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Fibre reinforcement in earthen construction materials

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Corresponding Author:	Charles E Augarde, Ph.D. University of Durham Durham, UNITED KINGDOM
Corresponding Author Secondary Information:	
Corresponding Author's Institution:	University of Durham
Corresponding Author's Secondary Institution:	
First Author:	Douglas Readle
First Author Secondary Information:	
Order of Authors:	Douglas Readle
	Sarah Coghlan
	Jonathan Smith
	Andrew Corbin
	Charles E Augarde, Ph.D.
Order of Authors Secondary Information:	
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Fibre reinforcement mechanisms in earthen construction materials

by D. Readle[1], S. Coghlan[3], J.C. Smith[2], A. Corbin[2] and C.E. Augarde*[2]

[1] AECOM, Sunley House, 4 Bedford Park, Croydon, UK

[2] School of Engineering and Computing Sciences, Durham University, Durham, UK

[3] formerly School of Engineering and Computing Sciences, Durham University, Durham, UK

Full contact details of corresponding author.

Professor Charles Augarde CEng FICE

Chair in Engineering

School of Engineering and Computing Sciences

Durham University, South Road, Durham, UK

T: (+44 or 0) 191 334 2504

charles.augarde@dur.ac.uk

www.dur.ac.uk/charles.augarde

Abstract (200 words)

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 we present laboratory-based studies which attempt to fill this gap, covering pull-out behaviour of natural fibres embedded in earthen construction materials, both stabilized and unstabilized.

Keywords chosen from ICE Publishing list

Earth building; fibre reinforcement; recycling & reuse of materials;

List of notation (examples below)

D	Fibre diameter
E	Fibre Young's modulus
L	Fibre active length
F	Pull-out force
α	Fibre adhesion
τ_u	Limiting shear stress
σ_n	Normal fibre stress
δ	Fibre interface friction angle

1. Introduction

Unstabilized rammed earth is potentially a low-carbon replacement material for cement-based blockwork or fired clay brick in wall construction. However, due to its low strength and brittle behaviour, the limited guidance available in standards (e.g. Standards New Zealand, 1998) indicates that very thick walls are needed and this reduces the economic case for its use since it is labour-intensive. Stabilized rammed earth is of higher strength but still brittle and often has a limited carbon benefit due to the type and quantity of stabilizer 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 earthen construction materials of long-standing already incorporate materials doing this job, e.g. the straw in Cob and Adobe. It is natural therefore that there has been interest in fibre stabilisation of rammed earth, however much of this research has focussed on the behaviour of the composite material instead of the interaction between fibre and soil. In order to understand the material and, at some point in the future, move towards a modern design approach for fibre-reinforced rammed earth, improved understanding of the fibre-soil bonding mechanisms are required (much as concrete technology was advanced by the understanding of bond and anchorage length in the 19th & 20th centuries). To this end, this paper presents results from laboratory testing of fibres in earthen construction materials, both unstabilized and stabilized 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 has been widely researched, however there is little published research into the fibre-earth interface bond. In previous studies it was found that adding fibres to rammed earth or to composite soils either decreased the unconstrained compressive strength (UCS) (Schroeder *et al.,* 2005*;* Maniatidis and Walker, 2003) or gave a small increase at low fibre contents (Houben and Guillard, 1994; Marandi *et al.,* 2008; Galán-Marín *et al.,* 2010; Ghavami *et al.,*1999*;* Bouhicha *et al.,* 2005). The effect of fibre content on UCS was possibly governed by 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.

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. Houben and Guillard, 1994; Schroeder *et al.,* 2005*;* Bargh, 2010]. 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 in the strength 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 of 50mm lengths 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 1-5% by mass of solid soil particles. The results showed that the use of the natural fibre led to a greater improvement in the relative unconfined compressive strengths, 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.

More recently Hejazi *et al.* (2012) conducted a review of rammed earth research where fibres had been used, from a variety of different papers. 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, sand 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 done in the field of soil stabilisation using either randomly distributed fibres or continuous planar reinforcement such as geotextiles and geogrids and the similarities prompt the question, could any of these findings be transferred to rammed earth?

Useful examples of this research can be found in Zornberg (2002) and Li and Zornberg (2005) 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, i.e.

$$\tau_u = \alpha + \sigma_n \tan \delta \qquad (1)$$

Where τ_u is interface shear stress, α = an adhesion or cohesion, σ_n is the average normal stress on the fibre and δ = the interface friction angle. Li and Zornberg (2005) also highlight the effect on pull-out force of dilation or contraction of a soil to critical state values, this could equally affect fibre-rammed earth behaviour which is likely to be dilational being very dry.

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. Particularly of 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 critical state. Sobhi and Wu (1996) builds on this work looking at extensible sheet reinforcement. Analytical assumptions were key to the development of the Sobhi and Wu 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. A basic formula was thus established based on force equilibrium (used later in this paper). Alobaidi *et al.,* (1997) and Perkins and Cuelo (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 into 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, which is now described.

2. Experimental methods

To investigate the variables affecting fibre bonding in earthen construction materials, a large number of fibre pull-out tests were undertaken in the Civil Engineering laboratory at Durham University. Rammed earth samples, (27mm in diameter) 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 literature on soil anchors (Abramson *et al.* 1996; Hanna, 1982; Burland *et al.,* 2012) and geosynthetic reinforced soils (Sobhi and Wu, 1996; Alobaidi *et al.,* 1997) which suggested two modes of failure: interface between the fibre and the soil and material failure within the soil itself. To force tests towards these two failure modes, different restraints were placed on the sample holder in the test rig (described in detail in Readle (2013)). Forty-five tests were undertaken for unstabilized samples for each of the failure modes. The key variables were identified as water content (wc) at time of testing (tested at 3, 7, and 11%), length of fibre (25, 50 and 75 mm) and dry density (1.85, 1.90, 1.95 Mg/m^3). Previous work on earthen construction materials has clearly identified suction as a major source of strength in unstabilized materials (Jaquin *et al.,* 2009) and therefore lowering wc should increase sample strength (typically assessed via unconfined compression tests). Equally a higher dry density would also indicate higher material strength. A further programme of testing was carried out using stabilized rammed earth materials, all with 50mm long fibres.

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 unconfined compressive strength 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 greater than 2mm in diameter, this reduced the gravel content (defined as >2mm) 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 water contents for mixing (as opposed to testing) were obtained using standard Proctor tests.

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 which grows in arid regions of Central America, South West USA and Mexico. While sisal and jute are recognised as having good strength their long-term durability is questionable as they are biodegradable. For this reason there is interest in man-made fibres such as polypropylene and it was therefore included in this test programme.

3. Results

3.1 Unstabilized materials

A considerable data set was produced from the large number of tests undertaken and here we present excerpts from the data set to illustrate a number of trends observed via a more detailed ANOVA analysis presented elsewhere (Readle, 2013). The most useful results are those where interface failure has been obtained (as explained above, and for reasons we discuss 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 insitu 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.

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 75mm fibre takes over double the pull-out load recorded for the 25mm fibre and double the displacement. The mode of failure is via mobilisation of a 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 change in length.

Secondly, lower water content leads to higher pull-out forces. This is illustrated in Figures 3, 4 and 5 which plot results for 25, 50 and 75mm fibres respectively. The conclusion is clear for the 25 and 75mm fibres but less so for the 50mm case, something which 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 water content can however 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 water content and less marked differences for higher water contents. The link between water content and strength might be seen as counterintuitive when one considers shrinkage would be greater the drier the soil gets, 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 water contents but appears to be cancelled out for fibres of 50 and 75mm lengths. The ANOVA analysis of the results presented elsewhere (Readle, 2013) demonstrated that the most significant variables affecting pull-out force after fibre length were water content and then dry density.

A small number of tests were conducted on unstabilized samples, varying the fibre type and selected representative results are shown in Figure 8. All three fibres used in the tests were approximately the same diameter and, for the reasons given above no adjustment has been made to adjust for minor differences in diameter, therefore the pull-out forces are plotted rather than 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 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.

3.2 Stabilized materials

One might expect stabilisers to improve pull-out loads for fibres, just as they improve unconfined compressive strength (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 stabilized materials are for 50mm fibre length) showing in general an increase in pull-out load with percentage of stabiliser (although once again the variability inherent in these materials is obvious). Figures 10, 11 and 12 are plots for varying amounts of stabiliser (both cement and lime). On each plot the unstabilized 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 with greater ductility than the lime-stabilized samples and the unstabilized samples. In fact the lime-stabilized samples show decreases in pull-out loads as compared to the unstabilized 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 activation of effective bonding for the two additives. In the lime-stabilized samples it appears that free lime may be acting as a lubricant at the fibre-earth interface.

4 Analysis and Discussion

4.1 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. We assume that the fibre is linear elastic with a 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, τ_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

$$\tau_u = \frac{ED}{4L} \ln\left(\frac{4F}{E\pi D^2} + 1\right) \tag{2}$$

where F is the peak pull-out force and the active length L is now the fibre length. Readle undertook simple tension tests on unembedded fibres and found a mean value of Young's modulus of 730 MPa (Readle, 2013) for the fibres used in the unstabilized tests, which also had a mean diameter of 1.2 mm. Using Eqn (2) with these parameter values and the data on peak loads in Figure 6 yields values of 355 kPa, 341 kPa and 274 kPa for τ_u for 25, 50 and 75 mm fibres respectively. The drop in shear stress as fibre length increases is not an error to do with changing shear areas due to 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.

4.2 Implications for earthen construction

Pull-out tests on single fibres, as described above, are clearly somewhat different to the loading and configuration of fibres mixed into rammed earth and compacted into place, however some useful implications can be identified. Firstly, 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 stabilized with cement seems to work well with fibre reinforcement while with lime there does not seem to be much of advantage. Secondly, 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 insitu 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. 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 also seem clear that surface condition is important, i.e. 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 of the material, sisal clearly having some issues in this respect (Augarde, 2015).

5. 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 water content, 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 insitu in real structures.

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Figure captions

Figure 1: Testing arrangement

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)

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

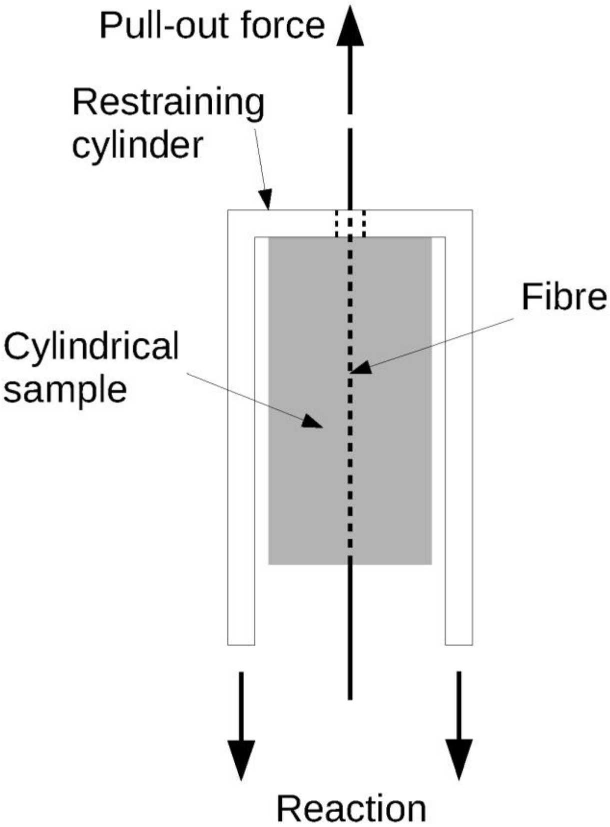
Figure 8: Pull-out tests on different fibre types in unstabilized samples.

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

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

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%).



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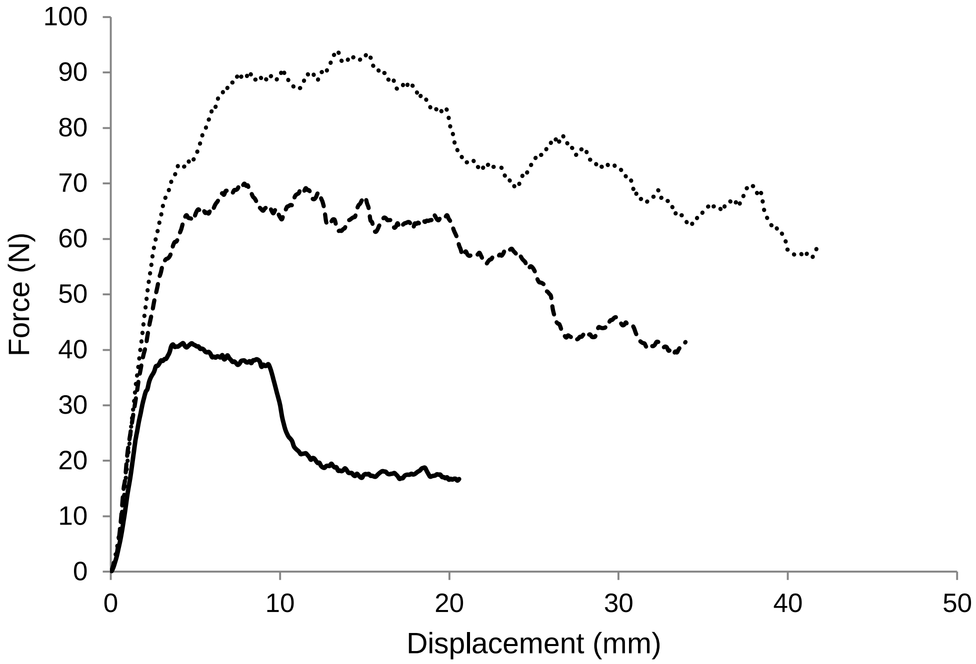

Figure 2: Interface failures for different length fibres (3% wc).

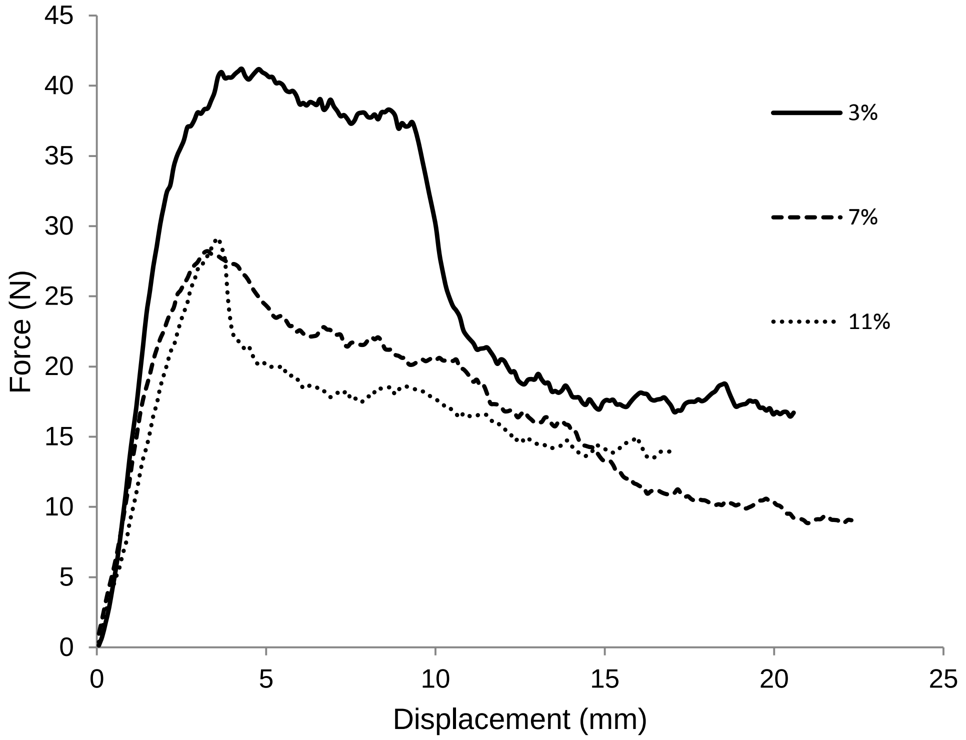

Figure 3: Interface failures at varying wc for 25 mm long fibres.

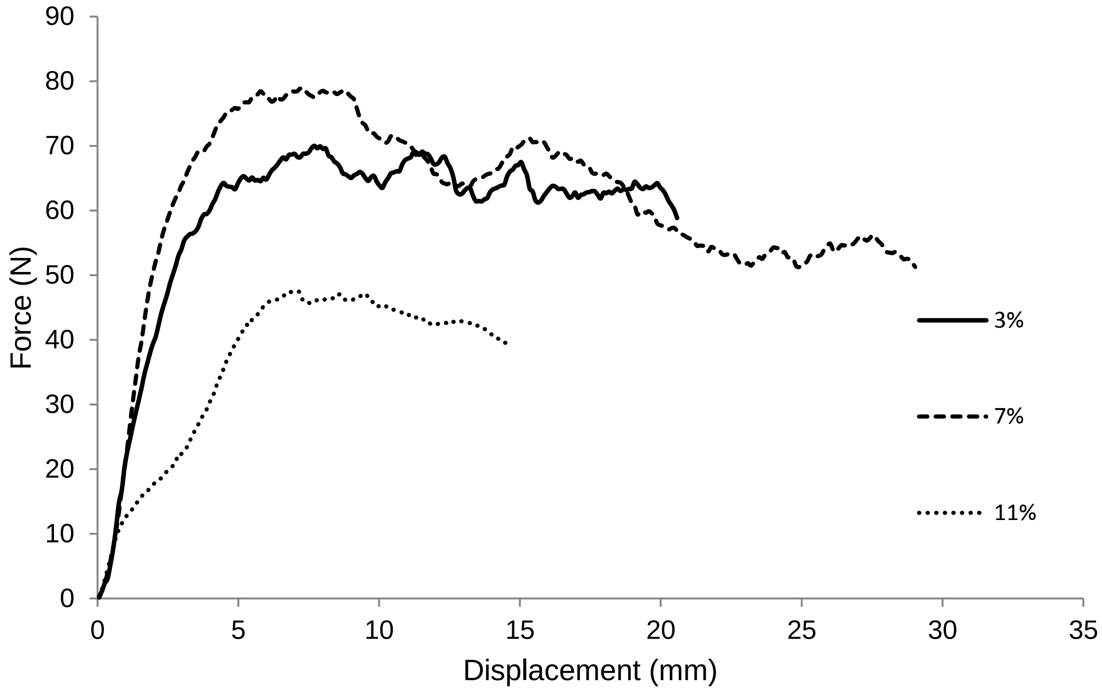

Figure 4: Interface failures at varying wc for 50 mm long fibres.

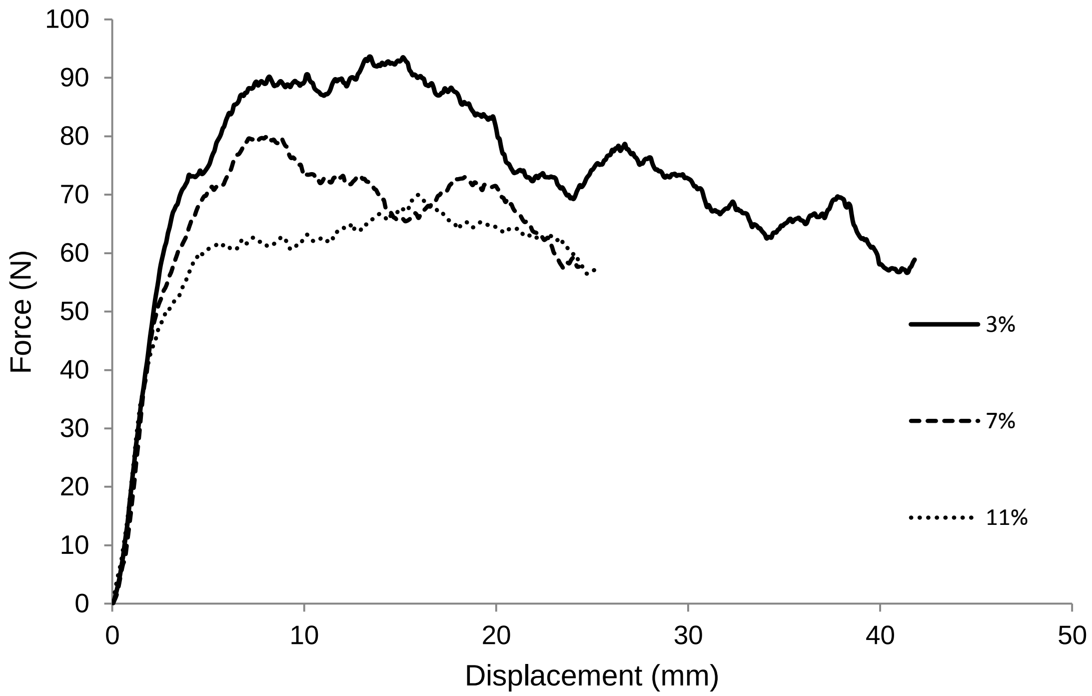

Figure 5: Interface failures at varying wc for 75 mm long fibres.

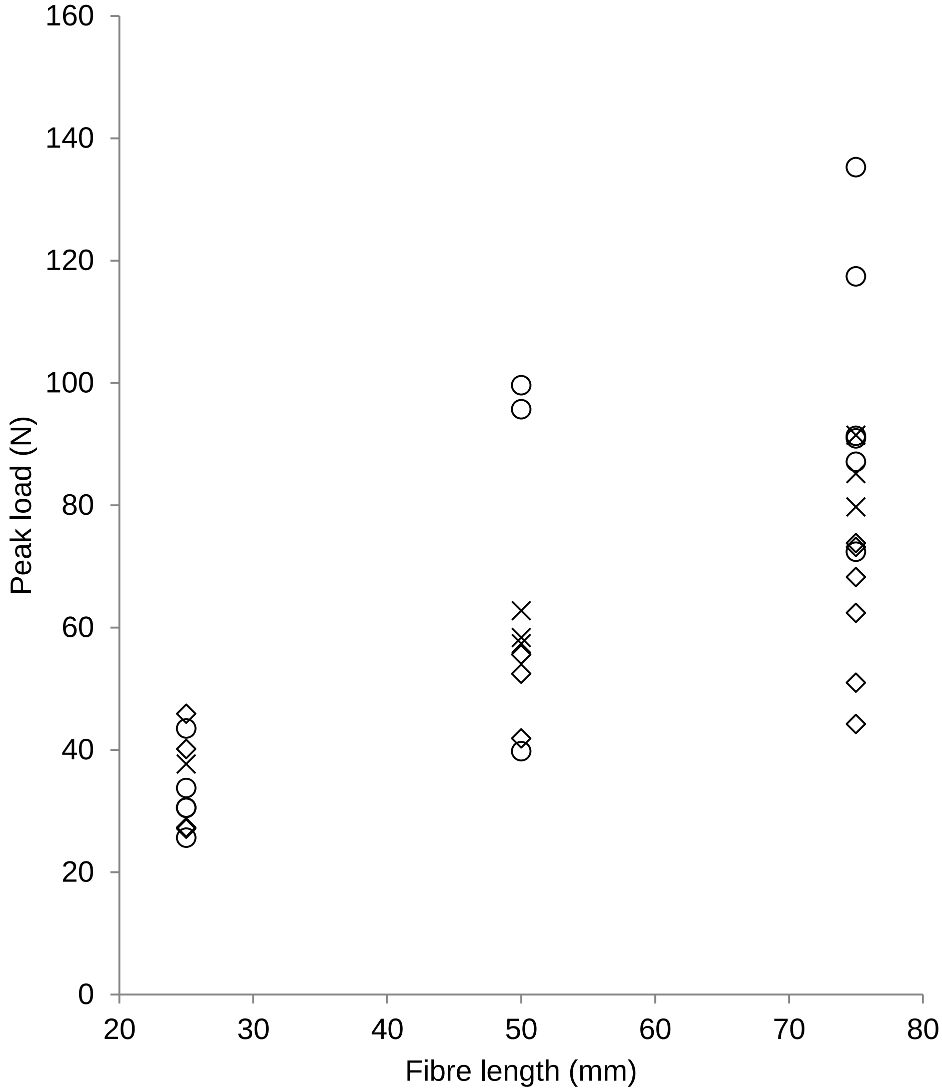

Figure 6: Peak loads from tests with an interface failure mode:3% wc (circles), 7% wc (crosses), 11% wc (diamonds)

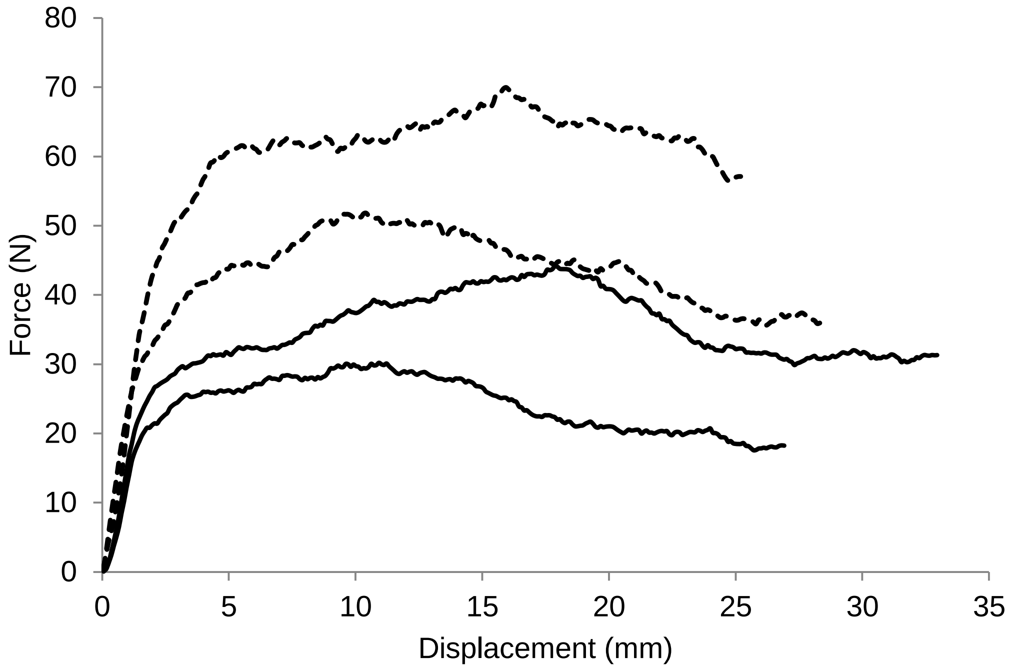

Figure 7: Load-displacement behaviour for 75mm fibre, 11% wc. Interface (dotted) and material (solid) failures.

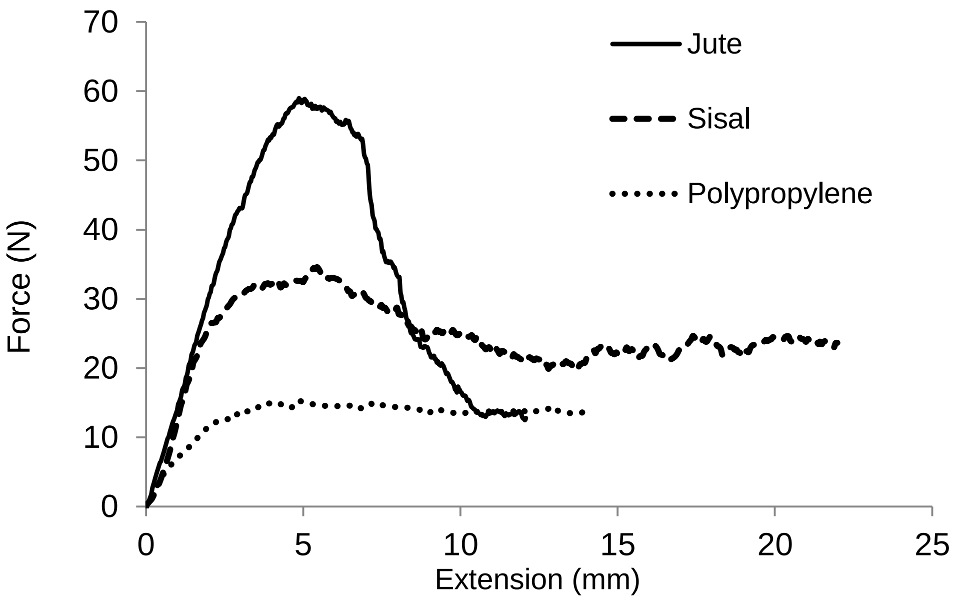

Figure 8: Pull-out tests on different fibre types in unstabilized samples.

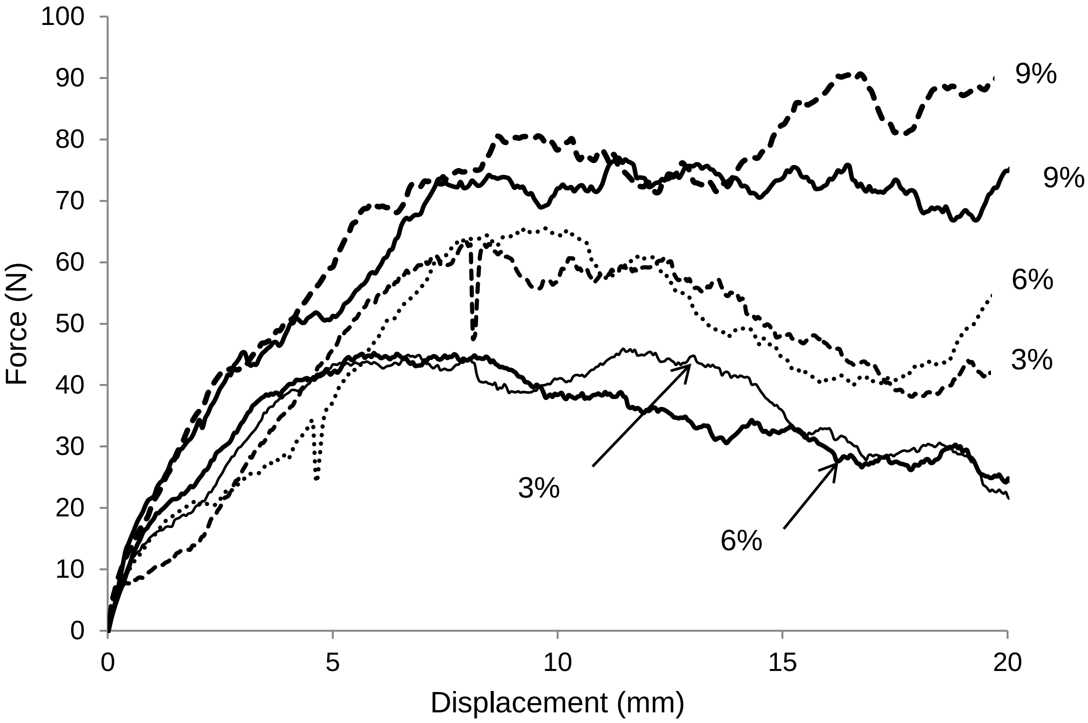

Figure 9: Force/displacement results for 50 mm fibres with varying % cement stabilisation: Interface (dotted) and material (solid) failures.

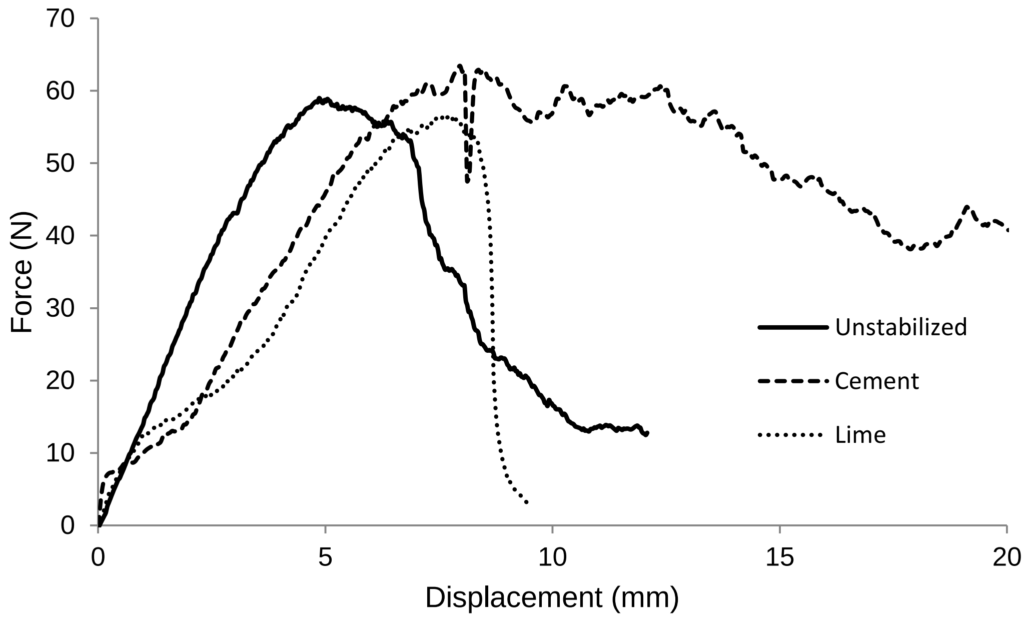

Figure 10: Force/displacement results for 50 mm fibres with and without stabilisers (3%)

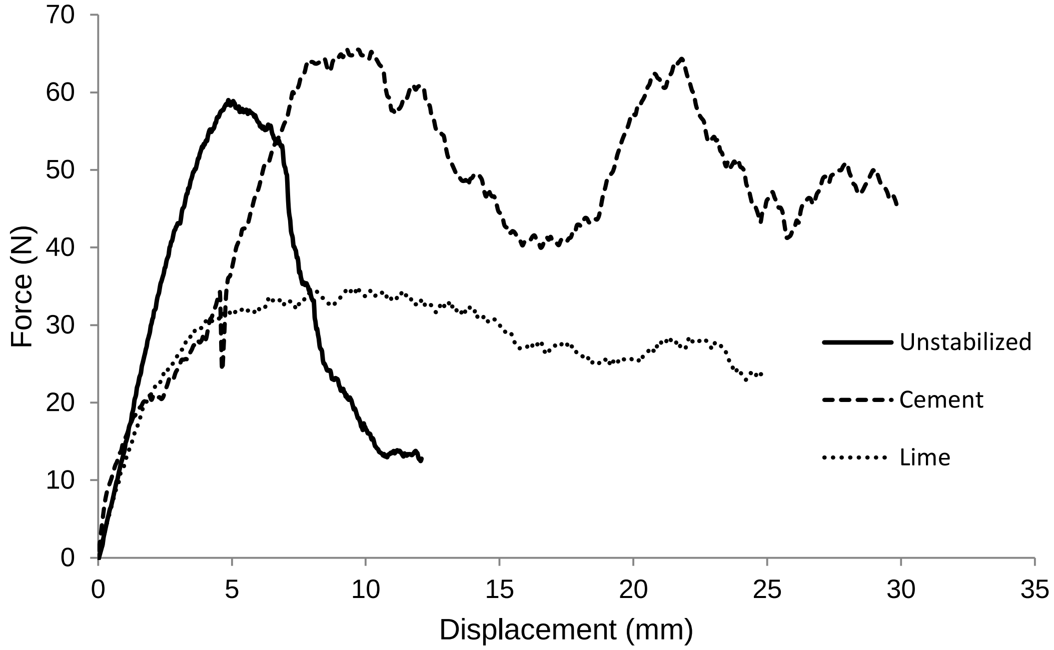

Figure 11: Force/displacement results for 50 mm fibres with and without stabilisers (6%).

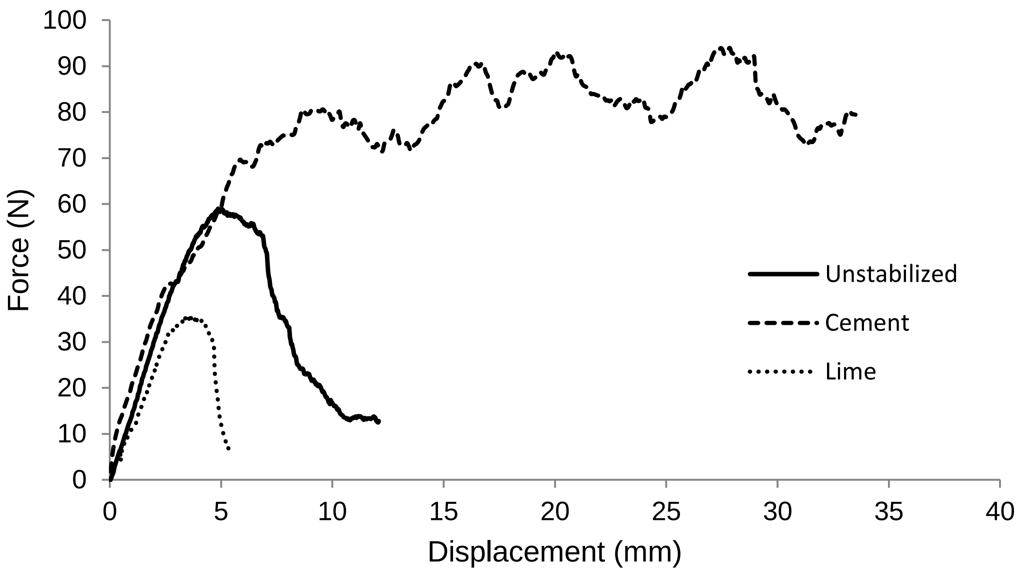

Figure 12: Force/displacement results for 50 mm fibres with and without stabilisers (9%).