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INVESTIGATION INTO THE SHEAR BEHAVIOUR OF RAMMED EARTH USING SHEAR BOX TESTS

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Abstract

Scientific investigations into the structural properties of rammed earth (RE) are gaining momentum and a number of parameters (e.g. suction, particle size distribution and water content), influential on material strength and other properties, have been identified and investigated. Cement stabilisation is undergoing continued investigation, while fibrous stabilisation, also known as fibre reinforcement, is beginning to gain attention. Recent experiments have shown that the addition of fibres such as straw or wool to RE or other earthen materials can improve its flexural strength. Less attention, however, has been paid to the fracture behaviour of RE, and to its shearing behaviour. This paper presents a preliminary investigation into the shearing behaviour of stabilised and unstabilised RE reinforced with waste natural fibres. The Direct Shear Test (DST) is used to obtain peak shear stresses and displacements, from which strength parameters (ϕ') and cohesion (c') are obtained. This paper also presents some scanning electron microscope (SEM) images of these materials. The results show that wool fibres decrease the density and peak shear strength of RE. The effect of water, wool and cement content on ϕ' and c' are also discussed.

Keywords:

rammed earth, shear behaviour, direct shear test, scanning electron microscope, SEM

1 INTRODUCTION

Rammed earth (RE) can refer to both the construction material and the construction method. RE is traditionally composed of sand, gravel and clay to which water is added until it reaches the desired consistency, which varies according to the soil particle size distribution [Hall 2004]. It is rammed in-situ within a temporary formwork, which is then removed to allow the soil mixture to air dry. Modern RE construction often includes the addition of a stabiliser, typically cement, which enhances the compressive strength of the material by replacing suction with chemical bonding.

Investigations have revealed that suction, caused by shrinkage of water menisci between particles in unstabilised RE, is the primary source of unstabilised RE's strength [Jaquin 2009]. Water ingress, therefore, can be devastating for unstabilised RE, and damaging to stabilised RE, as proved by Hall [2006]. X-ray computed tomography (XRCT) scans of RE have been taken to investigate changes in internal structure after compressive loading and failure [Smith 2015].

Recently, RE has been subjected to a number of structural investigations, including three-point bending tests [Aymerich 2012], wind loading [Ciancio 2013] and fracture energy [Corbin 2014]. Aymerich [2012] investigated the effect of natural sheep's wool microfibres on the flexural behaviour of rammed earth using the three-point bending test on a notched beam and found that adding microfibres does little to affect the 'first-crack' strength of the material, although it did improve residual strength and ductility of the sample. The paper notes that little other work has been done in this area. Ciancio [2013] performed full-size wind-loading tests on RE walls. Her analytical methods for studying RE "correctly estimate[d] the capacity of the wall to resist wind pressure only when the assessment of the material properties is done rigorously", accepting that in reality, the many variables in RE construction are difficult to control.

Corbin [2014] performed a large series of tests investigating compressive strength and fracture behaviour of samples reinforced with wool and cement, finding that wool could be added to replace a portion of cement in the soil to maintain the required compressive strength.

Research into fibre-reinforced compacted soil has also been performed in order to stabilise and strengthen large earthwork constructions (such as embankments and dams). Consoli [1998] describes an investigation into the addition of fibre and cement to sandy soil. He found that the addition of fibreglass fibres increased shear strength and reduced rigidity within the samples

- shown by an increase in peak shear stress and an improvement in post-peak behaviour. Cement was found to increase stiffness and shear strength.

Diambra [2010] performed a series of triaxial tests on sand reinforced with crimped polypropylene fibres. Like Consoli, he found that the addition of fibres provided a “considerable” increase in strength of the material. He also performed triaxial tests in extension and found that fibres had little effect on the soil behavior for that case.

This paper investigates the effect of stabilisation (cement and fibrous) on the shear behaviour of RE in order to further understand failure behaviour. Cement stabilization was selected due to its prevalence within modern RE construction, and waste wool fibres from a carpet manufacturer was sourced as an environmentally-friendly, reliable waste stream for use as reinforcement. The Direct Shear Test (DST) was used to determine the ultimate shear behaviour of the material. Values of cohesion (c’) and angle of shear resistance (ϕ’) are presented and the effect of stabilisation on these material properties discussed.

2 METHOD

2.1 Materials and Sample Production

The soil used was designed to the ID 30*:70:0[2.2] (percentage ratio by mass of silty-clay : sand : gravel [percentage error] respectively) as described by Smith [2013]. The asterisk indicates that the clay and silt fractions have been combined. Speswhite, a 100% Kaolinite clay, was used for the clay fraction of the soil. Sharp sand, sieved to 2 mm, was used for the sand fraction of the mix.

The soil was mixed in a Hobart planetary mixer and left for 24 hours in sealed containers to allow the water to equilibriate through the soil. A 1 kg soil sample was retained in order to perform wet sieve, dry sieve and sedimentation tests. The resultant particle size distribution curve of the soil is shown in Fig. 1.

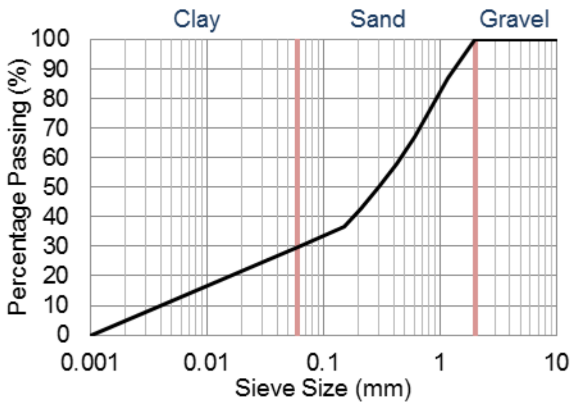

Fig. 3: Particle Size Distribution Curve for soil ID 30:70:00[2.2]*

Wool was sourced as waste from a carpet manufacturer. This wool came in strands, 0.7 mm in diameter when compressed and around 3mm diameter when relaxed, measured using a micrometer. It was cut into lengths of 30-50 mm. Tensile tests found that the average strength was 69.2 N/mm^2. Portland cement was used for the cement stabilisation.

DST samples (60 x 60 x 20 mm) were constructed in batches of six. Each batch contained a different percentage of cement (0, 2, 4, 6, 8 or 10 % by mass) and a different percentage of wool (0, 0.5, 1.0 or 1.5 % by mass). Soil batches with all possible combinations of cement and wool content were constructed, producing 24 batches of soil and 144 samples in total.

Each sample was given an ID (eg. W2C4-1) which provides a description of the contents of the sample. The numbers after the ‘W’ (wool) and ‘C’ (cement) refer to the amount of each material in the batch. The ‘-1’ suffix identifies the particular sample within a batch. It is noted that the number that indicates the wool content needs to be divided by 2 to obtain the actual percentage wool content of the sample, whereas the number indicating the cement content can be read directly. For example, sample W2C4-1 contains 1 % wool and 4 % cement, and is the 1st of 6 samples with this wool-cement combination.

Four additional sample batches with no wool or cement were created, each with a different water content at compaction (8 %, 10 %, 12 % and 14 %) in order to investigate the effect of initial water content, and hence density of the sample, on shear strength. These soil batches were given the IDs L1 to L4.

All samples were statically compacted within specially constructed formwork to fit within the DST rig. All samples, excluding the unstabilised samples specifically mentioned above, were compacted at the optimum water content of 11 %. This had been determined using a static load compaction test performed within an unconfined compression rig. Samples were then weighed and left to air dry for 7 days before testing.

2.2 Testing Procedure

Samples were re-weighed and tested 7 days after construction. Each sample was tested in a shear box rig with a vertical load applied to the top surface of the sample as detailed in BS EN 1377-7:1990. The test was performed at a rate of 1 mm/min, which was selected as a compromise between efficiency and obtaining reliable results. Within every batch of 6 samples, 2 were tested at 25 kPa, 2 at 50 kPa and 2 at 75 kPa vertical pressure. Maximum shear stress of each sample was plotted against corresponding vertical stress following standard procedures in geotechnical use of the DST. Assuming a Mohr-Coulomb failure criterion, apparent cohesion (c’) and angle of shear resistance (ϕ’) could subsequently be determined from the y-intercept and gradient of the line of best fit respectively. Fig. 2 shows an example case, batch W1C6, where the c’ value was 113.89 kPa and the ϕ’ value was 59.04°.

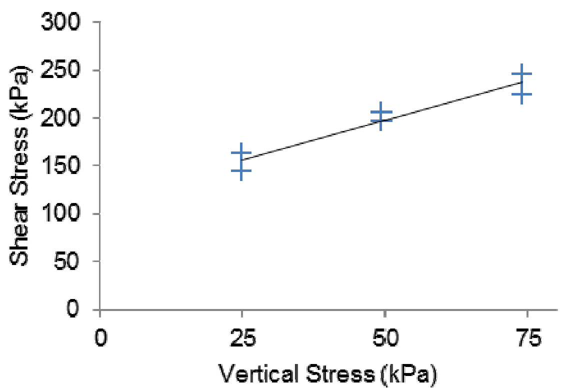

Fig. 4: Example plot of the determination of c’ and ϕ’ (Sample W1C6)

3 RESULTS AND DISCUSSION

3.1 Sample preparation and testing observations.

During sample construction, it was observed that the wool on the surface of the samples visibly expanded after the sample had been removed from the formwork. This suggested that wool within the sample was being compressed during compaction and would likely remain compressed within the sample, whereas the compression of the wool on the sample surfaces was released when the formwork was removed. Possible effects are discussed in Section 3.4.

Fig. 3 shows the fracture plane of sample W1C4-1. The soil appears pale in the image as the clay fraction of the soil was purchased clean and is hence white. Grey sections indicate areas of cement. The wool is obviously visible in the image which suggests that the wool was present within the crack zone. It was observed that samples with no wool sheared along a macroscopically straight crack plane, while samples with increasing amounts of wool had increasingly rough fracture planes. Assuming that failure initiates via fracture propagation, the following contrary hypotheses are suggested:

a) Wool within the sample adds areas of weakness. This would decrease the crack energy needed for the sample to fail and therefore decrease the maximum shear capacity.
b) Wool forces the crack plane to divert around some areas, which made the crack path longer. This would increase the crack energy needed for the sample to fail and therefore increase the maximum shear force required.

Fig. 5: Photograph showing the top (L) and bottom (R) halves of the fracture plane of sample ID W1C4-1.

3.2 DST response curve

6 samples were made with each batch of soil, but in some cases, due to incorrect sample failure either before or during testing, fewer than 6 repeat samples were used to calculate ϕ' and c'. The lowest number of samples in a batch was 3 (batch W0C3).

Fig. 4 shows an example DST response curve, displaying shear force and vertical displacement of the sample. This sample exhibited some vertical expansion after around 1.5mm horizontal displacement. This is in line with the fact that over-consolidated soils tend to dilate when sheared so is to be expected.

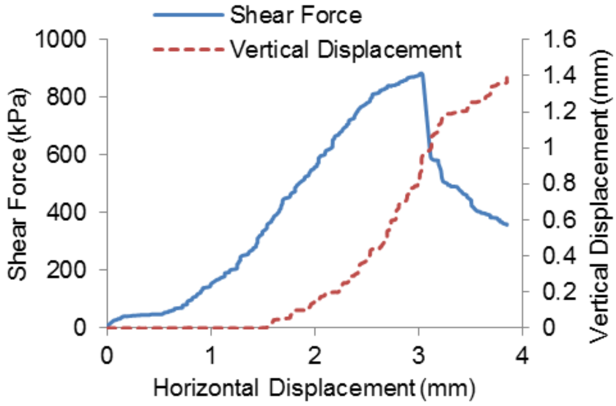

Fig. 6: Graph showing an example DST response curve, plotting shear force and vertical displacement against horizontal displacement.

3.3 Effects of Cement Content

Fig. 5 plots peak shear stresses of samples (tested at 75 kPa vertical pressure) with no wool content against their cement content. It shows that an increase in cement content results in an increase in peak shear stress, although it is noted that there is considerable variation in the results. Adding cement to a RE mix increases compressive strength, obviously, up to a point where further cement may actually lead to a decrease in compressive strength. In stabilised RE cementitous bonds are the major source of strength, whereas at lower or zero values of cement content (i.e. unstabilised RE), matrix suction may become a significant source of strength [Jaquin 2009]).

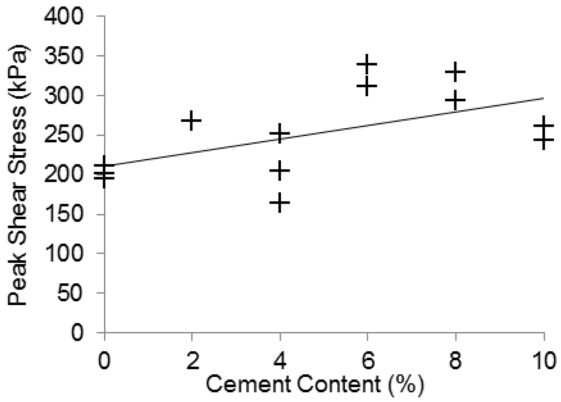

Fig. 7: Graph showing the relationship between peak shear stress and cement content in cement-stabilised samples without wool reinforcement, tested at 75kPa.

Values of ϕ' and c', obtained through the calculation method detailed in Section 2.2, were then plotted and arranged by cement content (Fig. 6). Batches W2C0 and W3C8 are not included in the graph as they have been identified as outliers; those batches yielded ϕ' values of 7.87 and 6.93 respectively. The authors are uncertain what factors caused this error; but it is suspected that it was due to poor compaction.

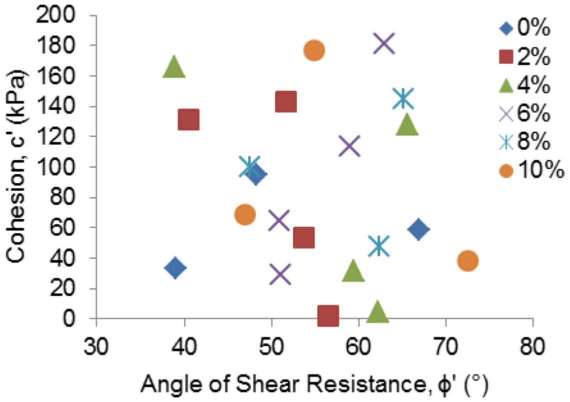

Fig. 8: Graph showing ϕ' vs c' of samples arranged by cement content

Fig. 6 plots ϕ' against c', arranged by cement content. The graph shows a wide variation in c' (0 kPa - 180 kPa) and in ϕ' (39° - 73°). Geotechnical engineers might react strongly to the idea of such large angles of friction but it has to be remembered that the material is unsaturated and also bonded, so very different to a natural soil. Similar high values have been found in other studies, e.g. Consoli [1998] found that adding 1% cement by mass increased c' by 46.8 kPa from 9.9 kPa to 56.7 kPa and increased ϕ' by 6° from 35° to 41°. Fig. 7 shows no evidence of a similar increase in this investigation. It is noted that the lowest ϕ' value is from a sample batch with 0% cement and the highest ϕ' value is from a sample batch with 10% cement, implying a very weak correlation.

3.4 Effects of Wool Content

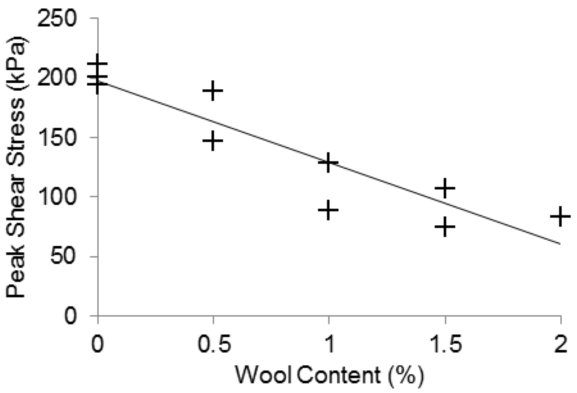

Fig. 9: Graph showing the relationship between peak shear stress and wool content in wool-reinforced samples without cement stabilisation, tested at 75kPa.

Fig. 7 shows the relationship between wool content and peak shear stress of non-cement-stabilised samples. There is a clear decrease in peak shear stress as wool content increases, confirming that hypothesis (a) in Section 3.1 is more likely.

Values of ϕ' and c' were then plotted against each other as in Section 3.3 and arranged by wool content. The resultant plot can be seen in Fig. 8.

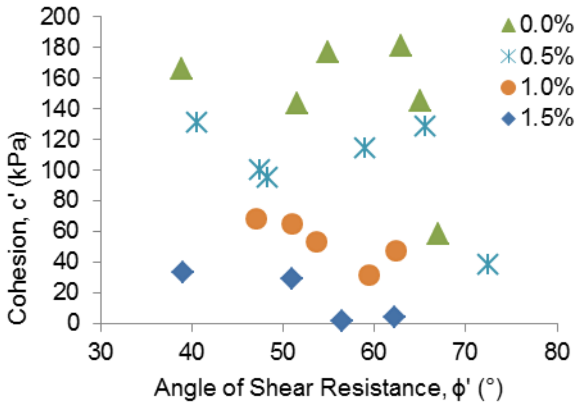

Fig. 10: Graph showing ϕ' vs c' of samples arranged by percentage wool content

Diambra's 2010 study on the shear strength of fibre-reinforced sands obtained values of ϕ' of around 33° with no fibres and around 42.7° with 0.9% fibres using conventional drained triaxial compression tests. His samples also gave cohesion values of around 6 kPa (no fibres) to around 70 kPa (0.9% fibres). His tests used polypropylene crimped fibres of 25 mm length [Diambra 2010].

Fig. 8 clearly shows that cohesion c' decreases as wool content increases, apparently contrary to Diambra's experimentation. Wool compaction, described in section 3.1, might help to explain this different result. Compaction of the wool during manufacture could lead to relaxation on completion of manufacture which would create potential weaknesses adjacent to the wool fibres. During testing, samples with more wool therefore would have more initial "damage" than other samples with less wool resulting in a lower shear strength and lower cohesion.

Wool was also found to decrease the density of the sample, as can be seen in Tab. 1. The authors suggest that this is also linked to drop in cohesion and peak shear stress.

Tab. 3: Effect of wool on sample density

Wool Content	Average Density (kg/m3)
0%	2131.4
0.5%	2083.9
1.0%	2015.1
1.5%	1938.0

3.5 Effect of Water Content

As indicated above, samples with varying water content and no cement or wool were tested and the results are shown in Fig. 9. Each sample was compacted to the highest dry density for its water content to maintain consistency of construction method.

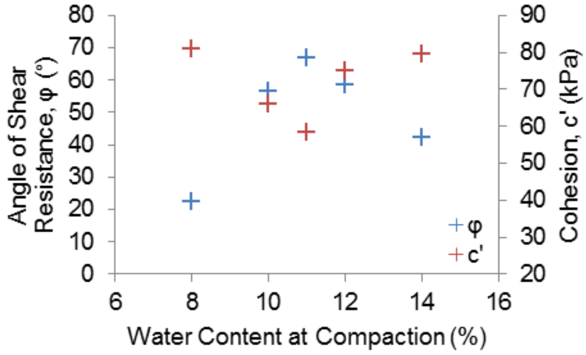

Fig. 11: Graph showing samples with varying water content

The graph shows clear variations in ϕ' and c' as water content increases. At optimum water content (11% for this soil), c' is at a minimum, while ϕ' reaches a maximum.

3.6 Scanning Electron Microscopy

It was observed after sample failure that many samples, particularly those that contained wool, retained a considerable residual strength after peak shear force had been reached (Fig. 4). This behaviour had been previously reported in Consoli [1998] from the addition of fiberglass fibres. It therefore follows that this behaviour, seen in the experiments described above, results from the presence of microfibre parts of the wool strands which had loosened from the main fibre. The microfibres were embedded into the sample and so continued to hold the sample together after a macrocrack had formed.

One of these microfibres was identified and scanned used a scanning electron microscope (SEM). The sample was coated in an ultra-thin layer of gold in order to prevent the sample from charging and hence improve the image quality. The sample was mounted on a specimen stub using epoxy resin before scanning. The resultant image is shown in Fig. 10, which shows the wool microfibre emerging from within the stabilised RE sample (W1C4-1) at the bottom of the image.

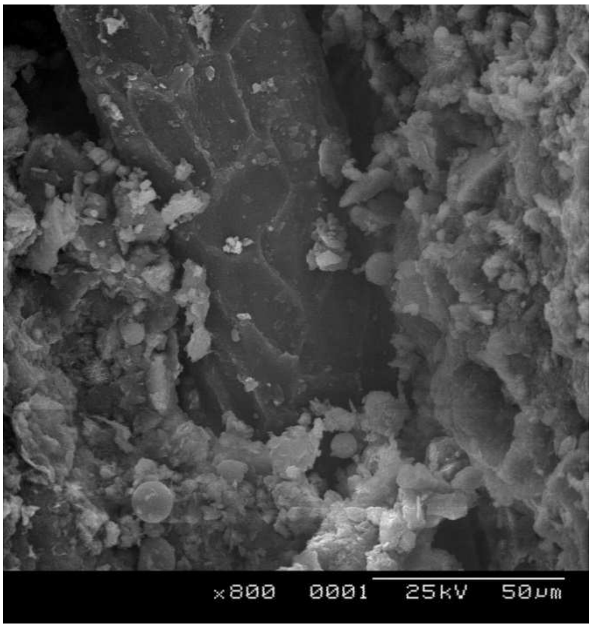

Figure 12: Composite image of an SEM scan of a wool microfibre embedded in a stabilised RE sample.

The image appears to show little or no bonding between the wool and the RE, implying that the strength added by microfibres is a result of contact friction alone.

Figs. 11 and 12 show additional SEM scans of samples without (Fig. 11) and with (Fig. 12) cement stabilisation. Both samples were scanned at the same voltage and scale. Lines in fig. 11 (seen on the left hand side of the image) are a result of charging within the sample, likely due to an insufficient coating of gold.

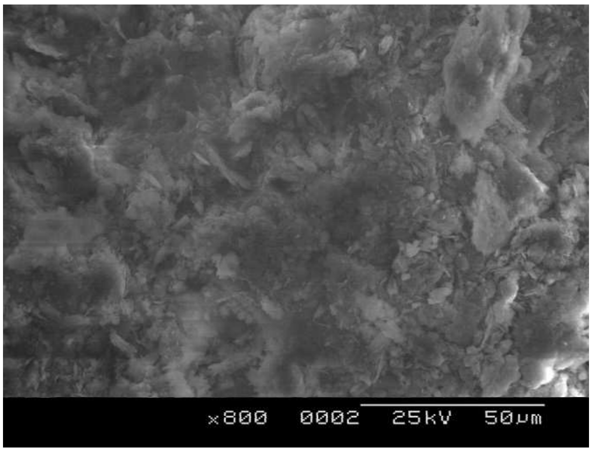

Fig. 13: SEM scan of an unstabilised sample.

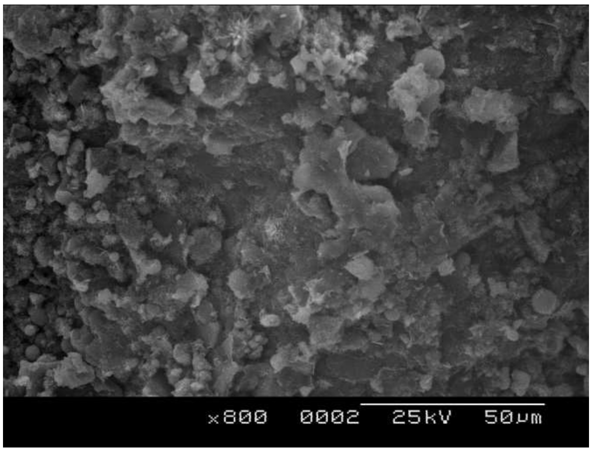

Fig. 14: SEM scan of a cement-stabilised sample.

It is clear that the sample in Fig. 9 has fewer nodules within the field of view and hence appears smoother. This is likely due to the lack of cement within the sample. Smoothness of the crack plane suggests a shorter, more direct crack path through the sample, which could be linked to a lower peak shear strength. It is suggested that addition of cement alters the length of the crack path, increasing the force required for sample failure. This hypothesis fits with work previously undertaken by the authors [Corbin 2014]. It therefore follows that samples with greater amounts of cement would provide a greater peak shear stress. This can be confirmed with the results shown in Fig. 6 in Section 3.3.

4 CONCLUSIONS

Results presented in this paper suggest that fibre-reinforcing a Kaolinite-clay RE mix, using wool that is compressible, and compacting the sample to maximum density has the effect of roughly doubling the angle of shear resistance and inverting the relationship between wool content and cohesion. Diambra's [2010] results suggest that adding fibres increases cohesion, but results in this paper suggest the opposite. Diambra used only microfibres, opposed to wool strands used in this study, which suggests that the difference in results might be due to the compression and relaxation effects of the wool used, as described in Section 3.1.

Consoli [1998] found that "peak friction angle increase[d] from a minimum of 35° for uncemented, nonreinforced soil to 41° or 46°, respectively, when cement or fiber is added". He also observed that adding both cement and fibre increased the peak friction angle to 46°, the same value as when fibre only is added. This paper has not found an relationship between cement content and the angle of shear resistance or cohesion of the sample, unlike Consoli.

This paper has also found that SEM scans can be used to observe RE at a large scale, although care has to be taken to maximize image detail. It has been found that wool does not appear to bind to RE, instead it appears to gets its strength from friction and interlocking around the soil particles, although more work should be done to confirm this. An SEM has also been used to observe that unstabilised fracture planes appear to be smoother than stabilised, possibly contributing to an increase in shear strength.

5 ACKNOWLEDGMENTS

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6 REFERENCES

[Aymerich 2012] Aymerich, F.; Fenu, L.; Meloni, P.; Effect of reinforcing wool fibres on fracture and energy absorption properties of an earthen material. *Construction and Building Materials*, 2012, vol. 27(1), pp 66–72.

[Ciancio 2013] Ciancio, D.; Augarde, C.E.; Capacity of unreinforced rammed earth walls subject to lateral wind force: elastic analysis vs. ultimate strength analysis. *Materials & Structures*, 2013, vol. 46, pp 1-17.

[Consoli 1998] Consoli, N.; Prietto, P.; Ulbrich, L.; Influence of fiber and cement addition on behavior of sandy soil. *Journal of Geotechnical and Geoenvironmental Engineering*, 1998, vol. 124(12), pp 1211-1214.

[Corbin 2014] Corbin, A.J.; Augarde, C.E.; Fracture Energy of Stabilised Rammed Earth. *Procedia Materials Science*, 2014, vol. 3, pp 1675-1680.

[Diambra 2010] Diambra, A.; Ibraim, E.; Muir Wood, D.; Russell, A.R.; Fibre reinforced sands: Experiments and modelling. *Geotextiles and Geomembranes*, 2010, 28, vol. 3, pp 238-250.

[Hall 2004] Hall, M.; Djerbib, Y.; Rammed earth sample production: context, recommendations and consistency. *Construction and Building Materials*, 2004, vol. 18, pp 281-286.

[Hall 2006] Hall, M.; Djerbib, Y.; Moisture ingress in rammed earth: Part 2 - The effect of soil particle-size distribution on the absorption of static press-driven water. *Construction and Building Materials,* 2006, vol. 20, pp 374-383.

[Jaquin 2009] Jaquin, P.; Augarde, C.; Gallipoli, D.; Toll, D.; The strength of unstabilised rammed earth materials. *Géotechnique*, 2009, vol. 59, pp 487-490.

[Smith 2013] Smith, J.C.; Augarde, C.E.; A new classification for soil mixtures with application to earthen construction. Durham University, 2013.

[Smith 2015] Smith, J.C.; Augarde, C.E.; The role of clay and sand in the mechanics of Soil-Based Construction Materials In: Ciancio & Beckett (eds.) *Rammed Earth Construction,* pp 145-149.