Construction and Building Materials 133 (2017) 433–442

Contents lists available at ScienceDirect

Construction and Building Materials

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

Structural behavior of rammed earth walls under lateral cyclic loading: A comparative experimental study

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HIGHLIGHTS

- Rammed earth walls were tested under cyclic loading.
- Comparisons were made with masonry brick and aerated concrete walls.
- Hinged loading test set-up was used.
- Load carrying capacities and total energy of the masonry walls were determined.
- Rammed earth wall stabilized using 10% cement has better performance.
- Performance of masonry brick wall fall behind of other masonry walls.

ARTICLE INFO

Article history:
Received 26 July 2016
Received in revised form 3 December 2016
Accepted 18 December 2016

Keywords:
Rammed earth
Masonry walls
Stabilization
Cyclic behavior
Hinged test setup

ABSTRACT

Rammed earth is one of the oldest masonry construction techniques such that there are many ancient structures built of rammed earth still existing. Recently, applications of rammed earth are encountered more often, due to its ecological advantages such as renewability, sustainability, environmental protection, insulation and use of environmentally-friendly materials. Although it has been widely used in masonry construction, knowledge related to behavior of these structures or structural members is limited. Under this circumstance, in this study, behaviors of stabilized and non-stabilized rammed earth walls were investigated comparatively with masonry brick and aerated concrete walls. For this purpose, non-stabilized, 10% cement stabilized, 10% cement stabilized with 1% glass fibers and 5% cement stabilized with 5% blast furnace slag mixtures were produced in dimensions of 20 cm × 150 cm × 150 cm rammed earth walls. Cyclic behaviors of the rammed earth walls were compared with masonry brick and aerated concrete walls with the same dimensions by using hinged loading test set-up. Structural properties such as load carrying capacities, total energy dissipation and stiffness degradation of the masonry walls were determined by utilizing the results of cyclic loading tests. At the end of the study, it was concluded that rammed earth wall stabilized using 10% cement showed the best structural performance. Surprisingly, performance of masonry brick wall fell behind of other masonry walls, even though it is the most commonly used material in masonry constructions.

1. Introduction

Rammed earth is a construction method in which walls are built by using natural earthen materials. At the beginning, the only reason to construct buildings with earthen materials was simply sheltering due to lack of materials but nowadays there are many reasons such as renewability, sustainability, environmental protection, insulation and use of healthy materials in order to prefer rammed earth to other structural materials [1–5]. In this manner, rammed earth technique has fulfilled the building requirements of modern societies. Soil is placed into a framework and compacted approximately as 15–20 cm layers in this test method. For stabilization, cement is added from 3% to 10% depending on the quality of the soil. The ideal soil consists of clay (10–40%), silt (10–40%), sand (35–65%) and fine gravel. There are several soil compositions in order to produce rammed earth [1,3–6].

There are mainly two methods for construction of earthen walls: Non-stabilized and stabilized rammed earth. Gravel, sand, water and soil are used in non-stabilized rammed earth as binder materials. For stabilization, cement, lime and asphalt emulsions

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http://dx.doi.org/10.1016/j.conbuildmat.2016.12.093
0950-0618/

are used in stabilized rammed earth walls. Even if rammed earth structures date back very old in history, surprisingly there are a few design codes related to rammed earth technique [2,4,7–10].

Gubta [11], presented a case study on full-scale rammed earth walls to determine the effect of two different types of shear detailing on the structural performance. Bui et al. [12] studied on durability of different types of stabilized and non-stabilized rammed earth walls exposed to natural weathering for 20 years, in a wet continental climate. Tripura and Singh [13], carried out a study on structural behavior of axially loaded cement stabilized rammed earth columns. Kariyawasam and Jayasinghe [14], conducted a study on cement stabilized rammed earth to obtain proper strength and durability at the same time. Liu et al. [15] proposed a retrofitting technique for rammed earth buildings by using externally bonded fibers. Miccoli et al. [16] presented a comparative study on mechanical performance of structural elements produced using three different techniques; masonry earth block, rammed earth and cob. Bui et al. [17] presented experimental and numerical analysis on tensile strengths and Poisson ratio of rammed earth specimens. Ciancio and Gibbings [18], carried out an experimental study to improve the quality control techniques related to cement-stabilized rammed earth construction sites. Bui et al. [19] performed an experimental study to determine dynamic parameters of buildings such as natural frequencies and damping ratio. Reddy et al. [20], investigated construction aspects, structural design and embodied energy analysis of a three-story building. Jayasinghe et al. [21] conducted a study on load carrying properties of masonry wall constructed with recycled demolition waste and cement-stabilized rammed earth. Silva et al. [22] performed an experimental study including the assessment of four representative soils. They proposed an alternative stabilization technique based on alkaline activation of fly ash using the results observed for each soil. Collet et al. [23] compared thermal conductivity of 20 cm-concrete block and 50 cm-adobe walls facing south. Darling et al. [24] investigated the effects of clay on indoor air quality.

Recent studies have showed that physical, mechanical, and thermal properties of rammed earth have been improved by reinforcing and/or replacing with some stabilizers such as cement, fly ash, and various fibers. There are few studies related to structural performance of rammed earth walls. Especially, studies about cyclic behavior to reflect seismic response of rammed earth walls were almost never encountered.

The main objective of this study is to comparatively investigate cyclic behaviors of rammed earth walls, masonry brick and aerated concrete walls with the same dimensions by using a hinged loading test set-up. For this purpose, displacement controlled loading protocol proposed by FEMA 461 [25] was used to apply lateral cyclic loading. At the end of the study, load carrying capacities, total energy dissipations and stiffness degradations of the test walls were determined and discussed according to the test results.

2. Experimental program

2.1. Materials and method

A wide range of subsoils can be used for production of rammed earth construction. One of the main criteria for selection of the raw materials for sustainable constructions like rammed earth is to use locally available natural materials. Clay content in the mixes should be sufficient to bind effectively together all other fractions without excessive shrinkage during drying in the rammed earth techniques [26]. For producing rammed earth walls, maximum grain size is 2 mm for the mixture of soil, clay, silt and sand provided from Duzce region where this experimental study was conducted. Most of the specifications limit the maximum aggregate diameter to 20–25 mm. In this study, maximum 4 mm-grain-size-aggregate was used in the mixes. Emiroğlu et al. [27] used similar clay and sand to produce earthen plaster and they pointed out that '1 part clay and 1 part sand mix' can be used to prevent shrinkage cracking in the earthen plasters [27]. Particle size distribution of clay and aggregate used in this study is given in Fig. 1. For stabilization of rammed earth walls, CEM I 42.5 R type Portland cement, and blast furnace slag were utilized. Also 12 mm chopped glass fibers were used in the fiber-reinforced mix. In addition, 60 cm × 25 cm × 20 cm aerated concrete blocks and 29 cm × 19 cm × 13.5 cm masonry bricks were used to prepare masonry walls for the purpose of comparison. Some mechanical and physical properties of masonry brick and aerated concrete are given in Table 1.

Soil and fine aggregate ratio were kept constant as 1/1 for all mixes. The aggregate were mixed in saturated surface dry condition, then soil was added and stirred for one minute. Afterwards materials used for stabilization were added and mixing was continued (approx. 15 mins) until a homogeneous mix was obtained. Mix designs of the test specimens were shown in Table 2.

Compressive strength values demonstrated in Table 2 were obtained by performing tests on the Ø150 × 300 mm cylinder specimens with each batch consisting of 3 specimens. Compressive strength tests have been performed after 28 days and the all specimens were oven dried. It is clear that, stabilizing the rammed earth mixes with cement, GGBFS and glass fiber has positively affected the compressive strength of the specimens. It is seen that cement is a successful stabilizer proved by numerous studies in the literature [1,28,29]. Besides, it can be said that, GGBFS is one of the sustainable alternatives that would allow using less cement while stabilizing the rammed earth mixes without much sacrifice in compressive strength. Furthermore, compressive strength results show that the use of 10% cement and 1% glass fiber by the weight of the mix has contributed the compressive strength of the rammed earth specimens.

The specimens were casted in the mold of 150 × 150 × 20 cm dimensions demonstrated in Fig. 2. The soil was compacted as 15–20-cm layers by a pneumatic sand hammer having 8.0 cm butt diameter and 8.0 kg weight. In this study, a total of six walls were produced and tested. These walls consisted of one non-stabilized rammed earth wall, three stabilized rammed earth walls, one masonry brick and one aerated concrete wall. Standard cement mortar joint, commonly used in structural applications, consists of 3 unit sand, 1 unit cement and 1 unit hydrated lime used for construction of Masonry Vertical Cored Brick. Besides, Ytong Inc.

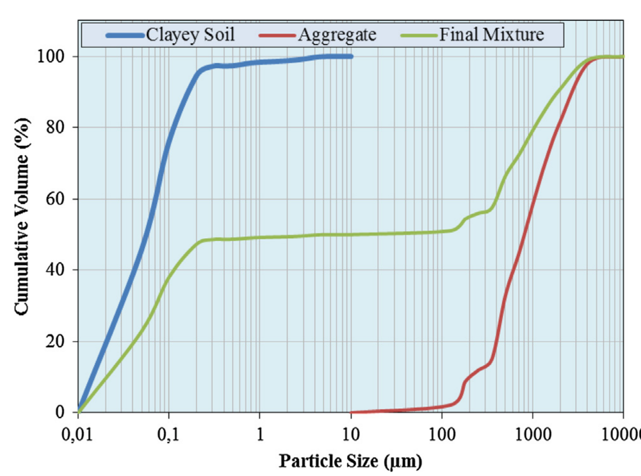

Fig. 1. Particle size distribution of soil, aggregate, and final mixture used in this study.