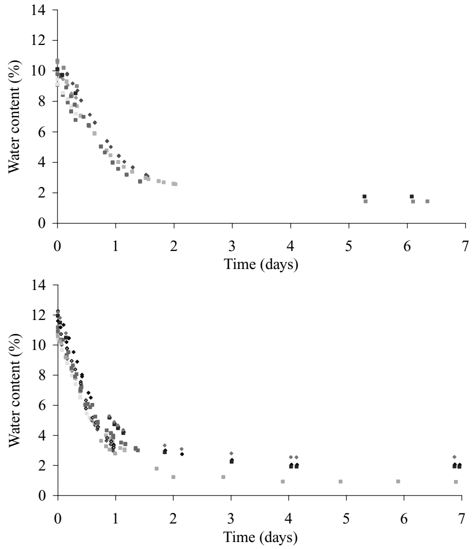

Figure 4. Drying of samples with time. Mix A (upper); Mix B (lower).

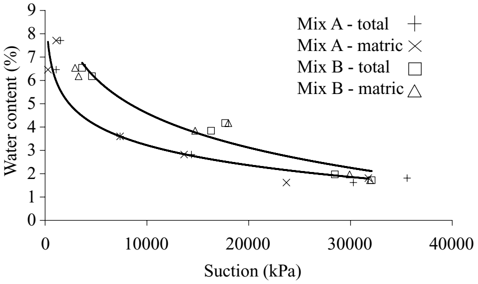

Figure 5. Soil-water retention curves for rammed earth mixes A and B.

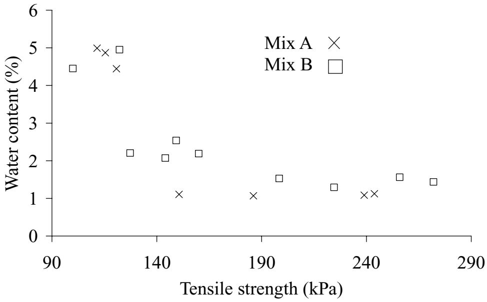

Figure 6. Brazilian test results.

two mixes, which has the greatest influence on drying. Rather it is the pore size distribution which must be critical, dependent on the former but also on compaction. From Equation 1 there is a direct link between suction and *RH* so it is natural that all samples dry to the same suction approximately.

Figure 5 shows the drying portion of the soil-water retention curves for the two mixes A and B taken from the filter paper results. Both matric and total suctions are plotted showing that osmotic suction is of secondary importance in these samples, as might be expected from the nature of the pore water. The suctions rise to a high level at the very low water contents reached by the samples indicating again the need for the filter paper test in the determination of suctions. The coarser mix (A) appears to have a SWRC lying below that of the finer mix (B) thus having a lower water content for a given suction value. This might be explained by consideration of the likely pore structures in these samples. The finer mix will have a more widespread network of smaller sized pores than the coarse mix. Therefore it is likely this mix will carry more of its pore water as bulk (funicular) water than the coarse sample. So for a given suction it will need more water as much will be trapped in the bulk masses, providing less potential than water in the pendular regime. This feature can also be linked to the theoretical analysis of Likos and Lu (2004) where theoretical soil-water retention curves for coarser materials lie below those for finer materials.

Figure 6 shows the results of the Brazilian tests. The water content at the time of the test is plotted against tensile strength calculated from Equation 2. As water content reduces so tensile strength increases as expected if suction is a source of tensile strength. For a given tensile strength there is more water in mix B than in Mix A. Again this links to the idea that in mix B more water is held in the funicular regime, contributing less to strength than "equivalent" pendular water. The plot also shows that tensile strength increases rapidly at very low water contents as might be expected to occur in the surface of a rammed earth wall under prolonged dry conditions.

3 DISCUSSION

It seems obvious from these results that suction must provide a significant component of the strength of unstabilised rammed earth and therefore understanding of its evolution from compaction, through drying to long-term changes in relative humidity is important for the stability of a rammed earth structure. Considering that most walls are of considerable thickness (usually >300 mm and much greater in heritage structures) it can be surmised that a gradient of water content exists through the wall thickness. At the surface water content is low and suction is high. Permeability will also reduce as water content decreases in these locations. Thus the centre of a rammed earth wall will be protected to some degree from water ingress, and will maintain a relatively constant level of suction and hence strength. This behaviour has been recorded in the laboratory by Hall and Djerbib (2004), referred to as the "Overcoat Effect". The high suctions present at the surface of a rammed earth wall will suck in impinging water. Surviving heritage structures often have design details that reduce impinging water, e.g. large overhanging eaves, features usually thought to aid longevity due to reduction in impact. The results above indicate that these features also serve to maintain surfaces at high suction and hence high strength.

While knowledge of unstabilised rammed earth is vital to the conservation of existing structures it is accepted that it is unlikely to become widely used in temperate parts of the world for new-build due to its surface friability which, despite the discussion above, is inferior to concrete. It is stabilised rammed earth, however, that is likely to be the choice in these areas. For this material, in addition to suction there will be cementation between agglomerations of particles to add to the tensile strength. The interaction between the free water available in the material at time of compaction and the stabiliser (e.g. cement) is clearly important and much more difficult to study. The relative contributions to strength from cementation and from suction will depend on many variables, such as pore size distribution, proportions of stabiliser, curing conditions amongst others. This is an important area of future research.

4 CONCLUSIONS

This study is the first (to the authors' knowledge) that has treated rammed earth as an unsaturated soil. The tests described above are intended to support this theory qualitatively and pave the way for further laboratory testing, which will be necessary if rammed earth materials are to be modelled in a modern geotechnical framework.

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