Kyriakides, M.A.[1 2], Panagiotou, R.[1], Illampas, R.[1], Tapakoudis, M.[3], Ioannou, I.[1]
[1] Department of Civil and Environmental Engineering, University of Cyprus,
[2] Department of Engineering, University of Nicosia, [3] Gigantas Antaios, Nicosia, Cyprus

Experimental investigation of non-stabilized compressed earth blocks

A specific form of an earth-based building material that nowadays receives particular attention due to its low production cost and excellent recyclability potential is Compressed Earth Blocks (CEBs). CEBs comprise of soil mixed at low moisture content and are formed under controlled pressure in compression without firing. The end-products can be non-stabilized or stabilized with the addition of a small quantity of stabilizer, e.g., cement or lime (< 12% by weight) (CRATerre-EAG Standards, 1998), mainly for enhancing their mechanical and durability properties.

Despite the long history of Cyprus in the construction of earthen structures (Illampas et al., 2011), it is only recently that CEBs have been introduced to the local market. In an attempt to promote the use of CEBs as an alternate "green" building material on the island, this paper investigates the suitability of four different types of locally sourced soils, with variable granular composition and plasticity characteristics, for the production of non-stabilized CEBs.

Materials and Methods

Soil Characterization

Four different locally sourced soil samples, hereafter referred to as "A"-soil, "D"-soil, "T'-soil and "L"-soil, were used in the present study. The granular composition of each soil sample is presented in Figure 1, together with the limits suggested by the literature for CEB production.

The specific gravity of the soils was determined according to ASTM D854 (2014). The Atterberg limits and linear shrinkage of all samples were determined according to BS 1377-2:1990, whilst the corresponding optimum moisture content and maximum dry density were determined according to BS 1377-4:1990. All the results are reported in Table 1.

In a study by Delgado and Guerrero (2007) reviewing soil selection criteria for non-stabilized earthen materials, the range of values identified for the liquid limit and plasticity index suited to the production of

01 Granular composition of the four soils used for the production of CEBs

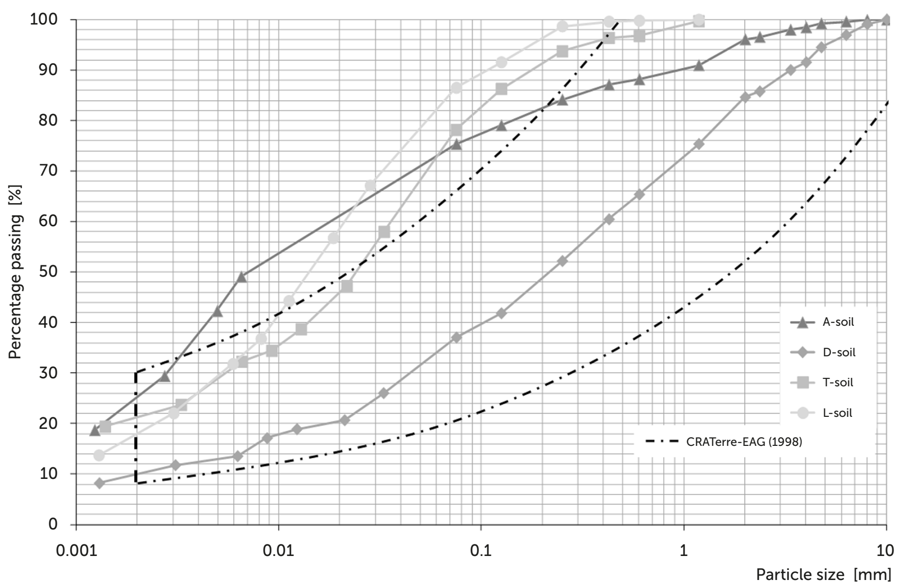


Table 1 Characteristics of soils used in the present study. LL=Liquid Limit, PL=Plastic Limit and PI=Plastic Index.

	Specific Gravity	Atterberg Limits			Linear Shrinkage	Compaction Test	
Soil		LL (%)	PL (%)	PI (%)	(%)	Maximum dry density (g/cm^3)	Optimum moisture content (%)
A	2.56	36	21	15	7.89	1.75	17.7
D	2.68	44	28	16	9.06	1.68	19.5
T	2.56	41	24	17	6.67	1.66	19.0
L	2.66	29	20	9	4.34	1.85	15.5

CEBs are 25%-50% and 2%-33%, respectively. From the soil characteristics reported above, it can be observed that all four samples satisfy the requirements specified by the literature (e.g., Rigassi, 1995) with regard to the liquid limit and plasticity index. One specific sample ("L"-soil) is strikingly different in that it comprises of much more silt, less sand and no gravel, and has lower Atterberg limits, linear shrinkage and optimum moisture content, compared to the other three samples hereby tested.

Production of CEBs

For the production of the CEBs examined in this study, a commercial mobile press used for the on-site production of CEBs was used. The soils investigated above were first mixed independently with approximately 10% water by volume – as per the recommendation of practitioners – in a planetary mixer, until uniform consistency was achieved. The mixture was then placed in the mobile press and a pressure of about 15 MPa was applied, as per the mobile press manufacturer's recommendations. All CEBs produced had dimensions 300 × 150 × 100 mm (l × b × h). After the fabrication of the CEBs, the samples were kept in the laboratory under ambient conditions (relative humidity 55% ± 10% and temperature 25°C ± 5°C) for at least three months before testing, in order to achieve air-dried conditions.

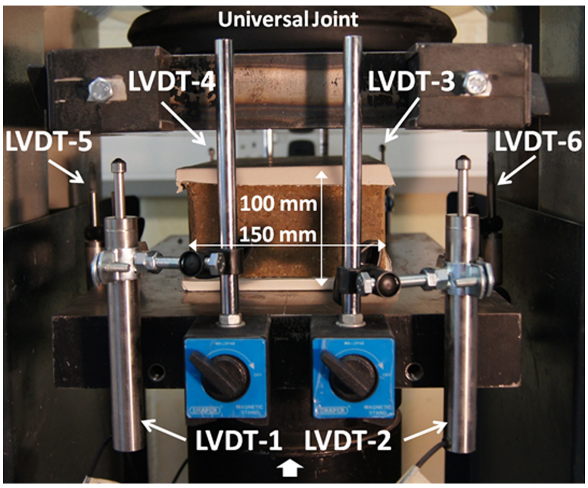
Compression test setup

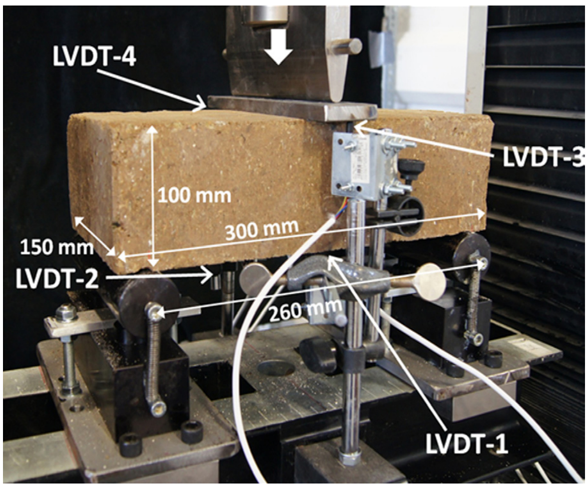
Compression tests were conducted on full-size CEB units adopting the procedure prescribed in ASTM C67-03a. In order to obtain the uniaxial strain deformation of each specimen, four 20 mm-range Linear Variable Differential Transducers (LVDT 1-4 shown in Figure 2a) were symmetrically attached to the test setup and monitored the relative displacement of the loading platen's corners. Strain measurements enabled the estimation of the secant elastic modulus. A displacement-controlled testing procedure – based on the average deformation of two 10 mm-range LVDTs (i.e., LVDTs 5 and 6 shown in Figure 2a), located at the middle, on either side of the specimen – was applied, with a loading rate of 1 mm/min.

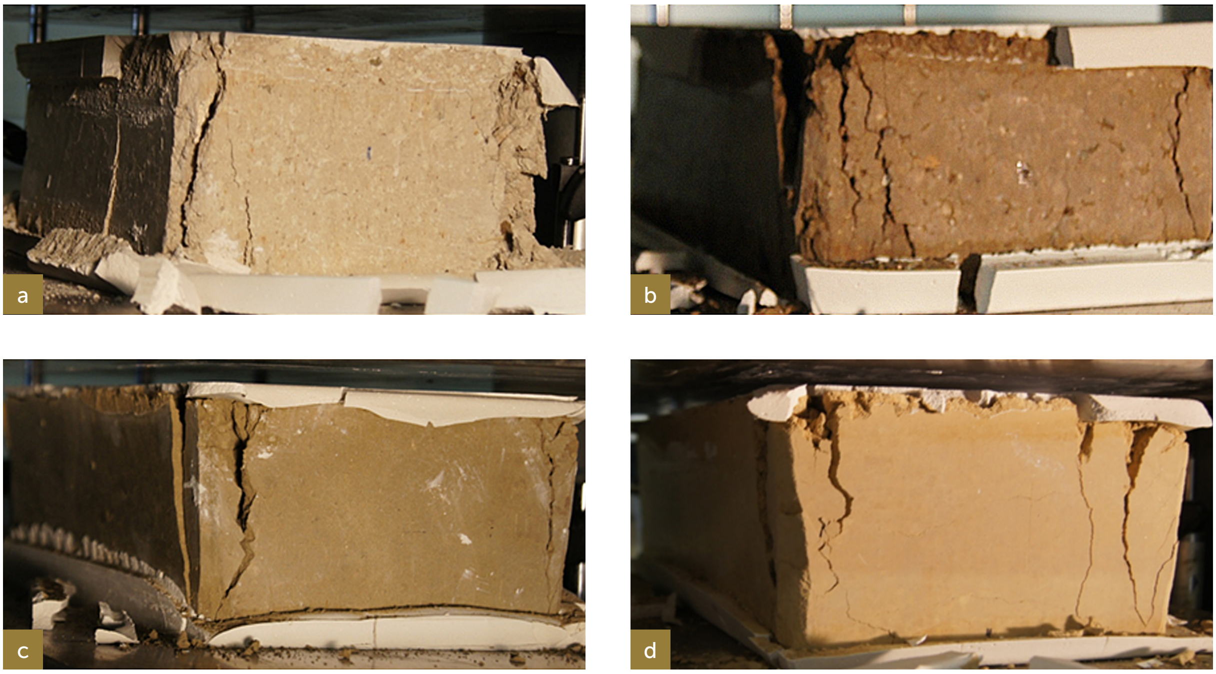
Three-point bending test setup

In order to obtain the flexural strength of the CEB units, three-point bending tests, as per ASTM C67-03a, were conducted. Figure 2b presents the corresponding test setup. Each specimen was simply supported on rollers located at a distance of 260 mm between them. The load was applied at mid-span

02 (a) Compression, and (b) three-point bending test setups







03 Compression failure mode of CEB units made of (a) A-soil, (b) D-soil, (c) T-soil and (d) L-soil

through another roller and a steel bearing plate placed between the roller and the upper surface of the specimen, specifying a displacement-controlled rate of 0.2 mm/min. In order to monitor the mid-span displacement, four 10 mm-range LVDTs (i.e., LVDT 1-4 shown in Figure 2b) were used, two of which were measuring the deflection of the bottom face of the specimen (LVDTs 1 and 2) and two (LVDTs 3 and 4) the movement of the upper face.

04 Compression stress-strain response of CEB units made of (a) A-soil, (b) D-soil, (c) T-soil and (d) L-soil.

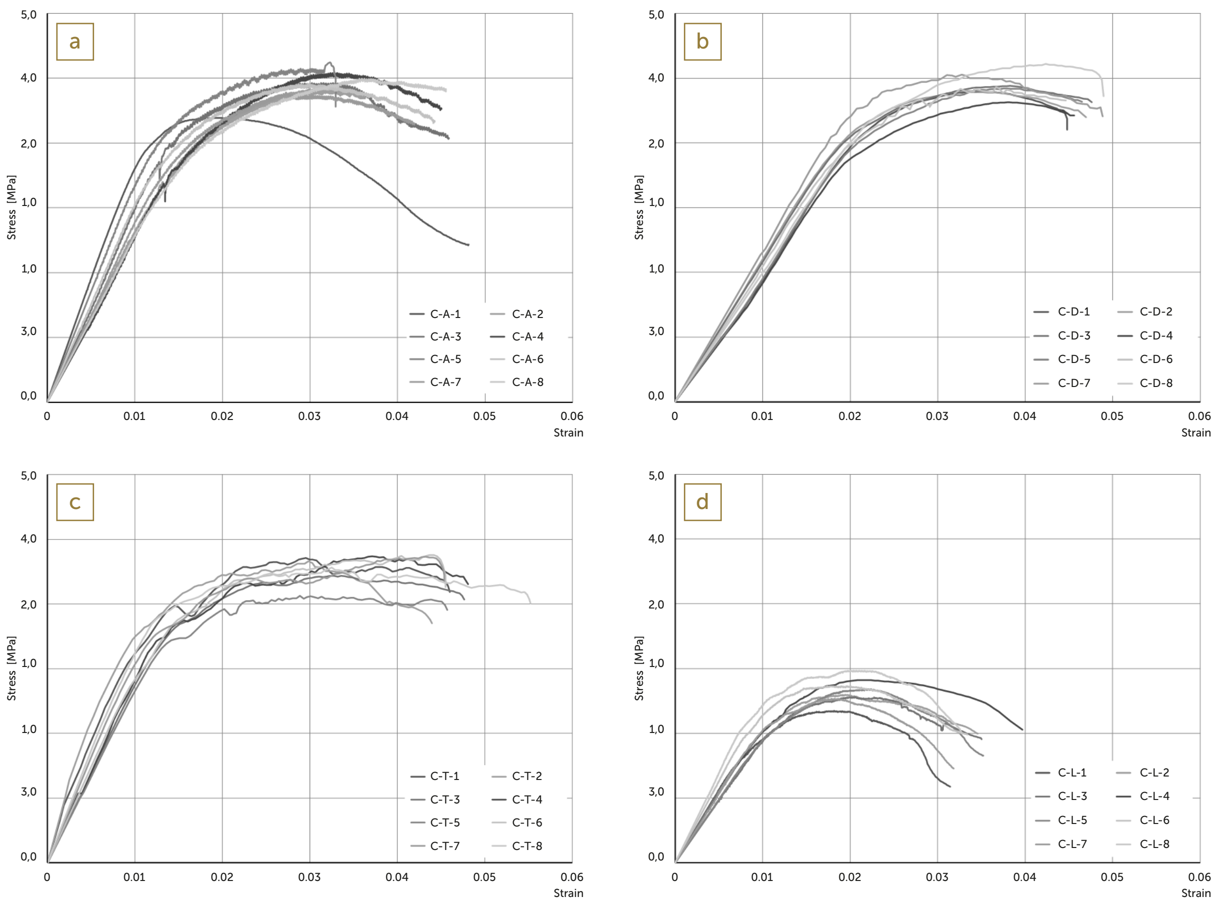


Table 2 Average compressive strength and modulus of elasticity of CEBs

Specimen group	Average compressive strength MPa (STD)	Average elastic modulus MPa (STD)	Average moisture content % (STD)
C–A	9.79 (0.47)	587 (87)	2.97 (0.09)
C–D	9.77 (0.33)	408 (35)	7.25 (0.08)
C–T	9.18 (0.41)	694 (162)	4.88 (0.11)
C–L	5.31 (0.36)	449 (52)	1.46 (0.01)

** Each group consisted of eight specimens.*
*** The standard deviation (STD) for each property is provided in parentheses.*

Results and Discussion

Compression response of CEBs

Figure 3 shows the characteristic compression failure of the CEBs hereby tested. All blocks experienced a similar failure pattern, namely near-vertical surface cracks. This failure pattern is attributed to the lateral restraint imposed on the specimen by the loading platens.

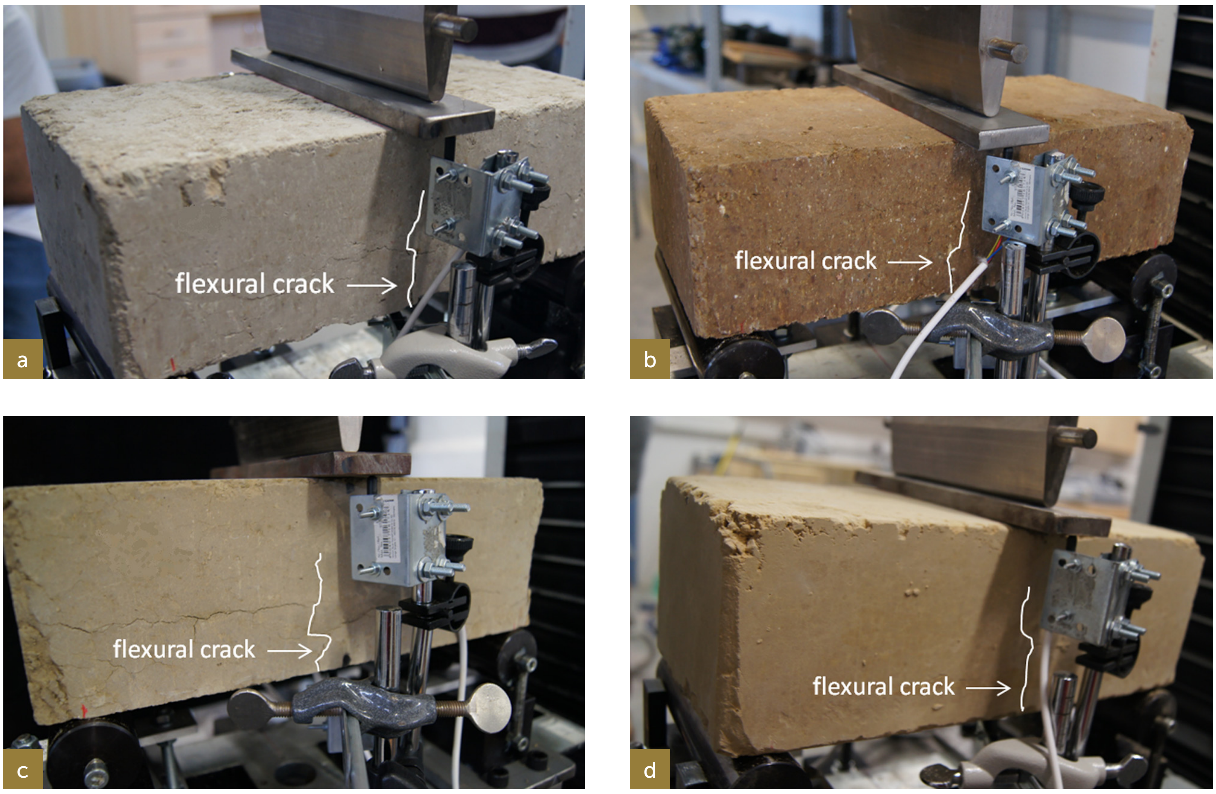
The compression stress-strain response of all CEBs tested is shown in Figure 4. The specimens are referenced as "C-x", where "x" refers to the type of soil used, i.e., "A"-, "D"-, "T"- or "L"-soil.

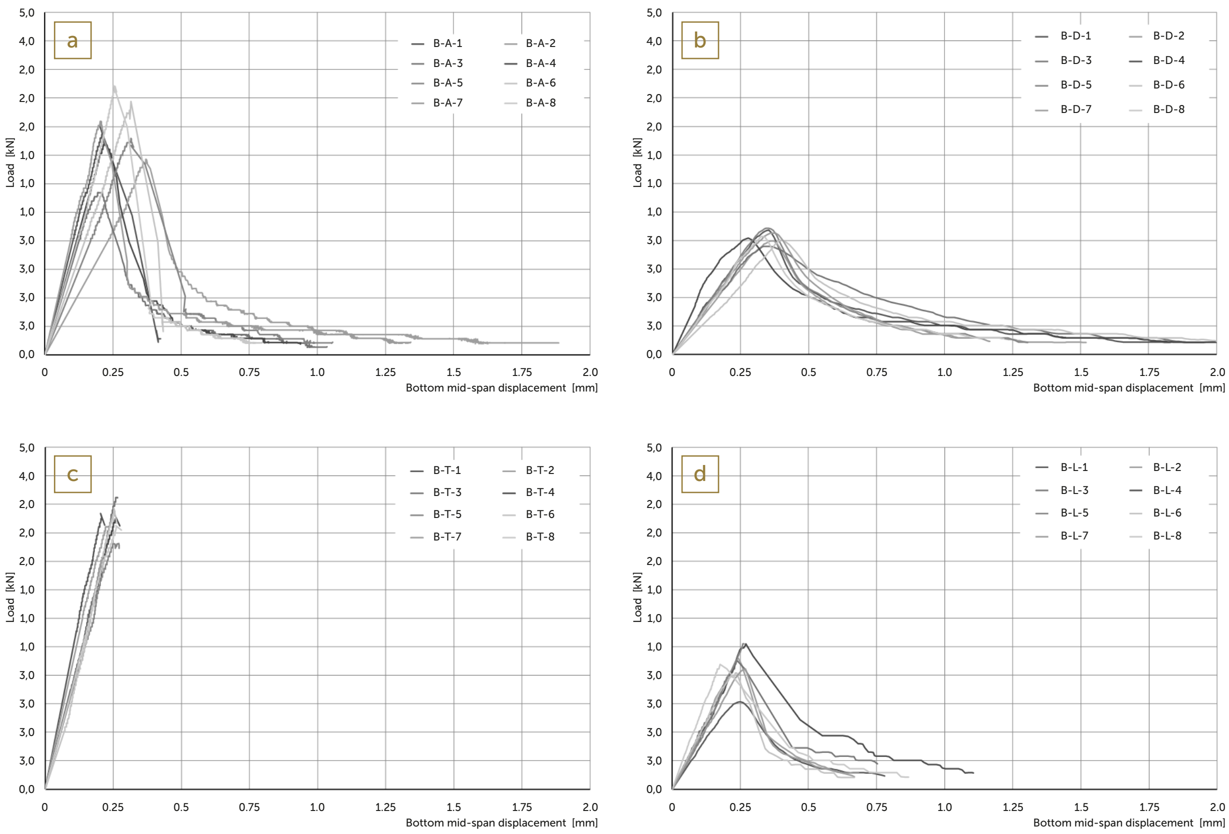
All CEBs maintained more than 50% of their ultimate capacity during their post-peak behavior. This ability is attributed on one hand to the redistribution and compaction of the soil grain particles during compression, and on the other hand to the lateral restraint imposed by the loading platens, as discussed earlier; the latter is further enhanced with the low height-to-width ratio of the specimens.

The average compressive strength and modulus of elasticity of all CEB units are provided in Table 2.

Specimens made of A-, D- and T- soils exhibited similar average compressive strength (> 9 MPa), despite the fact that only "D"-soil satisfies the grading requirements reported in the literature (Table 1). In contrast, CEBs made of "L"-soil exhibited much lower average compressive strength (ca. 5 MPa), despite the

05. Three-point bending failure mode of CEBs made of (a) A-soil, (b) D-soil, (c) T-soil, and (d) L-soil.





06 Load vs bottom-face mid-span displacement of CEBs made of (a) A-soil, (b) D-soil, (c) T-soil and (d) L-soil

lower moisture content recorded. All compressive strengths obtained, however, were higher than the lower bounds recommended by various international standards and guidelines, e.g., the NZS 4298:2020 (1.5 MPa), and the German Association for Building with Earth guidelines (2007) (2-4 MPa).

In terms of modulus of elasticity, CEBs made of "T"-soil exhibited the highest average stiffness, i.e., 694 MPa, albeit also recording the highest standard deviation. Specimens made of "L"- and "D"-soils showed the lowest moduli of elasticity (ca. 400-450 MPa).

Three-point bending response of CEBs

The failure mode of the CEBs under three-point bending is shown in Figure 5. All specimens made of "A"-, "D"- and "T"-soil and most specimens made of "L"-soil experienced brittle failure caused by a mid-span flexural crack at the bottom face, i.e., at the region with the highest bending moment.

Figure 6 shows the load-midspan displacement response of all specimens under three-point bending. The displacement corresponds to the average displacement of the bottom face of the specimens at midspan, measured by two LVDTs (i.e, LVDTs 1 and 2) located on either side (Figure 2b). The specimens are referenced as "B-x", where "x" refers to the type of soil used, i.e., "A"-, "D"-, "T"- or "L"-soil.

All specimens demonstrated a linear behavior almost until the corresponding peak load sustained. At peak, a flexural crack formed, causing the load to drop rapidly, as shown in Figure 6. The most brittle behavior was demonstrated by specimens made of "T"-soil.

The average flexural strength and average stiffness of all CEBs tested under three-point bending are provided in Table 3. The flexural strength, f_{fl}, has been estimated from Eq. 1,

$$f_{fl} = \frac{3P_{max}l}{2bh^2} \qquad (1)$$

where P_{max} is the maximum applied load, l is the distance between the supports, b and h are the width and height, respectively, of the cross-section of the specimen at midspan (i.e., at plane of failure). The bending stiffness, k_{fl}, is defined as the slope of the linear branch of the load-displacement response of CEBs under three-point bending.

CEBs made of "T"-soil experienced the highest flexural strength, followed by those made of "A"- and "D"-soil. These three groups of specimens also had

Table 3 Average flexural strength, f_{fl}, and stiffness, k_{fl}, of CEB specimens

Specimen group	Average flexural strength, f_{fl} MPa (STD)	Average stiffness, k_{fl} kN/mm (STD)	Average moisture content % (STD)
B–A	0.93 (0.12)	15.52 (3.78)	2.94 (0.18)
B–D	0.72 (0.04)	6.80 (1.47)	7.02 (0.14)
B–T	1.21 (0.09)	18.90 (2.80)	5.41 (0.22)
B–L	0.50 (0.08)	9.34 (1.64)	1.52 (0.03)

** Each group consisted of eight specimens.*
*** The standard deviation (STD) for each property is provided in parentheses.*

the highest compressive strengths (Table 2). The lowest flexural strength was experienced by CEBs made of "L"-soil, despite the fact that these specimens also recorded the lowest moisture content. All flexural strengths obtained were higher than the lower bounds recommended by various international normative documents, e.g., the NZS 4298:2020 (0.25 MPa) and the New Mexico State normative (2009) (0.34 MPa (50 lbs/in^2)).

A similar trend was observed with the stiffness results, with CEBs made of "T"- and "A"-soil experiencing the highest values (> 15 kN/mm). CEBs made of "L"-soil experienced an average stiffness equal to 9.34 kN/mm, whilst those made of "D"-soil had the lowest stiffness (< 7 kN/mm).

Conclusions

This paper presented the experimental investigation of non-stabilized CEBs produced using four different locally sourced soils. Soil characterization tests were conducted followed by compression and flexural tests on the CEBs. The results suggest that, although the particle size distribution alone does not seem to have a significant effect on the mechanical properties of CEBs, soils with a more uniform particle-size distribution and a small percentage of gravel can demonstrate superior mechanical properties over soils with larger percentages of silt and clay and no gravel. Furthermore, soils with very low plasticity index and liquid limit do not necessarily develop enhanced mechanical properties.

Contact details

Email: kyriakides.marios@ucy.ac.cy
panagiotou.rafail@ucy.ac.cy
rilamp01@ucy.ac.cy
antaios@antaiosblocks.com
ioannis@ucy.ac.cy

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