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Evaluating shear test methods for stabilised rammed earth

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Rammed earth is an accessible, sustainable and increasingly popular building material. Owing to a lack of research, current design standards for rammed earth have taken a conservative stance on material attributes like shear strength. Evaluating the shear strength of rammed earth is particularly important in seismic areas because of the material's high mass, low ductility and propensity to fail in shear. Shear test methods designed for other materials have typically been used in practice to determine the shear strength of rammed earth. In this research the design shear strength guidance available in current earth building standards was compared with experimental shear strength results for stabilised rammed earth. The triaxial (geotechnical) and triplet (masonry) tests were used to evaluate specimens reinforced with natural fibres: sisal and New Zealand flax. Both shear test methods showed that the shear strength capacity of cement-stabilised rammed earth was greater than the current guidance provided in the earth building standards. Recommendations were made to use the triaxial test to evaluate the shear strength of stabilised rammed earth and to allow the use of design shear strength equal to 7% of the compressive strength.

1. Introduction

Rammed earth walls are formed by compacting soil in layers, sometimes stabilised with cement or lime, inside temporary formwork. It is an ancient building material that has been used for millennia by many civilisations. Some of the earliest evidence of rammed earth building traditions has been found in the Yangshao culture (5000–3000 BCE) (Fu *et al*., 2002) but the technique is likely to have been developed from multiple origins given the material's use by ancient cultures around the world (Jaquin *et al*., 2008). The number of rammed earth structures being built in developed nations is increasing because there is a growing awareness of the need to use more sustainable building methods. Three modern rammed earth examples completed in the last 20 years include a three-storey cement-stabilised rammed earth resort in Kooralbyn, Australia (1992) (see Figure 1), the Chapel of Reconciliation in Berlin, Germany (2001) and a 7·2 m high, 14·4 m dia., circular lecture theatre at the Centre for Alternative Technologies in Machynlleth, Wales (2010) (see Figure 2).

Despite the re-emergence of rammed earth construction in recent decades it remains a specialist and novel building method in most developed nations. One aspect hindering a more widespread use of rammed earth construction, particularly in areas subject to seismic risk, is the method of characterising the shear strength of rammed earth. Rammed earth walls are built as monolithic structures so specimens have to be specifically manufactured for testing, calling into question their representation of the in situ wall. Problems with laboratory testing of rammed earth include: reproducing in situ compactive efforts and ramming methods; selection of specimen size, format and testing arrangements; choice of sample sizes; difficulties performing non-standard tests; and the costs of testing.

Figure 1. Kooralbyn Resort, Australia: an example of a modern rammed earth structure

Owing to a lack of a specific shear test for rammed earth, test methods have either followed geotechnical or masonry testing procedures. The present research compares the shear performance of fibre-reinforced, cement-stabilised rammed earth. Two different methods were used to evaluate the shear strength: the triaxial test (geotechnical) and the triplet test (masonry). Results are presented and recommendations for design and future work are given.

Figure 2. Sheppard Theatre, Centre for Alternative Technology, Wales: an example of a modern rammed earth structure

This study is part of an on-going project developing a rammed earth housing method for the indigenous rural communities in New Zealand. Their unique legal, geographic and social housing obstacles are detailed in Cheah *et al*. (2008b).

2. Previous work on the shear strength of rammed earth

Determining the shear strength of rammed earth is essential if an efficient and safe rammed earth structure is to be built. Geotechnical and masonry evaluations have both been used by researchers. In the literature reviewed, the Mohr–Coulomb failure criterion (see Equation 1) was used to characterise the shear strength of rammed earth.

$$1. \quad \tau = \sigma \tan(\phi) + c'$$

where τ is shear strength, σ is normal stress, ϕ is angle of internal friction and c' is apparent cohesion.

The apparent cohesion is an indicative measure of the shear strength when no normal stress is applied to the material. The strength is derived from a range of sources including negative pore pressures (suction) between soil particles and cementation. The tangent of the angle of internal friction ϕ represents the rate at which the shear capacity of the material increases when a normal stress is applied.

2.1 Experimental studies using geotechnical testing methods

Standard geotechnical shear tests such as the triaxial test and the shear box test have been used. Jaquin *et al*. (2009) used triaxial tests to better understand the source of shear strength in rammed earth and looked particularly at the contribution of matric suction. This suction results from the adsorption and capillary effects in a soil matrix and induces water to flow from a wetter soil (lower matric suction) to a drier one (higher matric suction) in an unsaturated soil. Their results showed that as pore water pressures decreased, matric suction and hence the apparent cohesion and shear strength increased.

Bouhicha *et al*. (2005) used the shear box test method to evaluate the strength of compacted earth reinforced with barley straw. Their work was part of a wider study of the physical and mechanical properties of fibre-reinforced compressed earth blocks. Their test results are presented in Figure 3 and showed that a 1·5% and 3·5% (by weight of soil) addition of straw increased the apparent cohesion by up to

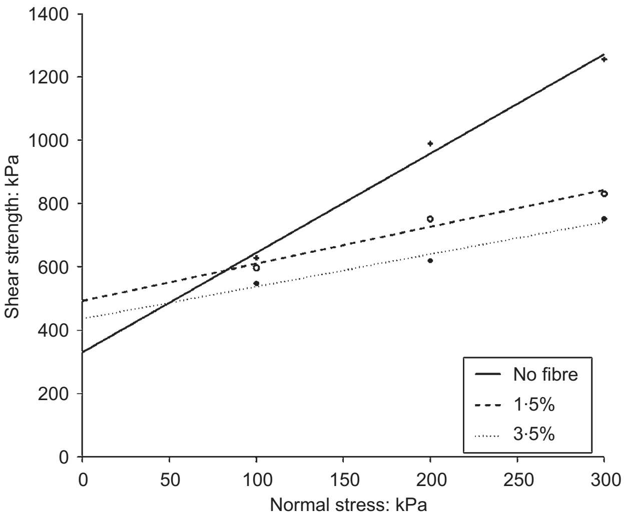

Figure 3. Shear strength of a compacted sandy clay reinforced with barley straw (Bouhicha *et al.*, 2005)

50% (from 330 kPa to 493 kPa), but decreased the angle of internal friction.

2.2 Experimental studies using masonry shear test methods

Unreinforced brick masonry is structurally comparable to rammed earth and has similar failure mechanisms, for example diagonal shear failure and sliding shear failure along mortar joints (Magenes and Calvi, 1997; Venkatarama Reddy and Prasanna Kumar, 2010). These shear failure modes were observed at the University of Auckland in a series of full-size rammed earth wall tests, which were subjected to cyclic horizontal loads (Cheah *et al.*, 2008a).

The current European standard for determining the shear strength of masonry (henceforth referred to as the triplet test) is designed to determine the shear strength along the horizontal bed joints. ASTM E519-00 (ASTM, 2000) is an alternative shear test that uses 1·2 m square test specimens. A larger test specimen represents the behaviour of a rammed earth wall panel more accurately but requires the use of specialised laboratory facilities and experience in order to conduct the test and thus has a limited practical application. The equation used in ASTM E519 to determine the shear stress is

$$2. \quad S_{\mathrm{s}} = \frac{0{\cdot}707P}{A_n}$$

where S_{s} is the shear stress, P is the applied load and A_n is the mean solid cross-sectional area in the x and y axes of the specimen.

Cheah and da Silva (2007) used the ASTM method to evaluate the shear strength of cement-stabilised rammed earth specimens reinforced with New Zealand flax fibres. Three 150 mm thick specimens (1200 mm × 1200 mm) were tested in compression diagonally. Each specimen failed in tension along the diagonal. The shear stresses and strains were calculated using formulae provided in the ASTM E519 standard. The compressive loads applied to the specimens were correlated to shear stresses of 612, 716 and 860 kPa (mean 729 kPa) (Cheah and da Silva, 2007). A photograph of the test set-up is shown in Figure 4.

The reported shear strengths in the research reviewed were of a similar magnitude. There was also a logical strength difference between the apparent cohesion values measured for compacted earth (330–493 kPa) to the shear stress results of the ASTM diagonal shear tests on cement-stabilised rammed earth specimens (ranging from 612 kPa to 860 kPa). It is clear from the research reviewed that rammed earth has an appreciable amount of shear strength that can be used in the design of structures. This is not recognised in many earth building standards at present.

2.3 Design guidance for the shear strength of rammed earth

The shear strength sections in national earth building design standards from Australia, New Zealand, USA and Zimbabwe were reviewed. The New Zealand and Australian standards cover cement-stabilised (and unstabilised) rammed earth design and the routine practice of using cement-stabilised rammed earth in the USA suggests the same of the New Mexico code (Walker and Maniatidis, 2003).

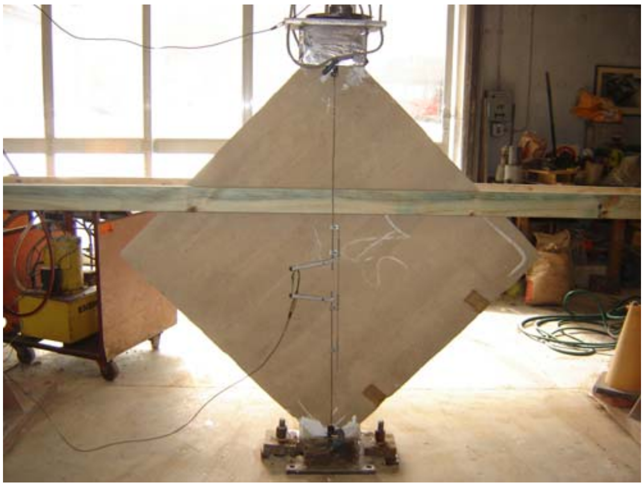

Figure 4. Diagonal shear test of stabilised rammed earth (Cheah and da Silva, 2007)

The New Zealand earth building standard NZS4297 allows a design shear strength of 0·08 MPa to be used for standard grade construction and provides an empirical formula that allows specifically engineered earth structures to use a shear strength equal to 7% of the design compressive strength (Standards NZ, 1998a).

Bulletin 5, produced by CSIRO Australia, allows a design shear strength of $10 + 10d$ kPa to be used, where d is the depth below the top of the wall in metres (Middleton, 1987). This guide makes an allowance for the increased shear strength available when a normal stress is applied to the earth. The allowance of 10 kPa per metre depth of rammed earth correlates to an angle of internal friction of 27°. This was determined by calculating the normal stress exerted by 1 m^3 of rammed earth (assuming a material density of 2000 kg/m^3) and thus calculating the angle which would result in a shear strength increase of 10 kPa using the Mohr–Coulomb failure criterion shown in Equation 1.

In many earth building standards design shear strengths are not addressed or allowed in design without further evidence, such as testing. These standards typically have design requirements based on the compressive strength of the earth material and the slenderness of the walls. Such standards, however, are not appropriate for use in seismic areas such as New Zealand. The Zimbabwe earth building standards (Standards Association of Zimbabwe, 2001) and the New Mexico adobe and rammed earth building code (General Construction Bureau, 1991) are two examples.

3. Experimental materials

In this research stabilised rammed earth specimens were reinforced with natural fibres; sisal and New Zealand flax. These two natural plant fibres were chosen because of their material properties and accessibility in local communities. The soil used was blended into a composition suitable for rammed earth construction and is detailed in Section 3.2.

3.1 Natural plant fibres

The inclusion of natural fibres in cement-based composites can increase material toughness and strength through energy-absorbing mechanisms like fibre debonding and pull-out, and by transferring loads across cracks (Filho *et al*., 1999). Galan-Marin *et al*. (2010) found that reinforcing soil with 0·25–0·5% of sheep wool (by weight) and alginate (a soil stabiliser derived from algae) prevented the formation of visible shrinkage cracks during the drying process and changed the failure mode from a sudden failure to one which continued to deform after the ultimate load had been reached.

In the present research hard plant fibres sisal (*Agave sisalana*) and New Zealand flax (*Phormium tenax*) were used owing to their good load-bearing properties. The fibres were cut to lengths between 50 and 60 mm and were added into the rammed earth mixture in concentrations of 0·05% and 0·1% (by dry soil weight). From seven different researchers the tensile fibre strength and Young's modulus of sisal was established to be between 298 and 577 MPa and between 9 and 19 GPa respectively (Filho *et al*., 1999; Silva *et al*., 2008). Research on New Zealand flax fibres indicated a similar tensile strength range between 371 and 588 MPa (Harris and Woodcock-Sharp, 2000; Ochi, 2006). King and Vincent (1996) proposed a Young's modulus of 31·4 GPa for the fibre.

3.2 Soil selection and preparation

Selecting a suitable soil for rammed earth construction is essential. Recommended soil constituent limits for rammed earth are 45–80% sand and gravels, 10–30% silts and 5–20% clay (Walker *et al*., 2005).

Wet sieve analyses and hydrometer tests were used to determine the grain size distribution of local fine (brick) clay and coarse (sand and gravel) sources. A mixture of 1 fine: 1 coarse was selected. The composition of the blended soil was 13% clay, 19% silt, 50% sand and 18% gravel. The soil was mixed with cement in a 13:1 soil to cement ratio (7·7% cement by dry weight of soil), which was selected based on past mix optimisation research (Haab, 1998).

A modified Proctor compaction test was conducted and determined that the optimal water content (O.W.C.) of the soil mix was 7·5%. Owing to the addition of cement and the use of a lower custom compactive effort in test specimens (explained in Section 3.3), a water content of 10% was selected. The New Zealand earth building standards allow a water content within 3% of the O.W.C. to be used (Standards NZ, 1998b).

3.3 Soil compaction

A custom compactive effort was used in this research for the manufacture of specimens. This arbitrary value was deemed to represent the compactive effort attained in a rammed earth wall more closely than a standard Proctor or modified Proctor compactive effort. The New Zealand earth building standards define that a sufficient compaction of rammed earth has been reached when the surface 'rings' when dropping a 6·5 kg hand rammer 300 mm on to the wall material (Standards NZ, 1998b). The standard Proctor compaction achieves a lower compaction than that achieved in rammed earth wall construction (Maniatidis, 2005) and this is supported by Lilley and Robinson's (1995) research, which measured the O.W.C. of standard Proctor specimens and simulated on-site rammed earth specimens. A custom compactive effort of 1560 kJ/m^3 was used for the present research (260% of a standard Proctor and 58% of a modified Proctor). This value was chosen based on the researcher's judgement of when the formwork began to resonate. For a given compactive effort and water content there is a maximum bulk density than can be achieved in a soil. When this is attained any further compactive energy travels through the compacted soil to the formwork where it is dissipated by creating vibrations. The compaction details and compactive efforts of the different methods are listed in Table 1.

The layer thicknesses were chosen so that all test specimens consisted of three rammed earth layers approximately 70 mm thick, with layer interfaces at one-third and two-thirds of the specimen height. The dry densities of the triaxial and triplet specimens ranged between 2040 kg/m^3 and 2150 kg/m^3.

4. Method

The shear strength of the rammed earth specimens was determined using the triplet test and the triaxial test.

4.1 The triaxial test

The triaxial test was conducted according to BS1377-8 – Part 8 (BSI, 1990), but the testing was performed without saturating the samples. Thirteen cylindrical specimens with a 2:1 aspect ratio (200 × 100 mm) were rammed in three layers using an automated mechanical rammer at the University of Bath. Four specimens were made with no fibre reinforcement and three specimens were made for each fibre content: 0·05% sisal fibre, 0·1% sisal fibre and 0·1% New Zealand flax fibre. Specimens were stored in a curing room held at 20℃ and at a relative humidity of 60-65% for 21 days. The specimens were then capped on the top and bottom face and stored in the curing room for a further 7 days. Specimens were tested at 28 days using a triaxial test at confining pressures of 0, 100 and 200 kPa. The confining pressures were chosen to cover the range of normal stresses that could be experienced in the walls of a one- or two-level structure. Compressed air was used to provide the confining pressures. Specimens from each of the different fibre contents were tested at the three confining pressures. A loading rate of 0·5 mm/min was used.

4.2 The triplet test

The triplet test was conducted according to EN 1052-3 (BSI, 2002). Twenty-eight stabilised rammed earth triplet specimens were made in total. Three sets of nine were rammed: one set with no fibre, another with 0·05% sisal fibre and the last with 0·1% sisal fibre. One triplet specimen was made with 0·1% New Zealand flax fibre. The dimensions of each triplet were 100 mm (width), 200 mm (length) and 200 mm (height). Each triplet was rammed in three layers approximately 70 mm thick after compaction. The triplet specimens were stored in a curing room held at 20℃ and at a relative humidity of 60-65%.

Nine triplet specimens from each fibre combination set were tested under three normal stresses of 0·1 MPa, 0·3 MPa and 0·5 MPa as specified in the test method. The single New Zealand flax fibre-reinforced triplet was tested under a normal stress of 0·3 MPa. The lateral load was applied using a hand-driven jack at a rate between 10 and 20 kN/min.

The triplet specimens were tested at ages between 3 and 4 weeks, and were capped with dental plaster 4 days before testing. The triplet test results did not show any appreciable difference in strength between 3- and 4-week-old specimens. An assumption was made that the strength of the rammed earth specimens was related to the water content at time of test. The water content of six rammed earth specimens rammed for the modified Proctor test was monitored for 40 days. After 2 weeks, the water content of all six specimens was below 4%, as seen in Figure 5. From the graph it can be seen that after 2 weeks in the curing room there was little further change in the water content. The graph also shows that the four specimens with an initial water content higher than the O.W.C. (7·5%) reached an equilibrium water content of 3·5%, whereas the two specimens with an initial water content of 7% and 6% levelled out at a lower water content around 2·4%.

5. Results

The shear strengths determined from the tests are reported with apparent cohesion values (c') and the angles of internal

Type of compaction	No. of blows per layer	Height of blows: mm	No. of layers	Weight of rammer: kg	Compactive effort: kJ/m^3
Standard Proctor	27	300	3	2·5	600
Modified Proctor	27	450	5	4·5	2700
Custom triaxial	26	450	3	4·5	1560
Custom triplet	88	450	3	4·5	1560

Table 1. Compactive effort of Proctor compaction methods and test specimens

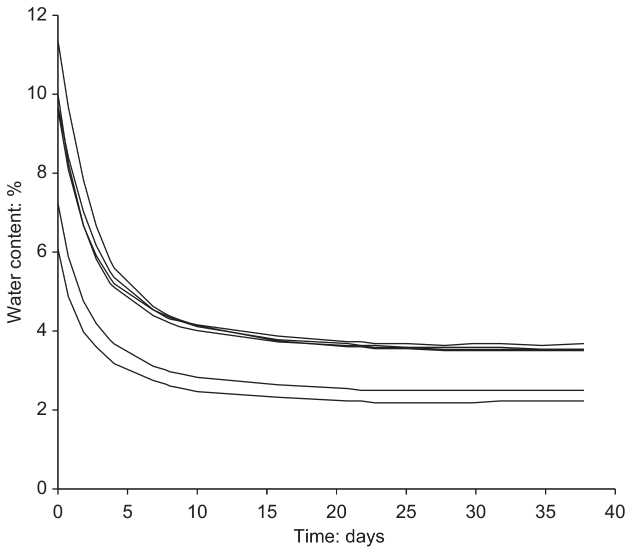

Figure 5. Water content over time of stabilised rammed earth specimens with different initial water contents

friction (ϕ). The results for the triplet tests are displayed in Table 2 and the results of the triaxial test in Table 3.

During the triplet tests the normal stresses applied on the specimens were kept at the set level during the test by the StrainSmart control software. The shearing force applied was recorded by the software and the maximum value was used to determine the failure shear stress of the specimen using

$$3. \quad \tau = \frac{F_s}{(2 \times A_n)}$$

where τ is the shear stress, F_s is the shearing force and A_n is the mean cross-sectional area of the two rammed earth layer interfaces.

Three specimens were tested for each fibre content and normal stress combination. Each test result presented in Table 2 represents the mean result of the three specimens tested for each combination. Only one triplet specimen was tested for the subset D1(F).

The shear stress results were plotted against normal stress and a linear regression on the data allowed the apparent cohesion and angle of internal friction to be determined.

During the triaxial test, the axial load, axial displacement and pore water pressures were recorded and the maximum axial load was used to determine the deviator stress. The deviator stress reported in Table 3 was adjusted to take into account the weight of the loading ram and effect of the confining pressure on the loading ram. Mohr's circles were plotted from the test results and the least-squares method was used to fit a linear line that was tangential to the Mohr's circles. The apparent cohesion and angle of internal friction values were determined from this line. The correlation coefficient shows how closely the line derived by the least-squares method met the requirement to be tangential to all of the Mohr's circles. A value close to 1 indicates a good fit.

Specimen subset[a]	Age at test: days	Fibre: %	Normal stress: kPa	Shear stress: kPa	Apparent cohesion, c′: kPa	Angle of internal friction, ϕ: deg
A1-3	27	0	107	453	328	45
A4-6	26	0	311	609		
A7-9	21	0	522	857		
B1-3(S)	20	0·05	108	435	286	53
B4-6(S)	20	0·05	318	700		
B7-9(S)	20	0·05	525	991		
C1-3(S)	23	0·1	109	465	383	45
C4-6(S)	21	0·1	383	744		
C7-9(S)	20	0·1	524	876		
D1(F)	19	0·1	318	745	—	—

[a] S denotes a sisal fibre addition; F denotes a New Zealand flax fibre addition.

Table 2. Shear strength test results of the triplet shear test

Specimen[a]	Age at test:days	Fibre: %	Confining pressure, $\sigma_{3,f}$: kPa	Deviator stress, σ_d: kPa	Principal stress at failure, $\sigma_{1,f}$: kPa	Apparent cohesion, c': kPa	Angle of internal friction, ϕ: deg	Correlation coefficient, R^2
M1	27	0	0	3709	3709	724	48	0·993
M2	28	0	108	4447	4555			
M3	28	0	200	4895	5095			
M4	28	0	0	3804	3804			
N1S	28	0·05	0	3816	3816	758	47	1
N2(S)[b]	28	0·05	100	3491	3591			
N3(S)	28	0·05	200	4883	5083			
O1(S)	27	0·1	0	3632	3632	554	56	0·998
O2(S)	27	0·1	100	4717	4817			
O3(S)	27	0·1	200	5619	5819			
P1(F)	27	0·1	0	3901	3901	648	53	1
P2(F)	27	0·1	100	4729	4829			
P3(F)	27	0·1	200	5520	5720			

[a] S denotes a sisal fibre addition; F denotes a New Zealand flax fibre addition.
[b] Specimen N2(S) was omitted from analysis owing to uneven bearing issues on the top face during the triaxial shear test.

Table 3. Shear strength results of the triaxial shear test

The triplet tests failed along the planes between the rammed earth layers and the triaxial samples failed along diagonal planes as shown in Figures 6 and 7.

6. Discussion and analysis

6.1 Lower apparent cohesion measured using the triplet test method compared with the triaxial test

The apparent cohesion measured using the triplet test ranged between 286 and 380 kPa (mean 332 kPa), whereas the apparent cohesion measured using the triaxial test was approximately double; between 554 and 758 kPa (mean 671 kPa). The apparent cohesion is an indicative measure of the stresses within the material that resist shear. For one- or two-level rammed earth structures, the normal stresses acting on the walls are small and the shear strength value of the material is derived predominantly from the apparent cohesion.

The difference in the measured apparent cohesion is not surprising although the reasons for the two-fold strength

Figure 6. Tested triplet specimens

Figure 7. Tested triaxial specimens

increase using the triaxial test is important to understand. The triplet test forced the specimens to fail at the planes between the rammed earth layers. The interface is weaker than the rammed earth layer for several reasons. As the soil is compacted in layers, the top of the layer receives more compaction than the bottom and bonds less effectively to the subsequent layer above. During the time between ramming subsequent layers, some loss of moisture (and, where cement is added, partial curing) will also occur. The fibres added to the triplet specimens did not extend between rammed earth layers and would not have contributed to the shearing resistance measured. The triaxial tests which failed diagonally through several rammed earth layers would have benefitted from the fibres. The triaxial specimens showed no evidence of failing along the weak planes between rammed earth layers. The slight intersection of the diagonal failure planes with the base in a few of the triaxial specimens indicate that an aspect ratio larger than 2:1 would provide a more accurate test of the material's shear strength.

The difference in apparent cohesion results arises because the triplet test measures the shear strength at the interface between rammed earth layers, whereas the triaxial test measures the shear strength of the material through several rammed earth layers. The larger apparent cohesion measured using the triaxial test method was attributed to the diagonal orientation of the failure plane through several rammed earth layers. This failure plane has greater frictional forces and tighter particle interlock than one located between rammed earth layers.

As a layered material the shear strength capacity of rammed earth will vary depending on the orientation of the applied load and this is clearly seen in the results. The tests have shown that rammed earth has a lower shear capacity along the horizontal plane between the layers than through the rammed earth layers. Despite the weaker shear strengths measured on the horizontal plane between rammed earth layers, a diagonal shear failure was deemed more likely to occur owing to the placement and geometry of structural rammed earth walls in practice. Structural rammed earth walls typically range between 0·7 and 4 m in length and are often built adjacent to other structural walls which would restrict horizontal movement in a layer. It is unlikely that a sliding shear failure would occur before a diagonal shear failure and thus the triaxial test provides a better measure than the triplet test of the shear strength capacity of a rammed earth wall.

6.2 Measured friction angles and earth building standard allowances

CSIRO Bulletin 5 (Middleton, 1952) was the only standard reviewed that specified design shear strengths which were proportional to applied normal stresses. The angle of friction assumed in that standard was calculated to be 27°. In this research the angle of friction measured for the cement-stabilised rammed earth test specimens ranged between 45° and 56°. This result was measured consistently in both test methods. For stabilised rammed earth structures subjected to high normal stresses, this result implies a significant increase in shear strength capacity. Apart from CSIRO Bulletin 5, no method is provided in any other earth building standard to use this shear strength component in the structural design of an earth structure.

6.3 Comparison of test results with earth building standard allowances for shear strength

Shear strength is an important design parameter for rammed earth buildings in seismic regions. The two earth building standards reviewed that allowed design shear strengths for rammed earth to be used in design were the New Zealand Earth Building Standards and CSIRO Bulletin 5.

Using the method provided in NZS4297 (Standards NZ, 1998a), a 95th percentile design compressive strength of 2·8 MPa was established for the stabilised rammed earth used in this research. Results were corrected for specimen aspect ratios (2:1) and sample size (5). Based on the New Zealand earth building standard NZS4297, a design shear strength of 200 kPa (with testing) was calculated for a structure with specific design and 80 kPa (without testing) for standard grade construction. The mean apparent cohesion values determined from the triplet and triaxial shear tests were 331 kPa and 671 kPa respectively, with the latter result being argued as the more representative value for the material.

The tests conducted have shown that stabilised rammed earth walls have greater shear strength than is currently allowed for in design by existing earth building standards.

6.4 Recommended method for characterising the shear strength of stabilised rammed earth

The recommendation from this research is to use the triaxial test method to establish the shear strength of stabilised rammed earth. Test specimens should be rammed to an aspect ratio of at least 2:1, using a compactive effort equivalent to a standard Proctor compaction test. Using the standard Proctor compaction avoids the complications and issues that may arise from using custom compactive efforts or compactive efforts based on the formwork 'ringing'. The standard Proctor compactive effort is lower than that typically achieved in rammed earth and thus errs on the conservative side.

For situations where only the compressive strength of stabilised rammed earth is known, a conservative estimate of shear strength can be made by using a design shear strength equal to 7% of the design compressive strength. This is currently permitted in the New Zealand earth building standards (Standards NZ, 1998a) for a specifically designed structure.

The triplet test was not recommended as a shear test method for rammed earth for the following reasons.

- Manufacture and preparation of triplet test specimens required a lot of time and effort. Custom formwork was also required.
- The triplet specimens weighed 10·5 kg on average. This was not as convenient or safe to transport and test as the triaxial specimens (<4 kg).
- Locating a laboratory that has the capability and expertise to conduct a triplet test is potentially more difficult and expensive than for a triaxial test.
- The test measures the shear strength of the interface between rammed earth layers but, owing to the limited horizontal deformation potential in practice, rammed earth walls are more likely to fail diagonally through several rammed earth layers.

7. Conclusion

Stabilised rammed earth construction is growing in use around the world. Although rammed earth technology has been used since historic times to the present day, there is still a lot of uncertainty in the area of determining and understanding the shear performance of rammed earth. A better understanding of the shear strength of rammed earth and how to characterise it will allow less conservative guidelines to be specified and more widespread use of the building method.

This research has used the triplet test (masonry) and the triaxial test (geotechnical) to establish the shear strength of a stabilised rammed earth material reinforced with sisal and New Zealand flax fibres. The main findings were that the apparent cohesion of the cement-stabilised rammed earth had a mean of 671 kPa when using the triaxial test and 332 kPa when using the triplet test. The difference in test results was due to the way the triplet test forced a shear failure to occur along the weak interface between rammed earth layers, whereas the triaxial test specimens failed along a stronger diagonal shear plane. Although the triplet test will provide a more conservative design, the triaxial test better represents the diagonal shear failure which is the predominant shear failure mode for rammed earth walls in practice.

A review of existing building standards for rammed earth construction showed that only the New Zealand earth building standards and CSIRO Bulletin 5 had specified an allowable design shear stress for rammed earth. The standards allowed design shear strengths of 80 kPa and 10 kPa respectively. A value of 210 kPa would be allowed by the New Zealand earth building standards for a specifically designed rammed earth structure using the soil mix employed in this research.

A recommendation is given to use the triaxial test as a shear test method for rammed earth, using specimens with an aspect ratio of at least 2:1 which are made using the same compactive effort as a standard Proctor compaction test.

The use of a lower bound design shear strength for stabilised rammed earth equal to 7% of the design compressive strength has been shown to be conservative and the use of this lower limit is supported by the results of this research.

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