International Workshop on Rammed Earth Materials and Sustainable Structures &
Hakka Tulou Forum 2011: Structures of Sustainability at
International Symposium on Innovation & Sustainability of Structures in Civil Engineering
Xiamen University, China, 2011

AN OVERVIEW OF SOME CURRENT RECOMMENDATIONS ON THE SUITABILITY OF SOILS FOR RAMMED EARTH

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Abstract: Rammed earth is a sustainable construction material, especially in remote areas where utilising the locally available soil means reduction of costs and environmental impact of construction. Before the soil could be used in construction, testing is required to determine whether it is suitable for rammed earth. Past research studies and current earth building technical documents provide some guidelines for the suitability of soils for rammed earth. Nevertheless, these guidelines are sometimes broad and vague making assessment of the soil difficult. This paper shows the limits of the currently available guidelines and determines whether the recommended assessment criteria are appropriate. From this study, it is evident that more research is needed to understand the effect of water suction, water-cement ratio and mineralogy of clay in the mechanical behavior of rammed earth. Furthermore, suitable tests to assess durability properties (such as erodibility) need to be implemented.

Keywords: Rammed earth, particle size distribution, compressive strength, erosion, shrinkage

1 INTRODUCTION

The first technical documents to provide recommendations on the use of cemented soil in building construction or technical guidelines for rammed earth procedures simultaneously appeared in different parts of the world (i.e. Australia, New Zealand, USA, UK, India) around the 1940s' and 50's (Alley, 1948; De Long, 1959; Middleton, 1952; RIBA, 1951; United Nations, 1964; Varma and Mehra, 1950). The reasons for this occurrence (mainly cultural, economical and environmental), are different from country to country but world-wide those years signed the commencement of a significant amount of research into earthen architecture conservation and construction (Jaquin et al, 2008). Despite the major amount of studies published in the last 60 years, the current knowledge and understanding of rammed earth material properties and design procedures are still far less than other civil engineering materials like steel, concrete and timber.

This paper presents a review of some relevant studies and recommendations currently available in literature, with a special emphasis on the criteria to assess the suitability of soil for rammed earth. For the majority of the guidelines considered in this paper, the soil suitability is determined by standard geotechnical tests of particle size distribution, plasticity index and liquid limit. The suitability criteria are defined in terms of strength and durability. More details are presented in Section 2.

Considering the infinite variations in clay, silt, sand and gravel content that a manufactured soil can present, it is clear how difficult it is to define a consistent and ever-valid suitability law applicable to any type of soil. Furthermore, the particle size distribution accounts only for the quantity of the soil particles, but not for their mineralogy. This aspect is further discussed in Section 3, together with the effect of cement and other admixtures in stabilised rammed earth.

To verify the correctness and validity of the currently recommended suitability criteria, 10 different artificial soils were created in the laboratory and tested for strength and durability. The details of the experimental program are reported in Section 4. The results presented in Section 5 show the limitations of the current guidelines for suitability of soils and that some different suitability criteria should be considered when assessing soil for rammed earth. This and other conclusions are discussed in details in Section 6 of this paper.

2. CURRENT RECOMMENDATIONS

2.1 Australian and British Relevant Books

It is not the aim of this paper to review all the current studies on soil suitability for rammed earth. For this purpose, an exhaustive evaluation can be found in the work of Jimenez Delgado and Guerrero (2007) and Maniatidis and Walker (2003). This paper reviews some relevant documents with the aim of clarifying the strengths and weaknesses of the suitability assessment.

In Australia there are currently two documents that provide directions for engineers and builders using rammed earth: *Bulletin 5: Earth-Wall Construction* (Middleton and Schneider, 1987) and *The Australian Earth Building Handbook 195* (Walker et al, 2002). It is important to note that neither is specifically written for stabilised rammed earth. The Bulletin 5 does not specify quantitative criteria for the suitability of soils. The two major tests recommended to determine the suitability are the unconfined compressive strength test (minimum strength equal to 0.25 MPa) and the accelerated erosion test. The Handbook 195 specifies grading and plasticity properties of soils suitable for rammed earth as shown in Table 1, but the maximum gravel size is not specified and appropriate clay types are not mentioned. The circumstances under which cement should be used and the amount of it are not well indicated. HB195 describes in details the experimental procedure to measure strength and durability parameters, but it does not give any indication of values that can be deemed satisfactory.

Table 1: Recommendations for soil suitability from Handbook 195 (Walker et al, 2002)

	% by mass	
	Min	Max
sand + gravel content	45	75
silt content	10	30
clay content	0	20
cement content	4	12
liquid limit	35	45
plasticity index	15	30

New Zealand Standard 4298 (Standards New Zealand, 1998) outlines construction details for earth building in general, including rammed earth. It does not provide quantitative guidelines for grading of suitable soils, but it focuses on testing procedures and required results; some of them are presented in Table 2.

Table 2: Recommendations for soil suitability from New Zealand Standard 4298:1998

Property	Required result
Compressive strength	>1.3 MPa
Flexural strength	>0.25 MPa
Durability (Accelerated Erosion Test)	Erodibility index<5
Shrinkage	Strain<=0.05%

A book specifically written for rammed earth is *Rammed earth, design and construction guidelines* (Walker et al, 2005). It recommends that suitable soils should meet the criteria specified in Table 3 or their particle size distribution curves should fall within two given upper and lower grading curves. It does however specify that "*influence of variation in grading on physical characteristics of rammed earth, including strength and durability, remains uncertain owing to lack of test data*". Indicative values for compressive strength (unstabilised compressive strength: 0.5-4 MPa, cement-stabilised: up to 10 MPa), shrinkage (less than 0.5%) are provided.

Table 3: Recommendations for soil suitability from *Rammed earth, design and construction guidelines* (Walker et al, 2005)

	% by mass	
	Min	Max
sand + gravel content (maximum particle size 10-20 mm)	45	80
silt content	10	30
clay content	5	20
cement content	4	12
liquid limit		45
plasticity index	2	30
linear shrinkage	0	5%

2.2 Relevant Peer Reviewed Journal Papers

Amongst the wide numbers of studies published in the last 30 years, the work of Akpokodje (1985) stands as an exhaustive analysis in which the soil particle size distribution is not used as the unique soil index. The soil mineralogy, the different effects of cement and hydrated lime and other material parameters such as strength, shrinkage and swelling are obtained as well. The exhaustive results are conclusive for the investigated soil, and it is not amongst the aims of the paper to provide general guidelines valid for any soil.

With the aim of offering further guidance for the identification of soils to be stabilised with cement, Bryan (1988) produced a chart in which the suitability of soil stabilised with 7.5% cement and compacted under 2 N/mm^2 is assessed only in terms of the particle size distribution. No mineralogy analysis was carried out in this study. Burroughs (2008) conducted a study on 111 different soils sourced from Australia in order to develop quantitative criteria for the selection and stabilization of soils for rammed earth. Soils were classified using particle size distribution, plasticity, and shrinkage tests. The suitability of soils for stabilisation was judged against a compressive strength criterion of 2 MPa. The results are in terms of charts in which soils are deemed favourable or unfavourable for stabilisation; if favourable, another chart recommends the amount of cement and lime (between 1 and 5.5 %) to be used. It is important to stress that none of the above mentioned studies takes into account the role of suction, as described by Jaquin et al. (2009) and the water cement ratio.

3 MATERIALS AND PRELIMINARY TESTS

To validate the recommendations for soil suitability presented in the previous Section, ten artificial soils comprised of different contents of kaolin clay, silica flour (used as silt), clean white sand, and gravel (10mm max size) were created. Five batches were stabilised with cement, and five batches had zero cement content (unstabilised). The grading of each soil is shown in Table 4, in term of mass percentage. The cement and lime contents are calculated as percentage by mass of the total mass of soil (clay, silt, sand and gravel). The 10 artificial batches have particle size distributions that make them suitable according to the selection criteria presented in Section 2.

Some preliminary tests (liquid limit, plastic limit and linear shrinkage) were conducted on soil samples in accordance with AS 1289.1.1 (Standards Australia, 2001). These tests were performed using only the fines of the soil mix, which is the fraction of soil passing a 425 μm sieve. The liquid limit and the plasticity index are all below the maximum values recommended by different studies. Only batches 5 and 9 do not satisfy the recommended maximum linear shrinkage strain value of 5% (Walker et al, 2005). The optimum moisture content (OMC) for each batch was calculated using the Modified Proctor test (Standards Australia, 2001). The results are presented in Table 5.

Table 4: Particle size grading of the 10 artificial soils (Contents are in mass percentage)

Unstabilised					Stabilised						
Batch	% clay	% silt	% sand	% gravel	Batch	% clay	% silt	% sand	% gravel	% cement	% lime
1	5	25	50	20	6	10	15	50	25	5	0
2	30	0	50	20	7	10	5	40	45	4.5	0
3	15	15	50	20	8	20	0	60	20	4	1
4	30	20	40	10	9	30	10	20	40	4	2
5	40	20	20	20	10	5	25	50	20	4.5	0

Table 5: Preliminary tests results

Unstabilised					Stabilised				
Batch (fines only)	Liquid limit (water content %)	Plasticity index	Linear shrinkage (%)	Optimum moisture content (%)	Batch (fines only)	Liquid limit (water content %)	Plasticity index	Linear shrinkage (%)	Optimum moisture content (%)
1	15.6	3.1	0.0	5.8	6	15.4	5.3	2.0	5.6
2	26.1	13.8	6.0	8.3	7	17.3	7.9	2.4	5.4
3	18.0	9.7	3.0	6.4	8	22.3	12.1	3.5	7.4
4	24.8	13.4	5.1	7.4	9	38.5	23.3	7.1	9.4
5	34.5	18.4	7.1	9.6	10	15.4	4.0	0.2	5.3

4 METHODS AND PROCEDURES

To achieve consistency, the compaction energy of all moulded samples was the same used in the Modified Proctor test to calculate the OMC. The water content at ramming was equal to the OMC. All samples were cured at ambient temperature and humidity conditions for at least 28 days before testing (Middleton and Schneider, 1987; Standards New Zealand, 1998). Following the guidelines discussed in Section 2, the unconfined compressive strength (UCS), the erodibility index and the shrinkage strain were the parameters obtained from the experimental program on the 10 artificial soils.

For each batch, 3 cylindrical samples of 100mm diameter and 200mm height (Middleton and Schneider, 1987) were moulded to obtain the dry UCS. The cylinders were dried in oven at 100°C for approximately 24 hours. After oven-drying, they were placed in a desiccator for approximately five hours while cooling to room temperature (Middleton and Schneider, 1987) so that they did not re-absorb moisture from the atmosphere.

Since from other studies (Ciancio and Boulter, 2011) the erosion measured using the Accelerated Erosion Test (AET) on cement-stabilised rammed earth was negligible, the AET was carried out only on the unstabilised batches (1 to 5 in Table 4). One prismatic sample per unstabilised batch with dimensions of 200 x 200 x 300mm (Middleton and Schneider, 1987) was prepared. The depth of the sample replicated the typical thickness of a rammed earth wall. One prismatic sample per batch with dimensions of 50 x50 x600mm was rammed for the shrinkage test (Standards New Zealand, 1998).

5 RESULTS AND DISCUSSIONS

The results of the experimental program are presented in Table 6. For the unstabilised batches, the measured dry UCS is far less than the value of 1.5MPa suggested by the NZS (Standards New Zealand, 1998). Only Batch 5 satisfies the conservative recommended value of 0.25 MPa proposed by Bulletin 5 (Middleton and Schneider, 1987). All stabilised batches satisfy the limit of 2MPa proposed by Burroughs (2008). The low values of UCS for the unstabilised batches might be explained by the water suction effect. The water suction in partially saturated pores significantly contributes to the strength of unstabilised rammed earth (Jaquin et al, 2009). Since all samples were oven-dried at 100°C before being tested, it is logical to assume that most of the pores were dry. There might have been some water trapped within the clay particles, but not enough to affect the strength of the sample. Therefore the measured strength might have comprised only the particles interlocking and the clay cohesion. Although this theory needs further investigation to be proven, it is reasonable to state that unstabilised samples tested at ambient conditions (hence with a moisture content different from zero) should show UCS values higher than those obtained on dry samples.

Table 6: Results in terms of characteristic UCS, shrinkage strain and erodibility index

Unstabilised				Stabilised			
Batch	Characteristic dry UCS (MPa)	Shrinkage strain (%)	Erodibility index (AET)	Batch	Characteristic dry UCS (MPa)	Shrinkage strain (%)	Erodibility index (AET)
1	0.2	<0.1	>5	6	2.5	<0.1	-
2	0.2	<0.1	>5	7	6.7	<0.1	-
3	0.2	<0.1	>5	8	3.1	<0.1	-
4	0.1	<0.1	>5	9	2.4	<0.1	-
5	0.4	<0.1	>5	10	5.3	<0.1	-

It is not clear where the lower limits of 0.25, 1.5 and 2MPa come from. It is difficult to set a minimum UCS value that rules the suitability of any soil and any structure. It is advised that the minimum value of UCS should be established by the design requirements of the structural elements.

None of the unstabilised batches passed the AET. Even though it is often recommended as a suitable test to measure the durability of rammed earth in terms of erosion, the main criticism towards this test is that it creates conditions that are very dissimilar from the real environmental conditions to which a rammed earth wall will be exposed during its life time. Bui at al. (2009) measured the real erosion of different rammed earth walls over 20 years, finding much less erosion than is created using the AET. Although the results are useful, more pertinent laboratory tests need to be developed to assess the durability of rammed earth wall.

All samples showed maximum shrinkage strain at 28 days lower than 0.1%. Similarly to what said for the minimum UCS value, the purpose of setting a maximum value of shrinkage for the suitability of soil is questionable. The design of a structural member should be based on the obtained experimental results, and shrinkage joints placed accordingly.

6 CONCLUSIONS

Based on the particle size distribution alone, the 10 artificial soils created in this study were all deemed suitable for rammed earth, although Batches 5 and 9 showed to not comply with the minimum requisites in terms of linear shrinkage established by Walker et al. (2005), as shown comparing results in Table 5 with limits in Table 3. Batches 1 to 5 failed to pass the AET according to the NZS (Standards New Zealand, 1998). All unstabilised batches (1 to 5) failed the UCS test according to the NZS, but batch 5 was suitable according to Bulletin 5 (Middleton and Schneider, 1987). It is clear that different guidelines give contradictory soil assessments. Furthermore, the measured dry UCS is believed to underestimate the real strength of all samples.

The mineralogy as well as the clay content should be taken into account, especially for unstabilised soils. For stabilised soils, none of the assessment criteria considers the crucial interaction between clay and cement. The recommended cement contents are based on empirical results, rather than a real understanding of the effect of the water-cement ratio on rammed earth strength.

It is recommended that rammed earth standards and guidelines provide details of meaningful laboratory tests to obtain mechanical (strength and durability) parameters upon which the design of a structure can be done. It is not recommended to give minimum and maximum values of such parameters as these can lead to misleading interpretations. It seems pertinent laboratory tests need to be developed to assess the durability indices.

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