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Fibre reinforcement in earthen construction materials

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Earthen construction materials are generally brittle with low tensile strength. To deal with this in practice, it is often proposed that reinforcement be added in the form of fibres of various materials. Construction in earthquake-prone parts of the world is thought to benefit from this form of reinforcement, and indeed fibres (in the form of straw) are a key part of many adobe (unit-based) materials. To remain in harmony with the generally excellent environmental credentials of these materials, the reinforcement should be obtained from a natural material ideally obtained as a waste stream, so natural fibres are often chosen. While some studies have been published on the macroscopic mechanical behaviour of reinforced earthen materials, little is known of what is happening at the interface between the soil matrix and the fibres. In this paper, the authors present laboratory-based studies that attempt to fill this gap, covering pull-out behaviour of natural fibres embedded in earthen construction materials, both stabilised and unstabilised.

Notation

D	fibre diameter
E	fibre Young's modulus
F	pull-out force
L	fibre active length
α	fibre adhesion
δ	fibre interface friction angle
σ_n	normal fibre stress
τ_u	limiting shear stress

1. Introduction

Unstabilised rammed earth is potentially a low-carbon replacement material for cement-based block work or fired clay brick in wall construction. However, due to its low strength and brittle behaviour, the limited guidance available in standards (e.g. SNZ, 1998) indicates that very thick walls are needed, and this reduces the economic case for its use since it is labour intensive. Stabilised rammed earth is usually of higher strength than its unstabilised counterpart, but still brittle and often has a limited carbon benefit due to the type and quantity of stabiliser used. A compromise could be reached by including a different mechanical form of stabiliser in rammed earth based on fibres, to provide tensile reinforcement, thus improving ductility and increasing strength, an approach that is found in heritage structures (Jaquin and Augarde, 2012). Other long-standing earthen construction materials already incorporate materials doing this job – for example the straw in cob and adobe. Therefore, it is natural that there has been interest in fibre stabilisation of rammed earth; however, much of this research has focused on the behaviour of the composite material instead of the interaction between fibre and soil. To understand the material and, at some point in the future, move towards a modern design approach for fibre-reinforced rammed earth, an improved understanding of the fibre–soil bonding mechanisms is required (much as concrete technology was advanced by the understanding of bond and anchorage length in the nineteenth and twentieth centuries). To this end, this paper presents results from laboratory testing of fibres in earthen construction materials, both unstabilised and stabilised, and draws some conclusions useful both for those considering this form of construction and those interested in further research.

2. Background

2.1 Fibre stabilisation in rammed earth

The effects of adding fibre stabilisation to rammed earth have been widely researched; however, there is little published research on the fibre–earth interface bond. In previous studies, it was found that adding fibres to rammed earth or to composite soils either decreased the unconfined compressive strength (UCS) (Maniatidis and Walker, 2003; Schroeder *et al.*,

2005) or gave a small increase at low-fibre contents (Bouhicha *et al.*, 2005; Galán-Marín *et al.*, 2010; Ghavami *et al.*, 1999; Houben and Guillaud, 1994; Marandi *et al.*, 2008). The effect of fibre content on UCS was possibly governed by the clay content of the soil; soils with larger clay contents responded to increased fibre content with a higher UCS, while more sandy soils showed a lower UCS with increased fibre content. The effect of fibres on the shear strength of earthen construction materials has received even less coverage than the published works on UCS. Cheah *et al.* (2012) compared shear strengths (assuming a simple Mohr–Coulomb failure criterion) measured for large rammed earth samples using standard triaxial and triplet tests (the latter similar to those used on masonry wallets). Their results indicate that the presence of fibres decreases apparent cohesion, but increases the friction angle when failure occurs by shearing involving fibres. Another recent study, which reports shear box tests on samples of rammed earth reinforced with wool fibres, did not, however, come to the same conclusion on friction angle (Corbin and Augarde, 2015). Either way, as with UCS, the addition of fibres does not appear automatically to increase strength.

All sources that investigated linear shrinkage of rammed earth samples showed a reduction with increasing fibre content, as might be expected. Equally, all sources noted that failures occurred in a more ductile manner (e.g. Bargh, 2010; Houben and Guillaud, 1994; Schroeder *et al.*, 2005). It is hypothesised in many of these references that the material property changes are due to additional tensile stresses being mobilised within included fibres. This would help to distribute forces throughout the entire sample, preventing shrinkage, limiting crack propagation and also leading to more ductile failures. If tensile forces within the fibres are indeed responsible for this behaviour, as seems reasonable, then fibre pull-out is one of the key factors affecting the properties of fibre-stabilised rammed earth.

The use of sisal and coconut fibres in composite soil blocks, sourced locally in Brazil, is investigated in Ghavami *et al.* (1999). The experiments used 4% of sisal or coconut fibres 50 mm length and the results showed an increase in ductility and a minor increase in compressive strength for both types of fibres. Using sisal fibres, the water absorption was shown to be greater than that with coconut fibres. However, both fibres prevented the creation of shrinkage cracks. Bitumen was added, although it did not improve bonding, but increased ductility. Ten years after this study, Attom *et al.* (2009) investigated the use of two fibres: one natural and the other synthetic (palmyra and nylon, respectively). The study researched the changes in mechanical behaviour using randomly oriented fibres in three different types of clay soil, sourced in Jordan. Tests were carried out at five different percentages, between 1 and 5%, by mass of solid soil particles. The results showed that the use of the natural fibre led to a greater improvement in the relative UCS than the synthetic fibre. This suggests that natural fibres may be better to use in soil-based construction materials than synthetic fibres; however, durability with the latter is clearly a concern. When using stabilisers, there is an additional concern as to the accelerated deterioration of fibres due to chemical effects. Studies involving cycles of wetting and drying of fibres in the presence of strong alkalis, as might occur during curing of mortars, show major drops in strength both of the fibres and then of the fibre-reinforced mortar (e.g. Ramakrishna and Sundararajan, 2005). However, this may be a minor concern with earthen construction materials where (*a*) the alkalinity during curing will be lower due to lower percentage additions of cement or lime and (*b*) there will be monotonic drying of the majority of the material, rather than cycles of wetting and drying.

More recently, Hejazi *et al.* (2012) conducted a review of rammed earth research where fibres had been used. The history, benefits, applications and possible problems of using different fibres are included in this study, and the fibres looked at are both natural and synthetic. This paper concludes that the increase of strength and stiffness is due to a variety of factors: fibre characteristics, soil characteristics and test conditions.

2.2 Pull out of fibres from soil materials

While there appears to be no published research into the modelling of fibre bonding or fibre pull-out in rammed earth in particular, there has been a large amount of geotechnical research conducted in the field of soil stabilisation using either randomly distributed fibres or continuous planar reinforcement such as geotextiles and geogrids. The similarities between the two construction materials prompt the question, could any of these findings be transferred to rammed earth?

Useful examples of this research can be found in Li and Zornberg (2005) and Zornberg (2002) where a slope stability framework is proposed that accounts for the behaviour of the soil and fibre inclusions separately, summing the two contributions to establish an overall strength for the composite soil. To establish a pull-out force, a variant on the standard Mohr–Coulomb failure criteria is used for the frictional interaction between soil and fibre – that is

$$\boldsymbol{\tau}_{\mathrm{u}} = \alpha + \boldsymbol{\sigma}_{\mathrm{n}} \tan \delta \qquad (1)$$

where $\boldsymbol{\tau}_{\mathrm{u}}$ is the interface shear stress, α is an adhesion or cohesion, $\boldsymbol{\sigma}_{\mathrm{n}}$ is the average normal stress on the fibre and δ is the interface friction angle. Li and Zornberg (2005) also highlight the effect on pull-out force of dilation or contraction of a soil based on critical state values. This could equally affect fibre-rammed earth behaviour as the material is likely to be dilational or very dry of critical.

The pull out of planar reinforcement in soils is also a well-established area of research, some of which is relevant to the bonding of fibres within rammed earth. Of particular interest are the load transfer models proposed in a number of papers. Juran *et al*. (1988) created an analytical model to predict stresses and displacements of a fibre while still accounting for the extension of the fibre and changes of volume to reach a critical state. Sobhi and Wu (1996) built on this work looking at extensible sheet reinforcement. Analytical assumptions were the key to the development of the Sobhi and Wu (1996) model. These were: confining soil was assumed to remain stationary and shear stress was assumed to be uniform and equal to the ultimate shear strength over the entire active fibre length. Thus, a basic formula was established based on the force equilibrium (used later in this paper). Alobaidi *et al*. (1997) and Perkins and Cuelho (1999) used similar mechanics to model the behaviour of sheet pull-out tests. Some of the assumptions made in the above papers can also be justified for modelling the behaviour of fibres in rammed earth.

In summary, past research has shown that there is an increased interest in rammed earth with fibre reinforcement, although there has been little in the way of work done looking at the fibre–soil bond in rammed earth in particular (a highly unsaturated soil as opposed to many of the saturated assumptions made in the papers cited above; Jaquin *et al*., 2009). These research papers also suggest that natural and synthetic fibres each have their own advantages when used in rammed earth. From this basis, a programme of tests was devised and carried out to fill the gap in the research.

3. Experimental methods

To investigate the variables affecting fibre bonding in earthen construction materials, a large number of fibre pull-out tests (precise details below) were undertaken in the Civil Engineering laboratory at Durham University. Rammed earth samples (27 mm dia.) in which single fibres were embedded longitudinally were made using static compaction. A standard bench-top tension testing rig was then used to pull the fibre through the sample while recording force and displacement data. The experimental set-up is shown in Figure 1. Analogues elsewhere in other reinforced materials were useful in designing the testing programme, notably the literature on soil anchors (Abramson *et al*., 1996; Burland *et al*., 2012; Hanna, 1982) and geosynthetic-reinforced soils (Alobaidi *et al*., 1997; Sobhi and Wu, 1996) which suggested two modes of failure: interface between the fibre and the soil, as well as the material failure within the soil, itself. To force tests towards these two failure

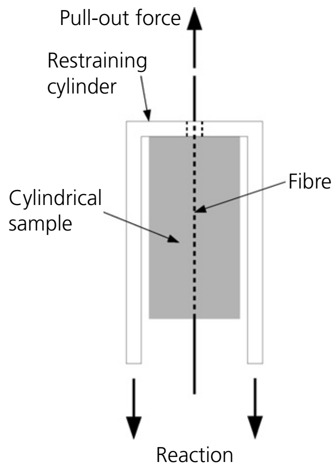

Figure 1. Testing arrangement

modes, different restraints were placed on the sample in the test rig. For the interface failure mode, the fibre exited the restraining cylinder (Figure 1) through a small hole, while for the other material mode the fibre existed through a much larger diameter opening (full details are given in Readle, 2013). Forty-five tests were undertaken for unstabilised samples for each of the failure modes (being 15 combinations of the key variables, each with three repetitions). The key variables were identified as water content (WC) at the time of testing (tested at 3, 7 and 11%), length of the fibre (25, 50 and 75 mm) and dry density (1·85, 1·90 and 1·95 Mg/m^3). Not all combinations were tested, due to time limitations. Previous work on earthen construction materials has clearly identified suction as a major source of strength in unstabilised materials (Jaquin *et al*., 2009) and, therefore, lowering WC should increase sample strength (typically assessed by way of unconfined compression tests). Equally, a higher dry density would also indicate higher material strength. A further programme of testing was carried out using stabilised rammed earth materials, all with 50 mm long fibres, where the key variables were the type of stabiliser (cement, hydraulic lime) and proportion (tested at 3, 7 and 9%). In this programme, a total of 18 tests were carried out (i.e. each variable combination with three repeats).

The soil used in all pull-out tests was a manufactured mixture, containing 30% clay, 60% sand and 10% gravel (classified as 30:60:10 in the system of Smith and Augarde, 2013). This mix was chosen for its high UCS and dry density as reported in previous studies of the material alone (Hall and Djerbib, 2004), providing confidence that the samples would be easy to handle during testing. Due to the small size of the samples, the mix was sieved to remove particles >2 mm dia., this reduced the gravel content (defined as >2 mm) to 0%. Initial grading tests were done on available coarse, medium and fine aggregates to find the proportions of each required to produce a 30:60:10 mix. The mix produced was then regarded as a check. Optimum WCs for mixing (as opposed to testing) were obtained using standard Proctor tests. WCs were not adjusted to take account of the presence of stabilisers due to very small size of the samples and the short time needed for compaction (in comparison with the same material in a full-size wall, for instance). For the stabilised samples, pull-out testing was carried out at 7 d for the cement samples and 48 d for those stabilised with lime.

To undertake compaction and testing of rammed earth samples without deforming embedded fibres, a bespoke mould was designed so that tension could be applied to the fibre throughout the compaction of the surrounding rammed earth. The apparatus consisted of a 27 mm dia. mould, a baseplate with a central hole and a plunger with a hole drilled through longitudinally. A fibre could then be passed through the plunger and the baseplate, tied off and then put under tension while the sample was being compacted. The sample was compacted against a smooth internal mould face thus producing a smooth face of material against which the restraining cylinder would bear in the testing (thus avoiding any stress concentrations).

Jute twine was the fibre chosen for the majority of tests. In addition, a small amount of testing was done using sisal and polypropylene, natural and synthetic fibres, respectively. Sisal fibres originate from the leaves of the sisal plant that grows in arid regions of Central America, Southwest USA and Mexico. While sisal and jute are recognised as having good strength, their long-term durability is questionable as they are biodegradable and man-made fibres such as polypropylene are often proposed as alternatives.

4. Results

4.1 Unstabilised materials

A considerable dataset was produced from a large number of tests undertaken and here excerpts from the dataset are presented to illustrate a number of trends observed by way of a more detailed analysis of variance (ANOVA) presented elsewhere (Readle, 2013). The most useful results are those where interface failure has been obtained (as explained above, and for reasons discussed in the conclusions below). In general, pull-out load is plotted against displacement. Alternative load measures could be pull-out load divided by fibre circumference, or a mean shear stress obtained from pull-out load divided by fibre surface area. Neither of these two measures are as informative as the pull-out load alone as (*a*) all the fibres were the same to start with, but the actual circumference once in situ is difficult to assess accurately and (*b*) the shear stress along the fibre will vary with distance from the end of the sample (see the analysis below), so an average measure may not be very revealing. Unless otherwise stated, all fibres are jute. In all plots, the mean response from three repeats is presented.

The first, and expected, conclusion to be drawn from the test programme is that longer fibre lengths lead to higher pull-out loads at longer travel. Figure 2 illustrates this clearly for the tests undertaken at 3% WC; the 75 mm fibre takes over double the pull-out load recorded for the 25 mm fibre and double the displacement. The mode of failure is by way of mobilisation of limiting shear strength either in the material or in the bond between the fibre and the material, and therefore, a longer fibre will require a greater force to mobilise this limiting shear strength along a longer length. Figure 2 compares results for the three lengths, all other variables being kept constant, and it is clear that the change in pull-out force is roughly proportional to the change in length.

Second, lower WC leads to higher pull-out forces. This is illustrated in Figures 3–5 which plot results for 25, 50 and 75 mm fibres, respectively. The conclusion is clear for the 25 and 75 mm fibres, but less so for the 50 mm case, something that appears to be a function of these particular results and an illustration of the variability inherent in testing earthen construction materials which will be well known to other researchers. Greater confidence in the assertion on WC can be drawn from Figure 6, which shows peak pull-out forces from a large number of tests where interface failure was obtained. The majority of results follow the conclusion in this plot with major increases in pull-out force for the lowest WC and less marked differences for higher WCs. The link between WC and strength might be seen as counterintuitive when one considers

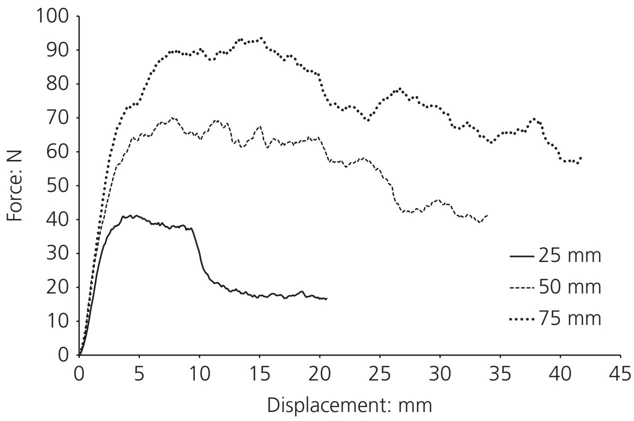

Figure 2. Interface failures for different length fibres (3% WC)

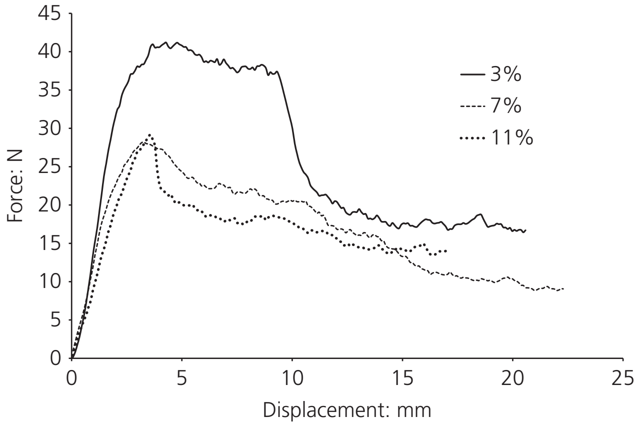

Figure 3. Interface failures at varying WC for 25 mm long fibres

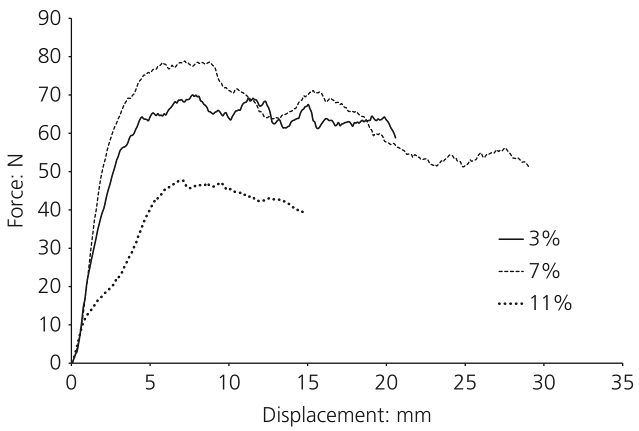

Figure 4. Interface failures at varying WC for 50 mm long fibres

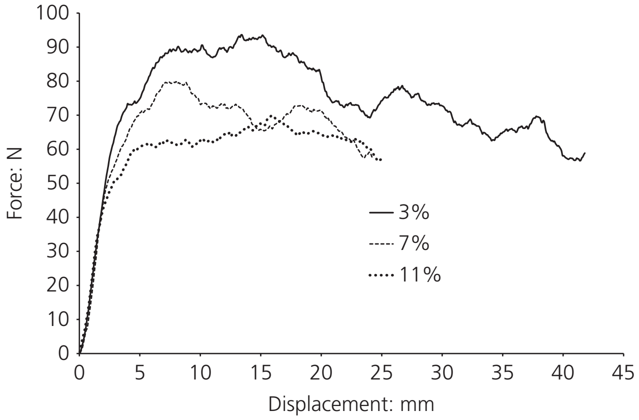

Figure 5. Interface failures at varying WC for 75 mm long fibres

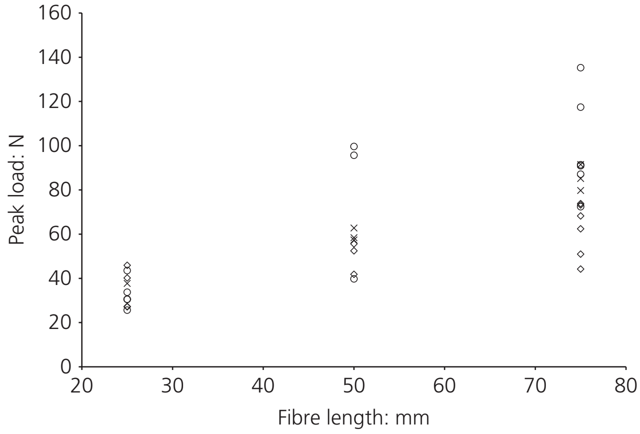

Figure 6. Peak loads from tests with an interface failure mode: 3% WC (circles), 7% WC (crosses), 11% WC (diamonds)

shrinkage would be greater as the soil gets drier, and hence one might conclude the interface strength should decrease as soil shrinks away from the main fibre axis. While this might be the case, other studies (e.g. Corbin and Augarde, 2015) suggest that the main bonding occurs between the soils and microfibres extending outwards from the main fibre axis, rather than the main fibre axis alone, and these would be less influenced by shrinkage.

Results comparing interface and material failures are shown in Figure 7 confirming what one would expect, that interface failures occur at higher pull-out loads than material failures, as the latter is constrained in the interface failure tests. Another useful conclusion from analysis of the tests is that shorter fibres tend to produce load–displacement curves with appreciable softening post-peak (see for instance Figure 2). To a limited extent, this brittleness is also associated with lower WCs, but appears to be cancelled out for fibres of 50 and 75 mm long. The ANOVA analysis of the results presented elsewhere (Readle, 2013) demonstrated that the most significant variables affecting pull-out force after fibre length were WC and then dry density.

A small number of tests were conducted on unstabilised samples, varying the fibre type and selected representative results are shown in Figure 8. The three fibres used in the tests were approximately of the same diameter and, for the reasons given above, no adjustment has been made for minor differences in diameter; therefore, the pull-out forces are plotted as opposed to anything else. The jute twine fibre gives the greatest strength and polypropylene the least, with sisal in between, and with the jute fibre the most significant in terms of post-peak softening. While no detailed investigation of fibre

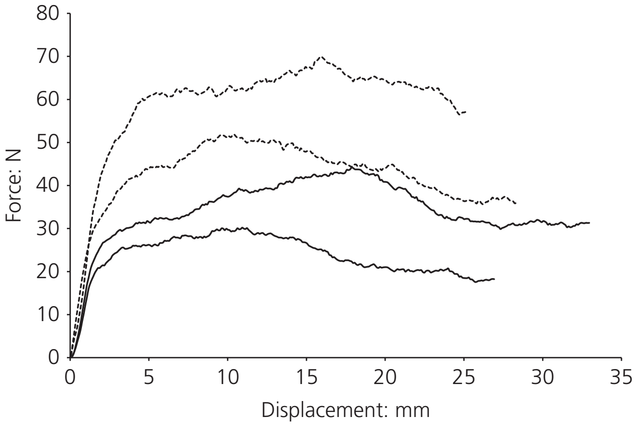

Figure 7. Load–displacement behaviour for 75 mm fibre, 11% WC. Interface (dotted) and material (solid) failures

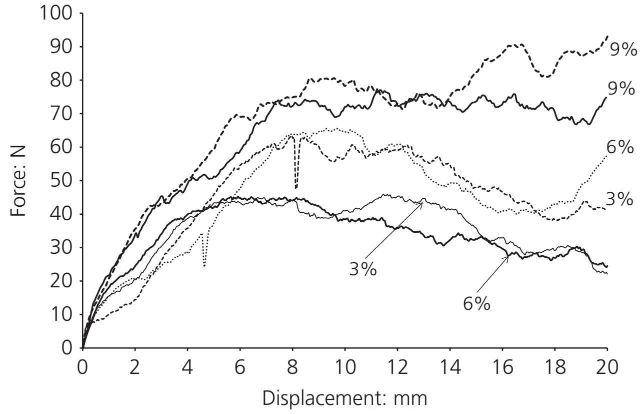

Figure 9. Force/displacement results for 50 mm fibres with varying % cement stabilisation: Interface (dotted) and material (solid) failures

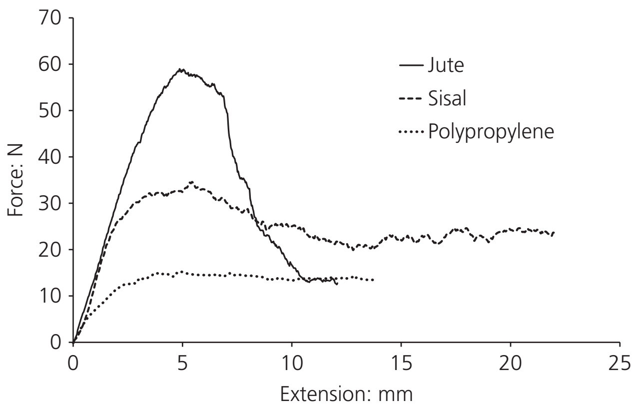

Figure 8. Pull-out tests on different fibre types in unstabilised samples

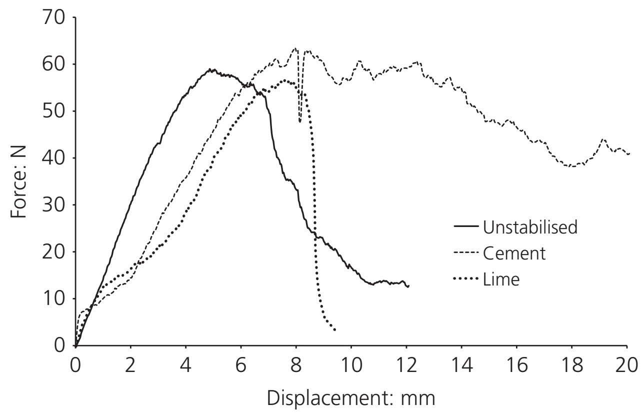

Figure 10. Force/displacement results for 50 mm fibres with and without stabilisers (3%)

surfaces was undertaken in this study, these results support the conclusion that surface roughness, or more likely the presence of microfibres extending out from the main fibre axis, are the key bonding location; polypropylene would not have this feature and therefore would lack the bonding of the other natural materials.

4.2 Stabilised materials

One might expect stabilisers to improve pull-out loads for fibres, just as they improve UCS (Hall and Djerbib, 2004; Venkatarama Reddy and Prasanna Kumar, 2011). However, the results of this testing programme suggest that the major effect is on ductility rather than increasing pull-out forces considerably. Figure 9 shows results from tests on samples with varying amounts of cement stabiliser (all results for stabilised materials are for 50 mm fibre length). In general, an increase in pull-out load with the percentage of stabiliser is evident, although once again the variability inherent in these materials is obvious. Figures 10–12 are plots for varying amounts of stabiliser (both cement and lime). On each plot, the unstabilised equivalent is plotted for comparison purposes. It is clear that cement stabilisation leads to an increase in pull-out load at all concentrations and increases as the concentration does. However, the benefit is generally marginal and the key difference is in the post-peak behaviour where there is greater ductility than seen with the lime-stabilised and unstabilised samples. In fact, the lime-stabilised samples show decreases in

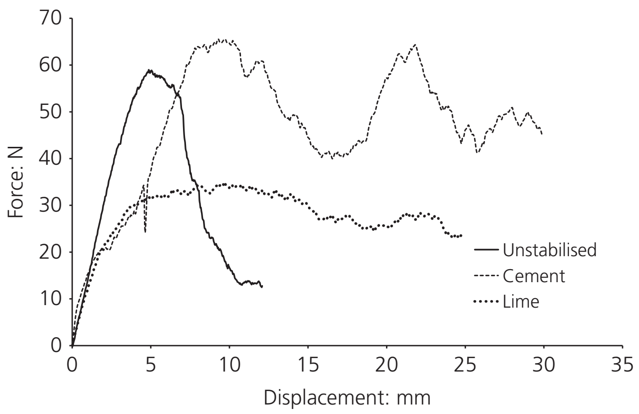

Figure 11. Force/displacement results for 50 mm fibres with and without stabilisers (6%)

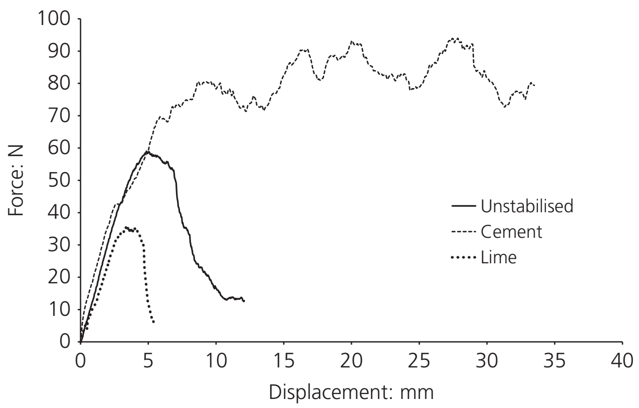

Figure 12. Force/displacement results for 50 mm fibres with and without stabilisers (9%)

pull-out loads as compared with the unstabilised case and very poor behaviour. The marked difference between the effects of the two stabilisers is interesting and possibly explained by differences in water requirement for the activation of effective bonding for the two additives. In the lime-stabilised samples, it appears that free lime may be acting as a lubricant at the fibre–earth interface.

5. Analysis and discussion

5.1 Bond shear stress

It is instructive to attempt an analysis of the pull-out forces by adapting a model developed for the pull out of geosynthetic sheets in Sobhi and Wu (1996). This model recognises that displacement along the embedded length of a sheet of material being pulled out of a soil matrix is not linear, and that this leads to the conclusion that the interface shear stress at failure is not simply the pull-out force divided by the interface contact area, but a smaller value. It is assumed that the fibre is linear elastic with Young's modulus E and diameter D. The fibre–soil interface is divided into two parts: an active length L along which the limiting shear stress $\boldsymbol{\tau}_\mathrm{u}$ has been reached and the remaining length which is unstressed and provides anchorage for the fibre. By changing the problem geometry adopted in Sobhi and Wu (1996) for a geosynthetic sheet to a circular section fibre, one can obtain the following

$$2. \qquad \boldsymbol{\tau}_\mathrm{u} = \frac{ED}{4L}\ln\left(\frac{4\boldsymbol{F}}{E\pi D^2}+1\right)$$

where $\boldsymbol{F}$ is the peak pull-out force and the active length L is now the fibre length. Readle (2013) undertook simple tension tests on unembedded fibres and found a mean value for Young's modulus of 730 MPa for the fibres used in unstabilised tests, which also had a mean diameter of 1·2 mm. Using Equation 2 with these parameter values and the data on peak loads in Figure 6 yields values of 355, 341 and 274 kPa for $\boldsymbol{\tau}_\mathrm{u}$ for 25, 50 and 75 mm fibres, respectively. The drop in shear stress as the fibre length increases is not an error to do with changing shear areas due to the changing fibre lengths as that is factored out in the development of Equation 2. However, it is not clear if this observation is significant or an artefact of the variability of materials.

5.2 Implications for earthen construction

Pull-out tests on single fibres, as described above, are clearly somewhat different from the loading and configuration of fibres mixed into rammed earth and compacted into place; however, some useful implications can be identified. First, the presence of fibres can be seen to improve the ductility of rammed earth and hence its safety for use in seismic regions; however, it is also clear that this would be strongly dependent on the concentration of fibres in the mix (something obviously not studied here). Rammed earth stabilised with cement seems to work well with fibre reinforcement, while with lime there does not seem to be much of an advantage. Second, the failures likely to occur in fibre-reinforced rammed earth in the field are interface failures rather than earth material failure, since in the field the in situ stresses will be much larger than those in the test specimens here, and hence the 'prestressed' earthen material is less likely to fail itself. It is clear that any use of lime stabilisation with fibres should be treated with caution. The results presented here suggest that interactions between stabiliser and fibre are markedly different between lime and cement stabilisers. Since the latter is much more widely used in rammed earth, this may not be a significant issue for modern earth construction. If fibres are used then it is also evident that surface condition is important – that is, if polypropylene fibres are to be used then they should be processed to obtain similar features such as microfibrosity seen with natural fibres. This might add to the cost of the material but may be acceptable if long life was required; sisal clearly has some issues in this respect (Augarde, 2015). Clearly, the failure of earthen structures in seismic events (such as described in New Zealand in Morris *et al*., 2011) involves a range of interacting mechanisms, perhaps dominated by brittle failure in flexure or shear, or loss of bond between mortar and unit. The performance of many fibres, oriented in many directions, in a large wall to such events is clearly complex to predict; however, fundamentally the fibres can only offer additional resistance through pull-out or fibre rupture, and it is hoped that this will help to justify the simple study presented here.

6. Conclusions

A programme of pull-out testing on fibres embedded into samples of rammed earth has been described offering some useful insights into the interactions between fibres and earthen construction materials. The most significant variables affecting pull-out strength are fibre length and WC, and cement stabilisation appears to add ductility to pull-out rather than a major strength benefit. Lime stabilisation does not appear to be a safe choice for fibre-reinforced earthen materials. Further work is needed to extend this fundamental study to develop understanding of multiple and many fibres embedded in earthen construction materials and then to the behaviour of the material in situ in real structures.

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