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TECHNICAL NOTE

The strength of unstabilised rammed earth materials

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Rammed earth is a manufactured material comprising sand, gravel and clay, which is compacted between forms to build walls. Primarily a historic method of construction, it is now receiving considerable interest worldwide owing to its zero reliance on materials such as cement, and its potential for recycling. Despite its longevity, the source of its shear strength is poorly understood. This paper presents initial laboratory test results that point to the main source of strength in rammed earth being suction, and indicating that recent advances in unsaturated soil mechanics may also be applied to this material.

KEYWORDS: compaction; laboratory tests; partial saturation; suction

Le pisé est un matériau manufacturé, composé de sable, de gravier et d'argile, qui est compacté dans des coffrages pour la construction de murs. Cette méthode de construction, principalement historique, fait l'objet d'un intérêt considérable à l'échelon mondial du fait d'une part qu'elle ne dépend aucunement de matériaux comme le ciment, d'autre part en raison de son potentiel de recyclage. La présente communication présente les résultats initiaux de tests effectués en laboratoire, qui indiquent que la principale source de résistance du béton d'argile est attribuable à l'aspiration, et que des progrès effectués récemment en mécanique des sols non saturés pourraient également être appliqués à ce matériau.

INTRODUCTION

The term 'rammed earth' refers both to a material (a mixture of sand, gravel and clay) and to a construction procedure whereby walls are built using this material rammed in layers between formwork. (When a cementing material is also added, the material is known as 'stabilised' rammed earth. This note is concerned only with 'unstabilised' rammed earth.) The technique has been in use by humanity for thousands of years, and many historic structures containing rammed earth features remain standing to this day. Examples include the Potala Palace in Tibet and the Alhambra in Granada, Spain.

Until recently, rammed earth was regarded much as masonry was regarded until the 1950s: that is, a building material for which design was, in general, based on heuristics and past experience. As with masonry, however, the need to use rammed earth and other earth building materials in unusual situations, or subject to unusual loadings, prompted further scientific examination.

The modern resurgence in rammed earth is concentrated in particular parts of the world, such as California and Western Australia (Hodsdon, 2006; Easton, 2007), but there is interest in the UK, as evidenced by the recent production of a design guide (Walker *et al.*, 2005). An example of a modern UK rammed earth wall is shown in Fig. 1. There has been surprisingly little investigation of rammed earth through laboratory testing to date, although it is clear that greater understanding is needed, both to conserve historic rammed earth structures and to promote the spread of new-build rammed earth. External rammed earth walls can be subjected to large changes in humidity and incident wetting from rainfall. The purpose of this paper is to record initial

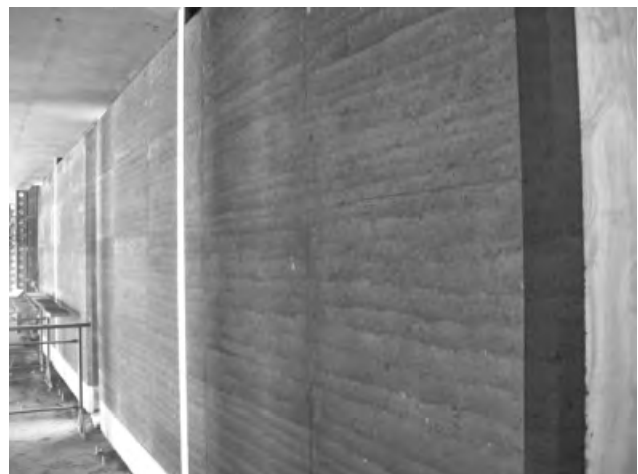


Fig. 1. A modern rammed earth wall at Rivergreen Developments, Aykley Heads, Durham

geotechnical testing to investigate the source of strength in rammed earth, linking it to suction and water content.

To date, rammed earth has been regarded as a structural material much like masonry or concrete, and rules for design have developed accordingly. Little advice is available on the analysis of rammed earth structures, and even less on the origins of the material's strength. Walker *et al.* (2005) contains much guidance for the design and construction of rammed earth walls, which indicates that the most widely used measure of strength is unconfined compressive strength. Various heuristic rules are also available to determine the strength of rammed earth (e.g. King, 1997), although these are specific to the local conditions studied, and few laboratory studies are available (Lilley & Robinson, 1995). Knowledge that moisture affects the strength of rammed earth is evident in a number of these studies, although most are concerned to ensure ramming is carried out at a moisture content for good workability rather than optimum for dry density. Walker *et al.* (2005) state that 'compressive strength of moist rammed earth materials is likely to be at least 50% lower than the final ambient values', one of the few

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instances where development of strength over time, due to drying, is recognised.

A GEOTECHNICAL MATERIAL

Thinking geotechnically, rammed earth can be regarded as a compacted soil, but constructed into a form that is not usually considered for soil (i.e. a wall). Since the material is initially compacted and then allowed to dry it will be unsaturated, where the soil particles are surrounded by air in addition to water.

It is widely accepted that unsaturated soils achieve a component of strength through matric suction, $s = u_a - u_w$ (where u_a is the pore air pressure and u_w is the pore water pressure), which can be considered as an apparent cohesion. As soils dry, so suction increases, and consequently there is an increase in apparent cohesion and hence strength.

Clearly this suction-induced increase of apparent cohesion is not unlimited. Toll & Ong (2003) show that the contribution to strength from suction in a sandy clay 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, 1991). The apparent cohesion is therefore expected to peak between the two limits of zero water content and saturation. It should, however, be recognised that zero water content corresponds to an ideal limit condition as, even for an oven-dry soil, adsorbed water will still be present on clay particles and will be available to generate suctions.

Total suction is the sum of matric suction and osmotic suction, which is a function of the salts dissolved in the pore water. Total suction Ψ is linked to the relative humidity RH of the pore air through Kelvin's equation, which can be expressed as

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

where R is the universal gas constant, T is absolute temperature, ρ_w is the density of water, and w_v is the molecular mass of water vapour (Likos & Lu, 2002). Equation (1) shows that variations in RH between 100% and 95% lead to total suctions up to 1000 kPa. Development of suctions beyond this point requires very large changes in RH. These appear more likely for soil in a rammed earth wall than, for instance, soil in the vadose zone (owing to the larger surface-to-volume ratio in the former case). Evaporation of pore water is affected by the relative humidity of the pore air compared with 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.

Given the above, it seems obvious that a component of the strength of rammed earth must be due to matric suction, although this has not been proposed in the past, to our knowledge. A small programme of simple geotechnical testing was carried out to provide evidence of a link between matric suction and strength in rammed earth materials using tests that would be accessible outside the specialist geotechnical testing community. All tests were undertaken at constant water content, and are similar to some of those described in Vanapalli & Fredlund (1997) and Vanapalli *et al.* (1998). The tests are preliminary, and form the first part of a larger programme of research under way at Durham University. In addition to suction, there must also be a component of strength due to the ramming process, which will produce increased strength due to densification and possibly particle interlock, but this aspect is not investigated here.

EXPERIMENTAL PROCEDURE

The rammed earth mixture used in this study was taken from a development site at Aykley Heads, Durham, which included a large rammed earth wall (located inside a new building; Fig. 1). The mixture used on site was blended from material dug locally (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. For the purposes of these tests this rammed earth mixture was sieved to remove material retained on a 14 mm sieve. The particle size distribution for the test material is shown in Fig. 2.

Prior to sample preparation, the compaction curve for this rammed earth mixture was obtained by using a vibrating hammer (to BS 1377). This is shown in Fig. 3, and indicates that a sample prepared at a water content of 12% is close to saturation: corresponding to site practice as outlined above, this was the water content used to compact all samples tested in this work. The vibrating hammer test was used in preference to the standard Proctor test as it better resembled the compaction effort in a real rammed earth wall and in the sample preparation described below.

Cylindrical samples (200 mm × 100 mm diameter) were prepared using a Proctor split compaction mould, as outlined in Walker (2002), with modifications developed at Durham. Samples were compacted in five layers using 15 blows of a 4.5 kg hammer each time, following which a screed of particles passing a 425 µm sieve was placed on the top surface of the cylinder. This screed produced a flat loading surface and a fine particle paste on which to place the tensiometer used to measure matric suction. Immediately

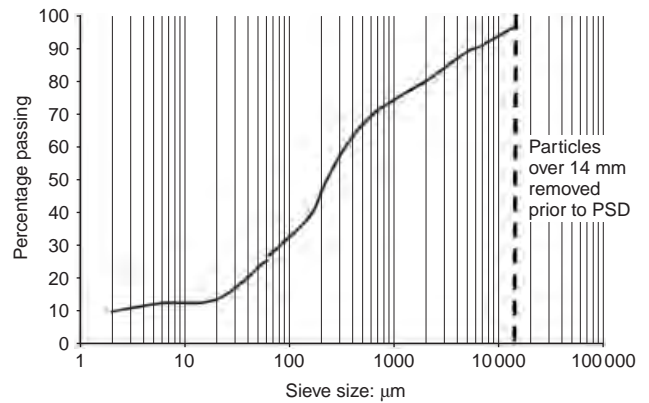


Fig. 2. Particle size distribution of rammed earth mix

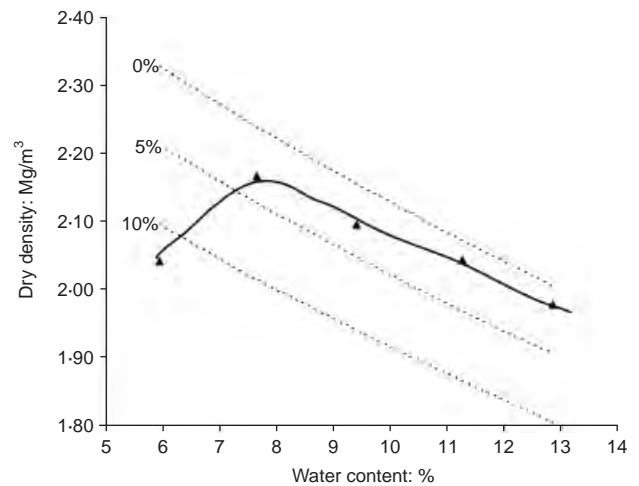


Fig. 3. Compaction curve from vibrating hammer test. Dotted lines correspond to different proportions of pore air volume

following application of this screed, the Proctor split mould was removed and the mass and height of the sample recorded. Dry densities between 2017 and 2061 Mg/m³ (similar to the dry density corresponding to a water content of 12% in the compaction curve of Fig. 2) were achieved using the same compactive effort each time. Once samples had air-dried to their respective target water contents (monitored through regular weighing), they were wrapped in an impermeable sheath secured with rubber O-rings placed against steel loading plates at the top and bottom. Target water contents were chosen to provide a well-spaced range of results. The samples were then left for at least 7 days to allow suctions to equilibrate throughout the sample, following which it was considered that the samples were ready for testing.

The samples were sheared under constant water content conditions in a triaxial rig. Displacement was controlled at a constant 0.1 mm/min and measurements of suction, load and axial displacement taken every 10 s. High-capacity tensiometers were used to allow direct measurement of suction at the top of the sample throughout the test (Lourenço *et al.*, 2006).

RESULTS AND INTERPRETATION

Six unconfined compression tests at constant water content were carried out on samples air-dried to different target water contents.

The suction measured on each of the six samples prior to shearing is shown against the corresponding water content in Fig. 4. Points on this plot represent measurements taken on different specimens dried to different water contents (i.e. it is not a continuous drying curve from a single specimen). The speculated behaviour for very low suctions is shown by a broken line back to the compaction water content of 12%, which corresponds to a suction around 1 kPa. The higher suction values in Fig. 4 are significant compared with those usually reported for unsaturated soils, either naturally occurring or arising from compaction.

Plots of deviator stress against suction are shown in Fig. 5. There is a clear link between initial water content and both suction and strength (measured as maximum deviator stress). In tests at low water contents (5.5–8.3%) suction is seen to drop during the test, whereas the opposite is apparent in the higher water content tests (9.4–10.2%).

The stiffness behaviour of the material is shown in plots of axial total stress against axial strain in Fig. 6. On a qualitative level the wetter samples have greater ductility whereas the drier samples are brittle. Fig. 7 shows the variation in suction during the tests against axial strain. The plot shows the rate of suction change reducing with axial

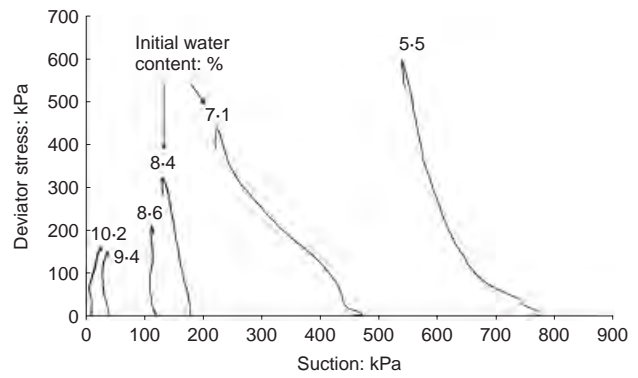


Fig. 5. Plots of suction against deviator stress

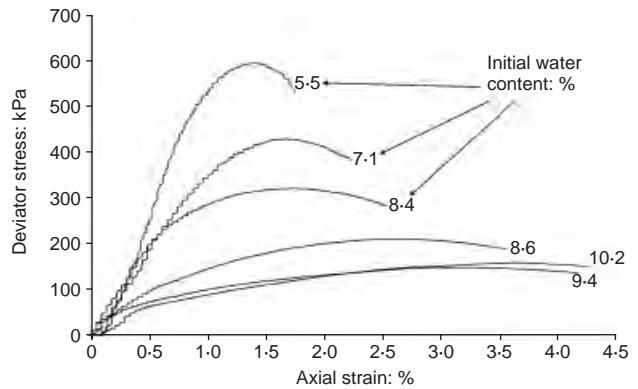


Fig. 6. Plots of deviator stress against axial strain

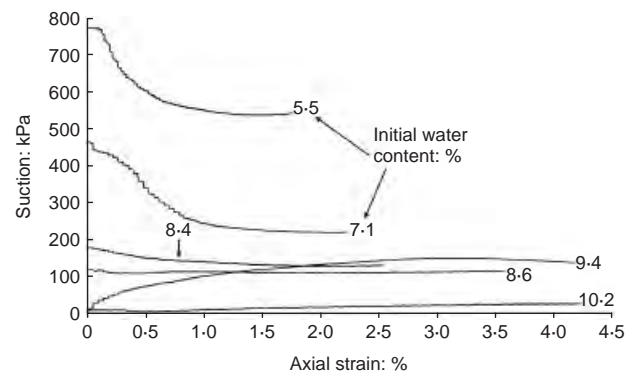


Fig. 7. Plots of suction against axial strain

strain, as seen in other studies of unsaturated soils (e.g. Toll & Ong, 2003).

For shearing under constant water content conditions, the fact that samples with initially low suctions show an increase in suction during shear whereas samples with high suction show the opposite is compatible with the existence of a unique water content–suction relationship at the critical state. Toll (1990) showed such behaviour for constant water content tests on lateritic gravel. There is a suggestion that there is a unique relationship between water content and suction at the critical state after the work of Croney & Coleman (1954), Brady (1988), Ridley (1995) and Tarantino (2007). The data show samples at low suction increasing in suction, whereas the reverse is true of samples at high suction.

It is also interesting to note that suctions may reduce (i.e. pore water pressures increase), even when the volumetric behaviour is dilatant, which might seem counter-intuitive. Toll (1990) explained this in terms of the aggregated fabric of compacted soils (often referred to as ‘double structure’).

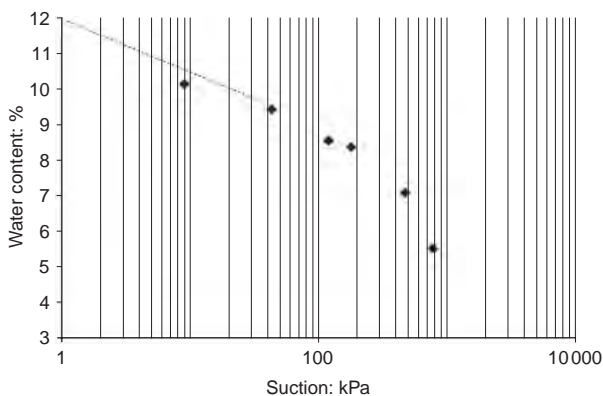


Fig. 4. Plot of initial suction against initial water content

The suction response results from compression within the aggregates (intra-aggregate), whereas the dilatant volumetric behaviour is controlled by the macro fabric (inter-aggregate) where shearing occurs between aggregates. Fig. 6 also indicates that the stiffness of the samples is suction dependent. In a critical state framework this could be accommodated as a link between elastic shear modulus and suction, similar to that suggested for bulk modulus in tests on compacted unsaturated soils by Mancuso *et al.* (2000).

The rammed earth tested in this work is clearly in different conditions from the rammed earth present in a heritage structure, for instance, and no in situ suction measurements of 'aged' rammed earth are presented here. However, if the link between suction and strength is maintained in rammed earth that has had time to dry in situ to relatively low values of water content, the results of Fig. 5 would indicate that the ratio of strength between aged in situ rammed earth and moist 'fresh' rammed earth may be much more than the factor of 2, as previously suggested by Walker *et al.* (2005).

Equally, if the in situ drying is taken further towards the limit when all water is removed from the material, then it is speculated that the apparent cohesion will start to drop back, due to the reduced efficacy of suction acting within the rammed earth. This failure due to drying is not seen in practice, because the pore structure of the material (due to the clay content) and the level of RH experienced do not allow for complete drying out.

CONCLUSION

The tests reported in this paper aim to show that suction is a source of strength in unstabilised rammed earth, and that the strength increases as water content reduces. The tests necessarily use laboratory-prepared samples of rammed earth, which may be in a different state from the rammed earth found in a wall, particularly one that is of some antiquity. However, the underlying source of strength should be the same. The soil materials in rammed earth are able to dry to a much lower degree of saturation than the majority of soils considered by geotechnical engineers because they are constructed as walls open to the atmosphere. Walls left to dry after construction, in a suitable climate, can be expected to develop very large suctions in the remaining pore water, and hence develop considerable strength over time. Further characterisation of rammed earth materials in geotechnical frameworks is necessary if the behaviour of existing heritage rammed earth is to be understood and the development of a design procedure for new-build rammed earth is to be rooted in a stronger scientific basis.

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