Notched mini round determinate panel test to calculate tensile strength and fracture energy of fibre reinforced cement-stabilised rammed earth

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ABSTRACT: The use of natural fibres (like hemp or bamboo) to improve the mechanical performances of rammed earth structures is not new in construction practice in many parts of the world. However, little scientific investigation has been carried out so far to better understand the real improvement obtained by the addition of fibres. In a recent publication [1], the feasibility of notched mini round determinate panels (mRDP) has been investigated with the aim of deriving a procedure to estimate the intrinsic material properties of fibre reinforced shotcrete (FRS). It was found that it was possible to recover the tensile strength and the fracture energy of the material using an inverse analysis of the experimental data and the well-known Olesen constitutive model [2]. In this paper, the use of the notched mini round determinate panel test to characterise the post-cracking performances of cement stabilised rammed earth (CSRE) was investigated. For quality control issues, in this study the soil mix consisted of crushed limestone stabilised with 8% cement by soil mass and compacted at its optimum water content (11%). Three specimens were made of CSRE alone and three samples were made of fibre-reinforced CSRE. The fibres used in this experimental campaign were unbundled synthetic copolymer fibres, 54 mm long and 0.3 mm thick. This paper discusses the applicability of a laboratory test conceived for concrete samples to rammed earth specimens. It also presents the comparison between the performances of CSRE materials with and without fibres.

1 INTRODUCTION

The addition of fibres (steel or synthetic) to concrete mixes is a well-established practice all over the world. It is well understood that the presence of fibres increases the post-cracking performance of concrete by controlling crack opening and improving load distribution. Natural fibres have been used in traditional (not cement-stabilised) rammed earth construction for a long time. Their function is however still not clear. There are two key arguments: i) that natural fibres help to control the opening of cracks; ii) that natural fibres help to create channels on the surface of rammed earth walls along which rain water flows. In this way, the erosion is localised and it is easier to repair the wall.

The addition of fibres to concrete is straightforward: a proper fluid state of the mix at casting guarantees a regular distribution. Furthermore, fibres orientation can be adjusted during casting. Rammed earth mixes are quite dry; the addition of fibres requires special care to produce a uniform spreading. Furthermore, the compaction process might bend or damage some fibres. If the fibre reinforced rammed earth mix is not properly put together and compacted, fibres might actually lead to a decrease of the mechanical performance of the material.

The aim of this work is to provide a preliminary understanding of the effects of macro-synthetic fibre addition on the post-cracking performance of SCRE. The mRDP test is used here, as opposed to other traditional tests (like flexural or Brazilian tests), to evaluate CSRE fracture energy, an essential component in modelling CSRE post-cracking behaviour. Results will also be used to determine the suitability of the mRPD test for use with rammed earth materials.

2 MATERIAL AND PROCEDURE

2.1 *Material*

Crushed limestone was used in this work in the place of natural soil due to its improved quality control, ready availability and preferential use for CSRE construction in Perth, WA. Oven-dried crushed limestone (particle size distribution shown in Figure 1) was combined with 8% cement by mass (again typical of CSRE construction in Perth).

For tests conducted with fibres, 0.2% by volume macro-synthetic fibres was added to the dry material mix. The fibres used in this investigation (Figure 2) were macro-synthetic polypropylene (54 mm long, 0.3 mm diameter, aspect ratio=180, tensile strength 680MPa) designed to increase the load transfer and post-crack performance in concrete mixes. Each bundle of fibres was broken down to individual strands to help spread fibres evenly during mixing. The relation of the dosage to material volume, rather than mass, is necessary due to the construction practise of preparing rammed earth mixes by known volumes.

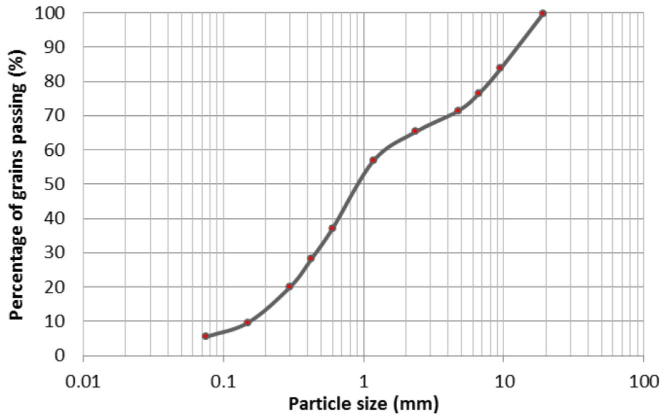

Figure 1. Particle size distribution of rammed earth mix.

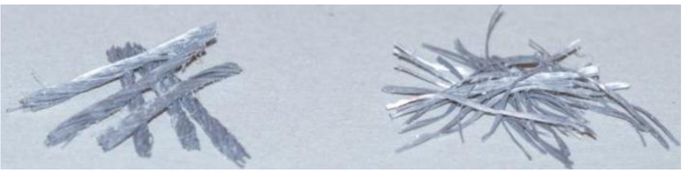
Figure 2. Macro-synthetic fibres used. On the left: bundles; on the right: individual strands.

2.2 *Procedure*

Specimens of size Ø540mm, 75mm depth were manufactured for use with the mRDP test as shown in Figure 3. This size was selected as being of sufficient size to be used with existing testing equipment whilst being light enough to be handled manually. Material was compacted at its optimum water content (OWC) of 11.1% (for both mix types), found using the modified Proctor compaction test (AS 1289.5.2.1 [3]) for CSRE mixes with and without fibres.

Specimens comprise a single compaction layer to prevent delamination during testing. Material was first compacted using a manual tamper, as shown in Figure 3, to ensure that it remained within the mould. An electric Bosch GHS 11 E jackhammer with a 100mm diameter round steel end plate was then used to compact the material to a thickness of 75mm. Finally, a light hand tamper was used to create a level surface, as shown in Figure 4. Specimens were then left to cure for 24 hours under moist hessian sacking prior to being removed from the mould and cured for an additional 27 days at 94±2% relative humidity and 21±1°C.

After curing for 14 days, three radial notches, symmetrically trisecting the specimen (i.e. at 120 degrees), were cut into the specimen underside; as this surface in contact with the mould baseplate it provided the smoothest surface for testing. The notch depth was of 14 mm.

At 28 days, samples were tested by placing them on three symmetric point supports and by applying a point load at the centre, at a rate of 4 mm/min. The load and the central vertical displacements were recorded until failure occurred. Furthermore, one micro-yoke per notch (3 per sample) was installed as shown in Figure 5 in order to record crack mouth opening displacements (CMODs). For further explanations on the testing equipment, please refer to [1]. Moment per unit length-crack rotation angle curves for each specimen were then determined according to testing conducted as per [1].


Figure 3. Initial manual compaction of specimen.


Figure 4. Levelled surface.

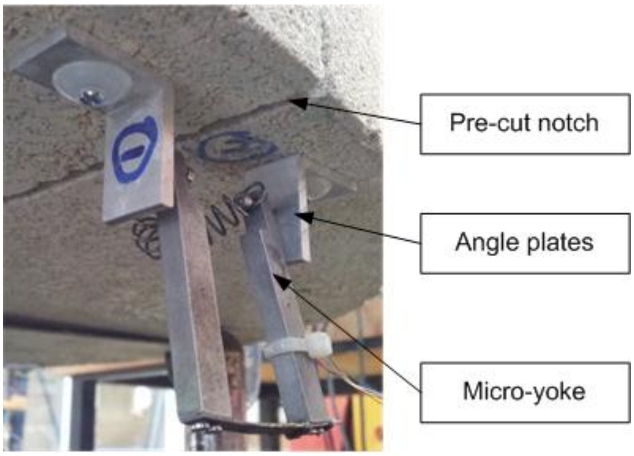

Figure 5. Positioning of micro-yoke and angle plates

3 RESULTS

Figures 6 and 7 show the moment per unit length m *vs* crack rotation angle θ curves, respectively for the unreinforced and fibre-reinforced RE samples. For each sample, 3 curves are reported, one per notch. The presence of the fibres does not seem to affect the peak value (around 1.6 kN mm/mm for both unreinforced and reinforced samples). The peak value of m is strictly related to the tensile strength properties of the material (for further details please refer to [1]). This means that the fibres do not alter the tensile strength properties of CSRE. This is similar to what observed in concrete.

However, the post peak performance seems quite different with and without fibres. For a crack rotation angle of 0.015 rad, the unreinforced samples show no residual strength while the fibre-reinforced samples show a residual strength of 12.5% the peak load.

The m-θ curves have been numerically obtained by inverse analysis using the constitutive model proposed by Olesen [2]. For further details on these type of analysis please refer to [1]. One of the mechanical parameters of the Olesen's model is the fracture energy. This parameter has been calibrated so that the moment per unit length vs. CMOD curve obtained via experimental procedure matches the numerical curve obtained using Olesen's model. The accuracy of this procedure is shown in Figure 8.

Table 1 reports the fracture energy values found in the inverse analysis. The fibre-reinforced samples show fracture energy values 4.3 times higher than the samples without fibres. It is clear that this is due to the presence of the fibres, which have a beneficial effect on the load transfer during the cracking process. In other words, a cracked structural element reinforced with fibres shows the ability to carry some loads when the same structural element without fibres would have no capacity at all. This is an interesting outcome that might open the discussion over the use of fibres for structural elements in earthquake areas, where the capacity of the material to dissipate energy is a crucial aspect of the seismic design.

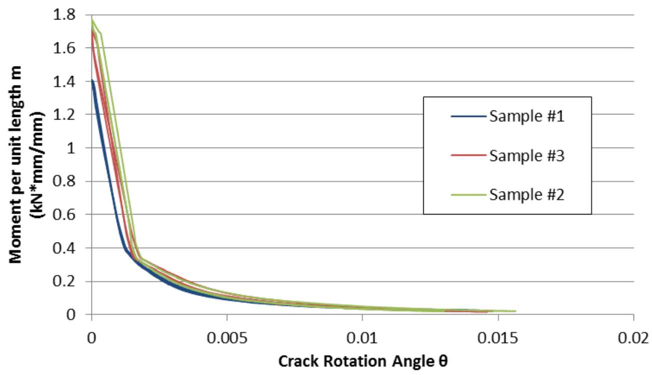

Figure 6. Moment per unit length-crack rotation angle curve for unreinforced RE samples.

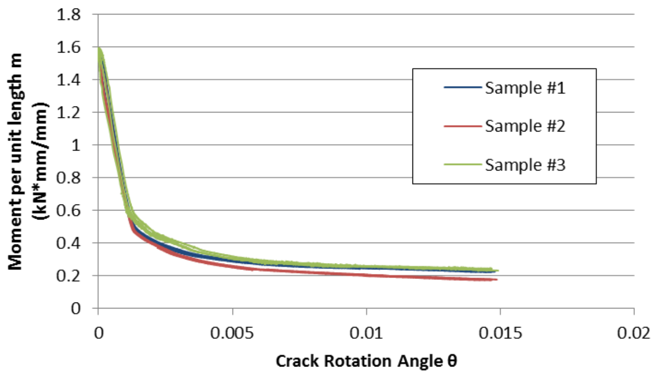

Figure 7. Moment per unit length-crack rotation angle for fibre-reinforced RE samples.

Unfortunately, the research available in the literature on the fracture energy of rammed earth is very limited. To evaluate the reliability of the proposed experimental procedure, the values of fracture energy obtained in this work have been compared to the ones found for similar materials. Petersson [4] found that for limestone concrete beams, the fracture energy obtained with the three-point bend test was in the range of 0.055-0.06 N/mm. The CSRE mix used in this work does not substantially differ from a limestone concrete and the similarity between the values of Petersson and the ones shown in Table 1 confirms the goodness of the use of the mini round determinate panel test for the evaluation of the fracture energy.

Carnovale [5] estimated the fracture energy of macro-synthetic fibre reinforced concrete panels to be around 0.31 N/mm. This value is of the same order of magnitude of those found in this study and reported in Table 1.

As mentioned in the Introduction section, the addition of fibres not always has a favourable effect in the post-cracking mechanical properties of the mix. Corbin and Augarde [6] used wool fibres to reinforce cylindrical rammed earth samples tested using the wedge splitting test. For samples stabilised with 8% of cement, the fracture energy decreased from

0.022 N/mm for samples without any fibre, to 0.010 N/mm for samples containing 2% of fibre by mass.

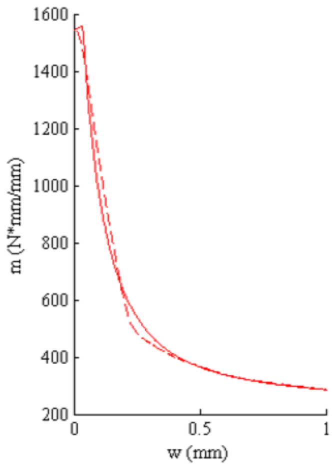

Figure 8. Numerical (dashed line) and experimental (continuous line) curves of moment per unit length m vs. crack mouth opening displacement w.

Table 1. Fracture energy values from inverse analysis

		fracture energy Gf [N/mm]				
sample #	fibres	crack 1	crack 2	crack 3	sample average	series average
1	no	0.058	0.055	0.056	0.056	0.063
2	no	0.065	0.066	0.076	0.069	
3	no	0.070	0.063	0.063	0.065	
1	yes	0.279	0.266	0.294	0.280	0.273
2	yes	0.240	0.223	0.282	0.248	
3	yes	0.276	0.281	0.317	0.291	

4 CONCLUSIONS

This paper investigated the improvement in the post-cracking mechanical performance of cement-stabilised rammed earth samples obtained by the addition of macro-synthetic fibres in the material mix. The improvement was quantified by the measurement of the material fracture energy, experimentally obtained using the mini notched round determinate panel test. It was found that the addition of 2% by volume of synthetic fibres to the rammed earth mix increased the material fracture energy of 4 times, providing some ductility properties that are usually crucial in structural elements used in seismic areas.

The values found in this work were compared with others available in the literature for similar materials (plain limestone concrete and micro-synthetic fibre reinforced concrete). The similarity between these values validated the use of the experimental procedure implemented in the experimental campaign proposed in this research.

5 ACKNOWLEDGMENT

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