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Mechanical Characterization of Masonry Built with iCEBs of Granite Residual Soils with Cement–Lime Stabilization

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Abstract: The environmental impact due to the overexploitation of nonrenewable resources, the processing and transportation of materials, and waste production is a global concern that the construction industry must urgently address, since it is among the greatest contributors. Earth construction can be seen as an alternative building solution, enhancing sustainability, despite traditional techniques being nowadays in disuse in most developed countries. Construction with interlocking compressed earth blocks (iCEBs) is a recently developed technique, put in evidence in the last few decades, for overcoming many earth construction limitations. Here, this technique is studied as a sustainable building solution for Northern Portugal, where the typical soils are sandy, granitic residual soils with low clay content. These soils typically demand cement stabilization to produce earthen materials, which compromise the sustainability of the construction solution. In order to improve sustainability, stabilization with hydraulic lime is proposed as a partial replacement of cement. For this purpose, the properties of the selected soil were characterized through a set of geotechnical tests, with different percentages of cement and lime in the mixture composition tested, concerning the compressive strength of the specimens. A mixture composed of 87.5% of soil, 7.5% of cement, and 5% of lime was shown to be the most suitable for producing iCEBs with adequate mechanical performance. The compressive behavior of the iCEBs masonry was characterized by testing prisms and wallettes, considering both dry stack and mortar joints cases. The obtained results showed that using mortar in the bed joints allows for the improvement of the compressive strength (a 5%–18% increase) and Young's modulus (a 65%–92% increase) of the masonry. Thus, it can be concluded that masonry built with locally produced iCEBs and stabilized with cement and lime is a feasible building solution, for a sustainable earth masonry built from sandy granitic residual soils, where the mechanical behavior is substantially enhanced by using bed-joint mortar.

Keywords: earth blocks masonry; interlocking compressed earth blocks; cement–lime stabilization; compressive behavior; sustainable construction

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1. Introduction

Raw earth has been used as a building material for centuries [1], defining the architecture of many ancient cultures worldwide [2,3]. Approximately 17% of the sites classified by the United Nations Educational, Scientific and Cultural Organization (UNESCO) as World Heritage are built with raw earth [4], while one-third to one-fifth of the world's population is estimated to live in a house built with this material [5]. Figure 1 illustrates the distribution of earth construction in the world, which concentrates mainly in Africa, parts of Asia, and South America. Nowadays, building with earth is still a common practice in developing countries, mainly due to its low cost. In developed countries, such as Portugal, Spain, and the United States, these materials fell into disuse in the last century, giving place to more modern materials such as concrete, steel, and brick masonry, which allow buildings with enhanced structural performance [6]. Nevertheless, earthen construction is currently being promoted as a sustainable construction solution, as part of the response to mitigate global warming.

Figure 1. Earth construction regions in the world and UNESCO World Heritage Sites [7].

More recently, the construction industry is becoming concerned with its impact on the environment due to the overexploitation of nonrenewable resources, the processing and transportation of materials, and waste production [4]. Thus, it has been putting the focus on the proper management of water, greenhouse gas emissions, energy consumption, and solid waste generation [8]. Large use of steel, concrete, and fired clay bricks has contributed to the carbon footprint, generating intense environmental pollution along with the consumption of resources. CO_2 emissions from concrete blocks and fired clay bricks are substantially high, about 200 kg/ton and 143 kg/ton, respectively [9]. These alarming numbers have driven society and the construction industry to pursue alternative solutions with enhanced sustainability. Despite earth construction techniques having been recently abandoned, due to their replacement by modern materials and a lack of institutional approval in most countries, they can be seen as a sustainable alternative to fill the aforementioned need. Earth construction is proven to be suited to the green building approach, which attempts more energy-efficient and environmentally friendly construction practices to achieve sustainability in construction and to promote environmental resilience [2], which makes it extremely competitive when compared to current materials and construction techniques [10].

The availability of earth as a building material led to the development of several building techniques around the world, yet the most common are adobe masonry, rammed earth, cob, and, more recently developed, masonry of compressed earth blocks (CEBs) [11]. Despite this last technique being proposed based on the relatively recent requirements of the construction industry, it still presents some limitations with respect to modern materials [12], such as the lack of manufacturing standards and building codes in most countries. Therefore, in spite of the increasing interest in earthen construction, further research is still needed to thoroughly understand its mechanical performance and durability properties [13].

It is important to note that not all soils are suitable for earth construction and that only their inorganic particles are used for this purpose. These particles compose fractions of different sizes, which are completely blended and define the behavior of the soil according to their characteristics and proportions [14]. Thus, CEB performance is mostly influenced by the soil characteristics and particle size distribution, where the best soil fractions are within the following ranges: sand and gravel 55%–75%, silt 15%–30%, and clay 10%–30% [15]. In this context, a fundamental step in earth construction is the assessment of the suitability of the available soil, which can be done through its characterization. Nevertheless, evaluating the performance of the produced earthen material is essential to conclude about the suitability of the soil for earth construction [16]. Earthen blocks present, in general, low mechanical properties (compressive strength of 0.45–4 N/mm^2 and Young's modulus of 60–650 N/mm^2) with significant dispersion between the diverse existing studies, which is mainly attributed to the heterogeneity of the materials used and also to the manufacturing and testing conditions [2,7]. On the other hand, building with CEBs has several advantages, such as the low embodied energy of the material, low waste production, high fire resistance, low cost, as well as the easiness of construction, and the possibility of using local labor without specific experience [17,18].

Even though available soils are often considered unsuitable for earthen construction, they can still be used for this purpose if properly enhanced with cementing agents. Portland cement is the most common stabilizer used in CEB manufacturing. The quantity of cement to include depends on soil type and composition; typical stabilization percentages are lower than 10% by dry weight of soil to fulfill the minimum saturated characteristic compressive strength criteria [3,19]. This process reduces some of the limitations associated with this type of material, namely by increasing the compressive and tensile strength and durability [4,20,21]. On the other hand, cement is a material with high embodied energy, meaning that its use in the production of CEBs compromises the sustainability of this building technique. This problem has been addressed in recent research by considering the incorporation of formulations of different types of natural and artificial fibers in CEBs [22], such as stabilization through alkali activation, the incorporation of various types of industrial wastes [23–25], or the combination of both, where fibers and alkali activators significantly improve properties of earth-based composites [26].

Another possibility to mitigate the environmental impact of the stabilization with cement is reducing its percentage by partially replacing it with materials with lower embodied energy, such as hydraulic lime.

Lime has been employed as a compatible stabilization method for CEBs because of its mechanical strength and water vapor permeability. Besides, lime works as a stabilizer when fine particles are present in the soil [27,28]. Several authors have concluded that when natural hydraulic lime was added to the soil, mechanical properties such as compressive strength, elastic modulus, and flexural strength were improved [13,29,30].

In this context, the research work presented here intends to contribute to the application of earthen solutions using locally available soils. However, in some regions, soils are poor in clay, so cement stabilization is normally used to guarantee the required mechanical behavior. In this case, the research work refers to the improvement of sandy granitic residual soils with low clay content, which characterizes many regions, not only in Portugal, but all over the world. Cement will be partially replaced by hydraulic lime in order to increase the sustainable character of the stabilized solution. Furthermore, mechanical characterization of interlocking compressed earth blocks (iCEBs) will also be performed for masonry with dry stack and mortar joints. Such a contribution is expected to support construction with this type of masonry as a solution for sustainable construction, namely in Northern Portugal, being, however, scalable for soils with similar composition. The mechanical characterization of these solutions will contribute to the scientific knowledge in this field, given the variability of locally available soils, and, at the same time, encourage stakeholders to integrate this sustainable solution into the building envelope.

2. Materials and Methods

This section starts by presenting the characterization of the raw materials used in the experimental program. Then, the composition study conducted to select the mixture used to produce the iCEBs is presented, which includes the analysis of the compressive strength of mixtures with different stabilization types and percentages. Subsequently, the characterization of the iCEBs produced with the selected mixture and of the mortar adopted for building the masonry specimens with mortar joint is presented. Finally, the procedures used to test different masonry specimens under compression are presented.

2.1. Characterization of the Raw Materials

The characteristics of the raw material used to produce the iCEBs are presented here, which include soil, cement, and hydraulic lime (see Figure 2). The soil was characterized based on geotechnical tests, while the characteristics of the cement and hydraulic lime are briefly referred to according to the specifications of the supplier.

(**a**) (**b**) (**c**)

Figure 2. Raw materials used to produce the iCEBs: (**a**) soil; (**b**) cement; and (**c**) hydraulic lime.

The soil was collected from the suburbs of the municipality of Vila Real, Portugal. This soil was selected as being representative of typical granite residual soils (GRS) available in the north of Portugal, meaning that the study presented here is expected to validate this type of construction in the region. It should be noted that the sustainability associated with earth construction demands using soils available nearby the construction site, which can be sourced from the excavation of the foundations or as waste from other construction sites. The properties of the selected soil were characterized through a set of geotechnical tests, which included particle size distribution (PSD) [31], consistency limits [32], standard Proctor test [33], particle density (PD) [34], methylene blue value (MB) [35], and sand equivalent value (SE) [36]. Figure 3a presents the PSD curve of the selected soil and compares it with the envelope of GRS from Northern Portugal, according to Viana da Fonseca [37]. The curve of the selected soil fits within the envelope, which validates the assumption of it being representative. Furthermore, the soil is characterized by a well-graded PSD and is constituted mainly of sand particles.

In Figure 3b, the PSD curve is compared with the envelope of soils suitable for the production of CEBs, according to the standard UNE 41410 [38], which regulates the production of this type of block in Spain. This comparison shows that the soil lacks clay content, with a percentage (6%) that is significantly lower than the minimum required by the standard (10%). Thus, the selected soil is deemed unsuitable to produce CEBs, as its insufficient clay content is expected to lead to a lack of initial cohesion necessary for production and poor strength and durability performance of the material. The low clay content of the soil was also evidenced by the consistency tests performed (liquid limit and plastic limit), which deemed the soil as non-plastic.

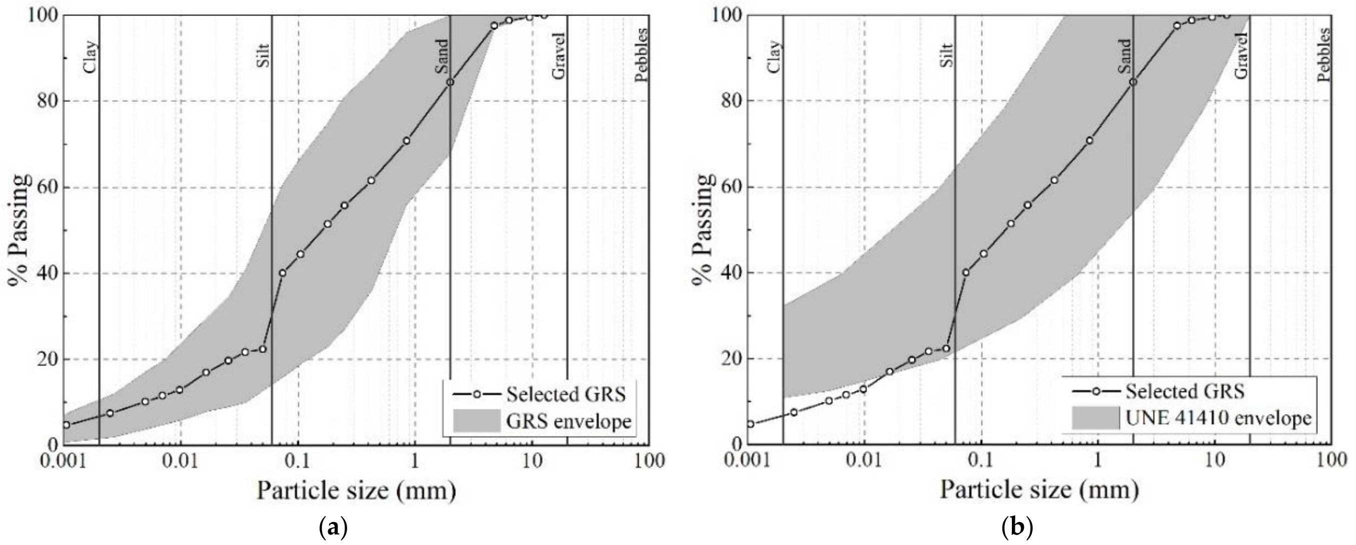


Figure 3. PSD of the selected soil and comparison with the envelope of (**a**) GRSs from Northern Portugal, according to Viana da Fonseca [37] and (**b**) soils recommended for CEBs production, according to UNE 41410 [39].

The standard Proctor test of the selected soil provided a maximum dry density of 1.71 g/cm^3 and a corresponding optimum water content of 12.3%. The value obtained for the maximum dry density is very low, which also anticipates a poor performance of CEBs produced directly with this soil [40].

In terms of the density of the particles of the selected soil, the performed test provided a value of 2.59 g/cm^3. Further testing of the soil included also the determination of the methylene blue value (MB), which was found to be 3.30 g/Kg. According to Fabri [41], this soil presents a clay fraction with low activity (MB < 11 g/kg), meaning that this fraction is expected to have a poor binding capacity, which would result in CEBs with insufficient performance. Furthermore, the sand equivalent test indicates a percentage of sand in the soil of about 36%, meaning that the fine fraction is mainly constituted by silt particles.

The characterization of the selected soil revealed that it is not suitable to produce unstabilized CEBs due to the low clay content of the soil, which is a common feature in the GRS from Northern Portugal. Thus, this type of soil is tendentially unsuitable for producing CEBs, yet its stabilization with binders has been shown to produce earthen materials with adequate performance [2,42,43].

In this regard, cement, soil with the classification CEM II/B-L 32.5 N, was one of the binders selected for stabilizing the available. The other selected binder was hydraulic lime type HL5. Both binders are readily available in the Portuguese market, yet the embodied energy of hydraulic lime is expectably lower.

2.2. Study of the Mixture Composition

The production of the iCEBs used in the experimental program also required the definition of the mixture incorporating the selected raw materials. For this purpose, a composition study was conducted, in which different proportions between the raw materials were tested through 5 different mixtures. The percentage of stabilization varied between 10% and 20% in weight, while incorporating at least 5% of each binder. A minimum percentage of 10% for stabilization (addition of fine particles) was initially assumed to provide sufficient initial cohesion to the material in its fresh state and allow the immediate demolding and handling of the CEBs during the production (see Silva et al. [43]). The compositions of the tested mixtures are presented in Table 1.

Table 1. Mixtures evaluated in the composition study.

Mixture	Raw Material (wt.%)		
	Soil	**Cement**	**Hydraulic Lime**
M1	90	5	5
M2	87.5	7.5	5
M3	87.5	5	7.5
M4	85	7.5	7.5
M5	80	10	10

The study of the mixture composition involved testing the compressive strength of the mixtures, which required manufacturing cylindrical specimens with 70 mm diameter and 140 mm height, performed by adapting the procedure originally presented by Soares [44].

Before the preparation of the specimens, the soil was air-dried for a few days and, subsequently, was crushed and sieved to remove any particle larger than 10 mm. Each mixture was prepared by, firstly, mixing the respective solid materials (i.e., soil, cement, and lime) in a table mixer, for 10 m and at a low rotation speed. Then, water was added in the proportion defined by the Proctor test optimum water content, and the mixing continued until full homogenization was observed. The mixture was divided into three portions with the same mass, each constituting a layer of a single specimen. Each portion was compacted in a metallic mold using a mechanical press, while controlling the height of each layer, such that the density would be similar to the maximum density obtained from the Proctor test. The surface of the first and second layers was slightly scraped after compaction, to grant adhesion to the subsequent layers. After compaction of the last layer, the specimen was left in the press for about five minutes without removing the compaction pressure, which aimed to prevent the expansion by relaxation of the material immediately following compaction. The specimens remained in the molds for 24 h, so that curing begins, and the damage risk due to demolding is minimized. Loss of moisture by evaporation was avoided by sealing the tops of the molds with cellophane film and by storing them in a humidity chamber (temperature of 21 ± 1 °C and relative humidity of 85 ± 5%). Then, the specimens were demolded, wrapped in cellophane film, and left to cure in the humidity chamber until being tested.

Three specimens were tested under compression for each mixture to obtain the Uniaxial Compressive Strength (UCS), at an age of about 28 days. The tests were conducted in a testing frame equipped with an actuator with a loading capacity of 100 kN, by applying a monotonic displacement with a velocity of 0.01 mm/s.

The average values of UCS of each mixture and the respective coefficient of variation are presented in Table 2. The mixture M2 presents the highest strength and is followed by mixture M5, despite the overall binder content of the last being substantially higher (from 12.5% to 20%). The comparison of the UCS values of the mixtures M2, M3, and M4 seems to show that considering a higher proportion of cement, with respect to hydraulic lime, promotes higher strength. Despite mixture M1 presenting the lowest overall binder content, it obtained an intermediate UCS value.

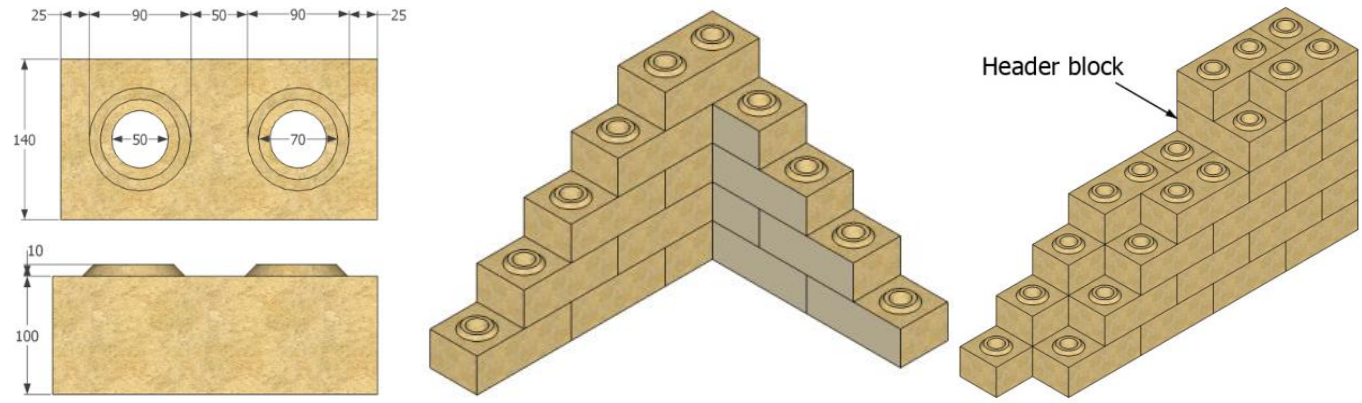
Table 2. Average UCS of the tested mixtures (CoV in parentheses).

	Mixture				
	M1	**M2**	**M3**	**M4**	**M5**
UCS (MPa)	3.6 (2%)	4.9 (6%)	3.2 (1%)	3.7 (2%)	4.5 (8%)

Selecting the mixture to produce the iCEBs requires establishing a compromise between mechanical behavior, durability, and environmental impact. Despite mixture M1 presenting the lowest environmental impact and acceptable strength, it was not considered for producing the iCEBs because, during the manufacturing of the specimens of the composition study, the binder content was not sufficiently high to allow the demolding and handling of blocks. On the other hand, all other mixtures seemed to obtain adequate initial cohesion. Thus, the mixture that obtained the best compromise was M2 (87.5% of soil, 7.5% of cement, and 5% of hydraulic lime, by weight), which was then selected for producing the iCEBs used in the experimental program. It should be noted that the total stabilization percentage (12.5%) is inferior to the maximum value prescribed by UNE 41410 [39], namely 15%. Furthermore, adopting a binary binder allowed to limit the cement content to as low as 7.5%, which otherwise would require a percentage higher than 10% for sake of production requirements regarding immediate demolding.

2.3. Production of the iCEBs

The geometry and dimensions of the iCEBs produced for the experimental program were previously studied by Sturm et al. [45], within the scope of project HiLoTec, Figure 4. The blocks have dimensions of 280 × 140 × 90 mm^3 (width × depth × height) and 2 perforations with 50 mm diameter, as depicted in Figure 3a. The masonry system consists of a mechanical dry stack interlocking pattern, which enables the construction of single and double-leaf walls (Figure 3b), while promoting a simple, fast, and inexpensive construction process [2].



(**a**) (**b**)

Figure 4. Building system adopted for the experimental program [45]: (**a**) geometry of the iCEBs and (**b**) running bond pattern for single-leaf and double-leaf walls.

Before producing iCEBs, the soil was air-dried and sieved to remove any particles larger than 10 mm. The mixture of each batch of blocks was initiated by weighing each solid constituent material, which was mixed using a vertical axis mixer with rotating blades for approximately 5 min to grant complete blending. The mixture continued for a few minutes with the addition of water using a watering can. The homogenization of the mixture was controlled by visual inspection, while the quantity of water was controlled by conducting trials of the drop ball test [46], as the mixing was conducted. The use of the drop ball test was preferred for the use of the Proctor test optimum water content because the last typically resulted in an excessively dry mixture for the compaction process. After mixing, the compaction was performed using a Terstaram manual press, which allows the application of static pressures up to 4 MPa. Then, the iCEBs were cured and exposed to air under laboratory ambient conditions to an average temperature of ~19 °C and relative humidity of about 65%.

2.4. Characterization of the iCEBs

After curing for about 60 days, the produced iCEBs were characterized in terms of dimensional stability, density, compressive strength, and flexural strength. To characterize the dimensional stability (Figure 5a), a total of 10 blocks were randomly selected and identified. The three main dimensions and the diameter of the perforations were then measured three times, using a caliper with a resolution of about 0.01 mm. It should be noted that each dimension resulted from the average of the three values obtained, while the average diameter of the perforations resulted from the averaging of six measurements (three from each perforation). Furthermore, the selected blocks were also weighed using a digital scale with a resolution of 0.1 g, which was then used to compute the average density of the blocks with basis on the calculated volumes. The average values of the dimensions and the respective coefficients of variation (CoV) are presented in Table 3, from which it can be concluded that the manufactured ICEBs exhibit high regularity in their dimensional properties, with a maximum CoV of 0.3%. The weight of the iCEBs also shows small variability, since CoV is about 0.5%. Regarding the density of the iCEBs, an average value of 1987 kg/m^3 was computed, with a corresponding CoV of 0.4%. The obtained density value is significantly higher than the maximum dry density of soil obtained from the Proctor test, since the incorporated binders form a more compact granular material and part of the water of the mixture incorporates the hardened binders.

(**a**) (**b**) (**c**)

Figure 5. Test set-up for the characterization of the iCEBs produced: (**a**) geometrical stability; (**b**) compression test; and (**c**) three-point bending test.

Table 3. Average dimensions and weight of the produced iCEBs.

	Height (mm)	Length (mm)	Width (mm)	Diameter (mm)	Dry Weight (g)
Average (10 iCEBs)	93.95	281.68	140.87	48.54	6716.18
CoV (%)	0.3	0.1	0.2	0.3	0.5

The iCEBs were tested under compression according to the procedure of NP EN 772-1 [47]. Nevertheless, the tests were conducted under displacement control with a velocity of 0.004 mm/s. Two conditioning conditions of the iCEBs were considered for the tests, namely being oven-dried at 40 °C (until constant mass) and being saturated by submersion in water for 48 h. For each condition, 5 iCEBs selected randomly were tested. It should be noted that the wet–dry appraisal of the compressive strength of the iCEBs allows to evaluate qualitatively their durability against water, namely under extreme moisture conditions. In order to grant adequate contact between the testing press and the blocks, the steel plates of the mold of the compaction press (Terstaram) were used to load the blocks, since they fit the shape of the bottom and top surfaces (Figure 5b).

The results of the compression tests are presented in Table 4, in terms of average oven-dry compressive strength ($f^{d}_{c,u}$) and saturated compressive strength ($f^{s}_{c,u}$). As can be seen, $f^{d}_{c,u}$ presents a relatively high value, which correlates with the minimum requirements of international documents regulating earth construction, namely: (i) Lehmbau Regeln [48]; (ii) HB 195 [49]; (iii) NC 103 [50]; (iv) UNE 41410; (v) NMAC 14.7.4 [51]; (vi) IS 1725 [52]; (vii) MS 777 [53]; (viii) NZS 4298 [46]; (ix) ARS 674 [54] and ARS 675 [55]; and (x) FDUS 849 [56]. Furthermore, according to the standard regulating CEBs production in Spain UNE 41410 [39], the iCEBs can be classified as class BTC 5, which is the most demanding class, where the normalized dry compressive strength must be higher than 5 N/mm^2. The masonry system adopted in this study has been used in previous investigations conducted by Sturm et al. [45], Silva et al. [43], and Miranda et al. [2], using different types of soils or stabilization solutions. A very broad range of values for the dry compressive strength is reported, namely from 2.4 to 12 N/mm^2. Thus, the $f^{d}_{c,u}$ value found in this experimental program is very close to the highest limit, demonstrating good stabilization effectiveness of the proposed solution.

Table 4. Results of the compression tests of the iCEBs.

	$f^{d}_{c,u}$ (N/mm^2)	$f^{s}_{c,u}$ (N/mm^2)	$f^{s}_{c,u}/f^{d}_{c,u}$
Average (5 iCEBs)	10.9	6.3	0.58
CoV (%)	10	11	-

The value found for $f^{s}_{c,u}$ also complies with international documents regulating earth construction that demand conducting compression tests under saturated conditions, namely: (i) NBR 8491 [57] and NBR 10834 [58]; (ii) NC 103 [50]; (iii) ARS 674 [54] and ARS 675 [55]; and (iv) FDUS 849 [56]. On the other hand, the saturation of the iCEBs with water resulted in an important decrease in the compressive strength, as the ratio $f^{s}_{c,u}/f^{d}_{c,u}$ is of about 0.58. This ratio is slightly lower than the range of values (0.64–0.67) presented by Silva et al. [43], indicating a higher susceptibility of the proposed composition of the iCEBs to the presence of liquid water. Nevertheless, the significantly high value obtained for $f^{s}_{c,u}$ seems not to raise any concern regarding the mechanical and durability performance of the blocks.

The flexural strength of the iCEBs was tested according to the three-point bending test procedure presented in EN 772-6 (2001) [59], but adjustments to the setup were carried out by considering the procedure of HB 195 [49]; the test setup is shown in Figure 5c. The same oven-dried and saturated preparing conditions of the compression tests were also considered for the bending tests. For each condition, 5 iCEBs were also tested. Before testing, a small notch was made at the middle section of each iCEB to promote the occurrence of failure at the midspan. The notch was cut with a circular saw with depth and width of about 10 mm and 3.5 mm, respectively. To conduct the tests, the blocks were supported on two steel rollers with a free span of 220 mm, while the loading was applied at the mid-span section under displacement control with a velocity of 0.002 mm/s.

The results of the three-point bending tests are presented in Table 5, in terms of average oven-dry flexural strength ($f^{d}_{b,u}$) and saturated flexural strength ($f^{s}_{b,u}$). It should be noted that the dry flexural strength is a parameter not so frequently used to control the performance of the material in the international documents regulating earth construction. Nevertheless, the obtained value complies with: (i) HB 195 [49]; (ii) NMAC 14.7.4 [51]; (iii) MS 777 [53]; (iv) NZS 4298 [46]; and (v) FDUS 849 [56]. Furthermore, the studies conducted by Sturm et al. [45] and Silva et al. [43] report a broad range of values for the dry flexural strength of 0.21–2.3 N/mm^2, meaning that the tested iCEBs present an intermediate value for this property.

Table 5. Results of the three-point bending tests of the iCEBs.

	$f^{d}_{b,u}$ (N/mm^2)	$f^{s}_{b,u}$ (N/mm^2)	$f^{s}_{b,u}/f^{d}_{b,u}$
Average (5 iCEBs)	0.93	0.57	0.61
CoV (%)	5	31	-

The flexural strength is also shown to decrease with the saturation of the iCEBs in the same order of magnitude as the compressive strength, where in this case the ratio $f^{s}_{c,u}/f^{d}_{c,u}$ is about 0.61. Silva et al. [43] report ratio values (0.40–0.49) lower than those obtained in the experimental program, evidencing that the flexural strength of the proposed composition is not considerably affected by the presence of liquid water. Nevertheless, it should be noted that Silva et al. [43] reports significantly higher values for saturated flexural strength (0.7–1.1 N/mm^2).

2.5. Characteristics of the Mortar

The testing of masonry specimens with mortar joints required using a mortar, which was defined with basis on a previous investigation [60], where a cement–soil mortar was studied with a composition of 1:4.3 in weight and a water/solids ratio (W/S) of 0.34. This mortar used the same raw materials adopted in this experimental program, namely cement and soil. In this last case, the soil was previously sieved to remove all particles larger than 2 mm and smaller than 0.85 mm, to allow the adequate laying and bonding of the iCEBs. Furthermore, this mortar was used in the previous investigation [60] to lay cement-stabilized iCEBs and to grout the perforations. The properties of the mortar are presented in Table 6.

Table 6. Properties of the cement–soil mortar used in the experimental program (adapted from Ribeiro [60].

Flow table value (mm) ǀ EN-1015-3 [61]	210
Flexural strength at 28 days (MPa) ǀ EN-1015-11 [62]	0.8
Compressive strength at 28 days (MPa) ǀ EN-1015-11 [62]	2.2

2.6. Compression Tests of Masonry Specimens

After producing the ICEBs, masonry specimens were built and tested to evaluate the possibility of further exploiting the mechanical performance of the masonry system. The compressive behavior of the masonry specimens with dry stack or mortar joints was, thus, studied. For this purpose, two types of specimens were built, namely prisms and wallettes. It should be noted that the testing of prisms allows to adopt simpler testing setups, while testing wallettes is expected to allow obtaining a more representative behavior of masonry walls. The subsequent sections detail the construction of the specimens and the adopted testing procedures.

2.6.1. Prisms

The compression tests of the masonry prisms were performed considering the procedure described in the standard ASTM C 1314-03b [63], where at least three specimens must be tested with a minimum of two stacked blocks in height and with a height to thickness ratio ranging from 1.3 to 5.0. Thus, the masonry prisms were built by stacking 5 ICEBs, to which corresponds a height to thickness ratio of about 3.6. The construction of the masonry prims considered two conditions of the joints, namely prisms with dry stack (DSP) or mortar (MP) joints. The DSP specimens presented approximate dimensions of 280 × 140 × 450 mm^3 (width × depth × height), while the MP specimens presented joints with about 10 mm of thickness, which resulted in approximated dimensions of 280 × 140 × 500 mm^3 (width × depth × height). Building this last type of prism required wetting the iCEBs before laying them, to mitigate the absorption of water from the mortar.

The compression tests were conducted using a testing frame equipped with a servo-controlled actuator. As in the compression tests of the iCEBs, the steel plates of the mold of the compaction press (Terstaram) were used to grant uniform contact between the bottom and top surfaces of the prisms with the plates of the testing apparatus. Furthermore, a hinge was placed on the top plate to allow adjusting the load application due to imperfections in the geometry. The axial deformation of each specimen was measured employing four LVDTs fixed between the second and the fourth iCEB, with a length between fixation points of about 200 mm. The tests were conducted under monotonic loading in displacement control with a speed of 0.010 mm/s. Upon testing, the iCEBs of all specimens were about 90 days old, while the mortar of the MP specimens was cured for at least 28 days. The test setup of both types of masonry prisms is illustrated in Figure 6.

(**a**)

(**b**)

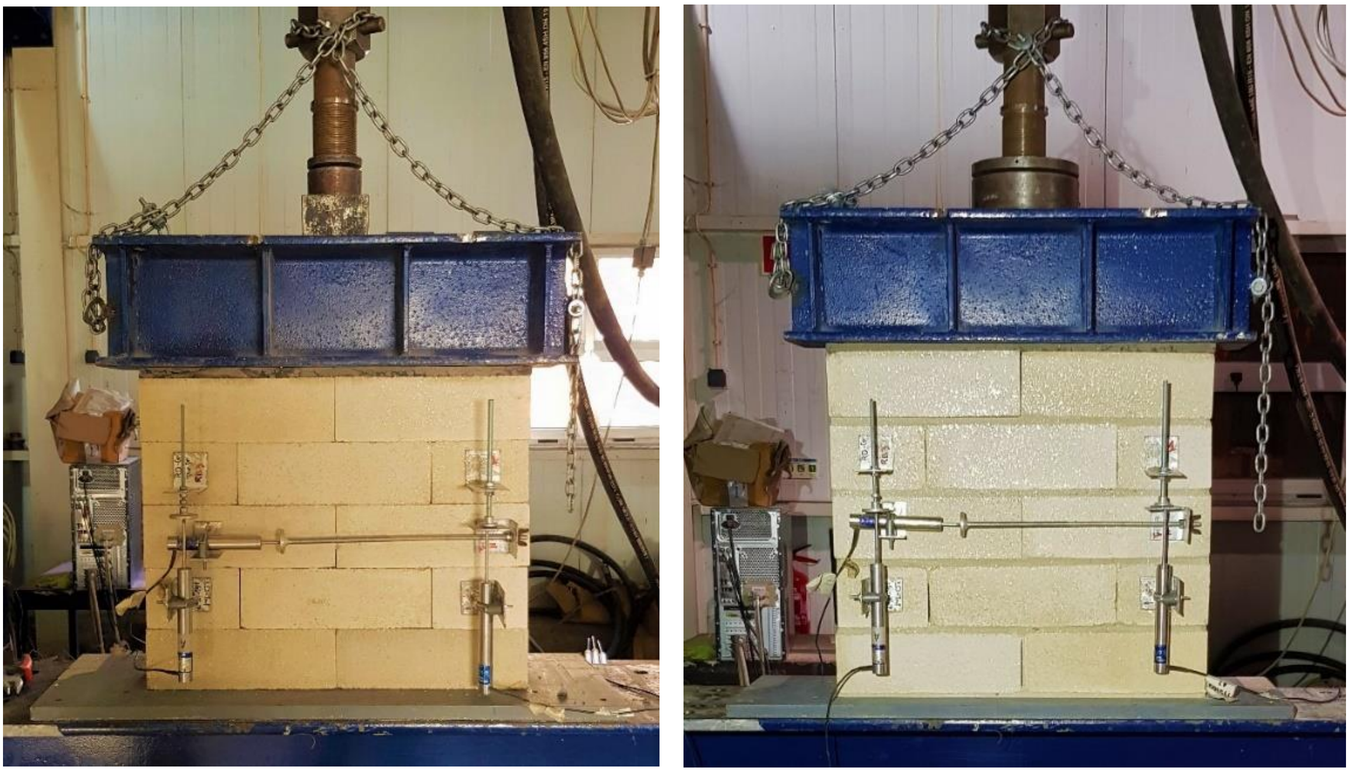
Figure 6. Setup of the compression tests conducted on masonry prisms: (**a**) DSP and (**b**) MP.

2.6.2. Wallettes

The compression tests on masonry wallettes were conducted by following the procedure described in EN 1052-1 [64]. Three wallettes were built for each joint condition (dry stack or mortar joints) using a procedure similar to that used for the masonry prisms. Each wallette was constituted by 5 courses with an extension of 2 iCEBs, where a running bond pattern was adopted. The dry stack masonry wallettes (DSW) present dimensions of $560 \times 140 \times 450$ mm^3 (width $\times$ depth $\times$ height), while the 10 mm thick bed joints of the masonry wallettes with mortar joints (MW) resulted in a dimension of $560 \times 140 \times 500$ mm^3 (width $\times$ depth $\times$ height). The construction of the MW specimens also required wetting the iCEBs before laying them.

Before conducting the compression tests, the top surface of the wallettes was regularized by applying a layer of fast hardening mortar with a thickness of about 20 mm.

The tests were conducted in a testing frame equipped with a servo-controlled actuator by applying a monotonic loading under displacement control with a speed of 0.013 mm/s. The deformations of the wallettes were monitored during the tests employing LVDTs, namely the vertical (axial) and horizontal (transversal) deformations. The vertical deformations were measured using 4 LVDTS fixed between the second and fourth courses of the two main sides of the wallettes (2 LVDTs on each side). The horizontal deformations were measured utilizing 2 LVDTs fixed to the two iCEBs of the middle course (1 LVDT on each side). Figure 7 illustrates the setup of the compression tests conducted on the two types of masonry wallettes.



(**a**) (**b**)

Figure 7. Setup of the compression tests conducted on masonry wallettes: (**a**) DSW and (**b**) MW.

3. Results and Discussion

The results of the compression tests conducted on the different masonry specimens are presented and discussed in the subsequent sections. The results are analyzed in terms of compressive strength, Young's modulus, the behavior of the stress–strain curves, and failure mode.

3.1. Prisms

The results of the compression tests conducted on the prisms are presented in Table 7, in terms of the average values of compressive strength (f_c), corresponding axial strain (ε_c), and Young's modulus (E) as well as the respective coefficient of variation (CoV). The Young's modulus of each specimen was computed as the ratio between the compressive strength and the respective axial strain value. It should be noted that one of the prisms with mortar joints was damaged during the preparation of the test; thus, it could not be tested. The mortar joint specimens (MP) present slightly higher (about 5%) compressive strength than the dry stack specimens (DSP), which is probably a result of a better and more uniform stress distribution through the joints, promoted by the bedding effect of the mortar. Yet, it should be noted that such an observation may be affected by the variability of the results and a reduced number of tested specimens. Furthermore, it should be noted that

Miranda et al. [2] has found a more expressive difference, where the compressive strength of masonry prisms with mortar joints was reported to be more than twice that of prisms with dry stack joints.

Table 7. Average results from the compression tests conducted on the masonry prisms and on the masonry wallettes (CoV in parentheses).

Specimen Type	f_c (N/mm^2)	ε_c (mm/mm)	ε_t (mm/mm)	E (N/mm^2)
DSP	4.5 (5%)	0.015 (1%)	-	283 (9%)
MP	4.7 (-)	0.008 (-)	-	544 (-)
DSW	3.7 (8%)	0.025 (-)	− 0.011 (-)	159 (-)
MW	4.4 (6%)	0.016 (11%)	− 0.005 (82%)	262 (1%)

Concerning the compressive strength of the iCEBs tested under dry conditions, reduction factors of 0.41 and 0.43 are observed for the compressive strength of the DSP and MP specimens, respectively. Such a reduction is explained both by the presence of joints and the increase in the slenderness from iCEBs to prism specimens. On the other hand, Miranda et al. [2] report less expressive reductions, with reported factors of 0.61–0.78.

The use of bed-joint mortar in the MP specimens is also shown to significantly increase (about 92%) the Young's modulus, with respect to the masonry prisms with dry stack joints. The lower stiffness of the DSP specimens is also clearly visible in the stress–strain curves of Figure 8 and is a consequence of relevant adjustment deformations occurring between the iCEBs (at the dry stack joints). On the other hand, the introduction of bed-joint mortar (MP specimens) clearly mitigates such deformations.

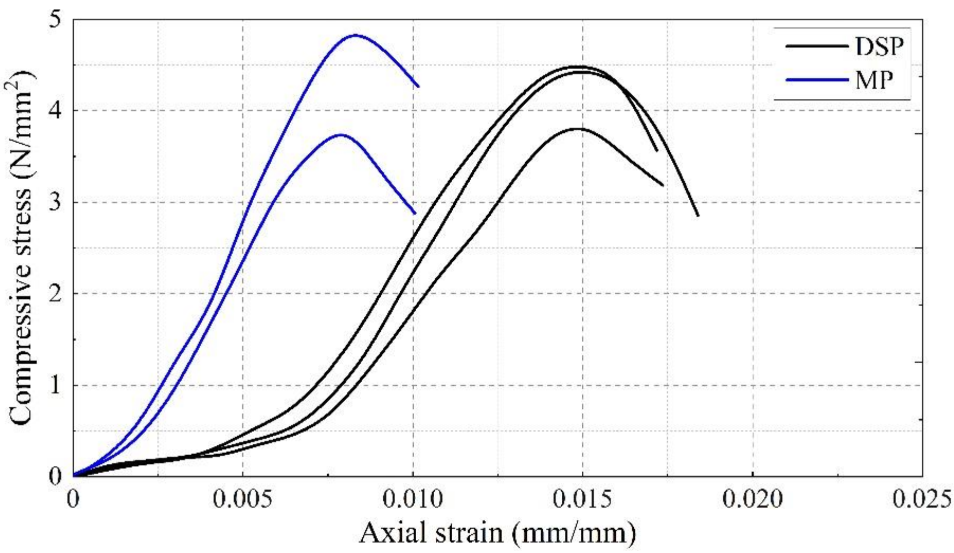


Figure 8. Stress–strain curves in compression of the prisms with dry stack (DSP) and mortar joints (MP).

The failure mode of the two types of prims is illustrated in Figure 9, where a clear difference can be observed. In the case of the DSP specimens, the failure mode is characterized by the formation of several vertical cracks spread through the prisms, with continuous development through dry stack joints. Such scattered cracking pattern seems to indicate the development of tensile stresses due to deficient contact between iCEBs, which apparently is resolved for the case of the MP specimens. In this last case, the failure mode is characterized by the formation of a main vertical crack continuously crossing several blocks.

(**a**) (**b**)

Figure 9. Failure mode of the prisms: (**a**) DSP and (**b**) MP.

3.2. Wallettes

The results of the compression tests conducted on the masonry wallettes are presented in Table 7, in terms of average values of compressive strength (f_c), corresponding axial strain (ε_c), transversal strain (ε_t), and Young's modulus (E) as well as the respective coefficient of variation (CoV). The Young's modulus was computed similarly to the prism specimens, namely as the ratio between the compressive strength and the respective axial strain value. It should be noted that the deformations of one of the wallettes with mortar joints could not be correctly measured during the respective test, due to technical problems.

As for the testing of prisms, the compressive strength of the masonry wallettes is shown to increase with the inclusion of bed-joint mortar, yet, in this case, the increase is substantially higher (about 18%). This result reinforces the idea that such an increase is promoted by the bedding effect of the mortar in providing a better and more uniform stress distribution through the joints. On the other hand, Miranda et al. [2] report a much more expressive difference of 220% to 280%. Concerning the compressive strength of the iCEBs tested under dry conditions, a reduction in the strength was also observed for the wallettes, where the reduction factors are 0.34 and 0.4 for the DSP and the MP specimens, respectively. On the other hand, the comparison of the compressive strength values from wallettes and prisms leads to the observation that both types of specimens produced similar results. Yet, the strength of the wallettes is slightly inferior, namely about 1.2 and 1.1 times for DSW and MW, respectively. Such a result seems to indicate a good correspondence between the two types of tests, which seems to contradict the higher differences observed in Sturm et al. [45] and Miranda et al. [2].

Eurocode 6 [65] proposes using Equation (1) to compute the characteristic compressive strength of masonry (f_k) with general purpose mortar.

$$f_k = K \cdot f_b^{0.7} \cdot f_m^{0.3} \quad (1)$$

where K is a constant depending on the masonry units used, f_b is the normalized compressive strength of the units, and f_m is the mortar strength. The validity of this equation was tested for the mortared masonry, by assuming a K value of 0.45, an f_b value of 10.0 N/mm^2 (see UNE 41410 [39] and NP EN 772-1 [47]), and an f_m value of 2.2 N/mm^2. This results in an f_k value of 2.9 N/mm^2, which is a safe side estimation for the obtained experimental value.

The Young's modulus of the wallettes was also found to increase substantially (about 65%) with the inclusion of bed-joint mortar. Nevertheless, the testing of prisms seems to result in significantly higher values of this parameter (about 2.1 times for DSW and about 1.8 times for MW), which can be attributed to the fact that the first is unable to completely reproduce the masonry pattern.

Figure 10 presents the stress–strain curves of both types of wallettes, where the positive side of the abscissas axis represents the axial strains, and the negative side represents the transversal strains. The curves also evidence the increment in stiffness promoted by the introduction of bed-joint mortar, which eliminates the adjustment deformations between blocks observed in the masonry wallettes with dry stack joints. Furthermore, the transversal deformations are also shown to decrease with the introduction of bed-joint mortar. Such behavior is probably explained by the cohesive bond introduced by the mortar, which limits the sliding between blocks.

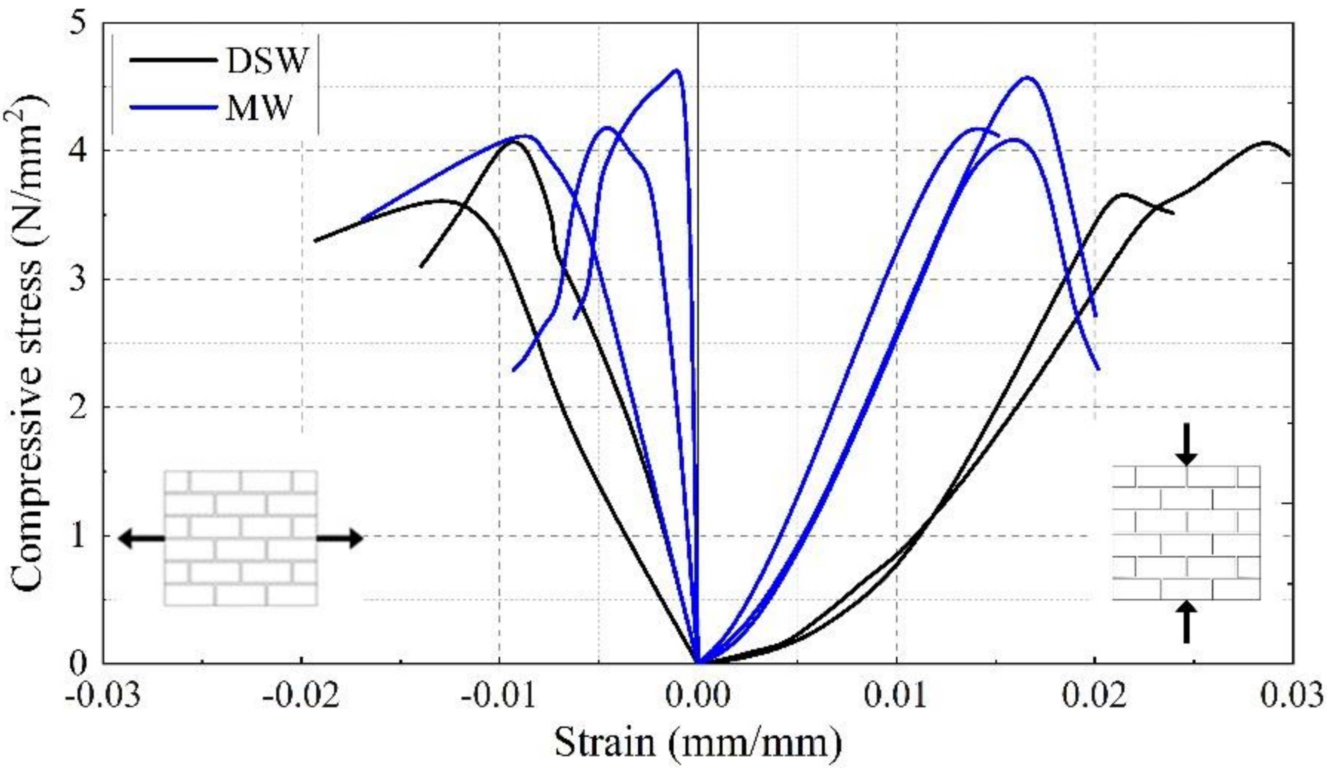
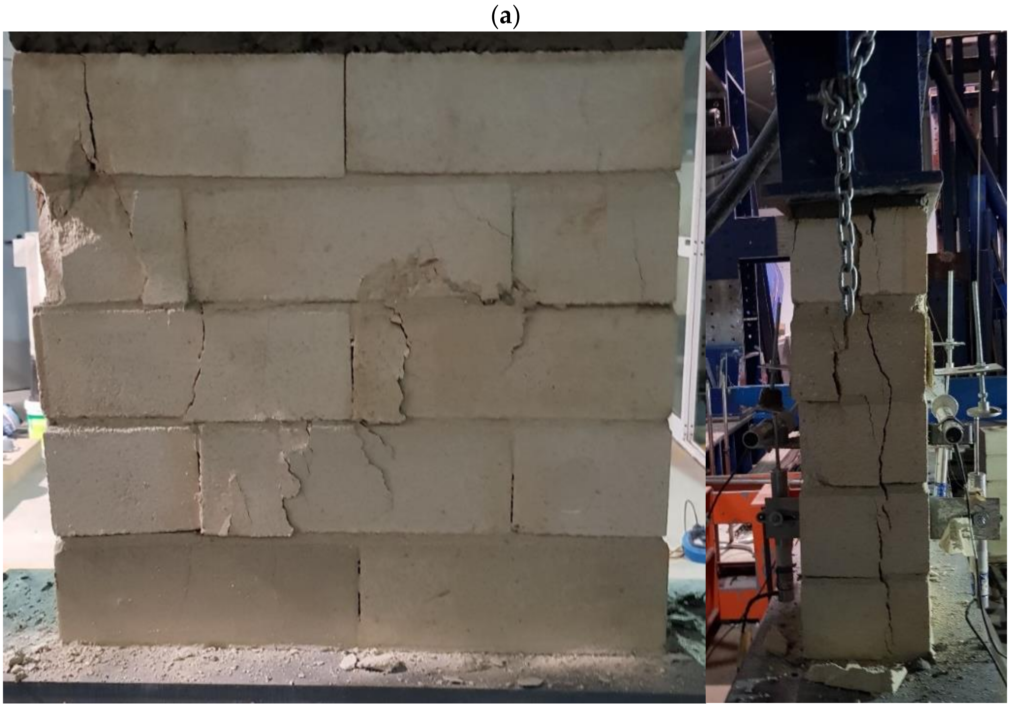


Figure 10. Stress–strain curves in compression of the wallettes with dry stack (DSW) and mortar joints (MW).

The typical failure mode of the wallettes is illustrated in Figure 11. In the case of DSW, the propagation of mostly vertical cracks that cross all the blocks of the wall can be observed, which indicates that the iCEBs fail due to bending tensile stresses. The cracks were also observed to initiate at the corners of the wallettes and develop towards the center. In the case of the MW specimens, failure is characterized by the detachment of material, which indicates the crushing failure of the iCEBs. Thus, the bed-joint mortar mitigates bending failure and leads to a better exploration of the compressive strength of the blocks.

(**a**)



(**b**)

Figure 11. Failure mode of the wallettes: (**a**) DSW and (**b**) MW.

4. Conclusions

This paper presents an experimental program dedicated to the characterization of the compressive behavior of masonry built with iCEBs, which intends to contribute to the development of a green building system that reuses, as the main raw material, excavated local soils from Northern Portugal, combined with a blended binder composed of cement and hydraulic lime. The main conclusions of this research work can be summarized as follows:

- The selected soil was characterized through geotechnical tests, which showed it to be representative of granitic residual soils typical from Northern Portugal, mainly constituted by sand size particles with little content of low activity clay. It was observed to be unsuitable for producing unstabilized CEBs, since it may lead to insufficient initial cohesion required for production purposes as well as to insufficient mechanical and durability performance.

- The conducted composition study aimed at improving the sustainability of cement stabilization of the selected soil by partial substitution with hydraulic lime. The mixture, composed of 87.5% of soil, 7.5% of cement, and 5% of lime, was shown to be the most adequate for producing CEBs with adequate mechanical performance. It was also evidenced that more than 10% of binder was required to produce CEBs, as sufficient initial cohesion was only observed to develop in the compositions with 12.5% or higher of these fine materials.
- iCEBs were produced with the selected mixture and were characterized for dimensional symmetry as well as for compressive and flexural strength under oven-dry and saturated conditions. In general, the tested iCEBs greatly exceeded the minimum required properties specified in international standards, demonstrating the viability of the production of the proposed building system in Northern Portugal.
- The compressive behavior of the iCEBs masonry was characterized by testing prisms and wallettes, considering both cases of dry stack and mortar joints. The conducted tests allowed to observe a strong reduction (reduction factor of 0.34–0.13) in compressive strength from the blocks to the masonry specimens, which is explained both by the presence of joints and the higher slenderness of the masonry specimens. Furthermore, the two types of specimens conducted similar results in terms of compressive strength, yet the Young's modulus values were considerably higher in the prism specimens. The tests also confirmed that using mortar in the bed joints allows to improve the compressive strength (5%–18% increase), promoted by a better and more uniform stress distribution through the joints and less severe bending failure of the blocks. The use of bed-joint mortar also allows to increase the Young's modulus (65–92%) of the masonry, since pronounced adjustment deformations occur in masonry with dry stack joints.

Finally, the conducted experimental program allows for the conclusion that the proposed building system constitutes a feasible solution for sustainable construction in Northern Portugal, based on iCEBs masonry, where the mechanical behavior is substantially improved by using bed-joint mortar. Furthermore, the adopted blended binder, composed of cement and hydraulic lime, seems to not compromise the performance of the building solution, so the study of the manufacturing cost and environmental impact should be addressed in future research.

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References

1. Guillaud, H.; Joffroy, T.; Odul, P. Compressed Earth Blocks: Manual of Design and Construction. 1995. Available online: https://old.ecohabitar.org/wp-content/uploads/2012/01/04-5793-1.pdf (accessed on 8 February 2020).
2. Miranda, T.; Silva, R.A.; Oliveira, D.V.; Leitão, D.; Cristelo, N.; Oliveira, J.; Soares, E. ICEBs stabilised with alkali-activated fly ash as a renewed approach for green building: Exploitation of the masonry mechanical performance. *Constr. Build. Mater.* **2017**, *155*, 65–78. [CrossRef]
3. Qu, B.; Stirling, B.J.; Jansen, D.C.; Bland, D.W.; Laursen, P.T. Testing of flexure-dominated interlocking compressed earth block walls. *Constr. Build. Mater.* **2015**, *83*, 34–43. [CrossRef]
4. Leitão, D.; Barbosa, J.; Soares, E.; Miranda, T.; Cristelo, N.; Briga-Sá, A. Thermal performance assessment of masonry made of ICEB's stabilised with alkali-activated fly ash. *Energy Build.* **2017**, *139*, 44–52. [CrossRef]
5. Thompson, D.; Augarde, C.; Osorio, J.P. A review of current construction guidelines to inform the design of rammed earth houses in seismically active zones. *J. Build. Eng.* **2022**, *54*, 104666. [CrossRef]
6. Gomes, M.I.; Lopes, M.; de Brito, J. Seismic resistance of earth construction in Portugal. *Eng. Struct.* **2011**, *33*, 932–941. [CrossRef]
7. Avila, F.; Puertas, E.; Gallego, R. Characterization of the mechanical and physical properties of unstabilized rammed earth: A review. *Constr. Build. Mater.* **2021**, *270*, 121435. [CrossRef]
8. Elahi, T.E.; Shahriar, A.R.; Islam, M.S. Engineering characteristics of compressed earth blocks stabilized with cement and fly ash. *Constr. Build. Mater.* **2021**, *277*, 122367. [CrossRef]
9. Islam, M.S.; Elahi, T.E.; Shahriar, A.R.; Mumtaz, N. Effectiveness of fly ash and cement for compressed stabilized earth block construction. *Constr. Build. Mater.* **2020**, *255*, 119392. [CrossRef]
10. Correia, M. Universalidade e Diversidade da Arquitectura de Terra. In *Terra: Forma de Construir Arquitectura. Antropologia*; Arqueologia: Porto, Portugal, 2016.
11. Miccoli, L.; Müller, U.; Fontana, P. Mechanical behaviour of earthen materials: A comparison between earth block masonry, rammed earth and cob. *Constr. Build. Mater.* **2014**, *61*, 327–339. [CrossRef]
12. CJ-G Engineering and Undefined 1979, Current Practice in Designing Earth Retaining Structures. Trid.Trb.Org. Available online: https://trid.trb.org/view/146595 (accessed on 8 February 2020).
13. Barbero-Barrera, M.M.; Jové-Sandoval, F.; Iglesias, S.G. Assessment of the effect of natural hydraulic lime on the stabilisation of compressed earth blocks. *Constr. Build. Mater.* **2020**, *260*, 119877. [CrossRef]
14. Van Damme, H.; Houben, H. Earth concrete. Stabilization revisited. *Cem. Concr. Res.* **2018**, *114*, 90–102. [CrossRef]
15. Kasinikota, P.; Tripura, D.D. Tripura, Evaluation of compressed stabilized earth block properties using crushed brick waste. *Constr. Build. Mater.* **2021**, *280*, 122520. [CrossRef]
16. Anglade, E.; Aubert, J.-E.; Sellier, A.; Papon, A. Physical and mechanical properties of clay–sand mixes to assess the performance of earth construction materials. *J. Build. Eng.* **2022**, *51*, 104229. [CrossRef]
17. Zami, M.S.; Lee, A. Economic benefits of contemporary earth construction in low-cost urban housing—State-of-the-art review. *J. Build. Apprais.* **2010**, *5*, 259–271. [CrossRef]
18. Morel, J.-C.; Pkla, A.; Walker, P. Compressive strength testing of compressed earth blocks. *Constr. Build. Mater.* **2007**, *21*, 303–309. [CrossRef]
19. Kasinikota, P.; Tripura, D.D. Prediction of physical-mechanical properties of hollow interlocking compressed unstabilized and stabilized earth blocks at different moisture conditions using ultrasonic pulse velocity. *J. Build. Eng.* **2022**, *48*, 103961. [CrossRef]
20. Ledesma, E.F.; Jiménez, J.R.; Ayuso, J.; Fernández, J.M.; de Brito, J. Maximum feasible use of recycled sand from construction and demolition waste for eco-mortar production—Part-I: Ceramic masonry waste. *J. Clean. Prod.* **2015**, *87*, 692–706. [CrossRef]
21. Riza, F.; Rahman, I.A. The properties of compressed earth-based (CEB) masonry blocks. In *Eco-Efficient Masonry Bricks and Blocks: Design, Properties and Durability*; Elsevier Inc.: Amsterdam, The Netherlands, 2015; pp. 379–392.
22. Jannat, N.; Hussien, A.; Abdullah, B.; Cotgrave, A. Application of agro and non-agro waste materials for unfired earth blocks construction: A review. *Constr. Build. Mater.* **2020**, *254*, 119346. [CrossRef]
23. Rivera, J.; Coelho, J.; Silva, R.; Miranda, T.; Castro, F.; Cristelo, N. Compressed earth blocks stabilized with glass waste and fly ash activated with a recycled alkaline cleaning solution. *J. Clean. Prod.* **2021**, *284*, 124783. [CrossRef]
24. Rivera, J.F.; de Gutiérrez, R.M.; Ramirez-Benavides, S.; Orobio, A. Compressed and stabilized soil blocks with fly ash-based alkali-activated cements. *Constr. Build. Mater.* **2020**, *264*, 120285. [CrossRef]
25. Poorveekan, K.; Ath, K.M.S.; Anburuvel, A.; Sathiparan, N. Investigation of the engineering properties of cementless stabilized earth blocks with alkali-activated eggshell and rice husk ash as a binder. *Constr. Build. Mater.* **2021**, *277*, 122371. [CrossRef]
26. Ojo, E.B.; Bello, K.O.; Mustapha, K.; Teixeira, R.S.; Santos, S.F.; Savastano, H. Effects of fibre reinforcements on properties of extruded alkali activated earthen building materials. *Constr. Build. Mater.* **2019**, *227*, 116778. [CrossRef]
27. Riza, F.V.; Rahman, I.A.; Zaidi, A.M.A. Durability of Lime Stablised Earth Blocks. In *Challenges of Concrete Construction: Volume 5, Sustainable Concrete Construction*; Thomas Telford Publishing: London, UK, 2002; pp. 645–654.
28. Riza, F.V.; Rahman, I.A.; Zaidi, A.M.A. Possibility of Lime as a Stabilizer in Compressed Earth Brick (CEB). *Int. J. Adv. Sci. Eng. Inf. Technol.* **2011**, *1*, 582–585. [CrossRef]
29. Miqueleiz, L.; Ramírez, F.; Seco, A.; Nidzam, R.; Kinuthia, J.; Abu Tair, A.; Garcia, R. The use of stabilised Spanish clay soil for sustainable construction materials. *Eng. Geol.* **2012**, *133–134*, 9–15. [CrossRef]

30. Nagaraj, H.B.; Sravan, M.V.; Arun, T.G.; Jagadish, K.S. Role of lime with cement in long-term strength of Compressed Stabilized Earth Blocks. *Int. J. Sustain. Built Environ.* **2014**, *3*, 54–61. [CrossRef]
31. *NP-EN-933-1*; Test for Geometrical Properties of Aggregates. Part 1: Determination of Particle Size Distribution-Sieving Method. IPQ: Caparica, Portugal, 2002.
32. *NP 143*; Soils: Determination of the Consistency Limits. LNEC: Lisbon, Portugal, 1969.
33. *LNEC E197*; Soils: Compaction Test. LNEC: Lisbon, Portugal, 1966.
34. *NP-83*; Soils, Particle Density Test, Portuguese Standard. IPQ: Caparica, Portugal, 1965. (In Portuguese)
35. *NP-EN-933–9*; Tests for Geometrical Properties of Aggregates—Part 9: Assessment of Fines—Methylene Blue Test. IPQ: Caparica, Portugal, 2009.
36. *NP EN 933–8*; Tests for Geometrical Properties of Aggregates—Part 8: Assessment of Fines—Sand Equivalent Test. IPQ: Caparica, Portugal, 2012.
37. Viana da Fonseca, A. Repositório Aberto da Universidade do Porto: Geomecânica dos Solos Residuais do Granito do Porto: Critérios Para Dimensionamento de Fundações Directas. Ph.D. Thesis, University of Porto, Porto, Portugal, 1996.
38. *UNE 41410*; Compressed Earth Blocks for Walls—Definitions, Specifications and Testing Methods. AENOR: Madrid, Spain, 2008.
39. *UNE 41410*; Bloques de Tierra Comprimada Para Muros y Tabiques: Definiciones, Especificaciones y Métodos de Ensayo. AENOR: Madrid, Spain, 2008.
40. Doat, F.; Hays, P.; Houben, A.; Matuk, H.; Vitoux, S. *Building with Earth*; The Mud Village Society: New Delhi, India, 1991.
41. Fabbri, G.T.P. Caracterização da Fração Fina de Solos Tropicais Através da Adsorção de Azul de Metileno. Ph.D. Thesis, Biblioteca Digital de Teses e Dissertações da Universidade de São Paulo, São Carlos, Brazil, 1994.
42. Silva, R.A.; Oliveira, D.V.; Miranda, T.; Cristelo, N.; Escobar, M.C.; Soares, E. Rammed earth construction with granitic residual soils: The case study of northern Portugal. *Constr. Build. Mater.* **2013**, *47*, 181–191. [CrossRef]
43. Silva, R.A.; Soares, E.; Oliveira, D.; Miranda, T.; Cristelo, N.M.; Leitão, D. Mechanical characterisation of dry-stack masonry made of CEBs stabilised with alkaline activation. *Constr. Build. Mater.* **2015**, *75*, 349–358. [CrossRef]
44. Soares, E. Melhoria do solo Residual Granítico com Recurso à Activação Alcalina de Cinzas Volantes. Master's Thesis, University of Trás-os-Montes e Alto Douro, Vila Real, Portugal, 2013.
45. Sturm, T.; Ramos, L.F.; Lourenço, P.B. Characterization of dry-stack interlocking compressed earth blocks. *Mater. Struct.* **2015**, *48*, 3059–3074. [CrossRef]
46. *NZS-4298*; Materials and Workmanship for Earth Buildings. New Zealand Technical Committee: Wellington, New Zealand, 1998.
47. *NP-EN-772-1*; Métodos de Ensaio de Blocos Para Alvenaria—Parte 1: Determinação da Resistência à Compressão. IPQ: Caparica, Portugal, 2002.
48. Regeln, L. *Lehmbau Regeln: Begriffe—Baustoffe—Bauteile (German Edition)*; Springer: Berlin/Heidelberg, Germany, 2008.
49. *HB-195*; The Australian Earth Building Handbook. Standards Australia International Ltd.: Sydney, NSW, Australia, 2009.
50. *NC-103*; Blocs de Terre Comprimée: Norme de Définition. Classification et désignation des Blocs de Terre Comprimée (French Version). Center for the Development of Industry: Brussels, Belgium, 2002.
51. *NMAC-14.7.4.*; New Mexico Earthen Building Materials Code. Construction Industries Division, Regulation and Licensing Department: Santa Fe, NM, USA, 2009.
52. *IS-1725*; 2013. Stabilized Soil Blocks Used in General Building Construction—Specification (Second Revision). Bureau of Indian Standards: New Delhi, India, 2016. Available online: https://nrega.nic.in/netnrega/writereaddata/Circulars/1568Specification_of_DifferentAppropriateTechnologiesforProductionofBuildingMaterials&ConstructionofBuildings.pdf (accessed on 12 July 2022).
53. *MS-777*; Stabilised Soil Blocks—Specification. Malawi Standards: Blantyre, Malawi, 2007; 15.
54. *ARS-674*; Compressed Earth Blocks—Technical Specifications for Ordinary Compressed Earth Blocks. Center for the Development of Industry: Brussels, Belgium, 1996; pp. 1–5.
55. *ARS-675*; Compressed Earth Blocks—Technical Specifications for Facing Compressed Earth Block Masonry. Center for the Development of Industry: Brussels, Belgium, 1996; 6.
56. *FDUS-849*; Specification for Stabilized Soil Blocks. Uganda Standard: Kampala, Uganda, 2009.
57. *NBR-8491*; Tijolo Maciço de Solo-Cimento. ABNT: Rio de Janeiro, Brasil, 1964.
58. *NBR-10834*; Bloco Vazado de Solo-Cimento Sem Função Estrutural. ABNT: Rio de Janeiro/São Paulo, Brazil, 1994.
59. *BS-EN-772-6*; Methods of Test for Masonry Units—Part 6: Determination of Bending Strength of Aggregate Concrete Masonry Units. BSI: London, UK, 2001.
60. Ribeiro, A.M.F. Análise Experimental do Comportamento ao Corte de Paredes Reforçadas em Alvenaria de BTC. Master's Thesis, Universidade do Minho, Braga, Portugal, 2015.
61. *EN-1015-3*; Methods of Test for Mortar for Masonry—Part 3: Determination of Consistence of Fresh Mortar (by Flow Table). European Committee for Standardization: Brussels, Belgium, 1999.
62. *EN-1015-11*; Determination of Flexural and Compressive Strength. European Committee for Standardization: Brussels, Belgium, 1999.
63. *A.C.-03b*; Standard Test Method for Compressive Strength of Masonry Prisms. *ASTM Committe Stand*. 2003. Available online: https://www.astm.org/DATABASE.CART/HISTORICAL/C1314-03B.htm (accessed on 24 November 2019).

64. *EN-1052-1*; Methods of Test for Masonry—Part 1: Determination of Compressive Strength. European Committee for standardization: Brussels, Belgium, 1999.
65. *EN 1996-1-1*; Eurocode 6: Design of Masonry Structures—Part 1–1: Common Rules for Reinforced and Unreinforced Masonry Structures. European Committee for Standardization: Brussels, Belgium, 2005.