RECOMMENDATIONS FOR THE SELECTION, STABILIZATION, AND COMPACTION OF SOIL FOR RAMMED EARTH WALL CONSTRUCTION

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ABSTRACT

Rammed earth possesses environmental advantages over most other competing construction materials. However, if it is to be more routinely used in the construction of modern, sustainable buildings, its material properties and production processes must be properly quantified. This paper proposes practical recommendations for soil selection, stabilizer treatment, and on-site compaction for rammed earth, based on a recent set of 219 stabilization experiments. The purpose of the recommendations is to maximize the probability of constructing rammed earth walls that meet or exceed a compressive strength criterion of 2 MPa. The recommendations cover: (1) Quantifying the natural soil properties of linear shrinkage and texture in a staged sequence in order to identify suitable soils to stabilize (and to reject unsuitable soils); (2) Quantifying the amounts of cement and/or lime to be added to the selected soil according to the values of soil properties measured; and (3) Quantifying the forces involved in on-site compaction of stabilized soil (for both manual and pneumatic ramming), and relating these to laboratory-based test standards. Although the recommendations need to be tested and verified/refined using new data, their initial application to rammed earth construction situations in Australia indicates that they have predictive utility. Further research will also indicate the degree of applicability of the recommendations to the production of compressed earth bricks.

KEYWORDS

building materials, rammed earth, soil stabilization, cement, lime, compressive strength, compaction

INTRODUCTION AND BACKGROUND

Rammed earth has been used for construction in many countries, dating back many centuries in some civilizations (Heathcote, 1995; Bahar et al., 2004). Rising public awareness in developed countries concerning sustainable living, combined with better knowledge of the thermal benefits (Taylor & Luther, 2004), safety (Byrne, 1982), and durability of earth (Heathcote, 1995), and of the lower energy inputs of construction (Lawson, 1996; Alcorn, 2003), have brought renewed interest in earth as a green building material. Problems associated with unstabilized rammed earth, including low strength and water absorption, can be overcome by the addition of stabilizers (such as cement and lime) in order to meet modern construction standards and requirements.

Environmental Performance of Construction Materials

In both developed and developing countries, the concept of sustainable buildings has drawn much attention from both scholars and building professionals (Boyle, 2005). Although the notion of sustainability is complex and contested (Boyle, 2005), much of the discussion and analysis continues to surround energy consumption and CO_2 emissions involved in the life cycle of buildings (e.g., Menzies et al. 2007). The resources consumed and pollutants emitted can be assessed with respect to three main parts of the building life cycle: (a) production of the building materials and actual construction; (b) operation of the building and maintenance during its life; and (c) recycling/disposal of materials at the end. These three aspects are discussed in turn

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below with respect to stabilized rammed earth and other competing building materials.

Because embodied energy represents a significant component of the life cycle energy associated with buildings (Hammond and Jones, 2008), many studies have been made regarding the embodied energy and carbon of a wide range of construction materials. Energy and carbon values are reported in many commercial and several scientific databases and inventories, an example being the Inventory of Carbon and Energy (ICE) database of the University of Bath (UK), which contains data (selected from peer-reviewed studies) for over two hundred different materials (Hammond and Jones, 2008). However, life cycle analysis (LCA) of built assets with respect to embodied energy and carbon is made difficult by significant data variation arising from various issues including differences in measurement methodologies, in boundary definitions (inclusions and exclusions), and in energy source assumptions (Menzies et al., 2007; Hammond and Jones, 2008). Notwithstanding such overall data variations, there is some consistency in how stabilized rammed earth compares with other construction materials in terms of embodied energy and carbon.

Although cement is a high-energy product, rammed earth stabilized with cement possesses less embodied energy than other masonry products (Alcorn & Wood, 1998; Treloar et al., 2001; Alcorn, 2003; Hammond and Jones, 2009). Estimates of the embodied energy for general (Portland) cement are 4.6 MJ/kg (with the best data ranging from 2.8–6.8 MJ/kg) (Hammond and Jones, 2009); for concrete blocks are 0.7–1.5 (Lawson, 1996; Hammond and Jones, 2009); for autoclaved aerated concrete blocks (AACs) are around 3.5 MJ/kg (Hammond and Jones, 2009); for general clay bricks are 2.6–3.0 MJ/kg (Lawson, 1996; Alcorn, 2003; Hammond and Jones, 2009); and for rammed soil cement (i.e. stabilized rammed earth) are 0.7–1.0 MJ/kg (Lawson, 1996; Alcorn & Wood, 1998; Alcorn, 2003; Hammond and Jones, 2009). Other relevant product values include averages for steel at 24.6 MJ/kg and general timber at 8.5 MJ/kg (Hammond and Jones, 2009). It should be noted that these values refer to "cradle to gate" conditions, i.e., the values do not include energy involved in transporting the materials from the production site to the construction site.

The different embodied energy values of various materials become more relevant to actual construction when typical wall assemblies of the component materials are examined. Lawson (1996) presented embodied energy values for various assemblies, including timber frame and weatherboard wall (169 MJ/m^2), steel frame and fiber cement clad wall (385 MJ/m^2), stabilized rammed earth wall 5% cement (405 MJ/m^2), AAC block wall (440 MJ/m^2), cavity concrete block wall (465 MJ/m^2), brick veneer wall (480 MJ/m^2), and cavity clay brick wall (860 MJ/m^2). Crawford (2009) remodeled the timber-weatherboard and brick veneer assemblies using a more comprehensive assessment method, and derived higher values than Lawson (1996) of 1250 MJ/m^2 and 1290 MJ/m^2 for the two assemblies, respectively. These results show that although rammed earth compares favorably with other construction systems, more work is needed in assessing and comparing energies associated with the different construction assemblies.

The cement content of stabilized rammed earth represents its embodied CO_2. General cement has an embodied CO_2 value of 830 g CO_2/kg (Hammond and Jones, 2009), as measured from cradle to grave. Soil-cement is assigned a value by the same authors of 140 g CO_2/kg, but this would equate to a cement percentage in rammed earth of over 15%, when the usual quantity for rammed earth construction is around 5%. A more realistic value for stabilized rammed earth may therefore be around 40–50 g CO_2/kg. These values compare with concrete blocks at 98 g CO_2/kg, AAC blocks at around 300 g CO_2/kg, general clay bricks at 220 g CO_2/kg, steel at 1770 g CO_2/kg, and general timber at 460 g CO_2/kg (Hammond and Jones, 2009).

Regarding the second aspect of the life cycle of a building—the environmental impacts of a building arising from its operation and maintenance—those associated with a rammed earth building are generally considered to be relatively low, although there are few definitive research findings regarding this claim. The thermal mass properties of stabilized rammed earth mean that earth walls provide a more constant internal environment with reduced fluctuation in temperature in both diurnal and seasonal cycles (Robertson, 1987; Taylor & Luther, 2004). These thermal properties reduce the need for heating during winter and for air conditioning during summer.

Viljoen & Bohn (2001), in a life cycle analysis of two houses in the UK, found that a house built from rammed earth and local timber would have a lifetime energy impact some 20% lower than a house built of medium-density concrete blocks. CO_2 emission differences identified in the life cycle analysis were significant, with a rammed earth house resulting in CO_2 emissions of around 10.3 kg/m^2/yr compared with medium density concrete blocks (1.1 t/m^3) at 20.9 kg/m^2/yr. Regarding the third aspect of a building's life, the energy costs involved with recycling or disposing of rammed earth relative to other building materials are at present unquantified.

Rationale and Purpose of Study

The aforementioned construction materials data indicate that the life cycle energies and CO_2 emissions of buildings constructed using rammed earth are likely to be lower than most other competing materials. If the environmental benefits of rammed earth buildings are to be realized, and given the resurgent interest in earth (Maniatidis and Walker, 2003), its adoption as a construction material needs to be encouraged. For this to occur, it is necessary that the methods and materials of soil stabilization continue to be assessed and improved in order that rammed earth buildings of sufficient quality can be routinely constructed. The three most important aspects are the selection of a suitable soil, the selection of an appropriate stabilizer treatment (type and quantity), and the application of an appropriate compactive effort.

Both the properties of the soil to be stabilized, and the choice of stabilizer treatment, are important in successfully stabilizing a soil for earth wall construction (Akpokodje 1985; Bryan 1988; Walker 1995; Reddy and Gupta, 2005; Burroughs, 2006, 2008). Despite the importance of selecting a suitable soil to stabilize, existing guidelines for soil selection (e.g. CSIRO 1987; UN 1992) are generally rather vague and involve time-consuming testing regimens. In addition, for those studies that have specified ideal, maximum, or minimum values of the various relevant soil parameters, such as particle size distribution and plasticity (e.g., Fitzmaurice, 1958; Spence, 1975; Bryan, 1988; Houben and Guillaud, 1994; Walker, 1995), there exists a range of recommended values for such parameters (also see Maniatidis and Walker, 2003). Overall, therefore, many types of soil are suggested as being able to be stabilized to some degree, but little direction exists concerning the relative merits of the potentially acceptable soils, as measured, for example, by their stabilized compressive strengths or compacted densities. Moreover, some guidelines (e.g. UN, 1992) propose extensive regimens of stabilization trials, which are time-consuming and expensive, and wasteful if the soil(s) subsequently prove(s) to be unsuitable.

Concerning compaction, although current guidelines (e.g. CSIRO, 1987) specify that on-site compaction of the soil-stabilizer mixture should resemble as closely as possible the compactive effort achieved in the laboratory specimen test, they provide no direction as to how to achieve such a relationship, in physical terms, during construction. Achievement of high compacted densities (in the range 1.75–2.2 t/m^3) is favorable as it assists in the development of compressive strength independently of other factors such as soil gradation and stabilizer quantity (Burroughs, 2009). Also, other parameters of earth walls and buildings, such as thermal conductivity (Adam & Jones, 1995), acoustic properties (Hall & Swaney, 2005), and measures of durability (Bryan, 1988), are positively related to the dry density of the stabilized earth.

The key requirements in the production of rammed earth, therefore, are to be able to select a soil suitable for stabilization (and reject unsuitable soils), to apply an appropriate corresponding stabilizer treatment, and to properly compact the material during on-site construction. This paper focuses on developing practical recommendations regarding these three aspects of rammed earth construction, continuing a research theme (Burroughs, 2006, 2008, and 2009) investigating materials for rammed earth production. The recommendations for soil selection and stabilizer treatment are based on a recent set of data involving 219 stabilizations tests on 104 different soils, using various quantities and combinations of cement, lime, and asphalt. Aspects of soil selection and stabilization have previously been addressed using the dataset in the study of Burroughs (2008). However, this paper presents a refined soil selection scheme and more customized stabilization treatment recommendations matched

to soil types, based on relating a 2 MPa compressive strength criterion to value ranges of soil properties and to stabilizer treatments. In addition, the paper presents new calculation-based recommendations for on-site compaction using either manual or pneumatic rammers, by reconciling the compaction forces between laboratory tests and on-site compaction techniques.

The recommendations are presented in the form of three flow diagrams intended to guide a rammed earth practitioner through the stages of soil selection, stabilization, and on-site compaction. The purpose of the recommendations is to improve the practice of rammed earth production/construction with respect to meeting the requirements specified in modern building regulations. It is hoped that such a contribution will lead to greater reliability of method and better quality of product, and increase the interest in, and use of, rammed earth as a green construction material.

METHOD USED IN STABILIZATION EXPERIMENTS

Sample Sites

A total of 104 different soils were used in the stabilization experiments, taken from 29 rammed earth construction sites located in the state of New South Wales, Australia. Between one and eight soil samples were taken from each site, depending on the amount of variation in soil type as indicated during mapping. Soil was sampled either by test pits or hand borings to a depth of 1–3 meters. In all cases, the layer of soil below significant organic accumulation (e.g. leaves, humus) and above unweathered parent material was sampled. This part of the soil is weathered, contains a range of particle sizes, and contains negligible organic matter. Forty kilograms of soil, as recommended by SAA (1977), were collected at each pit or bore. No attempt was made at the sites to assess the particular soils for their suitability for rammed earth construction, or reject possibly unsuitable soils, in order to allow the testing of as wide a spectrum of naturally-occurring soils as possible.

Soil Properties

The tests on the natural soil included particle size distribution, Atterberg limits, and linear shrinkage. These were chosen because several earlier studies have reported their importance regarding the qualities of stabilized earth (Croft, 1968; Spence, 1975; Bryan, 1988; Walker, 1995). The two textural variables measured were % sand (0.075–2.36 mm aperture sieves) and % clay-silt (< 0.075 mm aperture sieve), with all material >19 mm being discarded prior. The clay and silt fractions were combined in order that size distributions could be obtained by sieve analysis alone and the practical applicability of the results widened. Liquid limit (LL) and plasticity index (PI) were measured on the natural soil (i.e. on the soil prior to adding stabilizer and compacting). Linear shrinkage (LS) was also determined for the natural soil, using the <0.425 mm fraction. The procedures for the determination of soil particle size distribution, LL, PI, and LS followed those described in the methods of testing soil for engineering purposes AS1289.C6.1, AS1289.C1.1, AS1289.C3.1, and AS1289.C4.1, respectively (SAA, 1977).

Optimum Moisture Content and Maximum Dry Density

The optimum moisture content (OMC) is the moisture content at which a material reaches maximum dry density (MDD) under a given compactive effort. The aim during rammed earth construction is to compact the material under conditions of OMC and MDD (CSIRO 1987; UN 1992). OMC was determined in order to identify the moisture content at which each soil should be compacted and tested for uniaxial compressive strength (UCS).

OMC and MDD determinations were made on the sample after the addition of stabilizer and compacting, but before curing. The modified Proctor test was used to determine the moisture-density relationship under compaction (and hence to obtain the OMC and MDD of the soil-stabilizer mixture for each sample), and followed the specifications of Australian Standard 1289.E2.1 (SAA 1977). The modified Proctor test was used because the compactive effort applied (2703 kNm^2) provides a closer simulation (compared with the standard Proctor at 596 kN/m^2) of compaction using on-site ramming equipment. The compaction tests were made using a cylindrical mould measuring 115 mm in height and 105 mm inside diameter.

Uniaxial Compressive Strength

The method of determining the uniaxial compressive strength (UCS) of stabilized earth samples followed the procedure specified in Test Method T116 of the Department of Main Roading, New South Wales (DMR, 1983). After being compacted, specimens were ejected from their cylindrical moulds and inspected for deformities, cracks, or other defects, with imperfect specimens being discarded. The samples were then cured for 28 days in a humidity cabinet at 98% relative humidity and a temperature of 22°C. After curing, each specimen was immersed in water at room temperature for a period of 4 hours, and allowed to drain for 15 minutes. UCS was then tested by applying a continuous loading rate of 0.10 ± 0.02 MPa/second. The applied load was continued until each specimen failed, and the load at failure recorded to the nearest 0.05 MPa.

It is known that the specimen height:diameter ratio in compression tests influences the apparent strength of the specimen being tested, with the tested strength increasing as the ratio decreases (CSIRO, 1987; Walker, 2004). The aspect ratio (specimen height divided by diameter) for all tests performed in this study was 1.10, and therefore each compressive strength determination was adjusted for aspect ratio using the correction procedure as prescribed by CSIRO (1987). The aspect ratio correction factor with which the raw compressive strength value was multiplied to calculate the adjusted compressive strength was 0.72 for all specimens. All UCS determinations generated in this study are saturated, unconfined compressive strength determinations adjusted for aspect ratio and tested after 28 days of curing.

Stabilizer Treatments

The term 'stabilizer treatment' refers to the stabilizer type(s) and quantity(ies) mixed into a soil. Lime, cement, and asphalt were chosen as stabilizers because their use is widespread in the rammed earth building industry. The levels of stabilizer chosen were 0, 2, 3, 4, 5, and 6% of lime or cement by weight of dry soil, comparable to the amounts in other studies (Akpokodje, 1985; Bryan, 1988; Osula, 1996). The quantities of asphalt used were 0 and 3% (UN, 1992). The properties of the cement, hydrated lime, and asphalt used in the experiments conformed to the relevant Australian standards AS 3972, AS 1672, and AS1160, respectively (SAA, 1977).

Study Design and Data Analysis

The soils were tested with different stabilizer treatments yielding 219 stabilization experiments and determinations of UCS. The combinations of stabilizer used in various quantities for the experiments were lime only (29 determinations), cement only (72), lime-cement (65), cement-asphalt (27), lime-asphalt (2), and lime-cement-asphalt (24). Although asphalt was used in some experiments, this stabilizer has previously been shown to have no effect on stabilized strength, and should be regarded only as a waterproofer when used with cement and/or lime (Burroughs, 2006). Therefore, asphalt was ignored for the purposes of devising the soil selection and stabilization recommendations presented in this paper.

The textural, plasticity, and shrinkage properties measured defined the variables by which the soils were characterized. The five soil property variables were regarded as factors causing variation in the UCS of the cured specimen (Fitzmaurice, 1958; Spence, 1975; Bryan, 1988; Walker, 1995), and were therefore considered as discriminators of soil suitability for stabilization. OMC and MDD were not considered as discriminators because an aim of the recommendations is to construct easily-applied, practical methods of accurately assessing the suitability of soils and corresponding stabilizer treatments for constructing rammed earth structures.

The UCS of stabilized rammed earth was used as the outcome variable of interest because it can be compared both with the results of previous studies (Akpokodje, 1985; Bryan, 1988; Walker, 1995; Bell, 1996) and with construction standards and building codes (e.g., CSIRO, 1987; ICC, 2006; NMAC, 2006). Currently, a limited number of countries have standards for earth construction, including New Zealand, Australia, Spain, Germany, Zimbabwe, China, Peru, and the US (Maniatidis and Walker, 2003). There is a degree of uniformity across construction guidelines and building codes concerning the required strength of stabilized rammed earth. The CSIRO (1987) guideline of 2 MPa is based on a 14-day test, although this guideline publication may soon be replaced by an Australian Standard for rammed earth and other

forms of earth building. The 2 MPa value specified as a minimum in the International Building Code (ICC, 2006) is based on a 14-day test, but different jurisdictions in the US have their own particular amendments to the code. New Mexico was the first jurisdiction in the US to adopt a building code specifically for rammed earth (in 2001). The New Mexico Earthen Building Materials Code (Title 14, Chapter 7, Part 4) (NMAC, 2006) requires the 7-day strength to be ≥ 1.3 MPa and the 'ultimate compressive strength' to be ≥ 2 MPa.

A 2 MPa 28-day strength was adopted in this study as the measure of stabilization 'success', and relates to a test performed prior to construction to indicate material suitability. UCS values were coded according to whether they equaled/exceeded the criterion value ('success') or fell below it. Stabilization success rates (i.e., the percentage of samples in a soil group having UCS ≥ 2 MPa) were used to indicate the propensity of soils with particular properties to be successfully stabilized, thereby enabling different soil groups to be discriminated in terms of their suitability for stabilization. Stabilizer treatments were allocated by considering the mean stabilizer treatment and range of treatments for each group of soils identified as being favorable for stabilization.

RECOMMENDATIONS FOR SOIL SELECTION

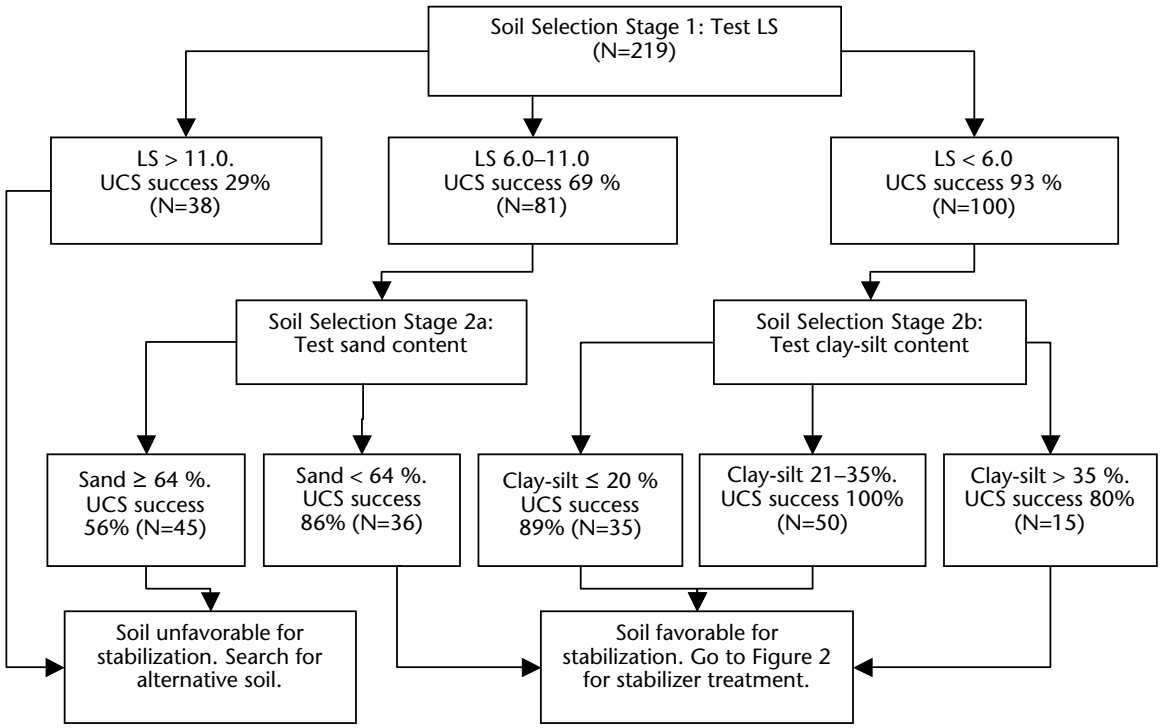
The soil selection scheme is similar to that of Burroughs (2008) but differs in that it does not use PI as a discriminator of soil suitability, and therefore is able to include samples that were not incorporated in the previous scheme on account of using LS and PI as simultaneous discriminators. In consequence, the scheme is now simpler and able to classify all possible soils. Existing soil categorization schemes (e.g. the Unified Soil Classification System) based on particle size and plasticity were not used to discriminate soils because such schemes appear to provide only limited utility in classifying soils for earth stabilization purposes (see Wolfskill et al., 1963; UN, 1992).

The soil selection scheme involves relating UCS criterion success rates to values of natural soil properties in order to discriminate between soils that are favorable or unfavorable, respectively, for stabilization. Each soil property (either alone or in combination with others) was used in a series of trials to identify the most efficient discriminators between samples that were successfully stabilized and those that failed the 2 MPa UCS criterion. A stabilization success rate of ≥ 80% was considered to be an appropriate threshold for a group of soils to be considered as favorable for stabilization, and a success rate of < 80% as unfavorable. The 80% threshold was essentially an arbitrary value chosen to divide a continuum of stabilization success rates for different groups of soils, and individual success rate values are reported for the different groups of soils identified in the selection procedure (Figure 1).

On the basis of the discrimination trials, the optimized discrimination process comprises two stages. The first stage of soil selection (Figure 1) uses LS to discriminate three classes of soil. The classes have different UCS success rates: 29% for soils with LS > 11.0 (the first class); 69% for soils with LS = 6.0–11.0 (the second class); and 93% for soils with LS < 6.0 (the third class). Soils in the first class are unsuitable for stabilization and should be discarded as candidates for stabilization without further testing. In the second stage of soil discrimination/selection, the second and third classes of soil are tested for sand content (Stage 2a) and clay-silt content (Stage 2b), respectively.

In the second stage of soil selection, the second class of soils is tested for sand content, producing two categories (Figure 1). The category with sand content < 64% has a success rate of 86% and is favorable for stabilization. In contrast, the category with sand content ≥ 64% (success rate 56%) is unfavorable for stabilization and such soils should be discarded as candidates for stabilization. For the third class of soils, clay-silt content is tested (Figure 1). For these soils, three categories are identified: soils with clay-silt content ≤ 20% have a stabilization success rate of 89%; soils with clay-silt-content 21–35% have a success rate of 100%; and soils with clay-silt content > 35% have a success rate of 80%. Although the third class of soils itself has an overall success rate of 93%, soils in that class containing clay-silt content > 35% (Figure 1) probably lie on the margin of favorability for stabilization, both in terms of achievable strength and with respect to shrinkage/cracking during curing.

FIGURE 1. Soil selection recommendations: testing of linear shrinkage (LS), sand content, and clay-silt content to determine soil favorability for stabilization. UCS success is the percentage of samples with UCS ≥ 2 MPa as tested in the study.



The soil selection scheme depicted in Figure 1 shows that soil suitability for stabilization can be assessed accurately using LS as the initial discriminating soil property and then using either sand (0.075–2.36 mm particles) or clay-silt (<0.075 mm particles) content as a second discriminator depending on the value of LS. The effectiveness of LS as the primary discriminator may be because the property reflects both the textural characteristics of the soil and how the soil responds to moisture, both of which influence the mechanical properties of the stabilized material (Burroughs, 2006). It should be noted that the large differences in stabilization outcomes (as indicated by UCS success rate, mean UCS, and mean MDD) between the favorable and unfavorable soil classes or categories are unlikely to be explained by the small amount of stabilizer variation between them (Burroughs, 2008; Table 1, this paper).

RECOMMENDATIONS FOR STABILIZER TREATMENTS

Cement and Lime Stabilization

The soil selection scheme described above should reduce the time and effort spent on performing stabilization experiments on soils that ultimately have a low chance of stabilization success (as indicated by the lower percentage of samples having compressive strengths ≥ 2 MPa). Overall, for the four soil categories deemed favorable for stabilization as identified in Figure 1, 124 samples out of 136 (91%) were successfully stabilized. The average amount of cement used for the samples in these categories was 4.2%, and the average amount of lime was 1.7%. The lowest total amount of stabilizer applied to a single sample was 3% cement and/or lime, and the highest amount was 10%.

TABLE 1. Stabilizer treatment and outcome summary for unfavorable and favorable soil classes and categories.

Soil	Mean % Cement	Mean % Lime	% UCS ≥ 2 MPa	Mean UCS (MPa)	Mean MDD (t/m^3)
Unfavourable soils					
LS > 11.0	3.3	2.7	29	1.90	1.68
LS 6.0–11.0 and sand ≥ 64%	4.2	1.8	56	2.32	1.84
Mean unfavourable	3.8	2.2	43	2.13	1.77
Favourable soils					
LS 6.0–11.0 and sand < 64%	3.6	2.7	86	2.75	1.86
LS < 6.0 and clay-silt ≤ 20 %	4.4	1.2	89	3.29	1.92
LS < 6.0 and clay-silt 21–35 %	4.2	1.7	100	3.07	1.93
LS < 6.0 and clay-silt > 35 %	4.5	1.5	80	2.54	1.90
Mean favourable	4.1	1.8	91	2.98	1.91

Notes:
LS is linear shrinkage; UCS is uniaxial compressive strength; MDD is maximum dry density.
Stabilizer precentages are by weight relative to dry soil.

Some differences between the four categories are apparent (Table 1). The two best categories of soil are those with LS < 6.0 and clay-silt ≤ 20% or with LS < 6.0 and clay-silt 21–35. These two categories have the highest stabilization success rates (89 and 100%, respectively), and the highest mean values for both UCS (3.29 and 3.07 MPa, respectively) and MDD (1.92 and 1.93 t/m^3, respectively). Soils whose properties coincide with the former category are recommended to be stabilized either with 4% cement and 1% lime, or with 4.5% cement only (Figure 2). Those falling in the latter category are recommended to be stabilized either with 4% cement and 1.5-2% lime, or with 5% cement only.

The next best category, comprising soils with LS 6.0–11.0 and sand content < 64%, has a stabilization success rate of 86% and a mean UCS of 2.75 MPa. Soils lying in this category are recommended to be stabilized either with 4% cement and 2–2.5% lime, or with 5–5.5% cement only (Figure 2). The remaining category, consisting of soils with LS < 6.0 and clay-silt content > 35%, should be regarded as marginally favorable for stabilization, given its stabilization success rate of 80%, the lower mean UCS of 2.54 MPa, and the fact that issues such as workability and shrinkage apply to soils with high clay-silt contents where clay is the dominant fraction. Given these considerations, such soils should not exceed 45% clay-silt content, and are recommended to be stabilized with 5% cement and 2.5–3% lime (Figure 2).

Treating any of the soils with lesser amounts of stabilizer, down to 3% total amount, will still stabilize some soils well but will provide an increasing risk of failing the strength criterion. In situations where there is a requirement for a higher strength criterion (e.g. 2.5 MPa), two options would be available with respect to the stabilization scheme recommended in the study. The first option would involve confining soil selection to those soils with LS < 6.0 and clay-silt ≤ 35% (combining the two best favorable soil categories), for which the success rate is 70% for a 2.5 MPa criterion. The second option would be to increase the percentage of stabilizer used in any of the favorable soil categories. In general terms, to achieve an increase in strength of 0.5 MPa, the amount of cement stabilizer needed is about 1% and for lime is about 2% (Croft, 1968; Ngowi, 1997; Burroughs, 2006).

Notwithstanding the recommendations given concerning the stabilization of suitable soils, complete certainty of the best stabilizer treatment for a particular soil would only be gained if multiple laboratory stabilization and strength tests were made with different amounts and combinations of cement and lime.

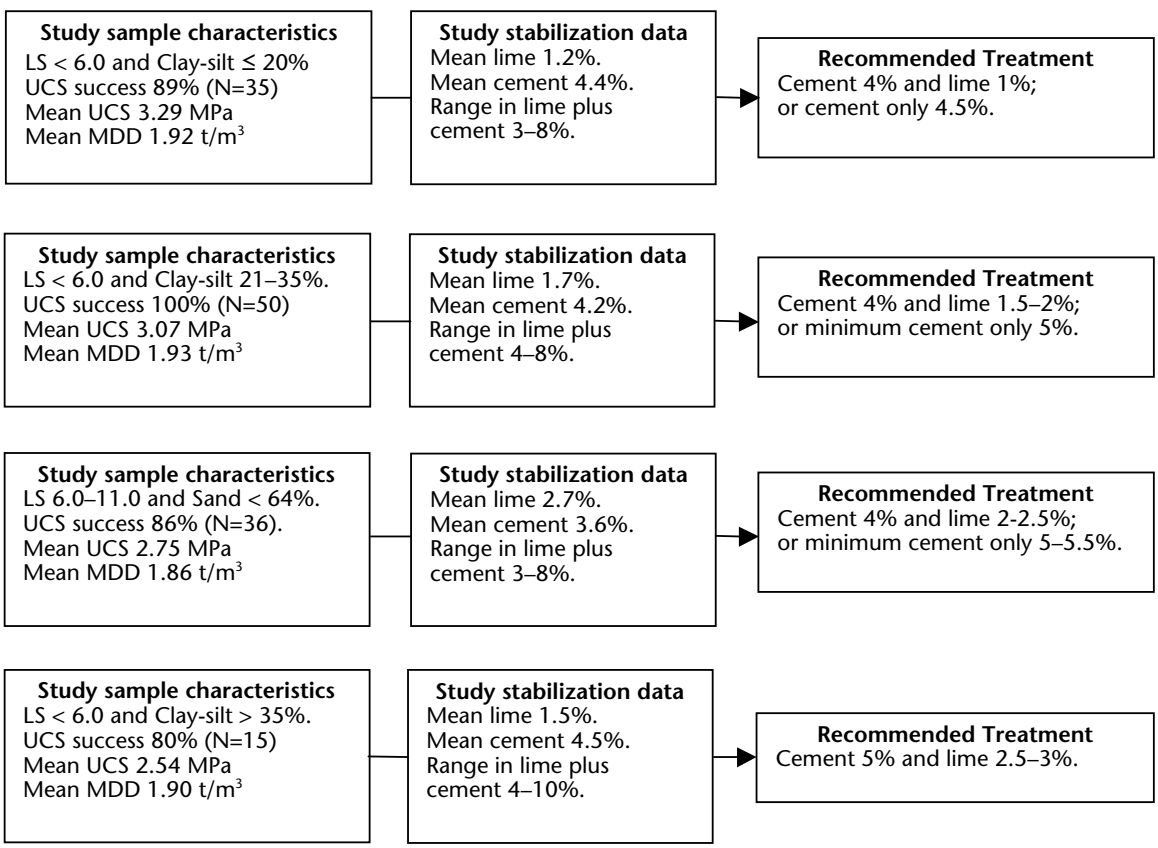
Reduction of Shrinkage

In addition to compressive strength, the shrinkage of stabilized soil should also be a considered as an outcome of stabilization (e.g. Akpokodje 1985; CSIRO 1987; Mesbah et al. 2004), given the potential for weakening of earth walls caused by shrinkage or tensile cracking. The degree of shrinkage on curing of stabilized soil depends on stabilizer content, soil type, water content, degree of compaction with rammers, and curing speed.

The linear shrinkage of stabilized soil decreases with increasing levels of cement and lime (Akpokodje, 1985), and therefore the potential for cracking is reduced by using these stabilizers. Shrinkage cracks should be considered inevitable in soil-cement stabilization, and are generally from 3–6 mm wide at a spacing of 3–6 m. CSIRO (1987) specify that shrinkage cracks in rammed earth walls should not be longer than 75 mm, nor wider than 3 mm, nor deeper than 5 mm. Therefore, the soil and stabilizer used should be able to meet these shrinkage criteria, although no guidelines have yet been generated which, when followed, would result in stabilized material having such shrinkage properties.

The results of Akpokodje (1985) indicate the amount of cement to use to achieve a satisfactory stabilized earth shrinkage value given the LS of the natural soil. The stabilizer quantities recommended here on the basis of compressive strength appear to coincide with the amount of stabilizer required to achieve a stabilized linear shrinkage value of ≤ 3%. For example, soils with LS of 6% require 4.5–5% of cement to achieve a stabilized shrinkage of 3% (Akpokodje, 1985), which is in accordance with the

FIGURE 2. Stabilizer treatment summaries and recommendations for the four categories of soils deemed favorable for stabilization. UCS success is the percentage of samples with UCS ≥ 2 MPa as tested in the study.



quantities of cement stabilizer recommended in Figure 2 for such soils, and soils with LS < 6.0 would achieve even lower values of stabilized shrinkage. As lime is more effective than cement at reducing shrinkage, lime should therefore be used for soils with higher natural shrinkage, which again is in agreement with the quantities of stabilizer recommended in Figure 2 for soils with LS 6.0–11.0.

RECOMMENDATIONS FOR ON-SITE EARTH COMPACTION

The recommendations concerning on-site compaction presented here are based on defining the forces involved in on-site compaction in order to ensure that equivalence with laboratory test compaction can be achieved. Such calculations of on-site ramming compaction forces and their comparison with laboratory standards do not appear to have been attempted previously. The two most widely used methods of determining the response of a soil to compaction are the standard Proctor and modified Proctor tests. Such compaction tests, when repeated at different material moisture contents, allow the relationship between moisture content and dry density to be determined and thereby values for OMC and MDD to be determined. These tests involve dropping a rammer of specified weight from a specified height onto a cylinder of soil of specified volume. Various professional organizations concerned with standards for compaction, for example AASHTO (American Association of State Highway and Transportation Officials), ASTM (American Society for Testing and Materials), and SAA (Standards Association of Australia), each have their own versions of these tests that differ slightly in the dimensions of the apparatus and experimental techniques used (Table 2). However, the result in all cases is that the compactive effort (quantum of energy) applied to the material is the same: for the standard Proctor test, the compactive effort is 596 kN/m^2 and is 2703 kN/m^2 for the modified Proctor test (SAA, 1977).

With regard to earth compaction and stabilization experiments, different authors have used different tests. Burroughs (2006, 2008) used the modified proctor, whereas Croft (1968) and Akpokodje (1985) compacted samples using the standard Proctor test (600 kN/m2), and Bryan (1988), Walker (1995), and Ngowi (1997) used intermediate compaction pressures of 2000 kN/m2. The author's experience in Australia is that the UCS and MDD of stabilized, rammed earth compacted in the laboratory using the modified test (compared with the standard test) are much better indicators of the strength and density of the actual rammed earth wall as constructed subsequently on-site using pneumatic ramming equipment. However, whichever test is used in the laboratory, it is generally recommended (CSIRO, 1987; Hall and Djerbib, 2004) that the field compaction be the same as, or similar to, that used in the laboratory. In this regard, it is necessary to calculate the compactive effort of on-site ramming conditions, which involves the following equation in the case of manual ramming:

TABLE 2. Test specifications for standard and modified Proctor compaction tests for SAA (1977) and AASHTO.

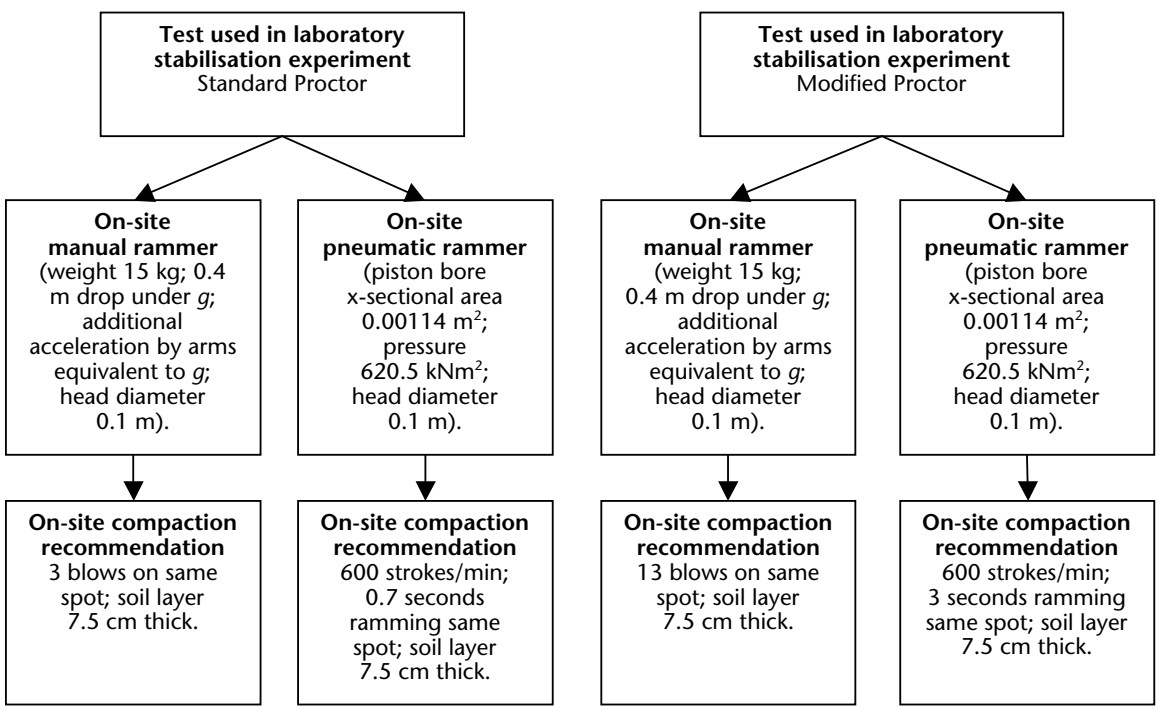
	SAA test specifications (Tests AS 1289.E1.1 and 1289.E2.1)		AASHTO test specifications (Tests T-99 and T-180)	
Variable	**Standard**	**Modified**	**Standard**	**Modified**
Weight of rammer (kg)	2.7	4.9	2.5	4.55
Height of drop (m)	0.300	0.450	0.305	0.457
Number of drops (total)	75	125	75	125
Internal diameter of cylinder (m)	0.1050	0.1050	0.1016	0.1016
Length of cylinder (m)	0.1155	0.1155	0.1164	0.1164
Number of soil layers	3	5	3	5
Volume of soil compacted (m^3)	0.001000	0.001000	0.000944	0.000944
Compactive effort (kN/m^2)	596	2703	596	2703

$$CE = (H*F*n_1*n_2)/V$$

Where:
CE = Compactive effort (kN/m^2);
H = height of drop (m);
F = force of hammer (kN)
(mass in kg multiplied by 0.0098);
n_1 = number of drops of hammer;
n_2 = number of soil layers compacted; and
V = volume of mould (m^3).

Although manual rammers vary in their dimensions (Maniatidis and Walker, 2003), a typical hand rammer used on-site, with measurements of 0.1 m diameter, 15 kg weight, and with a drop of 0.4 m onto a single soil layer thickness of 0.075 m, would require a calculated 27 blows (on the one spot) to achieve the compaction effort equivalent to the modified Proctor laboratory test (where the number of soil layers is 1 and V is calculated as the volume of a cylinder with dimensions 0.1 m diameter and 0.075 height). The number of blows equivalent to the standard proctor in this case would be 6. Altering the weight of the rammer will affect the number of blows needed in an inverse, linearly proportional fashion. However, these values do not account for the fact that manual ramming also utilizes the downward force provided by the laborer's arms which, if the effect was to double the acceleration of the rammer achieved by freefall, from 0.0098 m/s^2 to 0.0196 m/s^2, would reduce the number of blows required to 13 for the modified proctor equivalent and 3 for the standard proctor equivalent. Given these statistics, it is clear that considerably more physical exertion needs to be expended by a laborer lifting and thrusting a rammer to compact the soil to a degree equivalent to the modified proctor test than for the standard proctor situation. Therefore, the manpower available for the on-site compaction phase may be a consideration when deciding which laboratory test (proctor or modified proctor) of the moisture-density relationship for determining values of MDD-OMC should be used to simulate on-site compaction conditions for manual ramming (Figure 3).

FIGURE 3. Recommendations for on-site compaction considering both the compaction test used in the corresponding laboratory experiment and the rammer (manual or pneumatic) used on-site.



Pneumatic rammers used for compacting earth walls have a pneumatic force exerted as calculated by multiplying the cross-sectional area (0.00114 m^2) of the bore of the piston by the pressure of 620.5 kN/m^2, which equals 0.71 kN, per stroke (blow). With this force applied to a typical rammer head of 0.1 m diameter (a cross-sectional area of 0.007854 m^2), this pneumatic force translates into a compactive force of 90 kN/m^2 per blow (0.71 / 0.007854). Therefore, a compactive effort equivalent to the modified Proctor is achieved after around 30 blows, equivalent to 3 seconds ramming the same spot with a machine running at 600 strokes/minute (compared to 0.7 seconds equivalent to the standard Proctor). Although there are some dimensional differences between different models and makes of pneumatic rammers, it is likely that the compactive effort of on-site pneumatic ramming is more comparable to the value of the laboratory modified Proctor test than to that of the standard Proctor test. However, it is clear that the anticipated amount/style of pneumatic ramming should be a consideration in relating laboratory-based stabilization experiments to on-site compaction conditions (Figure 3).

During on-site compaction, the moisture content of the earth-stabilizer mixture must be closely monitored and maintained at or near the OMC, in order that the MDD (or as close to it as possible) can be achieved. This is important so that walls with the highest possible densities can be constructed, not least because MDD has a significant positive effect on the compressive strength of the cured material independent of that provided by natural soil properties and stabilizer quantity and type (Burroughs, 2009). An associated point that has not been covered in the literature is that the optimum moisture content from a strength perspective (i.e., one that provides maximum UCS) may be greater than the OMC associated with MDD as assessed from laboratory compaction tests, on the basis that cement and lime stabilizers require moisture for chemical activation and strength development. However, producing an earth-stabilizer mixture wetter than OMC to account for the use of water by stabilizers would reduce the compactable density of the resulting rammed earth, given the usual moisture-density relationship of a soil under compaction, which would in turn reduce strength. Given that the nature of the play-off between these two competing influences on strength is currently unknown, compaction of rammed earth should proceed at the OMC as determined for MDD in laboratory tests.

In addition to imparting strength, higher densities favor the thermophysical characteristics (Adam and Jones, 1995), durability (Bryan, 1988; Hall and Djerbib, 2006), and acoustic properties (Hall and Swaney, 2005) of earth walls. However, although laboratory tests are used to establish values of OMC and MDD, it is recognized that the MDD may not necessarily be achieved in actual on-site construction conditions. Therefore construction densities could be specified as a percentage (e.g., ≥ 95%) of the modified proctor laboratory-measured MDD (Burroughs, 2009), to allow for the moisture content of the mixture slightly exceeding or falling below the OMC. The maximum percentage deviation from OMC that would allow a ≥ 95% specification to be achieved would depend on the moisture-density relationship under compaction of the particular soil being used.

APPLICATION AND CONCLUSION

The recommendations for soil selection and stabilizer treatment are based on the results of a single study comprising 219 experiments on 104 different soils. The recommendations need to be applied to new situations before their usefulness can be properly assessed. Initial application of the recommendations to rammed earth construction situations in Australia indicates that they have predictive usefulness. As an example, a soil from a site for a proposed earth building project in Northern Territory was recently tested in order to evaluate the suitability of the soil for both rammed earth and mud brick production. The soil had a linear shrinkage of 6.0% and a sand content of 58%. From following the soil selection scheme for these soil property values (Figure 1), the soil was treated (Figure 2) with 4% cement and 2% lime in one experiment and 5% cement in another. Using modified proctor compaction, the 28-day mean UCS value for the cement-lime treatment was 5.05 MPa (two tests, 4.8 and 5.3 MPa), and for the cement-only treatment was 4.4 MPa (two tests, 4.3 and 4.5 MPa), with the MDD being 2.13 t/m^3. Both experiments therefore produced sample strengths well in

excess of the 2 MPa strength criterion and a high value of MDD exceeding the 1.75 t/m^3 threshold suggested by Burroughs (2009).

The soil and stabilizer recommendations for rammed earth will be able to be tested and potentially refined as more laboratory experimental data and results from actual construction sites become available. An additional future research requirement will be to examine the applicability of the soil selection and stabilization recommendations reported in this paper to compressed earth bricks. Improved guidelines for soil selection, stabilization, and compaction for both rammed earth and earth bricks, leading to greater reliability of method and better quality and consistency of product, should help increase the adoption of stabilized earth as a green construction material.

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