Construction and Building Materials 53 (2014) 59–65

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Optimum lime content identification for lime-stabilised rammed earth

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HIGHLIGHTS

- We have studied the strength and stiffness of lime-stabilised rammed earth (LSRE).
- Oven-drying curing conditions significantly altered the strength of LSRE.
- The existence of an Optimum Lime Content (OLC) was found that maximises the compressive strength.
- Plasticity limit and pH testings might help to identify OLC in LSRE.

ARTICLE INFO

Article history:
Received 12 September 2013
Received in revised form 21 November 2013
Accepted 21 November 2013
Available online 15 December 2013

Keywords:
Lime stabilisation
Rammed earth
Unconfined compressive strength
Optimum lime content

ABSTRACT

The rising price of energy and a recognition of the human impact on climate change has resulted in growing interest in environmentally–friendly construction techniques such as rammed earth. Modern rammed earth is generally stabilised with small quantities of Portland cement in order to improve its strength and durability, however an alternative is to use lime to stabilise the raw soil. This is common practice in road construction, for example, but is less common in RE. This paper presents experimental results illustrating the existence of an optimum lime content that maximises the unconfined compressive strength and stiffness of an engineered lime-stabilised rammed earth and the experimental procedures employed to determine it. The effect of curing regime (oven as opposed to natural drying) on the final unconfined compressive strength of the material was also investigated. An optimum lime content for the tested soil has been identified and several methods to determine its rough value presented which have the potential to reduce testing times and so associated costs.

1. Introduction

Climate change, growing energy costs and the impact of human activities on the environment have all become key concerns for future development in recent years. As construction processes required to develop infrastructure constitute major sources of carbon dioxide production and energy consumption, alternative methods are beginning to be explored in order to reduce their environmental impact. One such method is rammed earth (RE) construction.

RE is an ancient building technique which utilises moist, sandy-loam (USDA classification) subsoil compacted into formwork to form strong, durable and free-standing structures [15,19]. While the technique has changed little since its inception, it is now common to stabilise RE materials with small quantities of Portland cement in order to improve its strength and durability. The incorporation of Portland cement, however, seems to reduce the sustainability of RE and increases both its cost and environmental impact [7,26]. Although a comparative analysis of the sustainability of lime versus that of Portland cement in terms of their thermal and embodied energy finds conflicting results in the literature [26,35], depending on the mineralogy of the clay, availability and transportation, lime stabilisation can represent a more efficient solution than Portland cement for the improvements of the material mechanical properties (it is well established that using Portland cement to stabilise clayey soils does not always produce the expected enhancements in terms of material performance). In Australia, the cost of lime and Portland cement is fairly similar.

The interaction between lime and soil has been studied by several authors and it is quite understood that lime stabilisation improves the strength, stiffness, plasticity/workability and water adsorption of the raw soil [12,13,29]. The lime–soil reaction can be described by three general phenomena: (i) cation exchange, (ii) pozzolanic reaction and (iii) carbonation. Cation exchange takes place as soon as lime is added to soil in the presence of water. This reaction produces free Ca^{++} ions and leads to an increase in the pH of the soil–lime mix. pHs above roughly 12.4 (the pH of lime-saturated water), achieved through significant lime addition, encourage the solubility of silica and alumina present in the clay minerals and quartz [4]. The silica and alumina then react with

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http://dx.doi.org/10.1016/j.conbuildmat.2013.11.077

the Ca^{++} to form calcium silicates and aluminates. From here on, in the presence of water, the reaction is very similar to the Portland cement hydration process: calcium silicates become hydrates and form cementitious compounds. This pozzolanic reaction is exothermic and temperature dependent, with the rate increasing at higher temperatures. It is understood that the pozzolanic reaction is affected by soil mineralogy and that the hydration process might take place over a long period, potentially producing continuous strength development for periods longer than the standard 28-day hydration time for Portland cement concrete (for instance). The formation of cementing agents (mainly the products of silica hydrates) is assumed to be the main source of strength improvement in lime-stabilised soils [33].

Carbonation is another lime–soil reaction that happens when lime reacts with carbon dioxide present in the air, mostly associated with hot-dry climates where control of curing is difficult. It is a phenomenon that should be avoided because it inhibits the formation of cementitious products that hence reduces the material strength. However, it has been shown that this effect can be effectively mitigated through the proper design and control of stabilisation regime and curing conditions [2].

Although several examples of historical lime-stabilised RE (LSRE) structures survive to this day, the use of lime in the earthen building construction industry has not been exhaustively investigated so far [6]. This papers aims to understand whether an Optimum Lime Content (OLC) that maximises the Unconfined Compressive Strength (UCS) of a given soil mixture exists for RE materials and outlines an experimental procedure for its determination. The effect of lime stabilisation on the stiffnesses of these materials is also investigated in order to better characterise its elastic behaviour. The details of the experimental programme used in this study are illustrated in Section 2 and findings are extensively discussed in Section 3. The suitability of those procedures used to approximately identify the OLC for an RE soil are discussed in Section 4 and subsequent observations and recommendations provided at the end of this paper in Section 5.

2. Experimental procedure

An engineered soil was prepared by combining known quantities of kaolin clay powder, silica flour, sand and gravel, following guidelines available in RE literature [6,17,25,36]. The choice of using an engineered soil mixture was desirable due to the need to control material grading and mineralogy for testing. Individual component quantities were determined following recommendations made by [19] for the selection of a suitable soil for RE construction, with the final Particle Size Distribution (PSD) shown in Fig. 1. The gravel component was sieved to pass a 10 mm sieve.

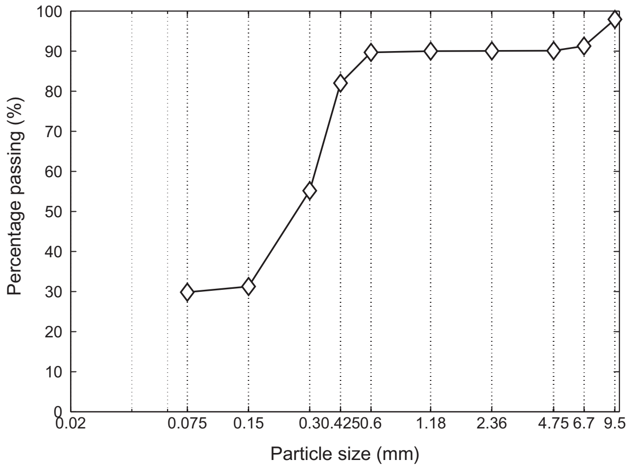

Fig. 1. Particle size distribution of engineered soil mixture used in the experimental programme.

Unstabilised RE materials are compacted at their optimum water content (OWC) in order to ensure the highest dry density and, by extension, strength [21]. This practice is also used for stabilised RE materials. For Portland cement stabilisation, the maximum amount of cement that can be added to stabilise the soil then becomes strictly related to the compaction OWC: it would be inefficient to increase the cement content if there was not enough water to hydrate it. Water also plays a critical role in the stabilisation process of lime-stabilised RE materials, as was discussed in the previous section. In this study, the initial water content, that is the water content at time of mixing and moulding of the specimens, was also taken as equal to the compaction OWC. This choice is motivated by the fact that rammed earth materials are always nominally compacted at their OWC during construction and it would be both unrealistic and impractical to use moulding water contents different from it; the assessment of stabilised soil mixes with other than optimum initial water contents is discussed elsewhere [10,11]. The focus of this investigation is on the existence of an OLC for a soil mixture with a fixed amount of clay. Although the strength and stiffness of compacted lime-stabilised soils depend on many other factors (mineralogy, curing temperature, relative humidity and duration, for example), those factors were set constant in all tests performed in this study in order to obtain results that were only lime-content dependent.

2.1. Determination of optimum water contents

Laboratory determination of the OWC is generally carried out using either the Standard or the Modified Proctor Test (MPT) [30]. The MPT has a compactive effort very similar to that used on-site and is a well specified, codified and widely established test and hence repeatable in any laboratory. For these reasons, the MPT was used in this study.

The MPT for the unstabilised material was performed according to AS 1289.3.2.1-2009. Oven-dried (for 24 h at 105 °C) soil mix was wetted with water and left to equilibrate for 7 days in sealed containers, in order to ensure a uniform water content, $w\%$, prior to compaction testing. After compaction, the samples were dried in an oven at 105 °C to measure $w\%$ and so dry density. The procedure was repeated for different values of $w\%$ and the OWC was found as the water content corresponding to the maximum dry density $\rho_{d,max}$ achieved.

For the lime-stabilised material, the procedure specified by AS 1289.3.2.1-2009 was slightly modified. Oven-dried soil material was combined with a selected quantity of hydrated lime and dry-mixed thoroughly for a minimum of five minutes. Then, batches were made with known values of $w\%$. As the addition of water initiates the cation exchange, flocculation and pozzolanic reactions, compaction was completed within 45 min of wetting in order to prevent undesired soil fabric changes from interfering with the test. Unlike for unstabilised materials, oven drying could not then be used to verify the material water content due to the loss of (non-evaporable) water via the above-mentioned reactions triggered by the high drying temperatures. Material water content was therefore taken to be the added water content $w\%$ used during compaction and the OWC determined as described above. The OWC, water/lime ratio (w/L) and $\rho_{d,max}$ for each of the investigated lime contents are given in Table 1. Note that lime and water contents are given as a percentage of the dry soil mass (i.e. not inclusive of the lime mass).

2.2. UCS specimen preparation

Material UCS is generally used to assess stabiliser effectiveness [25,28,37]. UCS was determined for 100-mm diameter, 200-mm high cylindrical specimens tested in uniaxial compression between Teflon sheets [8]. Five specimens were prepared per lime content, following the same mixing and compaction procedures used for OWC testing. Specimens were carefully extracted from the mould immediately following manufacture and transferred to wire racks to cure for 28 days under constant conditions of 94 ± 2% of relative humidity (RH) and 21 ± 1 °C of temperature. It is important to note that this allowed specimen water contents to reduce with time. That being said, it is beyond the purposes of this study to investigate the effect of the water content at testing on the compressive strength. The aim of this paper is to discover whether, for an initial water content equal to the OWC and under fixed curing conditions, samples made of the same soil but different lime contents show an OLC that maximises the compressive strength. The curing time prior to testing was set to 28 days following the recommendations of AS 5101.4 [31] and other Australian guidelines for lime stabilisation practices [1]. These curing conditions might not have represented those on-site, but allowed for the repeatability of the procedure to be assessed in a systematic manner. These specimens are hereafter referred to as "A-series" specimens.

Table 1
Lime content, OWC, $\rho_{d,max}$ and water/lime ratio results.

Lime content (%)	0	2	3	4	5	6
OWC (%)	7.6	7.7	8.1	8.0	9.6	8.5
w/L ratio	N/A	3.85	2.70	2.00	1.92	1.42
$\rho_{d,max}$ (kg/m^3)	2190	2130	2070	2140	2060	2030