

An Investigation on the Determination of Compressive Strength of Poured-earth/Earth-cobs (PEEC) Masonry Wall

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Abstract:

Excessive shrinkage as the cause of low compressive strength associated with the monolithic poured earth method of earth construction is always a discouraging factor for professionals in the built environment. Poured earth is becoming more widely used to construct buildings worldwide and has gained popularity as an aesthetically pleasing, low cost and sustainable building technique. Poured earth structures could be monolithic if cast completely from the same earth slurry or masonry if produced from two heterogeneous materials. Therefore, this research adopted spherical earth-cobs as plums in poured-earth for the construction of earth-based masonry wall. Three different types of earth-cobs and four different types of poured-earth were produced at different percentages of cement in the mixes. Prisms with a height-to-thickness ratio of 2.1 were used to determine the compressive strength of the Poured-Earth/Earth-Cob (PEEC) masonry wall. Twelve different types of cast prisms were produced from different combinations of poured-earth and earth-cobs. Additional four types of prisms were also produced by using poured-earth slurries alone for compressive strength compared with the types that have earth cobs. The result of IRA shows that the suction effect of the spherical earth-cobs through capillary action increases with an increase in cement added to the mixes and increases with time. The results of the compressive strength of the masonry wall samples show improved strength and approximately total elimination of shrinkage compared with the monolithic poured earth wall. The research, therefore, recommends the use of poured-earth with earth cobs as plums for the construction of earth masonry wall.

Keywords: Compressive strength, Earth-cobs, Initial rate of absorption, Masonry wall, Poured-earth

1 Introduction

Masonry structures are typically a non-elastic, heterogeneous and anisotropic element composed of two materials of different properties (Kaushik, Rai & Jain, 2007). It consists of two phases, namely, the unit phase and the mortar phase. Under lateral loads, masonry does not completely behave elastically, even in the range of small deformations. It is very weak in tension because it comprises two different materials distributed at intervals, and the bond between them is weak. Therefore, masonry structures are expected to resist mostly compressive stresses (Kaushik et al., 2007; Thaickavil & Thomas, 2018). Masonry walls are used in almost all types of building construction in many parts of the world because of their low cost, good sound and

heat insulation properties, easy availability of materials and skilled labour (Kaushik et al., 2007). It is one of the oldest structural elements known to man, which is believed to have been in use for over 6000 years, and its construction remains relatively popular in many parts of the world and is practised widely even today (Thaickavil & Thomas, 2018). As a well-proven building structure, Masonry possesses excellent properties in terms of appearance, durability, and cost. The quality of masonry in a building depends on the materials used, which must conform to certain minimum standards (Hendry, Sinha & Davies, 2004).

Peec masonry is a type of masonry comprising poured-earth slurry as the binding component and solid spherical earth-cobs as the unit component of the masonry (Adeleke, 2020). The two masonry components are used to form a masonry wall with properties similar to other types of masonry wall system. Examples of other types of masonry include bricks/mortar masonry, blocks/mortar masonry and stone/mortar masonry. The spherical earth-cobs are combined with the poured-earth slurry-like plum concrete construction. The word 'plum' in concrete means boulders of sizes between 150mm – 300mm. Plum concrete construction is a way of introducing these boulders into concrete construction to reduce the volume of concrete needed for a required structural element or probably to improve the strength of such an element (Adeleke, 2020). Plum concrete can be used below footing as a base so that water from the footing will not be absorbed by the earth below. Plum concrete is used in areas that need massive concrete placement, such as dams and bridge piers.

The problem of excessive shrinkage is associated with most of the earth methods of building construction. Some of the methods of earth construction that suffer excessive shrinkage include adobe rammed earth, cob and poured earth (Wolfskill et al., 2017). In the poured-earth method of earth construction, shrinkage and shrinkage cracks are developed because of the high moisture content in the slurries used to make the monolithic wall (Adeleke, 2015; Sackey, 2015; Williamson, 2012; Wolfskill et al., 2017). Therefore, reducing or eliminating shrinkage and shrinkage cracks in earth construction is of great importance.

Poured earth is a fluid mix that consists of a mixture of gravel, sand and silt, which is agglomerated by clay (Carlos, Edgardo & Yolanda, 2016). Poured earth is also considered soil in liquid mud form, but containing sandy aggregates can perform the same function as lean concrete (Houben & Guillaud, 1994). Poured earth walls have been known for the problem of low compressive strength. This has been attributed to the peculiarity of excessive shrinkage and shrinkage cracks in poured earth walling system (Adeleke, 2015; Sackey, 2015; Williamson, 2012; Wolfskill et al., 2017). If poured-earth samples shrink, shrinkage cracks will occur, and if the shrinkage stress is more than the ultimate tensile strength of the samples, it leads to a reduction in compressive strength of the poured-earth samples.

Earth-cob is an earth building technique that involves forming a lump of balls in a plastic state and stacking them wet/dry to build a load-bearing wall with/without mortar (Hamard et al., 2016). Cob construction is carried out with highly wetted soil material (water must be added above the plastic limit of the soil), kneaded by foot and piled on the wall in a plastic state. The primary advantage of this method of earth construction is the simplicity in technique and construction equipment (Wolfskill et al., 2018). Earth-cob, due to its flexibility, could be combined with other building techniques, such as poured earth, earth-bag technique, wood frame, concrete, straw

bale, adobe, wattle-and-daub, to reduce costs, time, or to improve its performance according to the surroundings (Estrada, 2013; Smith, 2000). If technologically combined with poured earth, the Cob method of earth construction will be an earth-based building technique that may be an alternative for constructing new homes in developing and developed countries. Earth-based constructions commonly used in the past, like adobe and wattle-and-daub, have increasingly been replaced by building using more processed methods.

Therefore, the study's outcomes could have structural, economic, ecological/environmental, and social benefits. The structural significance is the improved strength and durability properties that the study investigated. The combination of earth-cobs and poured-earth improved the compressive property of poured-earth/earth-cobs masonry walls. The economic importance of the use of local building materials will be of great benefits. The ecological and environmental benefits arising from using local building materials (especially those based on earth) are plentiful. It helps to reduce the amount of cement used in global building processes and, consequently, the amount of CO₂ emitted to the atmosphere, thereby reduces the effect of global warming. Socially, the poured-earth/earth-cob (peec) method of construction will meet the requirements of local production situations, such as using local existing or easily transferable skills, avoiding costly training of the workforce, and reducing societal or cultural disruption.

2 Material and Methods

2.1 Prism Samples for Peec Masonry Wall

Before producing the prisms used for the main experiments, many trials were carried out to ascertain the quality of the cast prisms. According to ASTM E447, tests on the prisms were carried out at 21 days (T1), 28 days (T2), 56 days (T3) and 90 days (T4). A total of 288 prisms were prepared from 3 types of earth cobs and four types of poured-earth with six samples for each type at a particular age. One sample was always used as a trial during crushing in order to have an idea of the probable failure load for each type of sample at a particular age. The other five were used for the main crushing and recorded.

Table 1. Different Combinations of Poured-earth and Earth-cobs of the Prisms

S/N	Poured earth	Earth-cobs		
		0% cem. addition (B1)	5% cem. addition (B2)	10% cem. addition (B3)
1	0% cement addition (S1)	S1B1	S1 B2	S1B3
2	5% cement addition (S2)	S2B1	S2B2	S2B3
3	10% cement addition (S3)	S3B1	S3B2	S3B3
4	15% cement addition (S4)	S4B1	S4B2	S4B3

Based on the experimental trials, the ratio of the volume of earth-cobs to that of poured-earth in all the prisms used for the main experiment was 0.25. There was a need to spray water on the dried earth cobs for proper bonding between the earth-cobs and poured-earth. The sizes of the 288 prisms produced for the experiment were 230mm length by 190mm thickness by 400mm high except for prisms produced without the use of earth-cobs, i.e., poured-earth alone (S₁B₀, S₂B₀, S₃B₀ and S₄B₀) that

suffered both vertical and horizontal shrinkage as established in similar research by Adeleke (2020) as shown in Plate I. Before producing the prisms, non-absorptive metal moulds were coupled and placed on the metal plate of similar materials. The moulds were lubricated for easy demoulding after the samples have set.



Plate I: Excessive Shrinkage Plate II: Placing the E.C on the Face of P.E Plate III: Test on IRA of Earth-Cobs

After pouring the first layer of earth slurry to about one-quarter ($\frac{1}{4}$) of the mould height and compacted by hitting the sides of the moulds, two pieces of dried spherical earth-cobs were placed on the face of the first layer, after which the second layer of earth slurry was poured to about half ($\frac{1}{2}$) of the moulds' height and compacted for another two pieces of the earth-cobs to be placed on its face. The third layer of earth slurry was also poured to about three-quarter ($\frac{3}{4}$) of the mould height and compacted for the last two pieces of the earth cobs to be placed on its face, as shown in Plate II.

The fourth layer of the earth slurry was then used to fill up the mould and compacted. The final face of the prisms was now dressed in hand-trowel and designated with appropriate code for easy identification. Therefore, a total of 6 earth-cobs (with an approximate weight of 1kg each) were used with the four layers of the poured-earth to produce the respective prisms. The cast prisms were now demoulded the next day after they had set and covered with polythene material to avoid rapid moisture loss in the samples.

3 Laboratory Test

3.1 Initial Rate of Absorption (IRA) of the Earth-cobs

This is a test on durability measure which give information about the quality of the earth-cobs. The suction of water from the poured-earth by earth-cobs due to capillary action was measured by the initial rate of absorption test. The test was carried out on samples of earth-cobs at 21, 28, 56 and 90 days according to BS EN 772-11:2011. It was measured in terms of the mass of water absorbed per minute by the earth-cobs per unit area of the earth-cobs immersed in about 5mm deep water, which was kept constant by adding water during the test as shown in Plate III. The IRA was calculated using equation 1. The IRA was measured before the usage of the earth-cobs in the production of the masonry prisms. This was to assist in the poured-earth selection and material handling in the production processes following similar researches.

$$\text{IRA (kg/m}^2\text{/min)} = \frac{\text{Mass of water absorbed by spherical earth-cobs (kg)}}{\text{Area of the spherical earth-cobs (m}^2\text{)}} \quad \dots\dots\dots (1)$$

$$\text{IRA (kg/m}^2\text{/min)} = \frac{M_2 - M_1 \text{ (kg)}}{A \text{ (m}^2\text{)}} \quad \dots\dots\dots (1)$$

Where M_2 = final mass of earth-cobs after immersion
 M_1 = initial mass of earth-cobs before immersion
 $A = \pi R^2$
 R = radius of the spherical earth-cobs = 50cm

3.2 Compressive Strength of Masonry Wall Samples (prisms)

Out of the 288 prisms cast and cured for compressive strength, 211 prisms were used to carry out compressive strength, as shown in Plate IV. There was no proper bonding between the masonry wall components for the remaining 69 prisms leading to major constructional cracks as shown in plate V. These prisms (S_1B_1 , S_1B_2 , and S_1B_3) were the type produced from the unstabilized poured-earth (S_1) when combined with the different types of earth-cobs (B_1 , B_2 , B_3).

The 211 prisms were tested for compressive strength at 28, 56 and 90 days according to BS EN 1996-2: 2006. The test could not be carried out at 21 days due to the wetness of the sample. The load was applied in four stages to allow for deformation measurement on a dial gauge attached to a universal testing machine, as shown in Plates VI. The ultimate load was recorded, and the strength of the masonry wall was calculated with Equation 2.

$$f_p = \frac{F_{max}}{A} \quad \dots\dots\dots (2)$$

Where f_p is the compressive strength masonry wall (prism) (N/mm^2)
 F_{max} is failure load (N)
 A is the cross-sectional area of the face of the prism (mm^2)



Plate IV: Some of the Cast Prisms



Plate V: Prisms that Suffered Bonding



Plate VI: Test on Compressive Strength of Prisms

3.3 Stress-Strain Behaviour and Elastic Modulus

The stress-strain curves of the prisms were determined by the double averaging method in line with similar researches (Costigan et al., 2015; Kaushik et al., 2007; Thaickavil & Thomas, 2018). According to the researchers, the method is how

averaged strain values are plotted on the abscissa against the predetermined stress values on the ordinate, which are also averaged across different specimens. The modulus of elasticity was then calculated using equation 3, which was derived from stress-strain curves by measuring the slope of secant between ordinates corresponding to 33% (1/3) of the ultimate strength of the specimen samples according to BS EN 1996-2: 2006 and MSJC 2002.

To determine the strain values for all the samples used for the experiments, deformation was measured using a long-plunger dial gauge connected to the testing machine, as shown in Plate IX.

$$E_c = \frac{F (N)}{3\epsilon A (mm^2)} \dots\dots\dots (3)$$

Where E_c is the modulus of elasticity, ϵ is the compressive strain at any point on the stress-strain curve, F is the applied force at a particular stage, A is the loaded cross-sectional area of the face of the sample.

The dial gauge with serial number 213211 and 0.0001mm division was made in England by John Bull British Indicator limited. The deformations were measured at their corresponding loadings of the samples. The loadings on the samples of the prisms were in the range; 5-10KN, 10-20KN, 20-40KN and failure load, which varied depending on the samples. The process was carried out at 28, 56 and 90 days. To avoid errors, it was ensured that the displacement meter on the dial gauge was zeroed when the loading on each sample was also at zero and the head of the long plunger of the dial gauge was made to touch the face of the moving plate of the testing machine. This was ensured when the plates were already in contacts with the sample. After multiplying the readings on the dial gauge by its division (0.0001mm), the strain values were now calculated by dividing the distance travelled by the original height of the samples.

4 Results and Discussion

4.1 Initial Rate of Absorption of Earth-Cobs (IRA)

The absorption of moisture by capillary action in the earth cobs produces a suction effect that draws water from the poured earth, and the result is shown in Table 2. It shows the result of the IRA test on the earth cobs before their usage for masonry wall construction. The result varies from 0.63 to 2.95kg/m³/min according to the types of earth-cobs and age.

Table 2. Initial Rate of Absorption (IRA) of the Earth-cobs

S/N	Designation	Initial Rate of Absorption (kg/m ² /min)			
		21 Days	28 Days	56 Days	90 Days
1	B ₁	1.05	0.92	0.88	0.63
2	B ₂	2.74	1.52	1.22	1.21
3	B ₃	2.95	1.72	1.31	1.27

A higher value of IRA was found with earth-cobs of 5% and 10% cement stabilization (B₂ and B₃). This could be because of more hydration reactions in the stabilized earth cobs. It is also seen that IRA values decrease with an increase in age for all earth-cobs

used for the research. This could also be because of a reduction in the hydration processes as age increases. Therefore, the suction effect of the earth-cobs through capillary action increases with the percentage addition of cement and generally reduces as the age increases.

4.2 Compressive Strength of Masonry Walls

4.2.1 Compressive Strength of Masonry Walls with 0% Cement in Poured-earth Combined with Different Earth-cobs

In this set of prisms, the results show that only samples of S_1B_0 have the visible result, as shown in Table 3. The research is not visible for S_1B_1 , S_1B_2 and S_1B_3 because there is no bond between the earth-cobs and poured-earth for S_1B_2 and S_1B_3 , thereby causing major cracks in the samples. However, for S_1B_1 , there was a little bond that is not enough to hold the two components together, thereby causing lesser cracks in the samples. The results of S_1B_2 and S_1B_3 could be because of the high water-absorptivity (suction value) of B_2 and B_3 earth-cobs combined with poured-earth with very low water retentivity (S_1). The little bond formed for S_1B_1 could be because of the low suction effect of B_1 combined with very low water-retentivity of the poured- earth, S_1 . There was rapid sucking of water from the poured-earth by the earth-cobs leading to insufficient water for binding processes, thereby creating major cracks in the samples. The result of S_1B_0 increases with an increase in age, as shown in the table.

4.2.2 Compressive Strength of Masonry Walls with 5% Cement in Poured-earth Combined with the Different Earth-cobs

The results of compressive strengths of a masonry wall with 5% poured earth is shown in Figure 1. It shows that the research is visible for all the samples of the walls. Compressive strength of the walls increases with the increase in age and percentage increase in cement addition for the earth-cobs for all the samples except S_2B_3 . The two materials were seen to be properly bonded with very few light cracks in the samples except for S_2B_3 , whose cracks become obvious as the materials dry with age. The visibility of the bond could be because of the ability of poured-earth to withstand the suction effect of the earth-cobs in the combinations (S_2B_1 and S_2B_2) thus, making water available for hydration of cement in the poured earth. In the case of S_2B_3 , the result could be attributed to the very-high absorptivity of earth-cobs combined with the low water-retentivity of poured-earth (S_2). The increase in the strength as the age increases for S_2B_0 , S_2B_1 and S_2B_2 could result from a continuous increase in the hydration reactions in the poured earth, thereby making their bonds stronger. Nevertheless, in the case of S_2B_3 , the decrease in strength as the age increases could be because of continuous water absorption from the poured-earth through capillary action by earth-cobs, B_3 leading to insufficient water for hydration of cement in the poured-earth.

4.2.3 Compressive Strength of Masonry Walls with 10% Cement in Poured-earth combined with Different Earth-cobs

The results of compressive strengths of a masonry wall with 10% poured earth is shown in Figure 2. It shows that the research is visible for all the samples of the walls. Compressive strengths are observed to increase with the increase in age and percentage increase in cement addition for earth-cobs for all the samples. The two materials were observed to be properly bonded with no crack in the samples. This could be attributed to the high water-retentivity of poured-earth (S_3). It means that the

poured earth can retain water against the suction effect of the earth-cobs, thereby making enough water available for hydration of cement in the mix. The strength increase with age could be attributed to a continuous process of hydration of cement in the poured-earth mix.

4.2.4 Compressive Strength of Masonry Walls with 15% Cement in Poured-Earth combined with Different Earth-cobs

The results of compressive strengths of masonry wall samples with 15% poured earth is shown in Figure 3. It shows that the research is also visible for all the samples of the walls. The compressive strength of the masonry wall is observed to increase with the increase in percentage cement addition of the earth-cobs for all the samples. The two materials were seen to be properly bonded with no crack in the samples. The improved strengths in this case, when compared with when poured-earth with 10% cement addition was used, could be attributed to two reasons: availability of more binding material (cement) and very high water-retentivity of the poured-earth (S4) against the suction effect of the different earth-cobs making more water available for the hydration of cement. The strength increase with age could be attributed to a continuous process of hydration of cement in the poured-earth mix.

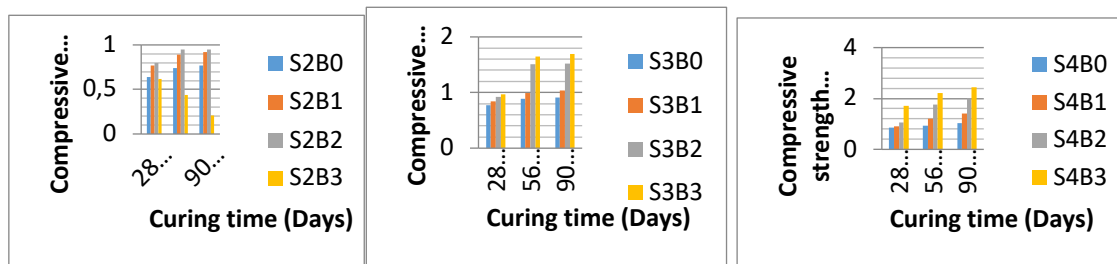


Fig 1: Compr str of 5% cement P.E masonry Fig 2: Compr str of 10% cement P.E masonry Fig. 3: Compr str of 15% cement P.E masonry

4.2 Stress-strain Curves and Elastic Modulus of the Masonry Wall

For the poured-earth/earth-cobs (peec) masonry wall, the stress-strain curves for the wall samples when the four types of poured-earth were combined differently with the three types of earth-cobs are shown in figures 4-12. The curves generally show that the curves consist of rising and falling parts, and the following were deduced as control points. According to Kaushik et al. (2007), these control points can be effectively used to define the performance limits states of the peec masonry wall.

- (i) One-third of maximum compressive strength represents the point up to which the stress-strain curve remains linear. Thereafter, several cracks start to develop in the peec masonry wall samples introducing non-linearity
- (ii) At the ultimate stress level, the maximum compressive strength is achieved. Then, the peec masonry wall samples drop the load and exhibit a sudden increase in strain value.
- (iii) 0.2 of maximum compressive strength is the maximum residual compressive stress and corresponding failure strain observed in the peec masonry wall sample

The results of the stress-strain curves in the figures show that clauses (i), (ii) and (iii) agree with the clauses already established by Kaushik et al. (2007) on brick masonry. Therefore, the elastic region of the masonry wall is between compressive stresses of zero to 0.33 of the maximum compressive stress (point of elastic limit), then the plastic

region begins up to a point 0.2 for the masonry wall. The materials are seen to be fully plastic from the point of maximum compressive strength.

The result of elastic modulus from the stress-strain curves shows that it generally increases with an increase in age. The increase in elastic modulus as the age increases is due to an increase in the elastic region of the material with age, thereby making it more elastic. Therefore, the resistance of the material to failure by fracture or excessive deformation when loaded (stiffness) increases with the age of the samples.

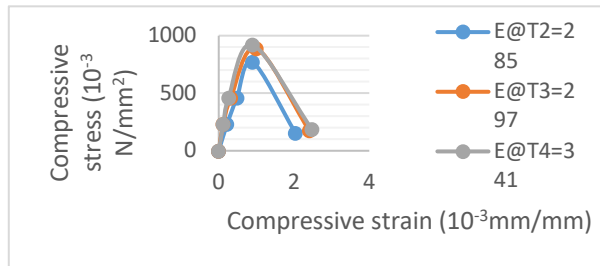


Fig. 4: Stress-Strain Curves for S₂B₁ at 28, 56 & 90 days

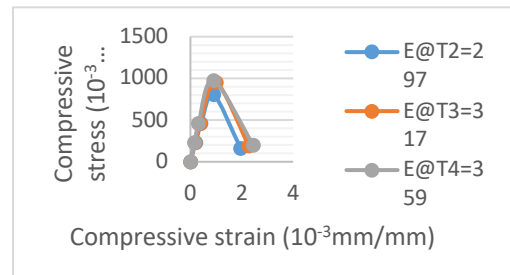


Fig. 5: Stress-strain Curves for S₂B₂ at 28, 56 & 90 days

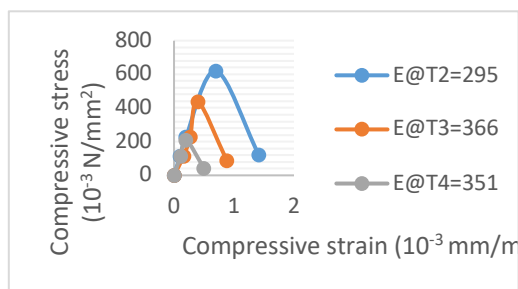


Fig. 6: Stress-strain Curves for S₂B₃ at 28, 56 & 90 days

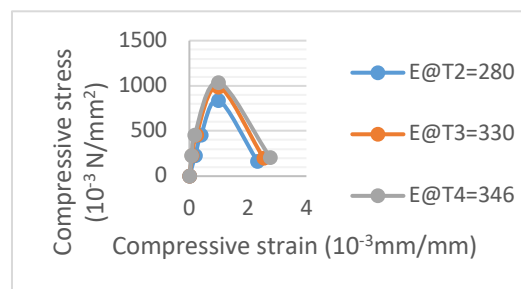


Fig. 7: Stress-strain Curves for S₃B₁ at 28, 56 & 90 days

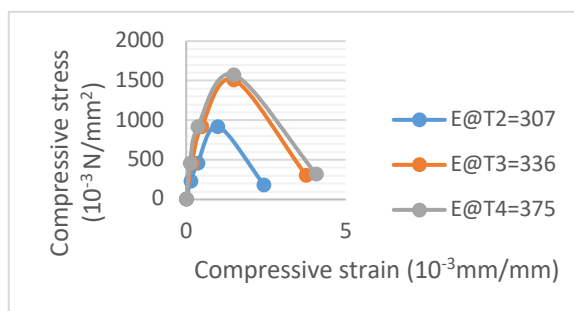


Fig. 8: Stress-strain Curves for S₃B₂ at 28, 56 & 90 days

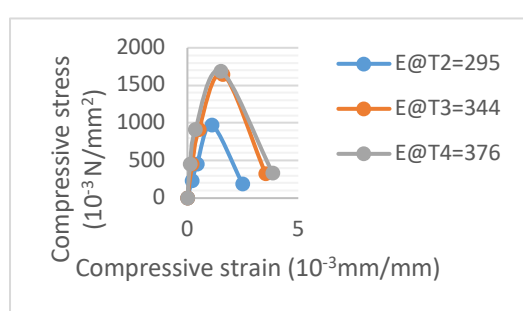


Fig. 9: Stress-strain Curves for S₃B₃ at 28, 56 & 90 days

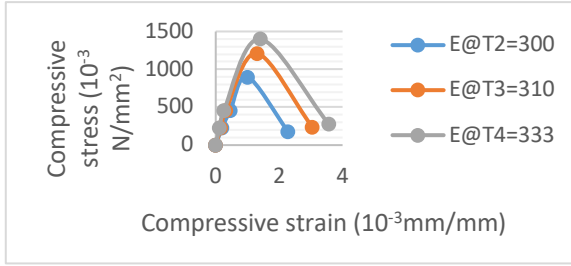


Fig. 10: Stress-strain Curves for S4B1 at 28, 56 & 90 days

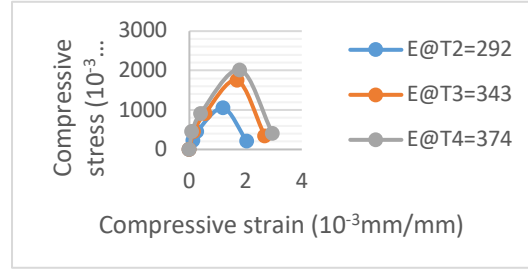


Fig. 11: Stress-strain Curves for S4B2 at 28, 56 & 90 days

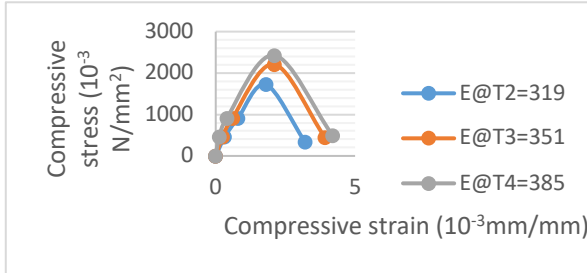


Fig. 12: Stress-strain Curves for S4B3 at 28, 56 & 90 days

5 Conclusion

1. From the experiments, the following factors were highlighted as factors responsible for major cracks and improper bonding between the spherical earth-cobs and poured-earth in the prisms.
 - a. unsuitable diameter of earth-cobs in the samples of prisms
 - b. the unsuitable ratio of the volume of earth-cobs to the volume of poured-earth in the prisms production
 - c. the high suction effect of earth-cobs in the cast prisms
 - d. low water retentivity of the poured-earth against the suction effect of the earth-cobs
 - e. non-availability of gravel size in the laterite
 - f. dryness of surroundings in terms of weather condition
2. The compressive strength for all the peec masonry wall samples shows that only the samples with S4B2 and S4B3 designations accurately meet the 2.0N/mm² load-bearing compressive strength for stabilized rammed earth walls in line with International Building Code (ICC), 2006. S3B1, S3B2 and S3B3 have values ranging from 1.04N/mm² to 1.69N/mm², which fall within the range of non-load bearing wall.
3. The performance limits states established for the peec masonry wall are elastic region, elastic limit, elastoplastic region and plastic region. The performance limits can be used in structural and numerical analyses of peec masonry structures. Therefore, their stress-strain curves conform with the stress-strain curve already established by BS EN 1996-2: 2006 for brick masonries.

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