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Tensile strength of compacted rammed earth materials

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Abstract

A rammed earth technique is a traditional architectural technique to build soil structures by compacting geo-materials in a form. In this study, tensile strength properties of rammed earth materials and effects of test conditions are evaluated by conducting direct tension tests and splitting tests on several specimens. It is inferred from the result of these test that the direct tension test should be used to evaluate tensile strength of a layer interface, while the splitting test might evaluate the strength related to the tensile strength inside a compaction layer. When rammed earth structures are constructed, the results from the experiments indicate that it is important to scarify interfaces during compaction in order to prevent reduction and variation of the tensile strength of the layer interfaces. The tensile strength of the rammed earth specimens made of compacted soils without lime increased with the decrease in their water contents. The tensile strengths of the specimens represent 5.0–12.5% of corresponding values of unconfined compression strength at the same water content range. The tensile strength of rammed earth specimens made of lime-mixed soil was in the range of 15–20% of the corresponding unconfined compression strength at 28 days curing. In the series of cyclic tensile loading test, no significant reduction of tensile strengths was observed even after undergoing the cyclic loading history.

Keywords: Tensile strength; Direct tension test; Splitting test; Rammed earth; Compacted soil; Lime-mixed material; Cyclic loading

International Geotechnical Classification Numbers: D00 [General]

1. Introduction

The rammed earth technique is an ancient construction technique to build soil structures by compressing soil mixtures consisting of clay and/or sand, and other materials such as lime or cement, if needed. The soil mixture is tamped by a rod in a form after adjusting the soil mixture's water content with water or liquid solution. The compacted soil mixture is cured to strengthen by drying or solidifying by chemical reaction of lime or cement. This technique, which was used in Yellow River Valley, China around B.C. 2000 in Asia (Onitsuka et al., 2007), is still used for walls of traditional houses in several places of the world (Minke, 2006).

For example, Rendell and Jauberthie (2009) reported that some rammed earth housings and agricultural housings that are in excess of 100 years old in east Brittany, France, were generally in a good state of repair. In addition, Al Hambra palace in Granada, Spain, Fujan *Tulou* and the Great wall, China were built with the rammed earth technique and were designated by UNESCO as a world heritage (UNESCO, 2014). In Japan, the rammed earth technique was used for a wall surrounding a temple and a shrine, such as "Abura-dobei" in

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Ryoan-ji temple in Kyoto, "Oo-neribei" in Nishinomiya shrine in Hyogo and "Oo-gaki" in Horyu-ji temple in Nara; these walls have been registered as the important cultural properties by the Agency of Cultural Affairs, Japan.

On the other hand, the advantages of rammed earth construction have attracted interest in construction projects of modern housing in recent years, e.g. the high capability for humidity control, potential for recycling, and the reduction in construction energy, among others (Minke, 2006). The compression strength of various rammed earth materials (e.g. Hall and Djerbib, 2004; Jayasinghe and Kamaladasa, 2007; Rendell and Jauberthie, 2009) and thermal conductivity of rammed earth walls (e.g. Hall and Allinson, 2009) have been studied in order to apply the rammed earth wall to a modern housing. However, the seismic performance of the rammed earth wall has not been investigated sufficiently, except for a limited number of studies which are summarized below.

Bui et al. (2009) conducted in-situ dynamic measurements and laboratory tests of rammed earth walls in order to evaluate elastic modulus. They reported that the elastic modulus depended on the specimen scale and measurement method because of the effects of adhesion between compaction layers, their water content, and so on. In addition, Bui et al. (2011) conducted in-situ dynamic measurements of rammed earth structures located in France in order to evaluate dynamic parameters, e.g. natural frequencies, damping ratio and Poisson's ratio which were used to determine the dynamic characteristics. They pointed out that the current seismic standard (Eurocode 8) could be applicable to the design of rammed earth structures.

Takadachi and Koshihara (2010) conducted a series of shaking table tests on a model of rammed earth wall, which revealed that tensile failure at a bottom part of the rammed earth wall model causes over-turning of the wall in earthquakes. Hence, the tensile strength of the material consisting of the rammed earth wall is one of important factors in evaluating its seismic behavior.

In order to evaluate the tensile strength of geo-materials, a direct tension test, a bending test and a splitting test are typically conducted. Namikawa and Koseki (2007) conducted these three kinds of tests on cement-treated sand and showed that the tensile strengths measured by the direct tension tests are larger than those measured by the corresponding splitting tests. They pointed out that partial shear failure that occurred nearby the loading plate in the splitting tests was one of the reasons behind the underestimation of tensile strength.

It should be noted that the above study by Namikawa and Koseki (2007) was conducted focusing on the tensile properties of cement-treated sand which was artificially cemented under the saturated condition. Rammed earth walls, however, are exposed to the atmosphere, and thus are under the unsaturated condition. The mechanical properties and water content of atmospherically-exposed soils are affected by soil suction, which is also related to the relative humidity of the atmosphere. Jaquin et al. (2009) reported that the water content of an unsaturated rammed earth material decreased with the increase in soil suction, which induced as well an increase in its compressive strength. Bui et al. (2014) also studied the influence of water content and soil suction on the mechanical properties of the rammed earth materials including sandy soil, clayey soil and stabilized soil with natural hydraulic lime, and showed that soil suction was an important factor for the compressive strength, secant modulus and Poisson's ratio. However, not all the possible effects of water content and soil suction on the tensile strength of rammed earth materials have been well studied.

In Japan, traditional rammed earth walls are often made of the mixture of soil and/or add-in materials such as slaked lime and quick lime, which are selected depending on soil properties. Artificial cementation with a chemical reaction would resist tensile stress mobilized in the rammed earth structure made of the mixture consisting of soil and add-in material, in a way that is similar to the cement-treated sands studied by Namikawa and Koseki (2007) among others. In the rammed earth structures without add-in material, on the other hand, soil suction might be assumed to resist the tensile stress as well as the compressive stress studied by Jaquin et al. (2009) and Bui et al. (2014).

In the traditional Japanese rammed earth technique, magnesium chloride solution or sea water is sometimes used to adjust the water content of soil mixture with/without add-in material. These solutions are believed to improve the performance of the rammed earth wall. For instance, Akatani et al. (2012) reported that the compressive strength of rammed earth specimens mixed with calcium hydroxide (slaked lime) and magnesium chloride solution increased with the increase of the concentration of the magnesium chloride solution in a case where the concentration was smaller than 15%.

On the other hand, negative effects of adding magnesium chloride have also been reported. Tanimoto et al. (2004) conducted unconfined compression tests of compacted mixtures consisting of soil, slaked lime and magnesium chloride at several mixing ratios, and they reported that the strengths of some compacted mixtures with magnesium chloride were smaller than that of the compacted soil mixture without magnesium chloride. They pointed out that the formation of artificial cementation by slaked lime was impeded because calcium hydroxide was non-easily ionizable in the solution containing high levels of magnesium chloride. Xing et al. (2009) conducted unconfined compression tests and mineralogical analysis on salt-rich soil cement. They showed that the unconfined compression strength of the salt-rich soil cement decreased with the increase of the amount of magnesium ion, chloride ion and sulfate ion in the soil because these ions impeded the formation of cementation compounds such as calcium-silicate-hydrate and calcium-aluminate-hydrate.

It is to be noted that magnesium chloride solution is also known as one of the materials used for magnesium oxychloride cement. The magnesium oxychloride cement, consisting of magnesium chloride solution and magnesium oxide, produces some crystal phases by the chemical reaction (e.g. Dehua and Chuanmei, 1999), and it has a suitable molar ratio of magnesium oxide, magnesium chloride and water for possessing a certain crystal phase to maximize the compressive