13TH CANADIAN MASONRY SYMPOSIUM
HALIFAX, CANADA
JUNE 4TH – JUNE 7TH 2017

STABILIZED COMPRESSED EARTH BLOCKS FOR SUSTAINABLE CONSTRUCTION ON THE JEMEZ PUEBLO

Trujillo, Nicole[1]; Emiroglu, Mehmet[2]; Bowen, Tom[3]; Stormont, John[4] and Reda Taha, Mahmoud[5]

ABSTRACT

Structures made of earthen materials have a long architectural and cultural heritage in New Mexico and certain regions around the world. Earthen structures, such as those constructed of compressed earth block provide an example of a sustainable building material. In this study, stabilized compressed earth blocks (SCEBs) were produced using local soils for residential construction on the Jemez Pueblo in New Mexico, USA. Two selected local soils were mixed with sand and stabilized with various amounts of Portland cement to make 9 different mixtures which were used to fabricate SCEBs. A variety of laboratory investigations including soils and sand tests, block and wall tests were performed in this study. Compressive and flexural strength tests of the SCEBs were performed for both dry and saturated conditions. Tests to characterize water transport in SCEBs including initial rate of absorption and total absorption were also carried out. Superior performance was achieved for both ambient and saturated conditions with SCEBs that were stabilized with 10% Portland cement. These SCEB assemblies had a suitable interaction with mortar and the SCEB wall assemblies had a favorable structural performance. This study demonstrates SCEBs can provide a sustainable and suitable structural masonry for residential construction in New Mexico.

KEYWORDS: *compressed earth blocks, sustainable masonry, soil cement*

---

[1] Former Graduate Student, Department of Civil Engineering, University of New Mexico, nbtrujillo@unm.edu; Design Engineer, Reid Middleton, San Diego, CA, USA, ntrujillo@reidmiddleton.com

[2] Visiting Scholar, University of New Mexico, Department of Civil Engineering, Albuquerque, New Mexico, USA, memiroglu@unm.edu; Assistant Professor, Duzce University, Technology Faculty, Civil Engineering Department, Duzce, Turkey, mehmetemiroglu@duzce.edu.tr

[3] President, Functional Earth Consulting, LLC, Erie, Colorado, USA, tom@functionalearth.com

[4] Professor, University of New Mexico, Department of Civil Engineering, Albuquerque, New Mexico, USA, jcstorm@unm.edu

[5] Professor and Chair, University of New Mexico, Department of Civil Engineering, Albuquerque, New Mexico, USA, mrtaha@unm.edu

INTRODUCTION

Earthen construction is a form of sustainable architecture. In the construction industry, there has been a persistent need to turn to more sustainable construction solutions. Consequently, many designers and engineers of the built environment are looking to locally resourced materials for construction to reduce energy consumption. Earthen materials have been suggested as one alternative to offer a sustainable construction material [1]. It is estimated that 30-40% of the world population currently live or work in earthen structures [2]. Earthen construction is widely used in New Mexico for producing adobe bricks [3]. Adobe blocks are the most popular and oldest form of earthen construction. Compressed Earth Blocks (CEBs) are a mixture by weight of angular sand aggregate, clayey soil, and water [4]. Stabilized compressed earth blocks (SCEBs) are CEBs with additives such as hydrated lime or Portland cement. The stabilizer aims to reduce the soil plasticity, improve its workability and provide resistance to erosion [1].

OBJECTIVE AND SCOPE

This project aimed to explore SCEB technology as a sustainable high performance adobe solution to satisfy the employment and housing needs of the Jemez Pueblo in New Mexico. The primary objective was to study the effect of varying soil types and clay-to-sand ratios on the resulting block compressive and flexural strength of SCEBs. This led to the development of a systematic engineering method to select the clay source and then the optimum mix proportions for SCEBs. The secondary objective was to evaluate the mechanical behaviors of SCEBs under ambient and saturated conditions. This included compression, shear, and bond behavior of SCEB prisms and the shear strength of SCEB wall panels.

EXPERIMENTAL METHODS

Soil samples obtained from potential borrow sites were tested for particle size distribution, plasticity parameters, and swelling potential. These soils were classified per the Unified Soil Classification System (USCS). A method for down selection of the soils suitable for compressed earth block production was developed. Two selected local soils were mixed with sand to create various clay-to-sand ratios to make 5 different mix ratios which were used to fabricate 7 different SCEBs. Because the structural strength of SCEBs are affected by moisture, compressive strength and flexural strength measurements were conducted under both dry and saturated conditions. Tests of the initial rate of absorption and total absorption were also conducted to characterize water transport in SCEBs. The mechanical and absorption characteristics of SCEBs are correlated to the mix design and the native soil classification. SCEB assemblies, including prisms and wall panels, were constructed with standard type S mortar. The 7-day and 28-day mortar compressive strengths and flowability were determined. The compressive strength, bond strength, and shear strength of prisms made of SCEB units and selected mortar were produced and tested. Finally, 570 mm x 570 mm SCEB wall panels made of the optimum SCEB mixture were tested under in-plane shear using a diagonal compression test.

Soil Testing

The soils were tested for the moisture content, grain size distribution, identification and quantification of fines, plasticity, soil classification, swelling potential and clay mineralogy. The natural moisture content for the soil specimens as received from the site was measured in general accordance with ASTM D2216 [5]. The grain size distribution of the soil samples was determined in accordance with ASTM D422 [6]. Using ASTM D422 [6], the hydrometer and sieve analysis of portion passing the No. 10 sieve was performed to determine the amounts fines in the soil sample. Tests to determine the liquid limit, plastic limit, and the plasticity index of the soil were performed in accordance with ASTM D4318 [7]. The soils were classified according to Table 1 in ASTM D2487 [8] based on the laboratory determination of soil particle-size, liquid limit, and plasticity index. The swelling potential of the soils were determined after being inundated in water using ASTM D4829 [9]. The soils were classified for their potential expansion using the expansion index (EI) according to Table 1 in ASTM D4829 [9]. The test method used to determine the wet and dry density of the soil was performed in accordance with ASTM D1557 [10]. Soils that classify as clay and were used in the SCEBs were evaluated using X-ray diffraction (XRD) analysis to identify the dominant clay minerals in these soils.

Block Production and Testing

The device used for SCEB production was a two-stage horizontal hydraulic compression machine. The SCEB soil mix was gravity fed into a mold which was then compressed horizontally first at a pressure of approximately 13.8 MPa and then at a pressure of 6.9 MPa. The blocks were field produced at a rate of 5 to 6 blocks per minute. The full size SCEB blocks were 35.6 cm x 25.4 cm x 10.2 cm. Once compressed, the blocks were palletized and wrapped with shrink-wrap and allowed to cure for 28 days at a temperature of 25°C and ambient relative humidity of 20%.

SCEBs were tested to determine dry and saturated compressive strength, dry and saturated flexural strength, water absorption, the initial rate of absorption, and modulus of elasticity. The New Mexico (NM) Earthen Building Materials Code [11] was used for determining minimum strength requirements. The dry and saturated unconfined compressive strength was determined for the SCEBs following ASTM C67 [12]. For the unconfined compression test, full size SCEB blocks, 35.6 cm x 25.4 cm x 10.2 cm were cut with a brick saw into half blocks. Five samples of each of the blocks were tested. For the saturated unconfined compressive strength test, the SCEBs were placed in a container filled with distilled water and saturated for 24 hours then tested according to ASTM C67 [12].

The modulus of rupture quantifies a SCEBs ability to resist flexural stress. The dry and saturated modulus of rupture were determined. The flexural strength of the SCEBs were determined in general accordance with the ASTM C67 [12]. For the dry modulus of rupture test, the full size SCEBs, 35.6 cm x 25.4 cm x 10.2 cm were used. Five samples of each of the blocks were tested. For the saturated modulus of rupture test, the full size SCEBs were placed in a container filled with distilled water and saturated for 24 hours at room temperature. After being saturated for 24 hours, the full size SCEBs were tested according to ASTM C67 [12].

For the absorption test, half-block specimens, 35.6 cm x 12.7 cm x 10.2 cm were used. Five samples of each of the blocks were tested following ASTM C67 [12]. For the initial rate of absorption (IRA) test, full size SCEB blocks, 35.6 cm x 25.4 cm x 10.2 cm were used following ASTM C67 [12]. The apparent density of each block specimen was determined by measuring three 50 mm x 50 mm x 50 mm samples of each block. The specimens were placed in an oven at 110°C for 24 hours, allowed to cool for at least 4 hours and then weighed. The specimens were then placed in a 400 mL beaker filled with 150 mL of distilled water. The displaced water volume was measured and used to calculate the apparent density.

Prism Construction and Testing

In order to understand the interaction of the block and mortar joint, prisms were constructed and tested for prism compression and shear strength. ASTM C270 [13] was used as a guide for choosing the mortar for use in the prisms. Type S mortar was used for all prism construction. The workability or flow of the mortar was determined using ASTM C1437 [14]. Prism compressive strength was determined using ASTM C1314 [15]. The shear strength of SCEB prisms was determined in accordance with British Standards, BS EN 1052-3 [16]. Procedure A from BS EN 1052-3 [16] was used to determine the shear strength of the prisms.

Wall Construction and Testing

Twenty-seven, 17.8 cm x 12.7 cm x 5.1 cm blocks cut from SCEBs were used to construct one wall panel. Four 570 mm x 570 mm x 127 mm wall panels were constructed using Type S mortar. The wall panels were placed in a loading shoe at the top and bottom of the wallet and tested under diagonal compression following ASTM E519 [17] as shown in Figure 1.

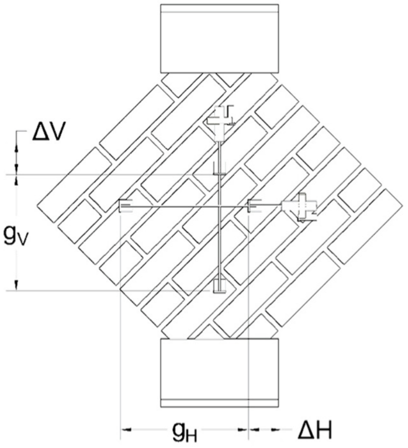

Figure 1: Schematic of wall panel showing loading and displacement measurement.

The shear stress (S_s) was calculated using Equation 1 by dividing the applied load (P), which was the maximum load applied to the wall, by the net area (A_n) of the wall. The vertical shortening (ΔV), the vertical gage length (g_v), the horizontal extension (ΔH), and the horizontal gage length (g_h) were used for calculating the shear strain as presented in Equation 2. The shear stress and strain was used to calculate the modulus of rigidity (G) as per Equation 3.

$$S_S = \frac{0.707P}{A_n} \tag{1}$$

$$\gamma = \frac{\Delta V}{g_v} + \frac{\Delta H}{g_H} \tag{2}$$

$$G = \frac{S_S}{\gamma} \tag{3}$$

RESULTS AND DISCUSSION

The results of soil testing are presented in Table 1. Clay 1 and 2 had more than 50% fines, and was classified as a fat clay (CH) based on their plasticity parameters. SCEBs made with Clay 1 and Clay 2 needed to be stabilized with at least 6% cement to produce a SCEB that met minimum strength requirements for the NM Earthen Building Materials Code [11]. In addition, the swelling potential of the soil as defined by the expansion index (EI) indicated the degree to which soils would expand when exposed to water. Clay 2 had an EI of 152 which is very high. In addition, a clay(ey) soil with a high EI (>130) needs to be mixed with high cement (at least 10%) to produce a SCEB that met minimum strength requirements for the NM Earthen Building Materials Code [11]. The predominant clay mineral found in the two clay(ey) soils obtained from the sourced soils for SCEB production was Kaolinite. Kaolinite is a nonexpandable clay mineral, meaning it will expand slightly in the presence of water. In determining the swelling potential of the clay(ey) soils, Clay 1 had a "very low" expansion index while Clay 2 had a "very high" expansion index. The XRD spectrographs of both clay(ey) soils showing the difference in their mineralogy is shown in Figure 2. The soil property criteria, namely the Plasticity Index (PI) and sand content recommended in this research can be compared to the results published by Burroughs [18] indicating that PI falls within the "fair" range with a 93% stabilization success.

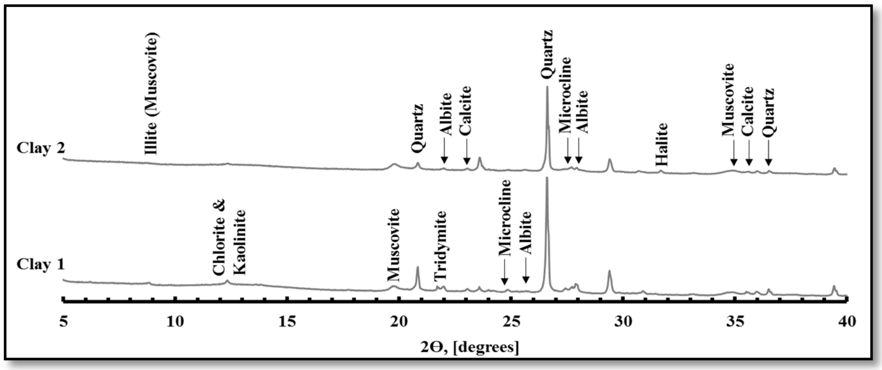

Figure 2: XRD spectrographs for two clay(ey) soils showing their difference in mineralogy.

Table 1: Soil Characteristics

Property	Clay 1	Clay 2	Sand 1	Sand 2	Soil 1	Soil 2
Grading						
Gravel (>2mm) (%)	0.14	0.48	20.86	11.90	0.08	5.98
Sand (<2mm/>0.075mm) (%)	11.40	16.34	78.02	86.16	56.40	44.06
Fines (<0.075mm) (%)	88.46	83.18	1.12	1.94	43.52	49.96
Atterberg Limits						
Liquid Limit	50	72	-	-	35	53
Plasticity Index	29	40	NP	NP	18	28
Soil Classification (based on USCS methodology from ASTM D 2487)						
Soil Classification	CH	CH	SP	SW	SC	SC
Swelling Potential						
Expansion Index (EI)	2	152	-	-	0	21
EI Classification	Very Low	Very High	-	-	Very Low	Low
Modified Proctor A Results						
Dry Density (kN/m^3)	17.8	17.2	18.2	18.6	17.5	19.1
Optimum Moisture Content (%)	16.8	17.0	8.4	9.3	11.8	13.0
XRD Spectra (Clay Mineral Identification)						
Predominant Clay Mineral	Kaolinite	Kaolinite	-	-	-	-

SCEB Mechanical Properties

Seven types of SCEBs were produced and their mechanical properties were tested. The mix designs for the seven SCEBs are presented in Table 2.

Table 2: SCEB Specimen Identification and Mixture Design.

SCEB ID	Clay:Sand Ratio (by Volume)	Stabilizer	Clay Soil Type ID	Sand Soil Type ID
SCEB 1	1:1	1% Lime	Clay 1	Sand 1
SCEB 2	3:2	4% Lime	Clay 1	Sand 1
SCEB 3	3:2	5% Cement	Clay 1	Sand 1
SCEB 4	3:2	6% Cement	Clay 1	Sand 1
SCEB 5	2:3	6% Cement	Clay 2	Sand 2
SCEB 6	1:1	6% Cement	Clay 2	Sand 2
SCEB 7	2:1	10% Cement	Clay 2	Sand 2

It should be noted the large increase in stabilizer from 6% Type II Portland cement in SCEB 6 to 10% Type II Portland cement in SCEB 7. The reason for the increase was due to the significant variability of the soil within each site and the need to produce a robust mix that can be used for construction by the Jemez Pueblo residents. A "robust" SCEB soil mixture would be able to take into account the soil variability and do not result in significant variability in the SCEB. The results of the mechanical characteristics of SCEBs are listed in Table 3. The absorption and density measurements of SCEBs are presented in Table 4. It should be noted that SCEB 1, 2, 3, 5, and 6 did not withstand the 24-hour saturation testing. The saturated unconfined compressive strength was compared with NM Earthen Building Materials Code [11] minimum saturated compressive strength of 2.1 MPa. SCEB 4 and 7 meet the minimum saturated compressive strength. The saturated flexural strength was compared with the NM Earthen Building Materials Code [11] which requires a strength of 0.35 MPa. SCEB 4 and 7 meet the minimum flexural strength.

Table 3: SCEB Compressive and Flexural Strengths and Modulus of Elasticity Results

Specimen ID	Dry compressive strength (MPa)		Wet compressive strength (MPa)		Modulus of Elasticity (MPa)	Dry Modulus of Rupture (MPa)		Wet Modulus of Rupture (MPa)	
	Average	CV (%)	Average	CV (%)		Average	CV (%)	Average	CV (%)
SCEB 1	5.6	16	-	-	-	0.30	12	-	
SCEB 2	3.8	13	-	-	-	0.17	28	-	
SCEB 3	10.1	15	1.15	34	-	0.48	13	-	
SCEB 4	11.9	18	2.19	17	-	0.93	17	0.43	8
SCEB 5	6.9	8	-	-	909	0.18	28	-	-
SCEB 6	6.1	16	-	-	816	0.13	64	0.75	11
SCEB 7	8.8	7	7.43	17	1275	0.91	28	0.23	52

Table 4: SCEB Absorption, Initial rate of absorption (IRA) and Apparent Density Results

Specimen ID	Absorption (%)		IRA (g/min/cm^2)		Apparent Block Density (kg/m^3)	
	Average	CV (%)	Average	CV (%)	Average	CV (%)
SCEB 1	-	-	-	-	2003	3
SCEB 2	-	-	-	-	1987	3
SCEB 3	-	-	6987	137	1976	1
SCEB 4	9.4	29	8652	61	2168	2
SCEB 5	-	-	18,620	13	2277	4
SCEB 6	-	-	18, 310	14	2124	2
SCEB 7	8.5	27	7955	13	2063	1

The mechanical and absorption characteristics of SCEB 4 and 7 were correlated to the mix design and the native soil classification. SCEB 4 had the maximum measured dry compressive strength of 11.9 MPa, which is 30% greater than the SCEB 7. SCEB 4 obtained a higher compressive strength than SCEB 7 even though SCEB 7 had 50% percent more Portland cement stabilizer than SCEB 4. Yet, SCEB 4 had a saturated compressive strength 3.3 times lower than SCEB 7. SCEB 4 had a dry modulus of rupture 2% greater than SCEB 7. SCEB 4 had a saturated flexural strength 54% lower than SCEB 7. SCEB 4 had about 50% higher Quartz and Kaolinite mineral content than SCEB 7. While SCEB 7 had higher Muscovite (Illite) mineral content than SCEB 4. Therefore, the difference in compressive and flexural strengths of SCEB 4 and SCEB 7 may be because of the difference in mineral content. SCEB 1, 2, 3, 5, and 6 did not withstand the 24-hour saturation test. SCEB 4 absorbed 10% more water during the 24-hour saturation test than SCEB 7. SCEB 1 and 2 did not withstand the IRA testing. SCEB 3 had the lowest IRA. SCEB 4 obtained an IRA 8% higher than SCEB 7. SCEB 1, 2, 3, 4, 5, 6, and 7 were tested to determine the apparent block density. SCEB 4 obtained an apparent density 5% higher than SCEB 7. The above testing suggested that SCEB 4 and SCEB 7 can be used for further testing of SCEB assemblies.

SCEB Assemblies Mechanical Properties

The flowability and compressive strength of type S mortar was measured and are presented in Table 5. The compressive strength of prisms produced using SCEB 4 and 7 and type S mortar are shown in Table 6. SCEB 7 prisms measured an average compressive strength 13% lower than SCEB 4. Flexural bond strength and shear strength of masonry prism was determined for SCEB 7 only and is shown in Table 6. SCEB 7 obtained a bond flexural strength of 49 kPa and a shear bond shear strength of 258 kPa. A clay fired brick masonry with a similar mortar mix obtained a bond strength of 460 kPa [19]. SCEB 7 obtained a bond strength 9 times less than brick masonry.

Table 5: Type S Mortar Average Compressive Strength and Flowability Results

7 day strength (MPa)	28 day strength (MPa)	Flowability (%)
20.4	24.2	84

Table 6: Prism Testing Results

Specimen ID	Compressive Strength (MPa)		Bond Strength (kPa)		Shear Strength (kPa)	
	Average	CV (%)	Average	CV (%)	Average	CV (%)
SCEB 4	4.8	8	-	-	-	-
SCEB 7	4.2	22	49	60	258	38

The diagonal compression test results of SCEB 7 are presented in Table 7. The vertical and horizontal displacements were measured on SCEB 7 in order to calculate the shear strain and determine the modulus of rigidity. The results for the diagonal compression tests of SCEB wallets are compared with the earth block masonry results of a 500 x 500 x 110 mm^3 wall from Miccoli et al. [2]. The shear strength of the earth block masonry wall was 0.09 MPa, which is 50% lower than SCEB 7.

Table 7: SCEB 7 Wall Panel Results of Diagonal Compression Testing

Parameter	Results
Max Force (kN)	13.7
Max Displacement (mm)	8.7
Shear Stress (MPa)	0.15
Shear Strain (mm/mm)	0.03
Modulus of Rigidity (MPa)	4.8

Figure 2 shows the crack patterns on the front face of the wall using SCEB 7 blocks under diagonal compression. It can be observed that most of the cracks are mortar joint cracks confirming the ability of SCEBs to resist the diagonal load. The cracking pattern of SCEB walls is very similar to that observed in clay fired masonry brickwork walls [20]. It is apparent that the SCEBs produced using native clayey soil of Jemez Pueblo and stabilized using 10% Portland cement by weight is a robust mixture with sufficient strength and volume stability and can be used to produce structural walls. As can be observed in Figure 3 that failure mode for SCEB 7 wall is a combination of bond slip between mortar joints and blocks, and diagonal tension through the blocks. Load vs displacement and stress vs strain graphs were given in Figure 4.

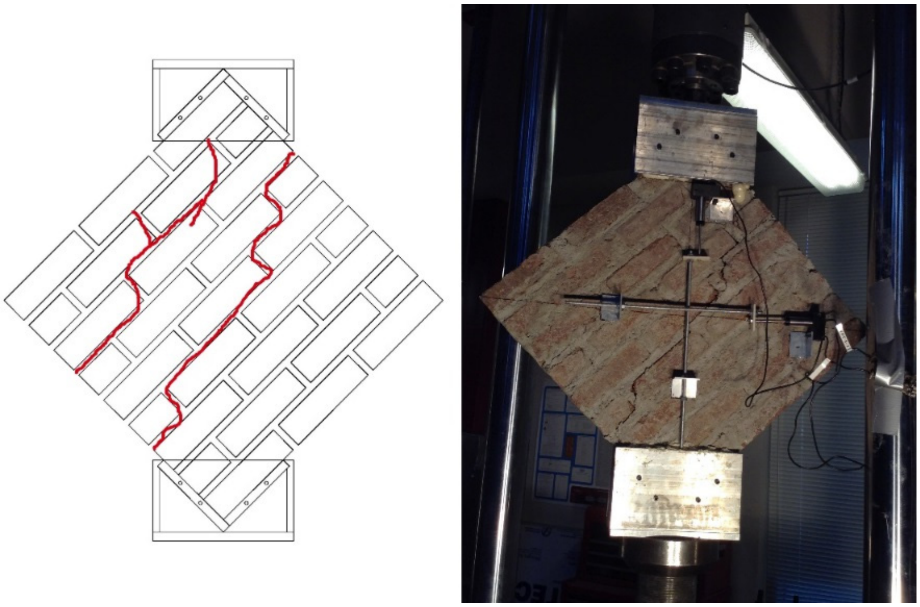

Figure 3: Behavior of masonry wall produced using SCEB 7 blocks under diagonal compression. Crack patterns show classical failure through mortar joint.

Post-peak behaviour of the load-displacement curve is proof of ductility of the SCEB (Fig. 3). Carrying capacity of the walls is still on increase despite shear cracks gently increase. After diagonal compressive test mean shear stress is obtained as 0.12 MPa in this study. Similar results reported by Silva et al. based on the diagonal shear test that operated on rammed earth walls. They obtained 0.14 MPa and 0.18 MPa shear stress values of different rammed earth walls produced with activation of fly ash [21]. It is typical in the diagonal compression test to observe more than one yield point due to sudden releases under load. This is because the insufficient bond between blocks and joint mortar [2, 22]. It is clear from Figure 2 that zigzag crack pattern was observed because of sudden release of the loading.

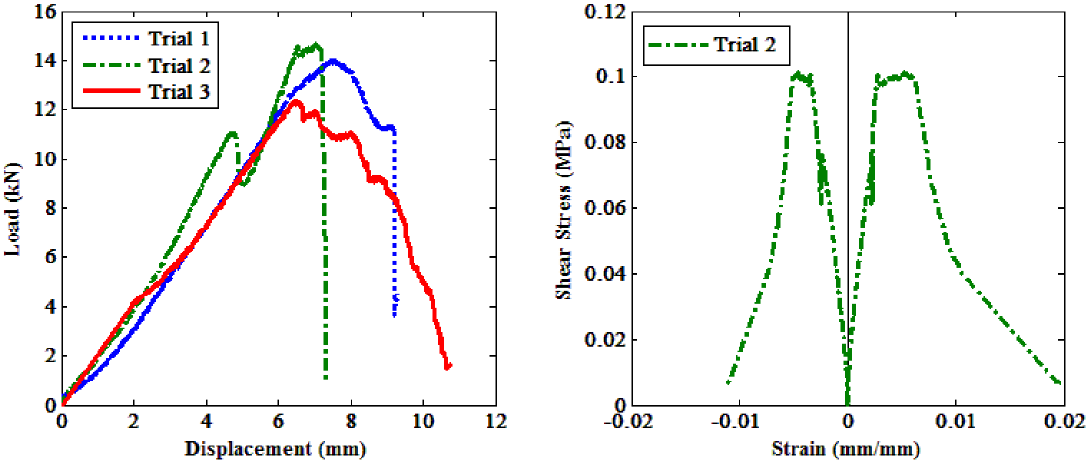

Figure 4. Load vs displacement and stress vs strain curves of SCEB 7 wall specimen.

CONCLUSIONS

SCEBs can provide a sustainable building material that meets strength criteria from the NM Earthen Building Materials Code. This investigation demonstrated that the SCEBs produced using clayey soil from Jemez Pueblo and stabilized using 10% Portland cement by weight met the strength and water absorption criteria and are suitable for use in residential construction for the Jemez Pueblo in New Mexico. The mechanical properties of specimen SCEB 7 indicated it as the optimum soil mixture. The prism compressive strength, bond strength and shear strength of SCEB 7 and Type S mortar had adequate performance. The diagonal compression test of masonry wall produced using SCEBs and type S mortar confirmed that the shear strength and ductility of SCEB 7 walls are comparable or improved compared to other earthen materials and are comparable to traditional clay fired masonry.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial support by the Jemez Community Development Corporation. The authors are indebted to the valuable field support by Mr. George Shendo and his crew at the Jemez Pueblo. We also like to acknowledge Dr. Eric Peterson at the UNM Earth and Planetary Sciences for the XRD analysis of the results presented in this paper.

REFERENCES

[1] Pacheco-Torgal, F. and Jalali S. (2012). “Earth construction: Lessons from the past for future eco-efficient construction.” *Construction and Building Materials*, 29, 512-519.

[2] Miccoli, L. Muller, U. & Fontanta, P. (2014). “Mechanical behavior of earthen materials: A comparison between earth block masonry, rammed earth and cob.” *Construction and Building Materials*, 61, 327-339.

[3] Smith, E.W. and Austin, G. S. (1996). *Adobe, pressed-earth, and rammed-earth industries in New Mexico (revised edition)*, New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico.

[4] Allen, G.T.R. (2012). Strength Properties of Stabilized Compressed Earth Blocks with Varying Soil Compositions (Master's thesis).

[5] ASTM D2216-10. (2010). *Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass*, ASTM International, West Conshohocken, PA.

[6] ASTM D422-63. (2007). *Standard Test Method for Particle-Size Analysis of Soils*, ASTM International, West Conshohocken, PA.

[7] ASTM D4318-10. (2010). *Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils*, ASTM International, West Conshohocken, PA.

[8] ASTM D2487-11. (2011). *Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)*, ASTM International, West Conshohocken, PA.

[9] ASTM D4829-11. (2011). *Standard Test Method for Expansion Index of Soils*, ASTM International, West Conshohocken, PA.

[10] ASTM D1557-12. (2012). *Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft3 (2,700 kN-m/m3)*, ASTM International, West Conshohocken, PA.

[11] NMAC. (2009). *New Mexico Earthen Building Materials Code*, *Title 14. Chapter 7. Part 4. Section 23*, New Mexico Administrative Code, NM.

[12] ASTM C67-12. (2012). *Standard Test Methods for Sampling and Testing Brick and Structural Clay Tile*, ASTM International, West Conshohocken, PA.

[13] ASTM C270-14. (2014). *Standard Specification for Mortar for Unit Masonry*, ASTM International, West Conshohocken, PA.

[14] ASTM C1437-13. (2013). *Standard Test Method for Flow of Hydraulic Cement Mortar*, ASTM International, West Conshohocken, PA.

[15] ASTM C1314-14. (2014). *Standard Test Method for Compressive Strength of Masonry Prisms*, ASTM International, West Conshohocken, PA.

[16] BS EN 1052-3. (2002). *Methods of Test for Masonry: Part 3: Determination of Initial Shear Strength*. London: British Standards Institution.

[17] ASTM E519/E519M-10. (2010). *Standard Test Method for Diagonal Tension (Shear) in Masonry Assemblages*, ASTM International, West Conshohocken, PA.

[18] Burroughs, S. (2008). Soil Property Criteria for Rammed Earth Stabilization. *Journal of Materials in Civil Engineering*, 20(3), 264-273.

[19] Reda, M. & Shrive, N. (2000). "Enhancing Masonry Bond Using Fly Ash*." Masonry International*, 14(1), 9-17.

[20] Ali, Q. Badrashi, Y. Ahmad, N. Alam, B. Rehman, S. & Shah Banora, F.A. (2012). "Experimental Investigation on the Characterization of Soil Clay Brick Masonry for Lateral Shear Evaluation." *International Journal of Earth Sciences and Engineering*, 5(4), 782-791.

[21] Silva, R. A., Oliveira, D. V., Miranda, T., Cristelo, N., Escobar, M. C., & Soares, E. (2013). "Rammed earth construction with granitic residual soils: The case study of northern Portugal." *Construction and Building Materials*, 47, 181-191.

[22] Malyszko, L. (2004). "In-plane shear and tensile strength tests of small brickwork specimens." *Proceedings of Structural Analysis of Historical Constructions*, 291-298.