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Axial load-capacity of rectangular cement stabilized rammed earth column

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ABSTRACT

The paper presents a novel study on structural behaviour of axially loaded cement stabilized rammed earth (CSRE) prisms and columns of square and rectangular cross-sections. The effects of slenderness ratio and aspect ratio on the load-capacity of columns and stress reduction factors were assessed. Experimental results were compared with that obtained by tangent modulus theory. Experimental capacity/stress reduction factors were compared with published codal values. The result shows that the load-capacity of column decreases as the value of slenderness ratio increases and aspect ratio of column was found to influence the load-capacity. The ultimate compressive strength of column predicted by tangent modulus theory tend to converge the experimental values at higher slenderness ratios. The stress reduction factors in earthen (NZS 4297, AS HB 195) and masonry (IS 1905) standards are found to be in close agreement with the experimental values. The characteristic strength of column yields relatively higher safety factor (∼23–35) indicating a possibility of using CSRE for construction of load-bearing houses.

1. Introduction

Rammed earth is an ancient form of monolithic earth wall construction [12,37,19]. Some of the well-known examples of rammed earth structures are: (a) a seven-storey load bearing rammed earth building in Weilburg, Germany; (b) a five-storey rammed earth chalk houses in Winchester, U.K.; (c) mud-brick buildings up to ten stories in Shibam, Yemen [31], (d) Basgo Fort in Ladakh, India [27], etc. The Great Wall of China and the wall surrounding Horyuji Temple in Japan are some of the ancient examples that are still performing well [17,5]. More than six modern (small to medium sizes) rammed earth buildings (e.g. schools, residential buildings, etc.) can be found in and around Bangalore, India (e.g. [47,38]).

In the recent past, rammed earth technique has gained renewed interest across the world due to its varied sustainable benefits such as low cost, and low embodied energy, (e.g. [38], etc.). Several studies on properties of soil and behaviour of walls have been carried out [46,13,18,17,48,30,28,10,39,11,44]. Several studies have been carried out on the performance of rammed earth and adobe walls experimentally and numerically (e.g. [14,8,20,32]). Besides studies under static loading (e.g. [31,40]), dynamic studies were also carried out on the performance of rammed earth walls and buildings (e.g. [14,8]). However, only few literatures on structural behaviour of rammed earth columns can be found [31,16,42,43]. Due to limitation of structural design regulations for earthen buildings, the building designers often use design rules developed for masonry constructions, often without modification [31]. Some of the well-known structural design standards/guidelines for modern earth constructions are NZS 4297 [36], IS 2110 [22], AS HB 195 [2] and ASTM E2392/E2392M [4]. Many of these standards are used in conjunction with masonry standards, such as the stress/capacity reduction factors (k) available in earthen standards are directly adopted from the masonry standards [1,21,7]. So far, no adequate experimental validations have been made on the application of masonry design rules to rammed earth columns. Maniatidis and Walker [31] first attempted to validate the use of masonry design rules for the design of rammed earth columns. Unstabilized rammed earth square columns were tested under axial loading with varying eccentricity. The study did not explicitly explain the stress reduction factors for concentrically axially loaded columns. Hence, there is a need for further validation of masonry design rules considering structural parameters such as slenderness ratio (λ), and aspect ratio (Φ) on the capacity reduction factors of axially loaded columns.

The present study investigates the structural behaviour of axially loaded CSRE prisms and columns of square and rectangular cross-sections. The effects of slenderness ratio and aspect ratio

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on the load-capacity of columns and stress reduction factors were assessed. Experimental results were compared with that obtained by tangent modulus theory and the experimental capacity/stress reduction factors were compared with published codal values.

2. Experimental program

2.1. Materials and equipments used for production of test specimens

The properties of soil determined as per Indian standards IS 2720 Part 4 [23], IS 2720 Part 5 [24] and IS 2720 Part 7 [25], comply with general published recommendations for rammed earth construction [45]. Table 1 outlines the properties of soil used and Fig. 1 shows density – moisture content curve. Ordinary Portland cement of 43-grade conforming to IS 8112 [26] was used in the experimental investigations. Generally, 5–10% cement (by weight) is used for soil stabilization to gain higher strength and durability and to avoid loss of strength when saturated with water and erosion due to wind/rain impact [35,28,15,40]. Therefore, 10% cement was used for production of test specimens throughout the test program.

For production of test specimens, the following equipments were used:

1. A 5.6 kg mild steel rammer with a 95 mm square ramming face and 1.02 m long solid handle of 25 mm diameter was used for ramming/compaction (Fig. 2a).
2. A wooden mould of 150 mm square section (inner dimension) and 1.5 m height (*h*) having 20 mm wall thickness was fabricated and fastened with nuts and bolts and further provided with a wooden base plate for fixing the mould in position (Fig. 2b). The same mould was used for production of rectangular columns, which is provisioned in such a way (i.e., extra holes have been provided to fix the bolts and nuts ensuring to obtain the desired cross-section) that the desired cross-sectional dimension of 190 mm × 150 mm and 230 mm × 150 mm (width, *a* × thickness, *d*) respectively can be easily set.
3. Out of four walls of the mould, one part of the wall was cut into half along the transverse direction to facilitate better compaction and positioning of rammer in the mould during compaction. The inner walls of the mould were covered/pasted with either thin polythene or sellotape to avoid adhesion of test specimen on the mould walls.
4. A 97 mm × 97 mm mild steel collar guide of 300 mm height and 0.5 mm thick was used to facilitate the location of the rammer in the mould when required.

During the test program, compaction was carried out with the help of a compaction machine developed in the laboratory, in which the rammer is connected to have a free fall of height of about 300 mm approximately. A typical CSRE column is shown in Fig. 2c.

2.2. Production of test specimens

Five prisms of 150 mm × 150 mm in cross-section and λ equal to 2 were produced to determine the compressive strength (σ) and stress–strain curve. In total 45 columns of three different cross-sections were produced having λ equal to 6, 8 and 10, comprising of five specimens from each series with an approximate height of 0.9 m (denoted S-0.9, R1-0.9 and R2-0.9), 1.2 m (S-1.2, R1-1.2 and R2-1.2), and 1.5 m (S-1.5, R1-1.5 and R2-1.5), respectively. (*Note:* Cross-sectional dimension of columns: Square (S) = 150 mm × 150 mm; Rectangular (R1) = 190 mm × 150 mm; and Rectangular (R2) = 230 mm × 150 mm, respectively). The dimensions are so chosen that one side remain constant i.e., depth/thickness, $d = 150$ mm, while the other side, i.e., width, a varies from 150 to 230 mm (see Fig. 2b), thereby increasing the values of Φ by about 26.7% and 53.3% for R1 and R2 respectively as compared to S columns.

Table 1
Properties of soil used.

Soil property	Percentage value
Grain size distribution	
Sand	79%
Silt	13%
Clay	8%
Atterberg limits	
Liquid limit	31.70%
Plastic limit	22.90%
Plasticity index	8.80%
Compaction characteristics	
(a) Soil with 10% cement	
Optimum moisture content	19%
Maximum dry density (kg/m^3)	1710

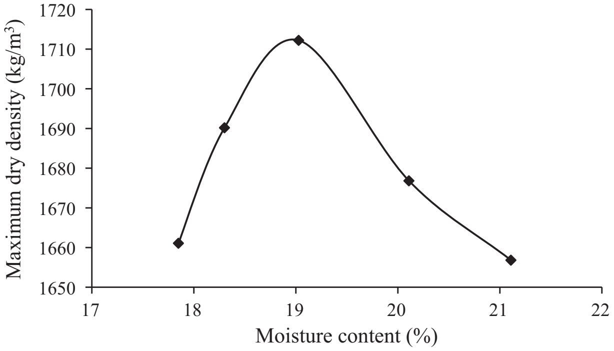

Fig. 1. Dry density vs. moisture content at 10% cement.

The soil sample was sun – dried, ground and passed through 4.75 mm sieve prior to production of test specimens. Dry mixing of soil with 10% cement (by mass of dry soil) was carried out before mixing with an optimum quantity of water equal to 19% (see Fig. 1). Further, a rapid moisture metre test was performed prior to adding optimum water to every freshly prepared soil–cement mix in order to maintain optimum water content of the mix. The mass of the mix and compaction on each layer was controlled, through prior experimentation, to provide the equivalent of standard Proctor effort in order to achieve the required density. The compaction energy/effort was determined using the formula given in ASTM D 698-12 [3] as follows:

$$E_c = \frac{(No.\ of\ layers)(No.\ of\ blows/layers)(Weight\ of\ rammer, kg)(Height\ of\ drop, cm)}{Volume\ of\ mould, cm^3} \tag{1}$$

where E_c = compaction energy, kg cm/cm^3.