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Fracture energy of stabilised rammed earth

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Abstract

Unstabilised rammed earth (RE) is the name given to both a construction method and a material that has been used by Man for thousands of years. Recently, it has received renewed interest as the desire for sustainable construction methods has increased, as it commonly uses subsoil from the construction site, hence reducing waste and transport costs. It has been established that the addition of stabilisers, such as cement or lime, increases the ultimate compressive strength (UCS) of RE, while the addition of fibrous material, such as straw or wool, has been shown to improve flexural strength. This paper describes experimental work investigating the fracture properties of RE, an area in which little research has been conducted to date, despite the brittleness of most variants of these materials. The effect of both stabilisation and fibre reinforcement are reported here from samples with 0 - 12% by mass of cement and different amounts (0%, 1%, 2% by mass) of waste fibres. Fracture energies were determined using a modified wedge splitting test (WST) and results are presented that demonstrate the clear effect of fibrous reinforcement on specific fracture energy.

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1. Introduction

Rammed earth (RE) is the name given both to a construction material and to the technique by which it is used to construct monolithic walls. The material comprises a mixture of sand, gravel and clay which is wetted to its optimum moisture content before being rammed insitu between formwork. As the material dries, suction forces increase providing considerable and surprising strength (Jaquin et al., 2009). Many significant heritage structures exist worldwide made of this material and there is considerable interest in effective conservation. In modern RE construction, cement is often added to the basic mix to improve strength and the material is described as “stabilised” RE. Some areas of research have received much interest, for example; stabilisation (Burroughs, 2008; Hall et al., 2012), the effect of water on compaction (Hall and Djerbib, 2004a), on-site tests for determining optimum water content (Smith and Augarde, 2013b), and the effect of water ingress (Hall and Djerbib, 2004b). Research into fracture in RE, however, is limited. Aymerich et al. (2012) investigated the addition of different lengths (1cm, 2cm and 3cm)

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of wool microfibres into an unstabilised RE mix, finding that fibrous reinforcement ‘improved the residual strength, the ductility and the energy absorption’ of the sample compared to the unreinforced soil. Ciancio and Augarde (2013) performed wind-loading tests on a 1.2m high RE wall and undertook subsequent elastic and ultimate strength analysis of the results, devoting some of the investigation to fracture although they concluded that it was difficult to estimate fracture energies for these materials without specific testing. Here, we describe a large suite of tests investigating the fracture properties of RE materials, using both cement as stabiliser and wool fibres as reinforcement.

2. Method

RE structures are made by compacting soil in layers 200-300 mm deep between two faces of metal or wooden formwork. When the desired height of wall is reached, the formwork is removed and the completed wall exposed. The tests described below were designed to mimic construction as much as practicable while maintaining the integrity that a laboratory environment can provide.

2.1. Soil Mix Design and Production

The soil mix in all tests was specified as 30*:60:10[2.1] (percentage ratio by mass of silty-clay:sand:gravel respectively) as described in Smith and Augarde (2013a). Speswhite clay was used, which is 100% Kaolinite. The optimum water content for the mix was established using the Vibrating Hammer Test as detailed in BS1377 (302, 1990). The soil was mixed in small 8.4kg ‘lots’ in a Hobart planetary mixer before 5 ‘lots’ were combined in a Croker rotating pan mixer to produce one soil batch of 42kg. A 1kg sample of each soil batch was then oven-dried to calculate water content before performing wet sieve, dry sieve and sedimentation tests.

Samples were constructed with a range of cement and fibre fractions. Cement was added up to 10% by mass of soil mixture, while wool fibres were added up to 2% by mass. Each mix was given an identification code of the form Wn-Cm where n and m are the percentages of wool fibres and cement respectively. Extra water was added according to the mass of cement and wool to keep the water content constant at 12%, immediately prior to compaction to minimise hydration of the cement before sample construction. The wool fibres used were waste material from a carpet manufacturer. The average diameter of each strand was 0.7mm, and the wool was cut into lengths of 30-50mm. Tensile tests on the fibres found that the average strength was 69.2 N/mm².

2.2. Choice of Test

Fracture energy is the amount of energy needed to generate and propagate a crack through a material, and is a measure of how resistant a material is to crack formation, and hence is one indicator of flexural strength in a brittle material. The amount of work done, \mathcal{W} , to extend a crack by length δa in a material of thickness b and resisted by a force \mathcal{R} , can be expressed as:

$$\mathcal{W} = \mathcal{R} \times b \times \delta a. \quad (1)$$

As RE is a very brittle material and hence the elastic energy is negligible, it may be assumed that the crack growth resistance \mathcal{R} is equal to the specific fracture energy, G_f , hereafter referred to as fracture energy Bazant and Planas (1998). Hence fracture energy equals the work \mathcal{W} divided by the crack area ($b \times \delta a$). The work done can be measured for a given test by calculating the area under a force-displacement plot.

The two main tests for calculating the fracture energy of concrete are the three point bending test and the wedge splitting test Brühwiler and Wittmann (1990). The latter was chosen for testing the materials in this study since it has some distinct advantages over the three point bending test for these materials Shah and Carpinteri (1991), i.e. it uses a much smaller sample so they are easier to transport, and the test sample shape and size eliminates any effects of the self-weight of the sample, as the samples are the same size as the test area. Figure 1 shows the sample shape and assembly of testing apparatus. A vertical force F_v is applied to the wedge plate and the crack opening displacement (COD) is measured at the crack mouth. The splitting force, F_s , is the resulting horizontal force applied to the sample through the wedge and bearings as shown in Figure 2.

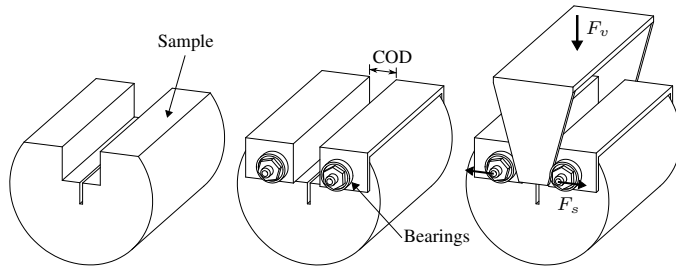


Fig. 1: Wedge Splitting Test Arrangement

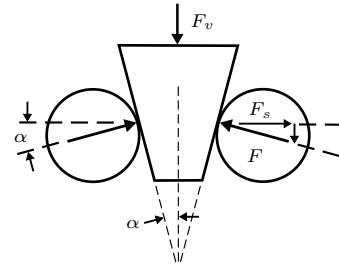


Fig. 2: Force Equilibrium

2.3. Sample Production, Testing and Analysis

Each soil batch contained enough soil for 6 cube samples to determine unconfined compressive strength (UCS) and 6 cylindrical samples for fracture testing. The cylindrical samples were compacted in 5 layers, each 30–40mm deep, and compacted using a pneumatic hammer for 60s per layer. The cube samples were constructed in 3 layers, each 30–40mm deep, and compacted for 30s per layer, after which the top was levelled to the top of the mould to ensure all cube samples were constructed with the same volume. All samples were removed from their moulds immediately after compaction and left to dry in an indoor, open environment for 14 days. The cube samples were then crushed and the peak load measured. The cylindrical samples were tested using a displacement-controlled triaxial test rig, which was set to move vertically at a rate of 0.1 mm/min. The test setup and arrangement is shown in Figure 1. COD was measured using two LVDTs and the vertical force, F_v , was measured using a load cell attached to the loading frame. α , the wedge angle, was chosen to be 30° , as a compromise between rig space limitation and friction, thus $F_s = F_v / \tan \alpha$.

The readings taken from the test rig were imported into Matlab MATLAB (2010). The force applied at the load cell F_v was converted into the splitting force F_s , then G_f and maximum F_s were calculated.

3. Results and Discussion

3.1. Experimental Observations

It was observed in each test, that after the peak load had been reached, a crack formed and began propagating down through the sample. As the crack progressed, the samples containing wool behaved very different to those without. In the latter, F_v dropped steadily following the peak until the test was halted (Figure 3a), whereas samples with wool dropped to between 60% and 80% of the maximum load then remained at that force ($\pm 20\%$) until the test was halted (Figure 3b). In the latter cases, it was evident that the force was being transferred from the RE onto the wool. Instead

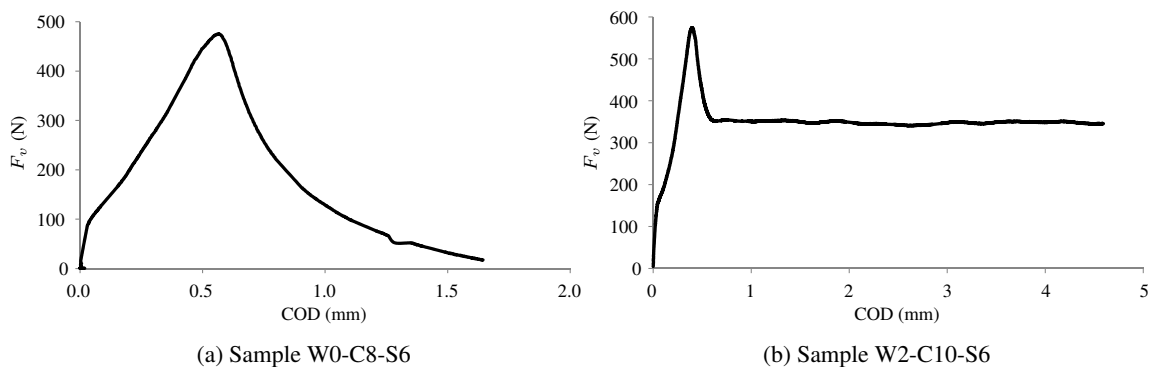


Fig. 3: Example force-displacement curves

of breaking, however, the wool was being pulled out of the sample, indicating that the bond strength between the RE and the wool was less than the tensile strength of the wool alone. This behaviour meant that fracture energy could only be determined from the portion of the graph before the crack appeared, which was also the portion of the graph up to the maximum load.

Once the samples were broken, it was clear that the percentage of cement altered the crack path. Samples with little or no cement generally created slightly longer paths, preferring to encircle areas of apparently higher crack resistance, such as areas with a greater density due to presence of larger soil particles. Samples with higher cement content, however, generally took straighter crack paths to the edge of the sample, often cutting through some pieces of gravel. In these cases, it is evident that the cement bonding between particles, together with the extra energy needed to make the crack change direction, was greater than the strength of the pieces of gravel.

3.2. Fracture Energy

Average G_f values are plotted against average UCS in Figure 4. Samples with the same wool percentage are grouped and lines of best fit provided (R^2 values are provided in Figure 4). It can be seen, in the majority of samples, the amount of wool makes negligible difference to the fracture energy, but does affect UCS. There is, however, an anomaly at 6% cement and 2% wool, where the fracture energy of the sample containing 2% wool is more than double that of the sample containing 1% wool. In this case, 2 of the 5 samples tested produced a fracture energy close to double that of the other three. It is notable that these results are linked by similar maximum forces but much larger displacements at maximum force, which creates a much larger area under the F_s -COD curve, hence a larger fracture energy. It is suspected that this behaviour is due to a difference in the wool arrangement within the sample. If those two results are disregarded, the average fracture energy drops to 15.53 N/m and the R^2 value increases to 0.8661. There is also a slight anomaly at 10% cement and 1% wool, although this may be due simply to the number of samples tested. Due to multiple sample failure, only 2 fracture tests were able to be performed successfully for this particular combination.

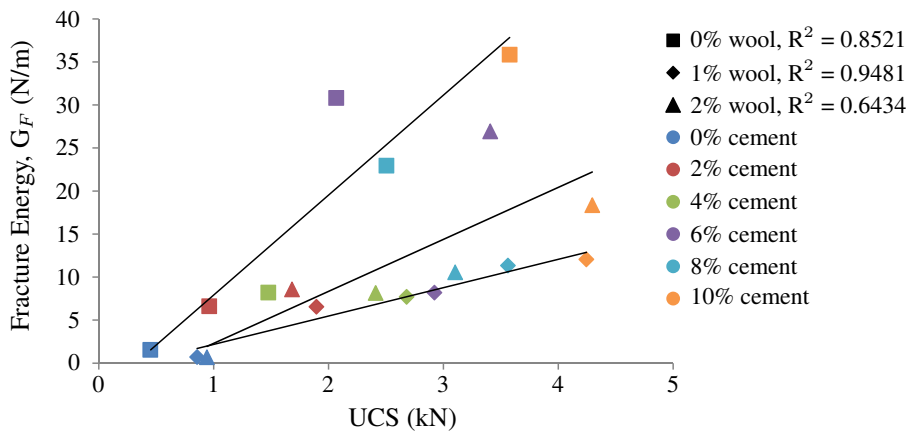


Fig. 4: Results of Fracture Energy and UCS

Figure 4 also indicates that for a given UCS, adding wool approximately halves the fracture energy. Adding wool was found to decrease the density of a sample by approximately 0.8%, which might contribute to, but would not be the main cause of, the large difference in fracture energy. Increasing wool content also increases the likelihood of any wool strands lying within, but not across, the crack zone. Any such wool would not only create an area of weakness, but also decrease the area of effective bonding within the crack zone. It is also noted that when subjected to tensile tests to determine maximum strain, the wool strands increased in length by approximately 35% before they failed. This means that the wool would take a negligible fraction of the load as RE is a very brittle material and undergoes very limited elastic deformation.

Table 1: Average values of UCS and G_f . Numbers in brackets indicate the number of samples tested. Where fewer than 6 samples have been tested, this was due to substandard sample quality.

Batch ID	UCS (kN/mm^2)	G_f (N/m)	Variability in UCS	Variability in G_f
W0-C0	0.45 (5)	1.53 (6)	+13%, -21%	+89%, -73%
W0-C2	0.96 (6)	6.62 (5)	+29%, -42%	+31%, -59%
W0-C4	1.48 (6)	8.21 (4)	+25%, -33%	+11%, -18%
W0-C6	2.07 (6)	30.81 (5)	+30%, -35%	+65%, -59%
W0-C8	2.50 (6)	22.94 (6)	+21%, -21%	+38%, -32%
W0-C10	3.58 (6)	35.85 (6)	+25%, -28%	+65%, -60%
W1-C0	0.86 (6)	0.71 (4)	+5%, -8%	+69%, -46%
W1-C2	1.89 (6)	6.55 (6)	+4%, -2%	+107%, -71%
W1-C4	2.68 (6)	7.70 (5)	+7%, -7%	+95%, -37%
W1-C6	2.92 (6)	8.19 (5)	+9%, -12%	+73%, -79%
W1-C8	3.56 (6)	11.33 (6)	+5%, -3%	+59%, -82%
W1-C10	4.24 (6)	12.06 (2)	+7%, -4%	+4%, -4%
W2-C0	0.94 (4)	0.68 (5)	+8%, -5%	+80%, -64%
W2-C2	1.68 (5)	8.56 (5)	+10%, -9%	+133%, -83%
W2-C4	2.41 (6)	8.15 (6)	+7%, -9%	+47%, -41%
W2-C6	3.41 (6)	26.93 (5)	+12%, -9%	+149%, -78%
W2-C8	3.10 (6)	10.55 (5)	+5%, -9%	+48%, -48%
W2-C10	4.30 (6)	18.35 (6)	+8%, -5%	+47%, -39%

Average values of specific fracture energy G_f and UCS are given in Table 1, alongside the variability of the results around the average values. It is clear that samples with no wool have a much greater variability in UCS than those with wool, with an average variability of $\pm 27\%$ opposed to $\pm 6\%$ or $\pm 8\%$ for 1% and 2% wool respectively. Variability in G_f follows the opposite pattern where samples with 0% wool have a $\pm 50\%$ average variability, whereas samples with 1% and 2% wool have variability of $\pm 74\%$ and $\pm 71\%$ respectively.

It is currently believed that, if constructed correctly, RE can generally assumed to be an isotropic material as long as the layers remain attached Bui and Morel (2009). The addition of wool fibres, which naturally lie parallel to the plane of compaction, may affect isotropy by creating lines of weakness parallel to the compaction plane, particularly in samples with large amounts of wool. This would imply that fracture energy parallel to compaction planes would be less than measured perpendicular, as has been measured in this paper. This is a less conservative approach, but necessary due to the construction method.

3.3. Cube Strengths

Figure 5 clearly shows that adding wool and adding cement both increase UCS independently. It appears, however, that the amount of wool is not a critical factor; the graph shows that 1% and 2% wool both follow similar lines of best fit. R^2 values indicate that the variability of the UCS of cubes with 0% wool is much greater than the variability of those with 1% or 2% wool. Samples containing 10% cement, in particular, had wide ranging values of UCS, ranging from 2.57 to 4.48 kN/mm^2 . Figure 5 also clearly shows that adding wool to the soil mix increases UCS by approximately 0.8 N/mm^2 .

4. Conclusions

This fracture properties of earthen construction materials have not been the subject of detailed investigation to date, despite the key role fracture must play in real structures. In this paper we have presented the results of a number of tests to measure fracture energy and compressive strength. The wedge splitting test has been found to be appropriate

for these materials. The addition of cement increases the fracture energy of these materials, but the addition of wool tends to do the opposite, although its presence actually alters the failure mode from brittle fracture to a quasi-ductile mode, so fracture energy may not be an entirely appropriate measure. The addition of wool and cement increase UCS. Cement is shown to increase UCS according to the amount added, while wool is shown to increase it by an apparent set amount. This implies that there must be a critical amount of wool, where adding more does not increase UCS. Interpreting the results differently, an alternative to stabilisation can be suggested: to design a mix to a given UCS, it is possible to add a percentage of wool to the mix and hence reduce the amount of cement needed to attain the desired strength. Addition of wool, therefore, does not only use a waste material from another manufacturing process, but also reduces amount, and hence cost, of cement needed, which reduces the carbon footprint of the construction.

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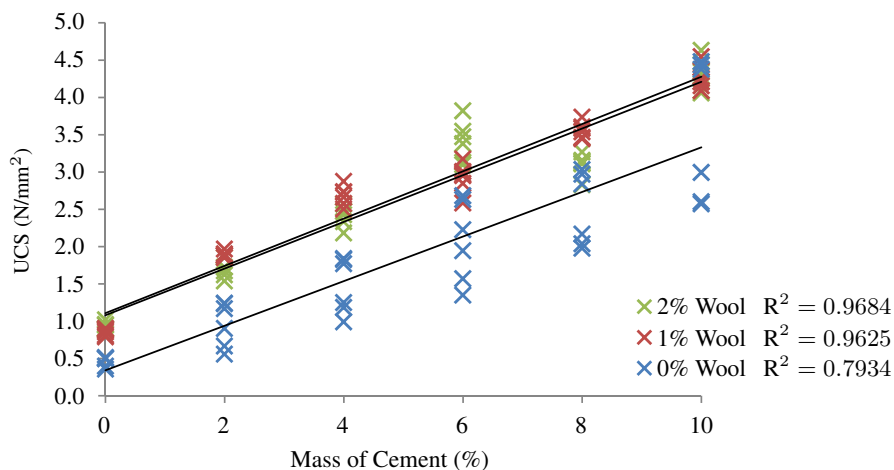


Fig. 5: Results of UCS and Cement Content

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