STRENGTH AND STRESS - STRAIN CHARACTERISTICS OF COIR FIBRE REINFORCED CEMENT STABILISED RAMMED EARTH

R. Sri Bhanupratap Rathod*, B. V. Venkatarama Reddy
Indian Institute of Science, Bangalore, India, 560012
*Corresponding author: email: rathodrsbp@iisc.ac.in

Abstract
Rammed earth is a monolithic construction that involves dynamically compacting processed soil in progressive layers in a rigid formwork. Cement stabilised rammed earth (CSRE) is used for the construction of load bearing walls in buildings. CSRE walls predominantly undergo sudden catastrophic shear failure under compressive loading. Fibre reinforced composites show high ductility under compression and shear avoiding the sudden catastrophic failures of the structural elements. Hence, the present investigation was focused on the behaviour of coir fibre reinforced cement stabilised rammed earth. The influence of fibre volume fraction and moisture content at the time of testing on the strength and stress strain relationships of CSRE were examined and compared. The variables considered include fibre volume fraction, moisture content at the time of testing for a given dry density, cement content and fibre aspect ratio. The strength and stress-strain relationships of CSRE with and without fibres were measured. The results show about 30-40% increase in compressive strength of fibre reinforced CSRE when compared to the unreinforced rammed earth. The stress-strain curves show large energy absorption capacity for fibre reinforced CSRE. The moisture content of the specimen during testing significantly influence the characteristics of fibre reinforced CSRE. Coir fibres can be used for improving the strength and ductility of the rammed earth.

Keywords
Coir; Rammed earth; Ductility; Fibre volume fraction; Cement stabilisation

1 INTRODUCTION

Rammed earth is a monolithic construction that involves compaction of processed soil in progressive layers in a rigid formwork. Two types of rammed earth construction can be identified: unstabilised and stabilised rammed earth. The rammed earth can be stabilised by adding inorganic additives such as cement, lime etc. Generally, about 6-10% of Portland cement is used in the stabilised rammed earth constructions [Reddy 2011]. Load bearing cement stabilised rammed earth (CSRE) walls are used for the construction of multistoried buildings. There is a growing interest in this low carbon building material. Increase in usage of CSRE walls in the buildings can be seen across the world since the last 5-6 decades.

There is a large amount of published literature available on stabilised rammed earth [Jayasinghe 2007, Bui 2009, Reddy 2010, Ciancio 2012, Windstorm 2013, Beckett 2014, Bui 2014, Reddy 2017, Kariyawasam 2016, Raju 2018 and many other publications]. However, there are only limited number of studies focusing on the strength and behaviour of CSRE. A brief summary of the literature on stabilised rammed is as follows. [Reddy 2011b] examined the strength and stress-strain behaviour of CSRE. The studies reveal high failure strains of about 1.5% and the failure pattern showed is shear failure. [Raju 2018] investigated the influence of layer thickness and plasticiser dosage on strength and stress strain behaviour of CSRE. The study reveals shear failure pattern irrespective of the layer thickness.

Historically, the fibres have been used as reinforcement in earthen construction techniques and methods. The natural fibres such as straw were used to reduce shrinkage cracks in traditional form of earth constructions such as adobe and cob [Quagliarini 2010, Millogo 2014, Sharma 2015, Preneron 2016]. Some recent studies show use of fibres to reinforce the compressed earth blocks and the rammed earth [Ghavami 1999, Mesbah 2004, Bouhicha 2005, Danso 2015, Donkor 2015, Segetin 2007, Cheah 2012].

There is hardly any information on the strength and the stress-strain characteristics of fibre reinforced CSRE. However, there are studies on fibre reinforced earthen materials. [Millogo 2014] examined the physical and mechanical properties of fibre reinforced pressed adobe blocks (PAB). Hibiscus cannabinus fibres were used in this study (0.2 - 0.6% by mass). The results show reduction in the pore size in PAB with the addition of fibres and attributing it to be the reason for the improved compressive and flexural strengths of the adobe blocks. [Quagliarini 2010] investigated the influence of straw fibre on the properties of adobe blocks. Different fibre volume fractions (0, 0.25, 0.5 and 0.75%) with average fibre length of 50 mm were used. The reduction in the compressive strength and stiffness of the blocks was indicated. The addition of fibre enhanced the plastic behaviour of the composite and influenced the failure pattern of the adobe specimens by formation of multiple cracks. [Mesbah 2004] studied the characteristics of short sisal fibre reinforced compacted earth blocks. The fibre inclusion resulted in improved post cracking behaviour of the material by inhibiting the crack propagation. [Anggraini 2015] studied the effect of coir fibre addition on the tensile and the compressive strength of the unstabilised and the lime treated soil. The fibre reinforced composite showed considerable strain hardening behaviour and the optimum results with 1% fibre content. [Bouhicha 2005] investigated the physical and mechanical properties of soil reinforced with chopped barley straw. Four different fibre contents (0 - 3.5% by mass) with 3 different fibre lengths were used in the study. The fibre reinforcement showed positive results in reducing shrinkage, enhancing flexural and shear strength. The study shows that the specimens had undergone a more ductile failure compared to unreinforced ones. The literature on unstabilised fibre reinforced earth reveals that the use of fibres can significantly improve the ductility and post cracking behaviour of the earthen materials.

The main objective of the present investigation was to examine the influence of the coir fibre reinforcement on the strength and stress-strain characteristics of CSRE.

2 PROPERTIES OF THE MATERIALS USED

Locally available red soil, manufactured sand, ordinary Portland cement and coir fibre were used in the current investigation. The natural soil had 42% clay (kaolinite) fraction and hence was reconstituted by mixing with sand.

The previous studies on CSRE indicate the optimum clay content to be between 12 - 16% for achieving maximum compressive strength [Reddy 2011a]. Hence, the natural soil was mixed with manufactured sand in 1 (soil): 2 (sand) ratio (by mass). The clay content of the reconstituted mix was 14.8%. The soil grading curve for the reconstituted soil is shown in Fig. 1. The properties of the reconstituted soil mix are given in Tab. 1. Ordinary Portland cement (OPC) conforming to [IS 12269-1987a] was used for casting the specimen.

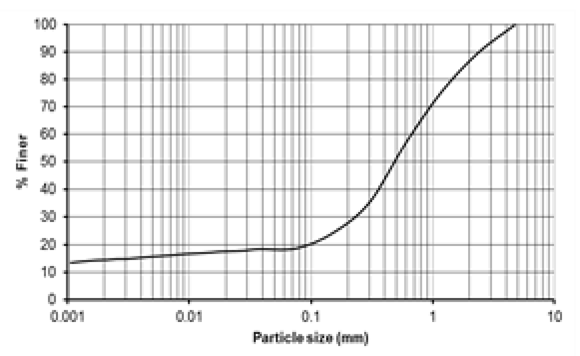

Fig. 1: Grain size distribution curve of the reconstituted soil.

Tab. 1: Properties of reconstituted soil.

Soil property	Details
Textural composition (% by mass)	
Sand (4.75mm - 0.075mm)	81.1
Silt (0.075mm - 0.002mm)	4.1
Clay (0.002mm)	14.8
Atterberg limits	
Liquid limit (%)	26
Plasticity index (%)	11.2
Compaction characteristics (Standard Proctor)	
Maximum dry density (kg/m^3)	2070
Optimum moisture content (%)	9.83

Coir fibres procured from the local market were used.

Tensile strength of the fibres was determined. The results of the tests on the fibres are given in Tab. 2. They represent the mean of 50 experiments. The values in the parenthesis indicate the standard deviation values.

The length of the coir fibres were in the range of 26 to 280 mm. The cross section of the coir fibres were elliptical (or) circular in shape. The dimensions of the cross section was measured using an optical microscope, Leica 2500M. The diameter reported in the Tab. 2 are the equivalent diameter to a circle. The fibres have varying cross section along the gauge length. The high variation in the tensile strength, Young's modulus and strain at failure can be attributed to the variations in the physical dimensions across the length of the fibres. The stress-strain curve resembles a bilinear plot with initial linear portion followed by high plastic zone. The coir fibres show high tensile strength and failure strains of about 107 MPa and 23.9% respectively. The properties of the fibres fall well within the range found in literature [Tomczak 2007, Ramirez 2018]. The fibres show little necking at the fracture.

Tab. 2: The properties of coir fibre.

Lengt h (mm)	Diamete r (mm)	Tensile strengt h (MPa)	Young's modulu s (MPa)	Strain at failur e
26 - 280	0.1 - 0.51	107 (28.67)	2250 (600)	0.239 (0.08)

3 EXPERIMENTAL PROGRAM

The cylindrical specimens with two different fibre volume fractions: 1% and 2% were considered. The CSRE specimens were tested in both wet and dry conditions. The plain CSRE specimens (with zero fibre fraction) were tested for the purposes of comparison. Six specimens were tested in each category for 0 and 1% fibre volume, whereas only 3 specimens were tested in the case of 2% fibre reinforced CSRE specimens. The CSRE specimens had 7% cement (by mass) and a dry density of 1800 kg/m^3.

4 CASTING PROCEDURE

The cylindrical specimens were cast in the metal moulds having inner dimensions, 150 mm diameter and 300 mm height. The reconstituted soil passing through 4.75 mm mesh was used for casting the specimens. The soil was oven dried at 60˚C till the constant weight was achieved and mixed with the dry sand. The required quantity of cement (7%) was added to the soil and then mixed in the dry condition. The requisite quantity of fibres were added to the dry mix and mixed thoroughly. The amount of water added to the dry mix of soil-sand-cement mixture was 1% higher than the standard proctor OMC. The studies of [Reddy 2011a] suggested compaction on the wet side of standard Proctor OMC for CSRE construction to achieve better strength. The water added was corrected for moisture content in the oven dried soil. The coir fibres were chopped to an approximate length of 25 mm i.e. aspect ratio of 125 and used in casting the fibre reinforced CSRE cylinders. Water was sprinkled and the mixing continued till the uniform mixture was achieved. The mixing process was manual. The lumping of fibres was high for 2% fibre volume fraction. The cylinders were cast by compaction using 6.1 kg rammer and the compacted layer thickness was maintained at 100 mm. The mass of the wet mix to be added in each layer was controlled such that the compacted dry density was at 1800 kg/m^3. The moulds were dismantled after 24 hours of casting. The cylinders were kept under burlap and cured for 28 days. The cured cylinders were allowed to dry in air inside the laboratory for two weeks.

Fig. 2: Experimental setup of uniaxial compression test.

1 TESTING PROCEDURE

The cured and air dried specimens were oven dried at 50˚C until constant weight was achieved and then allowed to cool down to ambient temperature before testing. A thin layer of capping was applied with plaster of paris on either faces of the cylinder prior to testing. The experiments were conducted in a displacement-controlled testing machine at a piston displacement rate of 6 µm/s. The vertical strains were recorded using extensometer and strain gauges at the middle one third

5. .

height of the specimen. The gauge length of the extensometer and strain gauge was 100 mm and 60 mm respectively. The Fig. 2 shows the experimental setup for uniaxial compression test. The cylinders tested in oven dry condition give dry strength. For wet strength, the oven dried specimens after allowing to cool inside the laboratory, were soaked in water for 48 hours prior to the testing. The moisture content at the time of the test was measured by collecting samples from the failed specimens and oven drying them at 110˚C for 24 hours.

2 RESULTS AND DISCUSSIONS

The effect of fibre reinforcement on the compressive strength and stress-strain relationships of cement stabilised rammed earth was examined as a function of fibre content and moisture content during testing. The stress-strain relationships for the CSRE specimen are shown in Fig. 3. The strength, modulus and strain values derived from the stress-strain relationships are given in Tab. 3. The Fig. 4 shows a plot of strength, modulus and volume fraction.

6.1 Stress-strain relationships

The stress-strain curves (Fig. 3) show a linear initial portion, followed by nonlinear and drooping portion. Based on the linear fit for the initial portion of the stress-strain curves, the initial tangent modulus was determined for all the cases. The following observations can be made from the stress-strain relationships and the results given in the Tab. 3:

1. The modulus decreases with the increase in volume fraction of the fibres for both the cases of dry and wet conditions. Nearly one-third decrease in the modulus as the fibre volume was increased from 0 to 2% in the dry case. In the wet state there is 25% drop in modulus.
2. The strain at peak stress and the failure strain drastically increase due to inclusion of coir fibre in CSRE. For example in the dry case the strain at peak stress increases by three times (0.0028 to 0.0133) as the fibre fraction increases from 0 to 2%. In the wet case it is about 2.3 times.
3. There is a phenomenol increase in failure strain due to the inclusion of coir fibre. In the dry case the strain at failure increases from 0.008 to 0.035 and in the wet case it increases from 0.006 to 0.06.
4. The moisture content during testing has considerable influence on the modulus as well as failure strains. The CSRE has higher strain values and higher modulus in the dry condition when compared to the values in wet condition.

Tab. 3: Stress-strain characteristics of coir fibre reinforced CSRE.

Volume fraction V_F (%)	Initial tangent modulus (MPa)		Compressive strength (MPa)		Strain at peak stress		Failure strain	
	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
0.0	3250 (350)	2100 (670)	3.79 (0.20)	2.18 (0.10)	0.0028	0.0022	0.008	0.006
1.0	2900 (500)	2000 (570)	5.09 (0.29)	2.48 (0.08)	0.0058	0.0035	0.022	0.035
2.0	2300 (484)	1550 (210)	5.35 (0.51)	2.03 (0.09)	0.0133	0.0073	0.035	0.059

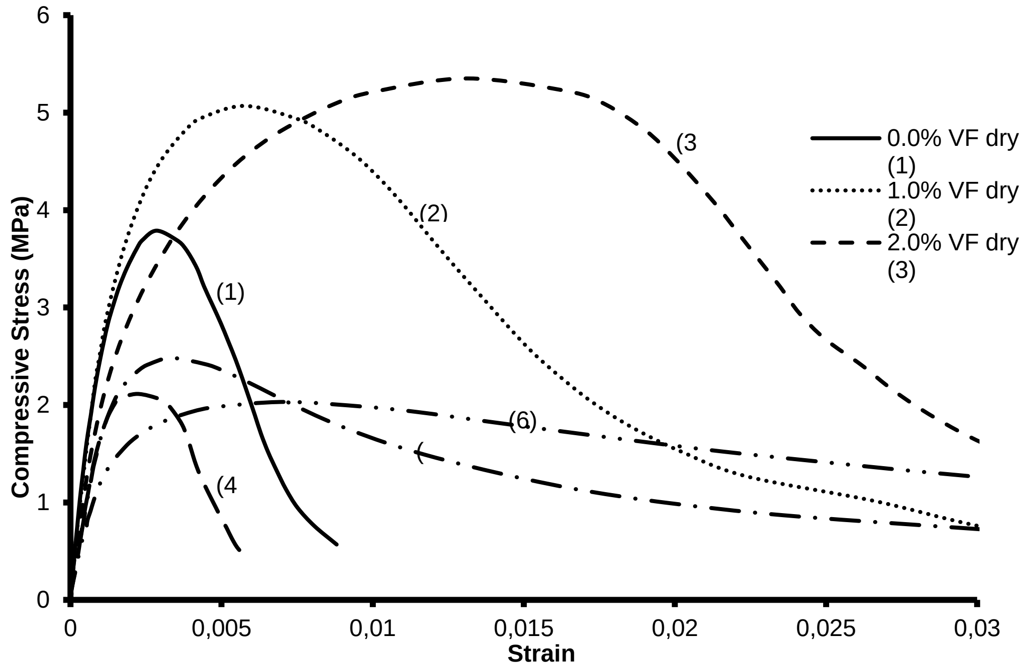

*Fig. 3: Stress-strain relationships for unreinforced and fibre reinforced CSRE.*XXXXXX

6. There is a phenomenol increase in failure strain due to the inclusion of coir fibre. In the dry case the strain at failure increases from 0.008 to 0.035 and in the wet case it increases from 0.006 to 0.06.
7. The moisture content during testing has considerable influence on the modulus as well as failure strains. The CSRE has higher strain values and higher modulus in the dry condition when compared to the values in wet condition.

Inclusion of coir fibre in the CSRE results in imparting ductility to the CSRE matrix. The fibre inclusion has significantly increased the post peak response. The area under the stress-strain curves for fibre reinforced CSRE is much larger when compared to the CSRE without fibres. The strain at peak stress increased with fibre content irrespective of wet and dry condition indicating improved ductility of the composite material.

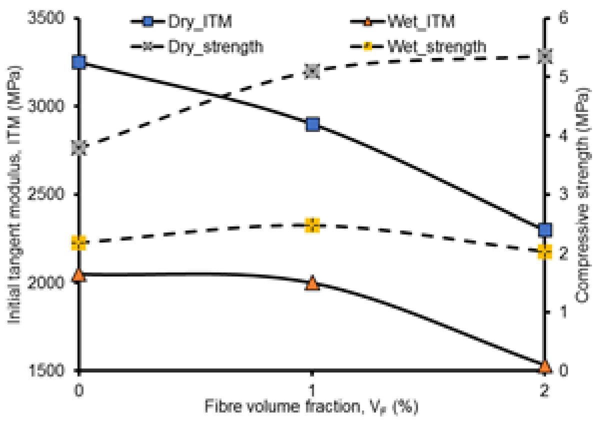

Fig. 4: ITM, compressive strength Vs fibre volume fraction.

6.2 Compressive strength

The compressive strength increases with increase in fibre volume fraction in dry condition. There is 40% increase in compressive strength as V_F changes from 0 to 2% for the dry condition. The compressive strength initially increased by 14% for the wet condition. For 2% V_F, there is a marginal decrease in compressive strength beyond 1% V_F.

The increase in the compressive strength of fibre reinforced CSRE specimens can be attributed to the development of bond strength between the fibre and matrix [Bouhicha 2005, Donkor 2015, Anggraini 2015]. This can also be attributed to reduction in dimension of pore size in the micro structural level [Millogo 2014]. The increase in fibre volume can increase the possibility of more fibres participating in the crack arrest mechanism. At the same time, an additional increase in the fibre content can result in lumping or balling of fibres. Thus weak zones are likely to be developed in the composite. The balling of fibres could be seen in 2% fibre reinforced specimens. In wet condition, the increment in compressive strength is less compared to the dry specimens. This can be attributed to the lower bond strength between the fibre and the matrix in wet state [Tang 2010].

In the case of natural fibre reinforced concrete and cement mortar composites, the compressive strength is not significantly affected, whereas, the tensile strength, flexural strength and toughness are all subtantially increased for optimum values of fibre volume fraction and aspect ratio [ACI 544.1 R-96, Sedan 2008, Filho 2000].

6.3 Failure Patterns

Addition of fibres did not alter the failure pattern of the material i.e. shear failure. Fig. 5a and Fig. 5b shows the typical failure pattern of plain and fibre reinforced specimen. However, the failure has taken place gradually with the formation of multiple finer cracks. The specimens bulge out considerably and the failed specimen remains intact. Sudden and catastrophic failure is avoided. The fibres bridge the cracks and inhibit the crack propagation as shown in the Fig. 6. Both the fibre fracture and the pull out mode of failures could be observed in the crack. Majority of the fibres had undergone pull out failure and the fibres in the internal core of the cylinders experienced fibre fracture in the dry specimens. The nature of fibre pull out mode of failure is gradual, which is responsible for the post crack ductility of the material [ACI 544.1 R-96].

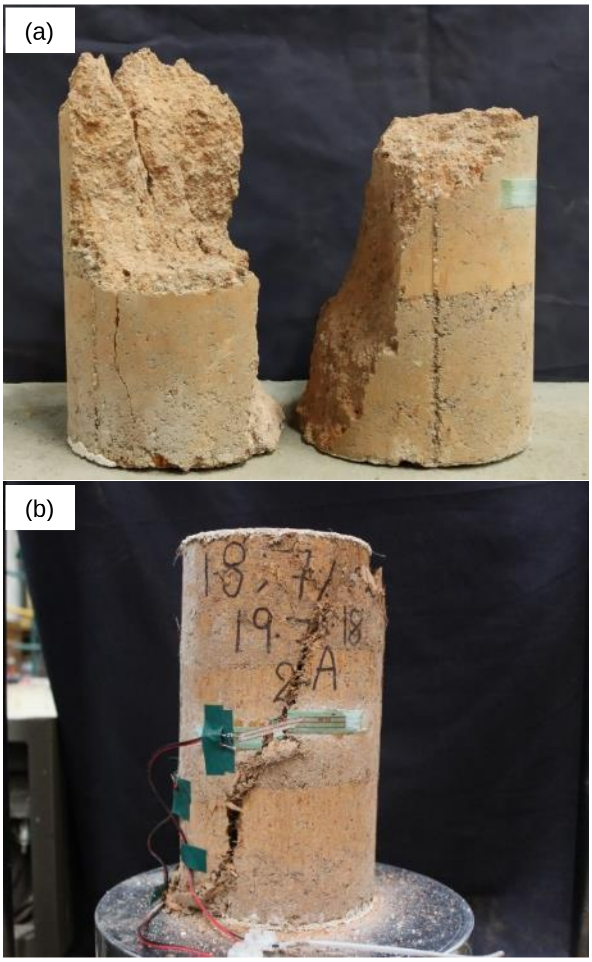

Fig. 5: (a) *Plain CSRE specimen failed into more than one piece. (b) Failure of coir fibre reinforced CSRE specimen.*

Fig. 6: Fibres bridging a crack during compression test.

3 CONCLUSIONS

The study presented experimental results on strength and stress-strain characteristics of plain and coir fibre reinforced cement stabilised rammed earth. Based on the test results and observations made during the experiments, the following remarks could be made:

1. The fibre inclusion improves the post peak response of cement stabilised rammed earth and helps in improving the ductility of the material in both dry and wet conditions. The failure strains as high as 6% were reached in the fibre reinforced CSRE.
2. The modulus of fibre reinforced CSRE decrease with inclusion of fibres in the CSRE.
3. The compressive strength increases upto 1% fibre fraction and beyond which the variation in strength is marginal. Hence, the optimum fibre volume is 1% in this case to achieve maximum strength.
4. The specimens remain intact even after failure with the fibre reinforcement. Thus catastropic shear failure observed in the unreinforced CSRE was eliminated by inclusion of fibres.
5. The moisture content of the specimen during testing has signficant influence on the strength, modulus and failure strains. The CSRE possess higher strength and modulus in dry condition when compared to the wet condition during testing.

There is need for further studies using different cement contents and densities for CSRE.

4 REFERENCES

[ACI 544.1R-96] State of the art report on fiber reinforced concrete. ACI 544.1R-96(2002), American concrete institute, USA.

[Anggraini 2015] Anggraini, V; Asadi, A; Huat, B.B.K; Nahazanan, H; Effects of coir fibers on tensile and compressive strength of lime treated soft soil. Measurement, 2015, 59, 372-381.

[Beckett 2014] Beckett, C; Ciancio, D; Effect of compaction water content on the strength of cement-stabilized rammed earth materials. Canadian geotechnical journal, 2014, 51(5), 583-590.

[Bouhicha 2005] Bouhicha, M; Aouissi, F; Kenai, S; Performance of composite soil reinforced with barley straw. Cement and concrete composites, 2005, 27, 617-621.

[Bui 2009] Bui, Q.B; Morel, J.C; Reddy, B.V.V; Ghayad, W; Durability of rammed earth walls exposed for 20 years to natural weathering. Building and environment, 2009, 44, 912-919.

[Bui 2014] Bui, Q.B; Morel, J.C; Hans, S; Walker, P; Effect of moisture content on the mechanical characteristics of rammed earth. Construction and building materials, 2014, 54, 163-169.

[Ciancio 2012] Ciancio, D; Gibbilngs, J; Experimental investigation on compressive strength of cored and molded cement-stabilized rammed earth samples. Construction and building materials, 2012, 28(1), 294-304.

[Cheah 2012] Cheah, J.S.J; Walker, P; Heath, A; Morgan, T.K.K.B; Evaluating shear test methods for stabilised rammed earth. Proceedings of institution of civil engineers, Construction materials, 165(6), 325-334, ISSN 1747 - 650X.

[Danso 2015] Danso, H; Martinson, D.B; Ali, M; Williams, J; Effect of fiber aspect ratio on mechanical properties of soil building blocks. Construction and building materials, 2015, 83, 314-319.

[Donkor 2015] Donkor, P; Obonyo, E; Earthen construction materials: Assessing the feasibility of improving strength and deformability of compressed earth blocks using polypropylene fibers. Journal of materials and design, 2015, 83, 813-819.

[Filho 2000] Filho, R.D.T; Scrivener, K; England, G.L; Ghavami, K; Durability of alkali - sensitive sisal and coconut fibers in mortar composites. Cement and concrete composites, 2000, 22, 127-143.

[Ghavami 1999] Ghavami, K; Filho, R.D.T; barbosa, N.P; Behaviour of composite soil reinforced with natural fibers. Journal of cement and concrete composites, 1999, 21, 39-48.

[IS 12269-1987a] IS (Bureau of Indian Standards). Specification for 53 grade ordinary Portland cement. IS 12269-1987a, Newdelhi, India.

[Jayasinghe 2007] Jayasinghe, C; Kamaladasa, N; Compressive strength characteristics of cement stabilized rammed earth walls. Construction and building materials, 2007, 21, 1971-1976.

[Kariyawasam 2016] Kariyawasam, K.K.G.K.D; Jayasinghe, C; Cement stabilized rammed earth as a sustainable construction material. Construction and building materials, 2016, 105, 519-527.

[Mesbah 2004] Mesbah, A; Morel, J.C; Walker, P; Ghavami, K; Development of direct tensile test for compacted earth blocks reinforced with natural fibers. Journal of materials in civil engineering, 2004, 16(1), 95-98, ISSN 0899-1561.

[Millogo 2014] Millogo, Y; Morel, J.C; Aubert J.E; Ghavami, K; Experimental analysis of pressed adobe blocks reinforced with hibiscus cannabinus fibers. Construction and building materials, 2014, 52, 71-78.

[Preneron 2016] Preneron, A.L; Aubert, J.E; Magniont, C; Tribout, C et al.; Plant aggregates and fibers in earth construction materials: A review. Construction and building materials, 2016, 11, 719-734.

[Raju 2018] Raju, L; Reddy, B.V.V; Influence of layer thickness and plastizers on characteristics of cement-stabilized rammed earth. Journal of materials in civil engineering, 2018, 30(12), ISSN 0899-1561.

[Ramirez 2018] Ramirez, M.G.L; Anda, R.R; Satyanarayana, K.G; Muniz, G.I.B.D et al.; Comparative study of the characteristics of green and brown coconut fibers for the development of green composites. Bioresources, 13(1), 1637-1660.

[Reddy 2010] Reddy, B.V.V; Kumar, P.P; Embodied energy in cement stabilised rammed earth walls. Journal of energy and buildings, 2010, 42, 380-385.

[Reddy 2011a] Reddy, B.V.V; Kumar, P.P; Cement stabilised rammed earth. Part A: compaction characteristics and physical properties of compacted cement stabilised soils. Material and structures, 2011, 44, 681-693.

[Reddy 2011b] Reddy, B.V.V; Kumar, P.P; Cement stabilised rammed earth. Part B: compressive strength and stress-strain characteristics. Materials and structures, 2011, 44, 695-707.

[Reddy 2011] Reddy, B.V.V; Kumar, P.P; Structural behavior of story-high cement stabilized rammed-earth walls under compression. Journal of materials in civil engineering, 2011, 23(3), 240-247.

[Reddy 2017] Reddy, B.V.V; Suresh, V; Rao, K.S.N; Characteristic compressive strength of cement stabilized rammed earth. Journal of materials in civil engineering, 2017, 29(2), ISSN 0899-1561.

[Sedan 2008] Sedan, D; Pagnoux, C; Smith, A; Chotard, T; Mechanical properties of hemp fiber reinforced cement: influence of fiber matrix interaction. Journal of european ceramic society, 2008, 28, 183-192.

[Segetin 2007] Segetin, M; jayaraman, K; Xu, X; Harakeke reinforcement of soil-cement building materials: manufacturability and properties. Building and environment, 2007, 42, 3066-3079.

[Sharma 2015] Sharma, V; Vinayak, H.K; Marwaha, B.M; Enhancing compressive strength of soil using natural fibers. Construction and building materials, 2015, 93, 943-949.

[Tang 2010] Tang, C.S; Shi, B; Zhao, L.Z; Interfacial shear strength of fiber reinforced soil. Geotextiles and geomembranes, 2010, 28, 54-62.

[Tomczak 2007] Tomczak, F; Sydenstricker, T.H.D; Satyanarayana, K.G; Studies on lignocellulosic fibers of brazil. Part II: morphology and properties of brazilian coconut fibers. Composites part A: applied science and manufacturing, 2007, 37, 1710-1721.

[Windstorm 2013] Windstorm, B; schmidt, A; A report of contemporary rammed earth construction and research in north america. Sustainability, 2013, 5, 400-416.

[Quagliarini 2010] Quagliarini, E; Lenci, S; The influence of natural stabilizers and natural fibers on the mechanical properties of ancient roman adobe bricks. Journal of cultural heritage, 2010, 11, 309-314.