Properties of Compressed and Stabilized Earth Blocks Produced with Recycled Soil Mixes

Nitin Kumar

Ph.D. scholar, Department of Civil & Environmental Engineering, University of California Davis, USA
ntnkumar@ucdavis.edu

Michele Barbato

Professor, Department of Civil & Environmental Engineering, University of California Davis, USA
mbarbato@ucdavis.edu

Abstract

This study investigates the use of recycled soil obtained by crushing earth blocks as replacement of natural soil in the production of the compressed and stabilized earth blocks (CSEBs). An experimental campaign was conducted to assess the behavior of CSEBs produced using different levels of recycled soil. The prototype CSEB (referred to as N-CSEB) was manufactured by compacting a mixture of natural soil, water, and 12% (by weight) Type-II ordinary Portland cement using a manually-operated compression machine. After determining the properties of the N-CSEBs, these blocks were crushed to obtained recycled soil by using a mechanical pulverizer machine. Recycled CSEBs (R-CSEBs) were fabricated by substituting the natural soil with 25%, 50%, 75%, and 100% (by weight) of recycled soil and by adding 12% cement. R-CSEBs were examined by measuring their compressive and flexure strength, mass loss after 12 wetting/drying cycles, dry density, and water absorption. Scanning electron microscopy images were used to study the CSEB's surface topography, and energy-dispersive X-ray spectroscopy data were used to gain quantitative information on their chemical composition. One-way analysis of variance was employed to determine the statistical significance of the obtained experimental results. The results indicate that the use of the recycled soil (crushed earth blocks) improves the mechanical properties of the CSEBs while a constant proportion of cement is added to the mix.

Introduction

Compressed and stabilized earth blocks (CSEB) structural systems are becoming popular due to their low cost, low carbon footprint, use of indigenous materials, and inherent simplicity when compared to other traditional construction typologies, e.g., reinforced concrete, fired brick masonry, and wood construction [1]-[4]. Well-built CSEB structures are typically very durable, with buildings surviving even hundreds of years [5]. However, even these buildings have a finite design life, sometimes controlled by changes of use more than by structural safety considerations. The proper quantification of this type of construction's sustainability requires a cradle-to-grave life cycle assessment that includes the environmental effects of the construction waste after demolition. In particular, it is important to identify beneficial uses for this waste. However, there is a knowledge gap on potential uses of demolition waste of CSEB construction [3].

This study investigates the recycling of CSEB demolition debris as partial or total replacement of natural soil when fabricating new CSEBs, to address the need for disposing of earthen construction debris [3]. This paper presents the results of an experimental investigation of mechanical and durability properties of CSEBs fabricated by using a recycled soil-cement mix obtained by crushing CSEBs as a partial or total replacement of natural soil.

Materials and Methods

The experimental campaign included the preparation of a total of 48 CSEB specimens: 24 ordinary CSEBs (i.e., fabricated using natural soil and labeled as N-100), and 24 recycled CSEBs (i.e., fabricated using a combination of natural soil and soil-cement mix recycled from ordinary CSEBs), as shown in **Table 1**. The recycled CSEB specimens were fabricated in four groups of six specimens each, corresponding to the replacement of natural soil with 25%, 50%, 75%, and 100% in weight of recycled soil-cement mix (referred to as R-25, R-50, R-75, and R-100, respectively). The natural soil was collected in East Baton Rouge Parish, Louisiana, by extracting soil from the layer between 1 m and 2 m below the ground surface to minimize inconsistency and inorganic content. Standard laboratory tests were performed to determine different physical properties of the soil (i.e., particle size distribution, Atterberg limits, and compaction characteristics), the results of which are presented in **Table 2**. The results indicate that the natural soil had a high content of fines (i.e., the sum of the clay and silt content was approximately 89%), and, thus, the composition of the soil was sub-optimal for the fabrication of CSEBs [4].

Specimen I.D.	Number of CSEBs	Mix composition (%)			Number of specimens tested in		
		Natural soil	Cement	Recycled soil-cement	Flexure	Compression*	Durability*
N-100	24	89.29	10.71	0.00	24	24	24
R-25	6	66.96	10.71	22.32	6	6	6
R-50	6	44.64	10.71	44.64	6	6	6
R-75	6	22.32	10.71	66.96	6	6	6
R-100	6	0.00	10.71	89.29	6	6	6

*Tests performed using half-block specimens.

Table 1. Details of experimental campaign.

The ordinary CSEBs were manufactured by compacting a mixture of natural soil, Type-II ordinary Portland cement (12% by weight of the natural soil) and water (23.42% by weight of the dry mix). After testing the N-100 specimens, the damaged ordinary CSEBs were crushed to obtain the recycled soil-cement mix by using a BICO UA V-Belt Driven pulverizer. The recycled CSEB specimens were fabricated by first combining the same natural soil used for the N-100 specimens with the recycled soil-cement mix, then by adding cement (12% by weight of the combined soil and recycled soil-cement mix) and water (23.42% by weight of the dry material), as shown in **Table 1**. All CSEB had nominal dimensions of 290 × 145 × 75 mm^3 and were manufactured using a single-stroke manual one-side compaction machine [4].

Properties	Values
Particle size distribution via sieve and sedimentation analysis (ASTM D6913-04 and D7928-16)	
Gravel (>2 mm) (%)	<1.00
Sand (2–0.063 mm) (%)	10.00
Silt (0.063–0.002 mm) (%)	58.00
Clay (<0.002 mm) (%)	31.00
Atterberg limits (ASTM D4318-10)	
Liquid limit LL (%)	35.47
Plastic limit PL (%)	22.94
Plasticity index PI (%)	12.53
Compaction based on proctor test (ASTM D698-12)	
Optimum moisture content (%)	23.42
Maximum dry density (Mg/m3)	1.57
Specific gravity	2.59

Table 2. Properties of the natural soil.

All CSEB specimens were first subjected to a standard three-point flexure test after 24 hours of water immersion [6]. The displacement was applied in the middle of the block, with a distance between edge and support equal to 20 mm and a clear span equal to 250 mm. The flexure test resulted in the formation of a well-defined large crack approximately in the middle of the CSEBs, as shown in **Figure 1(a)**. The two parts of the damaged specimens were then separated and trimmed using masonry cutting tools to produce two smaller (half-block) specimens of dimension 100 x 100 x 75 mm^3. The half-block specimens obtained for each group of CSEBs were divided into two subgroups of specimens, one from each of the original CSEBs (see **Table 1**). The specimens of the first subgroup were subjected to a direct compression test [7] after 24 hours of water immersion, whereas the remaining specimens of the second subgroup were subjected to a wetting/drying durability test. Both three-point flexure and direct compression tests were performed using displacement control via an MTS universal testing machine with a 50 kN load cell capacity. Polytetrafluoroethylene sheets were placed between the test specimens and the steel plates of the equipment during the compression test to minimize the confinement effects due to friction, as shown in **Figure 1(b)**. The wetting/drying durability tests were performed following ASTM D559-03 standards.

One-way analysis of variance (ANOVA) was performed on both mechanical and durability experimental results in order to determine the statistical significance of the obtained experimental data [8]. A Quanta™ 3D Dual Beam™ FEG FIB-SEM, with EDAX Pegasus EDS/EBSD detectors, was utilized to evaluate the CSEB morphology and chemical composition via Scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS), respectively. The EDS was used to collect spectra via area mode with a 20kV accelerating voltage and a 4pA current.

Results and Discussion

Mechanical Properties. The results of the mechanical strength tests are reported in **Table 3** in terms of sample means and coefficients of variation (COV) of the modulus of rupture (MOR), wet compressive strength (f_{bw}), and modulus of elasticity (MOE). As expected, the mean values of MOR, $f_{bw,}$ and MOE increase for increasing amount of recycled soil-cement mix (with increments ranging from 68%

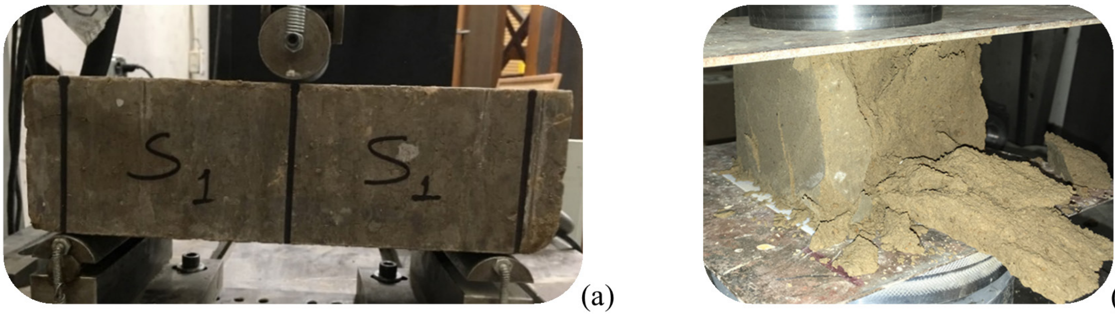

Figure 1. Mechanical tests: (a) specimen after flexure test and (b) specimen after compression test.

to 129%, 10% to 31%, and 6% to 42%, respectively, when compared to N-100 specimens). This result is explained by the higher overall cement content for specimens with higher content of recycled soil-cement mix (12%, 15%, 18%, 21%, and 24% by weight of the dry material for N-100, R-25, R-50, R-75, and R-100 specimens, respectively).

Specimen I.D.	MOR		f_{bw}		MOE	
	Mean (MPa)	COV (%)	Mean (MPa)	COV (%)	Mean (MPa)	COV (%)
N-100	0.46	23.81	2.08	12.12	63.70	28.79
R-25	0.78	8.21	2.28	10.00	67.54	10.35
R-50	0.85	17.78	2.53	17.28	77.54	35.15
R-75	0.88	9.81	2.62	16.74	87.31	30.41
R-100	1.06	21.97	2.72	12.91	90.22	22.00

Table 3. Mechanical properties of CSEBs for different recycled soil content.

The ANOVA results indicate that: (1) the mean values of MOR and f_{bw} of N-100 are statistically different from those of recycled CSEBs; (2) the differences in the mean values of MOR and f_{bw} for specimens R-25 and R-50 is statistically insignificant; (3) the differences in the mean values of MOR and f_{bw} for specimens R-50, R-75, and R-100 are statistically insignificant; and (4) the differences in the mean values of MOE among all CSEB specimens are statistically insignificant. It is also observed that all CSEB specimens satisfy the strength requirements set by the New Mexico Administrative Code [6].

Durability Properties. The results of the durability test are reported in **Table 4** in terms of sample means and COV for percentage loss in mass, change in density, and water absorption. The mean values of the percentage loss in mass of CSEBs vary from 1.57% to 2.14%. ANOVA results indicate that the mean value of the percentage loss in mass for R-75 specimens is statistically different from those of all other specimens. In addition, the R-75 specimens exhibit the lowest percentage loss in mass among all specimens. An expected decrease in dry density and increase in water absorption is also observed for all CSEB specimens. ANOVA results indicate that only the mean values of the dry density and water absorption for the R-100 specimen are statistically different from those of other specimens.

Specimen I.D.	Loss in mass			Change in dry density			Change in water absorption	
	Mean (%)	COV (%)		Mean (%)	COV (%)		Mean (%)	COV (%)
N-100	2.09	17.34		-1.80	85.15		8.93	85.15
R-25	2.14	16.22		-2.20	34.26		9.26	38.88
R-50	1.99	14.05		-2.05	40.29		10.07	18.46
R-75	1.57	17.46		-2.71	45.48		9.30	38.60
R-100	1.92	23.02		-3.75	46.82		7.55	31.05

Table 4. Wetting and drying durability test results.

The compressive strength and MOE of CSEBs subjected to wetting and drying cycles are reported in **Table 5** in terms of sample means and COV. All CSEB specimens exhibit an increase in f_{bw} and MOE after durability tests. When compared to the corresponding values for the original blocks, the mean values of f_{bw} after the durability tests are 3.09% to 7.47% higher, whereas the mean values of MOE after the durability tests are 2.46% to 10.74% higher. However, ANOVA results indicate that these differences in the mean values of f_{bw} and MOE before and after the durability test is statistically insignificant for all CSEB specimens.

Specimen I.D.	f_{bw}			MOE	
	Mean (MPa)	COV (%)		Mean (MPa)	COV (%)
N-100	2.23	15.84		68.88	25.33
R-25	2.36	23.60		74.79	24.59
R-50	2.59	18.40		79.45	22.62
R-75	2.76	13.42		90.21	18.85
R-100	2.87	14.22		92.83	20.32

Table 5. Compression test results of CSEBs after the durability test.

Morphology. **Figure 2** presents the SEM micrographs of CSEB specimens at 50 mm scale. For N-100 specimen, mostly compacted fine particles can be seen in **Figure 2(a),** with a few grain-like particles. The size and amount of particles increase for increasing recycled soil-cement content.

Chemical composition. The results of the EDS analysis are presented in **Table 6** in term of percentage mass of chemical elements contained in the CSEB specimens. As expected, the natural soil predominantly contains silicon (Si) and oxygen (O), with lesser amounts of aluminum (Al), Iron (Fe), calcium (Ca), potassium (K), magnesium (Mg), sulfur (S), and phosphorus (K). The Carbon (Ca) content is negligible. The chemical composition of CSEBs is similar to that of the natural soil, with a progressive increase Ca content for increasing amounts of soil-cement mix, which may be attributed to the increasing cement content.

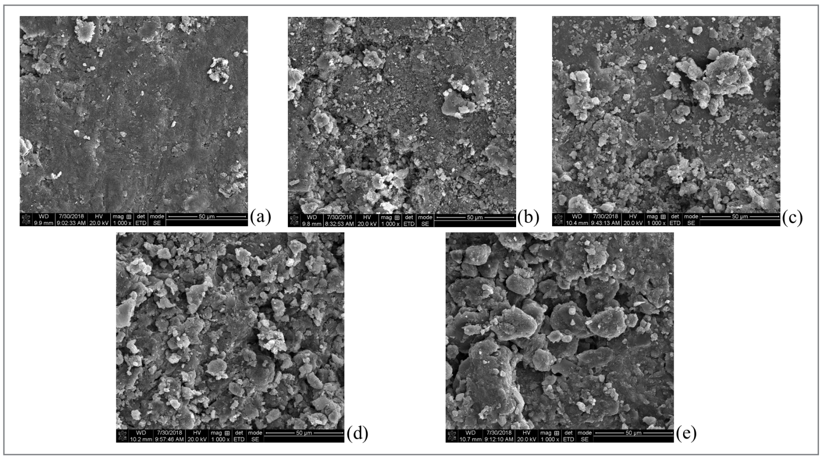

Figure 2. SEM micrographs of CSEBs: (a) N-100; (b) R-25; (c) R-50; (d) R-75; and (c) R-100.

Specimen I.D.	O	Si	Ca	Al	Fe	K	Mg	S	P
Natural soil	50.49	32.47	0.76	8.45	3.66	2.71	1.05	0.01	0.24
N-100	48.53	28.89	6.76	7.68	3.91	2.47	1.07	0.28	0.24
R-25	48.04	28.09	8.19	7.49	4.24	2.47	1.07	0.29	0.24
R-50	47.77	27.50	9.71	7.38	4.05	2.37	1.06	0.38	0.14
R-75	47.29	26.72	11.28	6.97	4.13	2.28	1.07	0.43	0.17
R-100	46.93	25.94	12.85	7.07	3.83	2.11	1.07	0.47	0.18

Table 6. EDS microanalysis results (% mass of chemical elements) of natural soil and CSEBs.

Conclusions

This study investigates some mechanical and physical properties of recycled compressed and stabilized earth blocks (CSEB), i.e., CSEBs produced using the recycled soil-cement mix obtained by crushing CSEBs as a partial or total replacement of natural soil. The experimental test results and their statistical analysis indicate that: (1) the compressive strength of recycled CSEBs increases with increasing recycled soil-cement mix content when a constant proportion of cement is added to the mix; (2) the compressive strength of recycled CSEBs is higher than that of ordinary CSEBs; (3) the recycled CSEBs satisfy the strength requirements set by the New Mexico Administrative Code; (5) the recycled CSEBs produced using recycled soil-cement mix to replace 75% of natural soil show the lowest percentage loss in mass among all specimens considered in this study when subjected to a durability test; (5) CSEBs experience a decrease in dry density and an increase in water absorption when subjected to wetting and drying cycles. The scanning electron microscopy micrographs show that the average particle size in CSEBs increase for increasing recycled soil-cement mix content.

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***Nitin Kumar** is a Ph.D. student Civil and Environmental Engineering at UC Davis. He worked as a graduate research assistant at Louisiana State University for four years and IIT Delhi for one year. He received his Master of Technology in Structural Engineering from IIT Hyderabad and Bachelor of Technology in Civil Engineering from Uttarakhand Technical University.*

***Dr. Michele Barbato** is a Professor of Civil and Environmental Engineering at UC Davis. He is a Fellow of the ASCE Structural Engineering Institute and of the ASCE Engineering Mechanics Institute. He authored more than 160 technical publications, including 46 peer-reviewed articles. He received several awards for research, teaching, and service and is an Associate Editor of several international journals.*