Engineering Geology 228 (2017) 137–145

Contents lists available at ScienceDirect

Engineering Geology

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

Characterization of coarse soils derived from igneous rocks for rammed earth

Hongjie Lin[a], Shuang Zheng[a], Sérgio D.N. Lourenço[a,*], Paul Jaquin[b]

[a] Department of Civil Engineering, The University of Hong Kong, Hong Kong Special Administrative Region
[b] Opus International Consultants, Queenstown, New Zealand

ARTICLE INFO

Keywords:
Rammed earth
Hong Kong
Coarse soils
Particle-scale studies

ABSTRACT

Rammed earth refers to a conventional construction method as well as a material comprising gravel, sand and fine soil. There has been an increasing interest due to it being a sustainable and environmentally friendly material. The strength of rammed earth depends on the material and environment (e.g. temperature and relative humidity). While rammed earth is an established and accepted construction material in some countries (e.g. Australia and New Zealand), its use in South China is mostly related to historical structures of which the UNESCO Tulou buildings in Fujian Province is an example. In addition, South China has a sub-tropical climate with a distinctive rainy, humid and hot season followed by a dry and cool season, and soils are granular due to the underlying igneous geology. With a coarse fraction (sand and gravel) in excess of 80%, their appropriateness as earthen materials is, at first sight, debatable. This paper aims to assess the pertinence of three representative soils from Hong Kong (residual soil, alluvium and completely decomposed granite) for unstabilised rammed earth. Unconfined compressive strength tests and shrinkage measurements at different relative humidity, as well as the organics content are determined. To aid the interpretation of the strength and shrinkage data, a fundamental characterization is conducted, namely of the wettability and particle attributes (size and shape). By comparing the results to established guidelines for earthen construction, the three soils are shown to achieve strengths in the range 0.2–1.4 MPa and shrinkage after equilibration for one week up to 4%, with the residual soil outperforming the others. Moreover, it was found the strength of the soils was influenced by the relative humidity and was strongly dependent on changes of dry density. The wettability results confirmed the higher organics for the alluvium while the more rounded particle shape and greater content of potassium feldspar of the completely decomposed granite corroborated with its lower strength. The results highlight the importance of conducting a fundamental characterization of natural soils for rammed earth via the particle attributes, wettability and mineralogy.

1. Introduction

Rammed earth has been used for hundreds of years in various geographies (Houben and Guillaud, 1994). In Mainland China, the UNESCO protected Tulou buildings in Fujian Province, are among the most known and better preserved. A total of 698 Tulou buildings have been constructed by the Hakka ethnic group with most of them erected before 1949 (Knapp, 2000). In Hong Kong, completely decomposed volcanics were used for the construction of private dwellings in rural areas up to the 1960′s (Lee, 2016). Nowadays, the benefits of rammed earth in terms of its inherent sustainability, low carbon footprint and its ability to maintain comfortable living conditions, suggest soil-based materials could be used, at least, as internal non-structural walls.

When assessing the suitability of soils for unstabilized rammed earth, opposite to stabilized rammed which uses cement or lime or other binding agents (Beckett and Ciancio, 2014), the main factors to be considered are the particle size distribution (PSD), unconfined compressive strength (UCS), plasticity index and liquid limit (PI and LL), tensile strength, durability and shrinkage (Walker et al., 2005; Delgado and Guerreo, 2007; Houben and Guillaud, 1994). Rammed earth is a structural material with guidelines developed to support its design and construction. PSD is the most frequently mentioned factor. The PSD controls the compaction behavior of the material which is reflected in its maximum dry density and ultimately in the UCS. Several PSD curves have been proposed. Houben and Guillaud (1994) proposed a maximum and minimum PSD for rammed earth (Fig. 1). Walker et al. (2005) highlighted the importance of the fines content (5% to 20% of clay and 10% to 30% of silt) suggesting that a higher proportion of fines

* Corresponding author.
E-mail address: lourenco@hku.hk (S.D.N. Lourenço).

http://dx.doi.org/10.1016/j.enggeo.2017.08.003
Received 24 February 2017; Received in revised form 29 May 2017; Accepted 1 August 2017
Available online 02 August 2017
0013-7952/

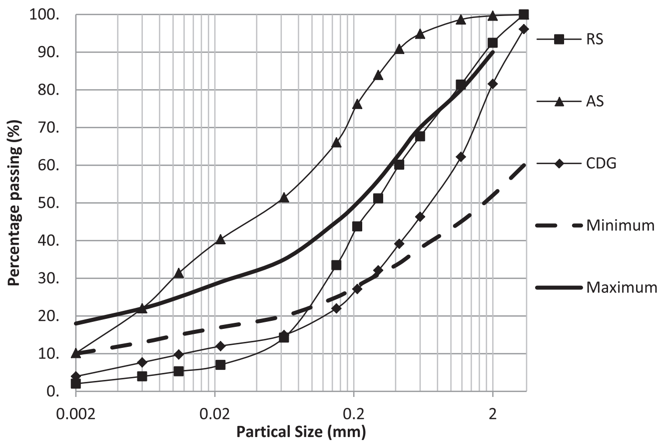

Fig. 1. Particle size distribution of the tested soils (completely decomposed granite – CDG, residual soil – RS, alluvium – AS) and the limits proposed by Houben and Guillaud (1994).

increase the UCS (Ciancio et al., 2013; Hall and Djerbib, 2004). For ten gravel-sand-silty clay mixture combinations, Hall and Djerbib (2004) found that for a dry density from 2.0 Mg/m^3 to 2.15 Mg/m^3 the UCS increases from 0.7 MPa to 1.5 MPa, respectively. For coarse rammed earth (fines content smaller than 20%), the UCS is ~0.8 MPa and for fine rammed earth (fines content larger than 40%), the UCS reaches ~1.4 MPa. The clay and silt content can also impact other properties such as the durability (Bui et al., 2009). At ~20% clay, the maximum erosion depth after 20 years was 7 mm, whilst for 40% clay, the erosion depth increases threefold to 21 mm.

A lower UCS boundary is necessary for rammed earth but this value varies in the literature. For instance, Walker et al. (2005) suggested the UCS should be larger than 1.0 MPa whilst the NZS 4298 (1998) standard proposes 1.3 MPa as adequate. Ciancio et al. (2013) suggested 0.2 MPa was sufficient for a 2.4 m high non-loading wall. This paper adopts the criterion that the UCS should be > 1.0 MPa. Other factors will equally play a role in the UCS. The microstructure of the compacted soil is sensitive to the compaction method, compaction energy and water content. For residual soils resulting from the in-situ chemical weathering of the parent rock, such as those that occur in Hong Kong, crystallization of new minerals through precipitation may create new inter-particle bonds increasing their bulk strength. Martins et al. (2005) and Bica et al. (2008) show that the bonding of the clay matrix, quartz grains and iron oxide increases the strength of the residual soil.

A control of the Atterberg limits have also been recommended by Walker et al. (2005), with a plasticity index (PI) in the order of 2% to 30% and liquid limit (LL) smaller than 45%. Walker et al. (2005) proposed a sand and gravel content in the range 45%–80% and clay content from 5% to 20%. However, such clay contents can induce significant shrinkage eventually leading to desiccation cracks. The NZS 4298 (1998) proposes that shrinkage should be smaller than 0.05% (deemed too small by Ciancio et al., 2013, thus unpractical). While Lehmbau Regeln (1999) and Walker et al. (2005) proposed the shrinkage after 7 days should be limited to 2% or 5%, respectively. It should be noted the recommended soil properties are indicative rather than to be strictly enforced in rammed earth construction. These properties are frequently soil and location-specific with other factors such as mineralogy and climate playing a role.

As for other factors, organics are not recommended in rammed earth with an upper limit of 2% (Walker et al., 2005), and the NZS 4298 (1998) sets a standard tensile strength > 0.25 MPa.

Assessing the suitability of coarse soils, such as those found in Hong Kong, for rammed earth implies not only determining the various parameters above and assessing whether they fulfill the existing criteria, both from the literature and the guidelines, but also assessing whether the criteria are appropriate for Hong Kong conditions. For instance, Hong Kong has the added complexity of its sub-tropical climate, with wet and warm summers and dry and cool winters, unlike countries at higher and lower latitudes where most of the guidelines originate. For this case, determining the UCS of rammed earth after oven drying at 105 °C, as proposed by Middleton et al. (1992), is not appropriate because high temperatures usually do not match with dry weather in Hong Kong. Determining the UCS of rammed earth at high relative humidity would be more representative instead. To highlight the importance of relative humidity, as an unsaturated material the strength of rammed earth is influenced by the moisture content and suction. Unsaturated soils have a degree of saturation lower than 100%, with their mechanical and hydraulic behavior controlled by the soil moisture content and suction (the difference between air pressure and pore water pressure across small water menisci at the inter-particle contacts). Drying soils develop increasing suction, increasing their strength (Fredlund and Rahardjo, 1993). Both Jaquin et al. (2009) and Bui et al. (2009, 2014) obtained similar trends for different soils. For instance, for Jaquin et al. (2009) suction decreased from 800 kPa to 9 kPa with an increase of water content from 5.5% to 10.2%. Others have established a link between the relative humidity and the UCS. Beckett and Augarde (2012) found the UCS to be greatly affected by the relative humidity in gravel-sand-silty clay mixtures. Gerard et al. (2015) found increasing UCS for increasing suction in samples equilibrated at different relative humidities with salt solutions with suction computed indirectly via the Kelvin's law (Fredlund and Rahardjo, 1993). The relationship between RH and UCS in coarse-grained soils is investigated in this paper.

Recent advances in testing and characterization of soils at the particle and particle-to-particle level may provide a new insight into the behavior of granular materials such as rammed earth. (1) The particle shape (quantified via particle sphericity or aspect ratio) has been found to reduce the shear strength for glass beads mixtures (Yang and Wei, 2012). The particle-to-particle friction is sensitive to the micron-scale (or smaller) roughness (Senetakis et al., 2013a). (2) Soil wettability quantifies the affinity of water for soils via contact angles and will provide pertinent information on the hydraulic behavior of the rammed earth. Increasing contact angles reduce the soil water retention (the relation between soil water content and suction) (Lourenço et al., 2015a) and evaporation rate (Shokri et al., 2009) and, if high (> ~110°) completely impede wetting (Doerr et al., 2000). Contact angles develop in all natural soils such as those used for rammed earth, and usually range from 0° to ~120° as a function of the soil water content and organic matter content (Doerr et al., 2000). The particle shape and wettability are investigated in this paper.

The aim of this paper is to assess the suitability of coarse soils derived from igneous rocks, such as those found in Hong Kong, for unstabilized rammed earth. The specific objectives are (1) to determine the strength of representative soil samples from Hong Kong under local climate scenarios, (2) to perform a fundamental characterization of the soils including the mineral content, wettability, particle attributes, and organics and, (3) to attempt to interpret the strength data and other relevant rammed earth properties based on the fundamental properties. Despite of the geographical focus in Hong Kong and South China, the results will find correspondence to other regions with similar sub-tropical climate and coarse-grained soils. Also, the combination of methods to be employed in this research is novel and unique, which may lead to new studies of rammed earth taking into account the small-scale properties.

1.1. Coarse soils derived from igneous rocks

Hong Kong's solid geology is made of ~85% volcanic and granitic rocks (Fyfe et al., 2000), with the remaining made of sedimentary and meta-sedimentary rocks. Three soils representative of Hong Kong were selected: completely decomposed granite (CDG, from Beacon Hill, Kowloon), residual volcanic soil (RS, from Lung Fu Shan, Hong Kong