The importance of soil characteristics on the resistance of Compressed Earth Blocks against water-mediated weathering

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ABSTRACT

The main drawback of earth-based building materials is their vulnerability against water-mediated weathering. Raw material selection for the production of earth-based building materials is critical for their performance in use. Currently, soil selection is based on empirical practices rather than on a standardized or widely accepted procedure. This study attempts to investigate the effect of soil characteristics on the durability of non-stabilized Compressed Earth Blocks (CEBs) against water-mediated erosion. Particle-size distribution, Atterberg limits, linear shrinkage, compaction and mineralogical analysis were carried out to thoroughly characterize 5 local soils and 2 soil-sand mixtures that were used to produce non-stabilized CEBs. The resistance of the CEBs against water-mediated weathering was assessed by spray erosion, drip, wet/dry and capillary absorption tests. The results indicate that no single soil characterization test can independently predict the resistance of non-stabilized CEBs to water-mediated weathering. Although some of the soils demonstrated satisfactory properties, according to the CRATerre-EAG, International Centre for Earth Construction recommendations, they failed to pass the durability criteria of the tests. However, in all cases, the mineralogical composition of the soils considerably affected the response of the CEBs when in contact with liquid water. Furthermore, both soil-sand mixtures tested demonstrated an improved performance, satisfying the durability criteria set; this shows that the addition of sand to soil may improve the resistance of CEBs against water-mediated weathering.

Keywords: CEBs; Durability; Mineralogy; Sustainability; Erosion; Resistance.

INTRODUCTION

Earth-based building materials have been used for millennia to build several structures and monuments around the globe [Houben and Guillaud, 1994]. Over roughly the last 70 years or so, however, they have been largely displaced by modern industrialized materials, e.g., concrete or fired-clay bricks, offering better physical and mechanical performance [Panagiotou et al., 2022]. Interest in earth-based materials has grown again in recent years, driven mostly by their environmentally friendly characteristics [Minke, 2013]. The lack of firing during their production and the wide availability of suitable soils result in notably low embodied energy [Gallipoli et al., 2017]. Among these materials, compressed earth blocks (CEBs) represent a more recent development, having been introduced in the 1950s. CEBs are, in fact, viewed as a modern progression of traditional adobes and are used either in contemporary structures or in restoration projects in replacement of adobes, as they generally show superior properties.

However, the absence of widely accepted standards or guidelines for soil selection for CEB production makes the use of this earth-based building material challenging. Some guidelines for earth construction recommend basic identification tests, but these methods often exist in multiple versions, whilst the suggested threshold values differ significantly. As a result, standardization is essential, since different procedures and/or threshold values for what should be the same test make it impossible to compare results reliably [Delgado and Guerrero, 2007].

The New Zealand Earth Building Standards (e.g., NZS 4298, 2024), whilst providing guidance to designers, builders and others involved in the construction of earth walled buildings in New Zealand and elsewhere in the world, they focus more on the performance of the end-products to check the suitability of raw materials for the production of CEBs. For example, the wet/dry appraisal test found in NZS 4298 assesses the suitability of raw materials and the presence of organic materials or swelling minerals through cyclic wet/dry testing of the produced CEB.

The aim of this study was to investigate both soil properties and CEBs durability performance in an effort to assess the effect of raw material on the end-products' performance. This has been achieved through extensive laboratory investigation of various local soils and soil mixtures including particle size distribution, Atterberg limits determination, linear shrinkage and mineralogical composition. Furthermore, spray erosion and drip tests, capillary absorption experiments and wet/dry cycles were conducted on CEBs produced with the aforementioned raw materials.

MATERIALS AND METHODS

Raw material characterization

Five different soils sourced from different areas of Cyprus and two soil-sand mixtures were used for the production of CEBs. A-, D- and T- soils were sourced from surficial excavations (depth of sampling < 1 m), while M- and L-soil are quarry products. The latter is, in fact, a fine aggregate waste resulting from the sand washing procedure.
The particle-size distributions of all the raw materials used to produce the CEBs were determined following ASTM D422-63 (2002). Initial characterization showed that A and T soils were the best candidates for combining with sand to create mixtures expected to offer enhanced durability. AS and TS are the soil-sand mixtures that include 25% and 50% sand by weight to A- and T- soils, respectively, added to enhance the overall gradation of the original soils.

Specific gravity was measured following ASTM D854 (2014), while the Atterberg limits and linear shrinkage were obtained in line with BS 1377–2 (1990). Compaction behavior was assessed using the Standard Proctor method, as described in BS 1377–4 (1990). Beyond these tests, the activity of each soil and soil mixture was evaluated using Eq. 1 [Skempton, 1953], which defines activity as the Plasticity Index (PI) divided by the percentage of particles smaller than 0.002 mm.

$$A = \frac{PI}{\%{<}0.002\ mm} \qquad (1)$$

Mineralogical characterization of the raw materials was performed using X-ray diffraction (XRD) along with combined differential thermal analysis and thermogravimetry (DTA/TG). Using both methods together allows clearer identification of mineral phases, particularly those sensitive to temperature, such as clays and organic components. XRD analyses were run on powdered samples from 2° to 70° 2θ at a scan speed of 1°/min, while DTA/TG tests were carried out on powdered samples from room temperature up to 1000 °C at a heating rate of 10 °C/min.

Production of CEBs

Each soil was individually used to produce CEBs with a commercial hydraulic press applying ca. 6 MPa compression pressure. Based on strength and durability results, A- and T-soils were then chosen and blended with S-sand to create soil–sand CEBs. All blocks had dimensions of 300 × 150 × 100 mm³. Following production, the CEBs were placed on pallets and kept in the laboratory for a minimum of three months to cure.

Characterization of CEBs

Capillary absorption was measured on six cubic samples with 70 mm edges, following the procedure outlined in EN 1925 (1999). Before testing, the specimens were oven-dried at 65 °C. Using water as the wetting medium produced non-linear results, deviating from the expected square root of time law, even when applying the Hall and Djerbib (2004) setup, which introduces an absorbent layer between the sample and the water. To address this issue, and to enable accurate determination of the capillary absorption coefficient, a non-reactive fluid, namely n-heptane, was adopted instead. All measurements were performed at 20 °C.

The drip test was performed on six prismatic samples measuring 100 × 100 × 50 mm, following Appendix L of NZS 4298 (2024). In this test, a custom-made apparatus was used. A wick was positioned 400 mm above an inclined specimen and 100 mL of water was allowed to drip onto the sample surface. The resulting erosion depth was recorded using a rod with a diameter of 3.15 mm.

The spray erosion test was carried out on six full CEB blocks, following Appendix K of NZS 4298 (2024). A custom-made apparatus was also developed for this test. Each specimen was positioned 470 mm from a nozzle that delivered water at approximately 50 kPa pressure. Specimens were exposed to the spray for one hour, after which the erosion depth was measured using a rod with a 10 mm diameter.

Finally, wet/dry appraisal tests were performed on six cubic specimens with 70 mm edges, following Appendix J of NZS 4298 (2024). Specimens were submerged in 1 cm deep water for a duration determined by the Limiting Erodibility Index (LEI) obtained from the spray erosion test. After immersion, they were oven-dried at 65 °C for 24 hours. The condition of each specimen was assessed both post-immersion and post-drying, checking for compliance with NZS 4298 (2024) criteria regarding crack types (crazing or star-shaped), swelling, pitting, fretting, water penetration, fragment loss, and efflorescence. Each specimen underwent six wetting/drying cycles to identify the CEBs suitable for construction use.

RESULTS AND DISCUSSION

Raw material characterization

Figure 1 presents the particle-size distributions of the soils and soil–sand mixtures. Of the five soils hereby tested, only D-soil met the CRATerre-EAG criteria for CEB production [Houben and Boubekeur, 1998]. M-soil displayed a well-graded texture but lacked fines, particularly clay, which is essential for adequate brick cohesion. A-soil had an acceptable clay content, but contained high amounts of silt and fine sand. T- and L-soils were both very fine, with low sand content. Incorporating sand into A-soil (AS mixture) and T-soil (TS mixture) improved their gradation according to CRATerre-EAG standards. Both resulting mixtures met the gradation criteria while retaining sufficient clay content (8%- 30%).

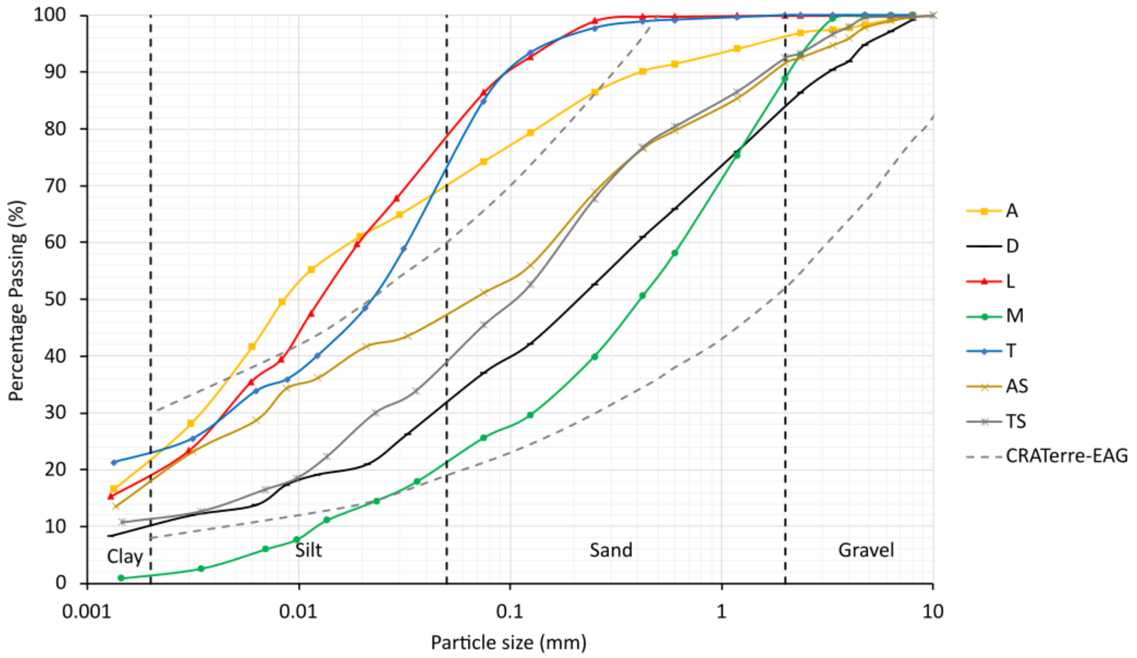

Figure 1. *Granular composition of the soils and soil mixtures used to produce non-stabilized CEBs.*

Table 1 summarizes the specific gravity, Atterberg limits, linear shrinkage, activity, and compaction results for the soils and soil–sand mixtures used in this study. The Atterberg limits indicate that all soils are generally suitable for CEB production. A-, L- and T-soils are classified as lean clays, D-soil as sandy silty clay with gravel and M-soil as sandy silty clay, according to the USCS classification system [ASTM D2487, 2000]. It should be noted that soils outside these Atterberg limits have been successfully used in several studies on earth-based materials. A-, D-, and T-soils exhibit high linear shrinkage compared to L- and M-soils. Regarding activity, D-soil shows a high value and is classified as active (A ≥ 1.25) according to Skempton's criteria. M-soil also shows a very high activity value; however, this is considered inaccurate due to the very low clay content and the presence of silt in the soil [British Geological Survey, 2002]. Compaction tests show that the maximum dry densities of the soils are acceptable for CEB production, although the optimum moisture contents are relatively high, likely due to the clay content or particle-size distribution of the soils. Still, soils with even higher optimum moisture levels have been employed for CEB production in previous works [Danso and Adu, 2019]. The optimized soil–sand mixtures demonstrate lower Atterberg limits and linear shrinkage, along with higher maximum dry density at reduced moisture content, meeting all relevant requirements. These soil-sand mixtures are classified as lean clays with sand according to the USCS classification [ASTM D2487, 2000], deviating from the respective initial soils classification.

Table 1. *Characteristics of the various soils and soil mixtures used in the present study. LL = Liquid Limit, PL = Plastic Limit, PI = Plasticity Index, A = Activity, MDD = maximum dry density and OMC = optimum moisture content.*

Raw material	Specific gravity	Atterberg limits			Linear Shrinkage	Activity	Compaction test	
		LL (%)	PL (%)	PI (%)			MDD (kg/m^3)	OMC (%)
A	2.56	36	21	15	8	0.65	1750	18
D	2.68	44	28	16	9	1.65	1680	20
L	2.66	29	20	9	4	0.54	1850	16
M	2.65	22	16	6	1	6	2090	10
T	2.56	41	24	17	7	0.69	1660	19
AS	2.58	27	17	10	3	0.55	1840	16
TS	2.53	30	21	9	3	0.75	1850	15
CRATerre-EAG criteria	-	25-50	-	3-29	-	-	1700-2200	≤15

XRD analysis indicated that A-, L-, and M-soils, as well as S-sand, are primarily carbonaceous, with calcite as the dominant mineral. D-soil contained a high proportion of silicate minerals, such as plagioclase, along with alteration products resulting from the weathering of the parent rock. T-soil exhibited a mixture of silicate and carbonate minerals, whilst a small amount of kaolinite was also detected.

DTA/TG results were generally consistent with the XRD findings. Specifically, kaolinite was identified in both T- and D-soils, while montmorillonite was present in D-soil. The occurrence of swelling clays indicates potential long-term durability concerns for earth-based materials. Organic matter was also found in soils from surface excavations (A-, D-, and T-soils). Both clay minerals and organic content influence the moisture-related behaviour of the soils and of the resulting CEBs.

Characterization of CEBs

Fig. 2 shows characteristic i vs $t^{1/2}$ curves, where i is the cumulative mass of liquid absorbed by the specimens per unit surface area, obtained from capillary absorption experiments, for all CEBs hereby studied. All the specimens exhibited a linear response, respecting the $t^{1/2}$ law.

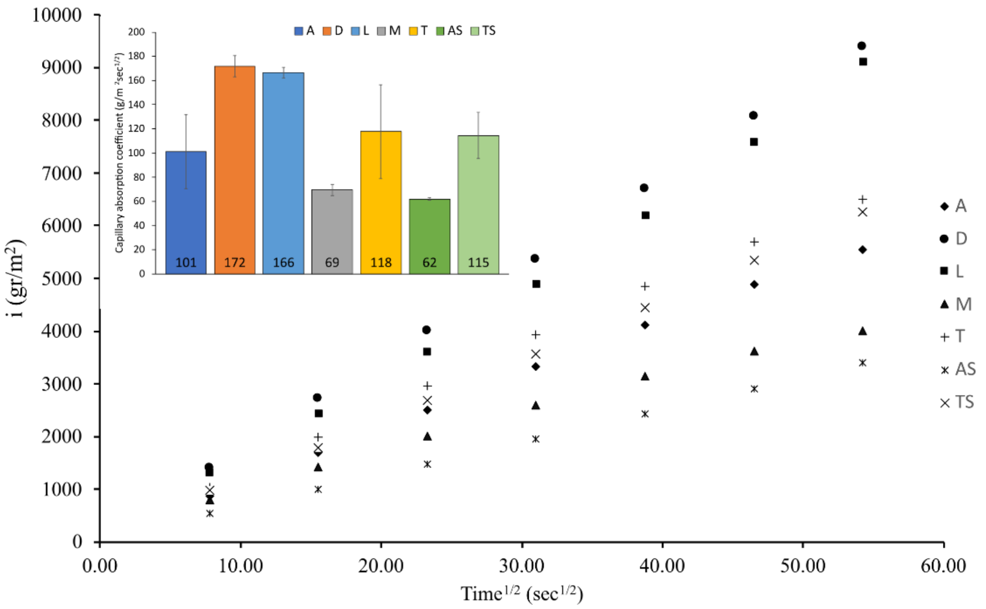

Figure 2. *Characteristic i vs. $t^{1/2}$ curves for CEBs, using n-heptane as the wetting liquid.*

Among the CEBs tested, those made with AS-soil mixture and M-soil exhibited the lowest capillary absorption coefficients (see Fig. 2, inset), while the highest values were observed in blocks produced from L- and D-soils. The reduced absorption in M-soil CEBs likely stems from its well-graded particle-size distribution (Fig. 1), which may have produced a denser microstructure. In contrast, despite D-soil also showing a favorable gradation, the corresponding CEBs showed a higher absorption. This behavior is likely linked to the presence of swelling minerals, e.g., montmorillonite, which can cause volume changes and microcracking as moisture levels vary. The addition of sand in A- and T-soils yielded a lower capillary absorption coefficient for the CEBs with soil mixtures, likely due to their denser microstructure.

The results of the drip test , along with the LEI assigned based on the pit depth at the end of the test [NZS 4298, 2024], are shown in Table 2. All specimens met the performance requirements of NZS 4298, exhibiting pit depths below 15 mm, consistent with findings from other studies on unstabilized CEBs. Blocks produced with M-soil showed the least erosion, whereas those made with L-soil experienced substantial degradation. Incorporating sand into A- and T-soils further enhanced erosion resistance, reducing the pit depths for both soil mixtures.

Table 2. *Drip test results for the CEBs studied.*

CEB	Pit depth (mm)	LEI
A	8.63	3
D	11.69	4
L	13.9	4
M	5.49	3
T	8.51	3
AS	2.45	2
TS	4.53	2

The spray erosion test results, along with the LEI assigned based on the erosion at the end of the test [NZS 4298, 2024], are shown in Table 3. The better performance was observed by the CEBs produced with A-soil, followed by those made with D- and M-soils. Blocks produced with L- and T-soils did not pass the test, showing erosion rates greater than 2 mm/min. This poor behavior is linked to the lack of coarse aggregates in these soils, which would otherwise help maintain the block's volume stability. The addition of sand in both soil mixtures improved the performance of the CEBs, compared to the blocks with the corresponding soil only. This is particularly interesting in the case of TS CEBs, whereby a soil that was considered unacceptable for CEB production improved a lot with the addition of sand.

Table 3. *Spray erosion test results for the CEBs studied.*

CEB	Rate of erosion (mm/min)	LEI
A	0.83	3
D	1.31	3
L	11.25	5
M	1.40	3
T	5.65	5
AS	0.16	1
TS	0.78	2

Representative images of the specimens after the final wetting–drying cycle are shown in Fig. 3. For CEBs produced from A-, D-, M-soils and TS-soil mixtures, the immersion duration based on the LEI determined from spray erosion tests was 1 minute, whereas AS CEBs were immersed for 4 minutes. CEBs formed from T- and L-soils had LEI values greater than 4, for which NZS 4298 does not specify an immersion time; however, an exposure of 0.5 minutes, the same as that for LEI = 4, was adopted for completeness.

Blocks made from soils alone (i.e., without the addition of quarried sand) did not meet the Wet/Dry appraisal performance criteria, except for those with M-soil. A-soil CEBs failed during the fourth cycle due to localized pitting. D-soil CEBs failed after the second cycle because of localized swelling linked to the high content of expansive clay minerals. L- and T-soil blocks failed during the first cycle, the former due to general fretting and the latter due to the formation of crazing cracks. Sand addition improved the wetting/drying performance of the CEBs. TS-mixture CEBs failed during the third cycle, again due to crazing-type cracking, though the cracks were smaller and shorter than those observed in T-soil blocks. AS-mixture CEBs withstood all six cycles without exhibiting any of the rejection criteria and are therefore considered suitable for construction use. These observations are consistent with previous findings reporting improved resistance to wet/dry cycling with sand addition [Guettala et al., 2002].

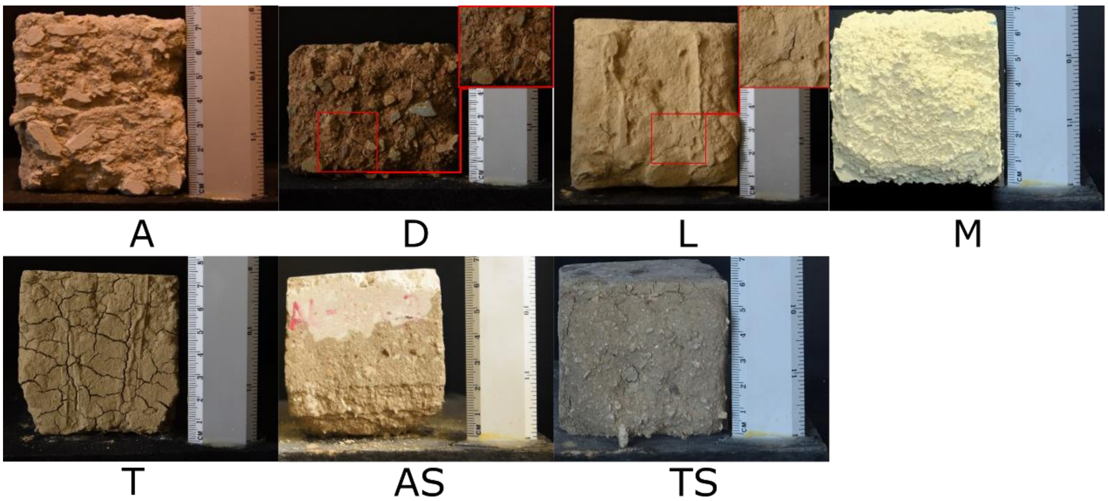

Figure 3. *Characteristic Images of the CEBs after the final wetting/drying cycle.*

CONCLUSIONS

This study showed that raw soils differ significantly in their suitability for producing high-quality compressed earth blocks (CEBs) that can be used in either contemporary construction or restoration projects. Although D-soil met the particle-size distribution criteria, its high plasticity and presence of swelling clays made it less reliable in practice. M-soil performed the best among the unmodified soils because of its well-graded texture, low plasticity, and high maximum dry density, which together resulted in a dense microstructure. In contrast, A-, T-, and L-soils showed limitations: A-soil contained excessive silt, while T- and L-soils lacked coarse fractions and were dominated by very fine particles. The addition of sand to A- and T-soils resulted in more balanced particle-size distributions, reduced plasticity and shrinkage, higher dry density, and overall improvements in mechanical and durability performance.

These mixtures, especially AS, showed marked improvements across all tested durability indicators, clearly demonstrating the effectiveness of particle-size distribution modification.

Mineralogical characteristics play a crucial role in explaining performance differences. Carbonate-rich soils, such as A, L, and M, tended to be more stable, while D-soil contained a substantial proportion of swelling clays, such as montmorillonite, which promoted volumetric changes in the presence of moisture, microcracking, and the eventual degradation of CEBs. Organic matter, present in A-, D-, and T-soils, also influenced the moisture-related behavior of the end-product and reduced its long-term stability. M-soil and sand-modified mixtures (AS and TS) consistently showed reduced absorption, improved erosion resistance, and better stability during wetting and drying cycles. In contrast, L- and T-soils, which lacked coarse particles and contained more fines, performed poorly, especially in erosion and wet/dry cycles. Swelling clays in D-soil led to noticeable volumetric changes and reduced durability, despite the favorable gradation of that soil.

Thus, it is clear that raw material properties affect the performance of the resulting CEBs. A well-graded particle-size distribution correlates with higher dry density and a denser microstructure, directly reducing pore connectivity and improving resistance to both moisture uptake and erosion. Excessive fines or an absence of coarse particles correlates with poor volume stability and vulnerability to surface degradation under drip and spray erosion tests. Plasticity and linear shrinkage indicate the likelihood of shrinkage cracking during drying; soils with high PI and shrinkage values tend to fail earlier in wet/dry cycling. Mineralogy is also crucial, as swelling clays correlate with microcracking, higher water absorption, and reduced durability. Organic matter also correlates with poorer, more moisture-sensitive behavior.

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