buildings

MDPI

Article

Improvement of Mechanical Properties of Compressed Earth Blocks with Stabilising Additives for Self-Build of Sustainable Housing

Jorge López-Rebollo [1,*], Xavier Cárdenas-Haro [2,3], Juan Pablo Parra-Vargas [2], Kevin Narváez-Berrezueta [2] and Julver Pino [3]

1 Department of Cartographic and Land Engineering, Higher Polytechnic School of Ávila, University of Salamanca, Hornos Caleros, 50, 05003 Ávila, Spain

2 Facultad de Arquitectura y Urbanismo, Virtual Tech, Universidad de Cuenca, Av. 12 de Abril s/n y Av. Loja, Cuenca 010201, Ecuador

3 Facultad de Ingeniería, Departamento de Ingeniería Civil, Universidad de Cuenca, Av. 12 de Abril s/n y Av. Loja, Cuenca 010201, Ecuador

* Correspondence: jorge_lopez@usal.es

Abstract: Earth building technologies are increasingly being used to promote a natural and sustainable construction model and to empower self-building in resource-limited areas. This work focuses on investigating the use of different types of stabilising additives in compressed earth blocks (CEBs). To this end, empirical studies and laboratory analyses of earth samples taken from different sites in Ecuador were combined. Once the most suitable earth for use as a building material was determined, four types of CEBs were produced using equipment designed ad hoc to encourage self-building: earth-based, fibre additives, cementitious additives, and additives of other origin. The panels were characterised by means of compression tests to analyse their mechanical behaviour, obtaining the most promising results for the additivated samples with the highest percentage of cement and for the sample containing ground reeds, with a compressive strength of 3.3 MPa and 0.7 MPa, respectively. These samples were then subjected to more extensive tests using digital image correlation to analyse their full field strains and cracks, where the samples stabilised with cement showed a more homogeneous and consistent behaviour. Finally, an economic and comparative study with conventional construction systems was carried out to demonstrate the feasibility of using the proposed earth materials for cleaner and more economical buildings, mainly due to cost savings and lower pollution in terms of transport when using local resources.

Keywords: sustainable construction; earthen architecture; compressed earth block; earthen materials; mechanical properties; digital image correlation

check for updates

Citation: López-Rebollo, J.; Cárdenas-Haro, X.; Parra-Vargas, J.P.; Narváez-Berrezueta, K.; Pino, J. Improvement of Mechanical Properties of Compressed Earth Blocks with Stabilising Additives for Self-Build of Sustainable Housing. *Buildings* **2024**, *14*, 664. https://doi.org/10.3390/buildings14030664

Academic Editors: Mariana Correia and Telma Ribeiro

Received: 2 February 2024
Revised: 20 February 2024
Accepted: 27 February 2024
Published: 1 March 2024

1. Introduction

The materials used for building and construction are abundant but non-renewable resources, so their availability is not unlimited worldwide. In fact, high exploitation and its associated costs can lead to shortages in the medium and long term in countries with very high production [1]. Together with the high consumption of resources, the production of this type of material, such as concrete, is responsible for up to 8% of world CO_2 emissions [2], so it is necessary to establish construction systems related to the concepts of sustainability and circular economy. On the other hand, there are certain regions in which the extraction of raw materials, such as aggregates, is not feasible due to their availability or the available means [3]. In this context, earth construction is seen as an alternative to the use of other materials such as concrete, taking advantage of its potential as a local material and reducing waste generation according to the concepts of economy and sustainable development [4].

The use of these earthen building technologies is so widespread that it is estimated that approximately one-third of the world's population lives in earthen buildings [5]. It is a type of construction that was widely used until the beginning of the twentieth century and that regained popularity at the end of the 1970s after the energy crisis in Europe [6], so it is essential to find the tools to improve its potential and continue its use in the 21st century.

There are different earth construction techniques, such as adobe, rammed earth, rammed earth blocks or compressed earth blocks (CEBs). Among them, CEBs are very versatile elements obtained from wet earth compression that can be used in load-bearing walls, enclosures, heat-accumulating walls or as a replacement for conventional bricks [7]. The production of these types of earthen materials requires only 1% of the energy used to produce the same volume of conventional concrete [8], which means a considerable saving in energy and CO_2 emissions. In addition, the savings in time, cost and pollution caused by their transportation make CEBs more environmentally friendly than other building materials [4].

There are different standards around the world that deal with the manufacture of these materials [9]. The most internationally recognised standards are the New Zealand standard [10,11], the American Society for Testing and Materials (ASTM) [12] or the Spanish UNE [13]. Nevertheless, to this day, there is no standardisation or accurate knowledge of these types of materials [14]. Differences in composition due to the local nature of these materials result in heterogeneous properties and behaviour [15], making global standardisation difficult.

Despite the fact that by increasing pressures, adequate strengths can be achieved for CEBs [16], in order to improve the mechanical performance of CEBs, the research trend is moving towards the introduction of stabilisers for the manufacture of stabilised compressed earth blocks (SCEBs) [17], also known as soil cement blocks or soil–cement bricks [18]. The most commonly used stabilisers are Portland cement, lime or asphalt emulsion [4]. In addition, other additives can be added to improve their properties. For example, natural fibres improve thermal properties [19]; oils, fats or waxes allow waterproofing [20]; and biopolymers improve cohesion so that they improve both the strength and durability of the soil [21]. Nevertheless, the efficiency of these types of stabilisers is related to the earth's composition, so it is necessary to carry out in-depth analyses and studies to verify the viability of these materials [22].

Furthermore, the incorporation of these types of additives entails an alteration of their mechanical properties, causing the material to behave differently. In this sense, composite materials with the incorporation of fibres or other additives usually present a high degree of heterogeneity [23]. Additionally, the failure of the material significantly depends on how and where the fracture occurs. This means that strains, especially the so-called peak strain prior to fracture, can differ greatly depending on the measurement area.

Generally, conventional mechanical characterisation techniques use devices such as extensometers, LVDT or strain gauges, which have a local nature and require direct contact with the material. In this sense, earth-derived materials generally present problems due to the disaggregation of the material when it begins to deform, even before failure [24]. Measurement with these devices is conditional on the absence of cracks and disaggregation of the material, as this would prevent further data collection. In contrast to this type of technique, other full-field techniques have emerged that allow monitoring of the complete behaviour without the need for contact with the material [25,26]. One of the most widely used techniques for the analysis of full-field displacements and strains is digital image correlation (DIC). This is a technique that allows analysis of the complete surface of the material using images of the sample acquired while it is subjected to load tests [27]. This technique can be used for flat specimens in its two-dimensional approach and for specimens with greater curvature through its three-dimensional approach [28]. In particular, the 2D approach employed in this study has been used to obtain the strains and to monitor damage progression [29] in works on materials with similar heterogeneous behaviour, including earth-derived aggregates such as sustainable concretes [30] and cementitious materials that incorporate fibres [31]. Nevertheless, it is a novel technique in the field of earthen materials, and there are few studies of its application due to the sample preparation requirements, although it has proved to be a promising technique for obtaining full-field strains and cracks [32]. Perić Fekete et al. studied the failure mechanisms of rammed earth walls under seismic behaviour using the DIC technique [33]. Nabouch et al. also used DIC to record the evolution of cracks in rammed earth walls [34]. In this way, the peak strain can be measured more accurately, and parameters representative of the real behaviour of the material can be obtained, as it is possible to analyse the strains over the entire surface, including the rupture zone and remote areas.

Consequently, this work aims to advance knowledge concerning the introduction of stabilising additives of different natures in CEBs made with earth from different locations in Ecuador. The aim is to move towards a more sustainable building model, where conventional materials such as concrete and steel can be replaced by these earthen materials with improved mechanical properties, which make use of local and natural resources and generate less pollution and waste. This study seeks to promote the self-build of sustainable housing so that areas with limited resources and difficult access to conventional materials can realise the potential of earthen materials. Empirical tests will be combined with laboratory tests to characterise these types of earth, which will allow the selection of the most adequate option for the manufacture of CEBs. Subsequently, mechanical characterisation tests will determine the feasibility of SCEBs in the manufacturing, transport and construction processes. Finally, these tests will be complemented with DIC analysis to monitor and evaluate its behaviour. In addition, an economic study comparing the production costs of the additive-enhanced CEB solution with other conventional construction techniques is proposed to promote earthen architecture.

Following this introduction, Section 2 describes the materials and techniques used for this research. In Section 3, the experimental results of the physical and mechanical tests are shown and a discussion of these results is included. Section 4 provides an economic analysis of the feasibility of the products studied. Finally, in Section 5, the main conclusions on the suitability of introducing these materials in the construction industry are drawn and future research directions are discussed.

2. Materials and Methods

This work focuses on the fabrication and characterisation of compressed earth blocks with different additives for stabilisation. First, earth samples from different locations are selected and characterised through the use of empirical and laboratory physical tests. Then, the production of CEBs is carried out using the selected earth samples. For their manufacture, different additives were selected in order to achieve stabilisation while considering both economic and environmental aspects. These blocks were mechanically characterised by means of compression tests to check whether they could be used as building elements in accordance with the standards. Finally, an economic analysis was carried out to compare the unit cost of the manufactured blocks with other conventional construction techniques and materials. Figure 1 shows a schematic diagram of the workflow followed.

2.1. Earth Materials

Initially, different types of earth were selected and analysed to determine the best option for the manufacture of the compressed earth blocks. In order to achieve greater variability in the samples and to analyse earth of different provenance, it was decided to select samples from four different locations, although all of them were located in the province of Azuay, Ecuador. The location was determined based on the availability of extractable material and the existence of construction material factories in the vicinity. In addition, different colours of earth were taken into account to widen the spectrum of selection and experimentation. The location and coordinates of the individual samples are shown in Table 1.

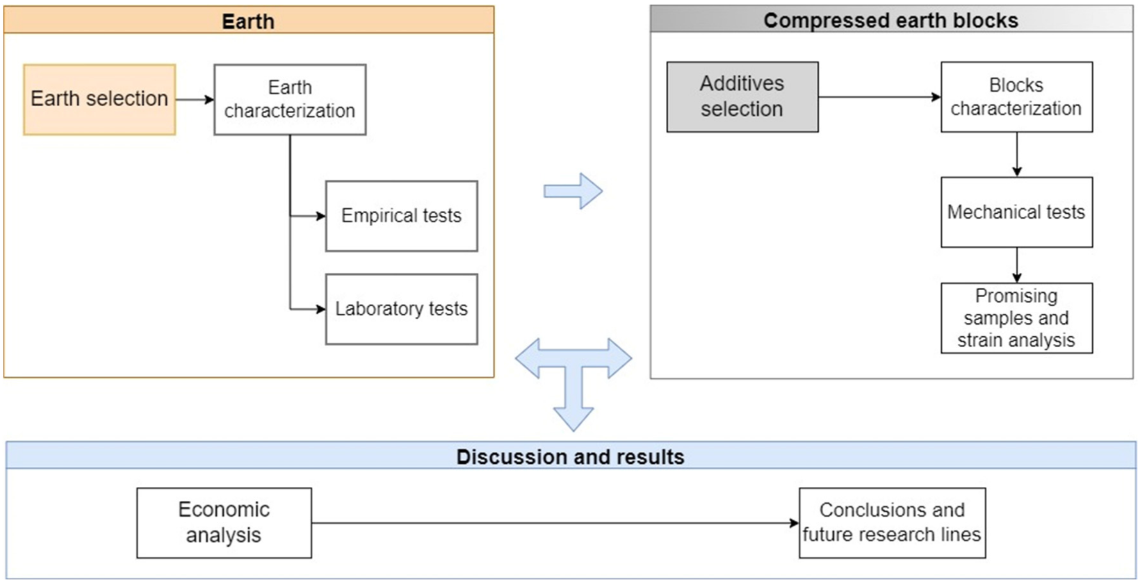


Figure 1. Workflow diagram.

Table 1. Location and coordinates of selected earth samples.

Nomenclature	City	Zone	Latitude	Longitude
E_CC	Cuenca	Challuabamba	−2.859099	−78.921227
E_CM	Cuenca	Monay	−2.916045	−78.973492
E_CN	Cuenca	Nulti	−2.866469	−78.923978
E_PD	Pucará	Deuta	−3.321508	−79.395789

2.2. Earth Characterisation

The selected earth samples were analysed and subjected to different types of tests. Since there are no specific standards for this type of materials and for all the tests in the country where the samples were taken, standards from nearby countries such as Colombia, Peru or the USA were also used.

On the one hand, empirical tests allow us to gain generic knowledge of the samples and to understand some of their properties, such as humidity or the presence of sand, silt and clay [35]. Among these tests, the following can be highlighted according to the Peruvian standard E.080 [36]:

- The odour test allows for the identification of organic matter or humus.
- The bite test allows for the differentiation of the predominance of clay in the stickiest samples.
- The washing test identifies whether the sample is sandy, silty or clayey, depending on the need to use less or more water to remove debris and dirt.
- The cut test consists of cutting the sample and determining whether clay is predominant when seen as shiny or silts if the cut is opaque.
- The ball test consists of dropping a ball on a flat surface and determining its composition so that the sample contains more clay if it does not flatten and crack and less if it breaks up.
- The consistency test requires moulding the sample into an earthworm shape, thus identifying the appropriate moisture content to form a 3 mm earthworm shape. This sample is then shaped into a ball to be dried for 48 h. If the ball is easy to break, it will have a low clay content, whereas if it is more consistent, it will have a higher clay content. If it is not possible to form the ball, it is identified as a sandy sample.

On the other hand, laboratory tests allow the composition and properties of the earth to be determined more accurately.

- Granulometric analysis allows the earth to be classified into gravel, sand, silt and clay according to the particle size that passes through each of the sieves [37].
- The plasticity test allows us to know the plastic limit. Thanks to this test, it is also possible to obtain properties such as the plasticity index, tenacity, liquidity and consistency [38].
- The compaction test or the standard Proctor test allows for the determination of the moisture–density ratio of the compacted material [39].

2.3. Compressed Earth Blocks

Once the study of the earth was carried out, the CEBs were manufactured using the selected solution as the raw material. The panels were designed to be used in the Sandino construction system, so the proposed dimensions were 30 cm × 45 cm × 7 cm, which are the height, width and thickness dimensions, respectively.

The CEB manufacturing process consists of three main phases: (i) drying and sifting of the material, (ii) dosing and compacting of the material, and (iii) the curing and drying of the CEBs.

Initially, 4 m^3 of earth was collected, spread and dried for seven days to facilitate sifting, as a maximum particle size of 4.8 and 5 mm is required, according to Brazilian and Colombian regulations, respectively. To facilitate the sifting process, as well as the large-scale implementation of the manufacturing methodology in isolated communities with low resources, a sifting cylinder was designed (Figure 2). The cylinder is 30 cm in diameter and 1 m long and is made of a perforated metal mesh with 5 mm holes. A gate is incorporated in the central section through which the material can be fed into the tank and the larger particles can be discharged. This cylinder performs the simultaneous function of crushing and sifting using a rotating mechanism with a speed of 40 rpm.

Figure 2. Sifting cylinder manufactured for the crushing and sifting of the earth.

Following the same criteria mentioned above, a hydraulic press (Figure 3) was designed for the manufacture of the CEBs, consisting of steel profiles with a capacity of 50 tonnes, which is equivalent to a pressure of 1.82 MPa, considering the surface area of the panels.

Figure 3. Hydraulic press manufactured for pressing compressed earth blocks.

The dosages used for the manufacture of the stabilised CEBs (Figure 4) can be grouped into four main groups (Table 2): (i) reference, consisting only of earth and water; (ii) fibres, using the base bio-fibres as additive and natural white glue paste to facilitate adhesion; (iii) cementing agents, in this case the cement acting as a stabiliser; and (iv) others, using additives such as asphalt emulsion. Based on the analysis of the earth samples, E_CM earth was used for the manufacture of all samples except for sample PR_01, where E_CN earth was chosen. Taking into account the Proctor optimum for the selected earth, a water content of 20% was used for the cementitious samples as they have a higher water loss during the curing process, and a lower water content of 15% was used for the rest of the samples.

Figure 4. Storage and curing of the manufactured compressed earth blocks.

Table 2. Dosages and additives used for the manufacture of stabilised compressed earth blocks.

Nomenclature	Water %	Additive
PR_01	15	-
PR_02	15	-
PF_01	15	5% glue + 5% sawdust
PF_02	15	5% glue + 5% cabuya
PF_03	15	5% glue + 5% ground reed
PF_04	15	5% glue + 5% skeleton reed
PF_05	15	5% glue + 5% totora
PC_01	20	20% lime
PC_02	20	5% cement
PC_03	20	10% cement
PC_04	20	15% cement
PC_05	20	20% cement
PC_06	20	25% cement
PO_01	15	7% asphalt emulsion

2.4. Mechanical Characterisation of Compressed Earth Blocks

The compressed earth blocks manufactured were evaluated by means of compression tests according to guideline NTC 5324 [40], which classifies CEB into three types according to their compressive strength: CEB 20 for a strength of 2 MPa, CEB 40 for 4 MPa and CEB 60 for 6 MPa.

To carry out these tests, an electromechanical test machine, Concrete 2000X by Shimadzu (Kyoto, Japan), was used. The machine was equipped with a UH-X type control measuring unit and a load cell of 2000 kN. For the compression tests, steel profiles were used as compression devices with a 4 mm triplex sheet to homogenise the surfaces in contact. The test was set up at a constant displacement rate of 0.02 mm/s according to guideline NTC 5324 [40].

The compression tests were complemented by strain analysis. For this purpose, the digital image correlation technique [27] was used in a two-dimensional approach. This technique allows displacements and strains to be obtained during tests by acquiring images under different loading states. The images in each state are compared with an initial image without strain in order to obtain the displacement and strain of the sample.

The fundamentals of the DIC technique are based on the comparison of consecutive images by selecting a Region of Interest (ROI), which is divided into subsets [27]. These subsets are compared using the zero mean normalised cross-correlation criterion (ZNCC) [41]. Interpolations and optimisation algorithms are then applied to archive subpixel accuracy [42] for full-field displacements and strains. To facilitate this process, the sample must first be prepared by applying a pattern known as a speckle to its surface. This pattern consists of a distinct, unique, non-periodic and stable grayscale spot [43]. In this case, a matte white elastic primer was first applied to generate a greater contrast to the black speckle and to avoid the appearance of shiny spots on the surface. Random mottling was then generated using a matte black spray. Finally, the quality of the pattern was evaluated by means of the indicator known as the mean intensity gradient (MIG) [44]. A MIG value greater than 30 was obtained for all samples, and a coverage factor close to 50%, so that the quality of the pattern can be considered adequate [45].

The equipment used for the tests (Figure 5) consisted of a prototype similar to the one developed by García-Martín et al. [46], although the hardware and sensors were upgraded in order to achieve maximum accuracy. In this study, a high-resolution Manta G-917 1″ Monochrome CCD camera equipped with a 50 mm macro-prime lens was used for image capture. Additionally, a neutral LED light was used to improve illumination and allow for shorter exposure times. The camera shots were synchronised with the load data collected by the test machine using a microcontroller, which allowed the capture parameters to be set.

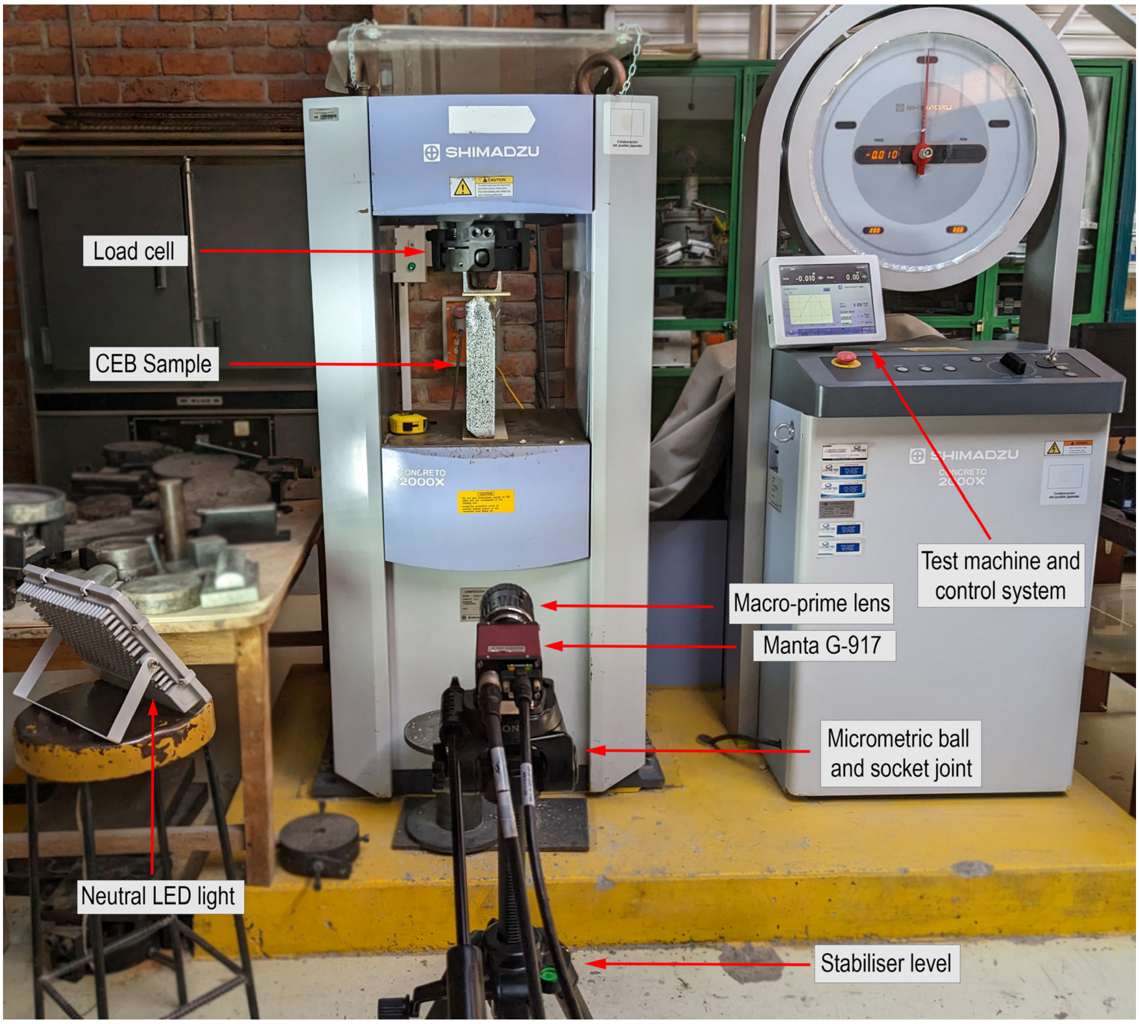


Figure 5. Equipment and setup for compression testing using digital image correlation.

Taking into account the slenderness of the sample, it was decided that DIC analysis would be performed on one side to check for significant lateral displacement. To ensure the perpendicularity of the camera and guarantee the 2D-DIC approach, a micrometric ball and socket joint was used. Given the dimensions of the sample, the camera was placed 1.5 m from the specimen, which allowed a GSD of 0.1 mm/px to be obtained. Artificial illumination allowed for a lens aperture of f8 to be set, thus ensuring an adequate balance for the depth of field. Considering that the displacement speed to which the test was subjected was low, the images were acquired at 1 FPS with a shutter speed of 1/100 s, capturing the first image before starting the test to obtain the reference image.

3. Experimental Results and Discussion

3.1. Earth Properties

3.1.1. Empirical Results

The empirical tests described in Section 2.2 were carried out. For this purpose, a small representative quantity was selected from each of the earth samples. A total of six tests were carried out for each of them, obtaining the results shown in Table 3 according to the criteria described above.

Table 3. Results of empirical tests.

Test	E_CC	E_CM	E_CN	E_PD
Odour	Low level of organic matter	Low level of organic matter	Low level of organic matter	Low level of organic matter
Bite	Sandy with clay	Sandy with clay	High level of clay	Sandy with low clay
Washing	High level of silt	Sandy with low level of clay	High level of clay	Silty-sandy
Cut	Medium level of clay	High level of silt	High level of clay	Medium level of clay as well as silt
Ball	High level of clay	Acceptable level of clay	High level of clay	Acceptable level of clay
Consistency	High level of clay	High level of clay	High level of clay	High level of clay

First, the empirical tests show that the level of organic matter is low for all samples. In terms of composition, the results are not very conclusive as the tests give different results for the same samples. The earth seems to show a higher or lower clay level depending on the water concentration and the mixing time, so the accuracy of these tests is not very high. The empirical tests had a low accuracy in terms of clay content, and some of the tests showed a predominance of sands or silts. In any case, the cracking after drying is very slight, indicating a low presence of expansive clay that could cause volume changes and problems in the curing of the CEBs. Therefore, they are tests that allow for a first impression of the samples in situ without the need to go to the laboratory. In this case, the results of these tests were combined with the laboratory tests to observe the correlation between them and to obtain the composition more precisely in order to select the most suitable sample.

3.1.2. Laboratory Results

The samples were subjected to laboratory tests to determine their granulometric composition, plastic behaviour and compaction. The results of these tests are shown in Figure 6.

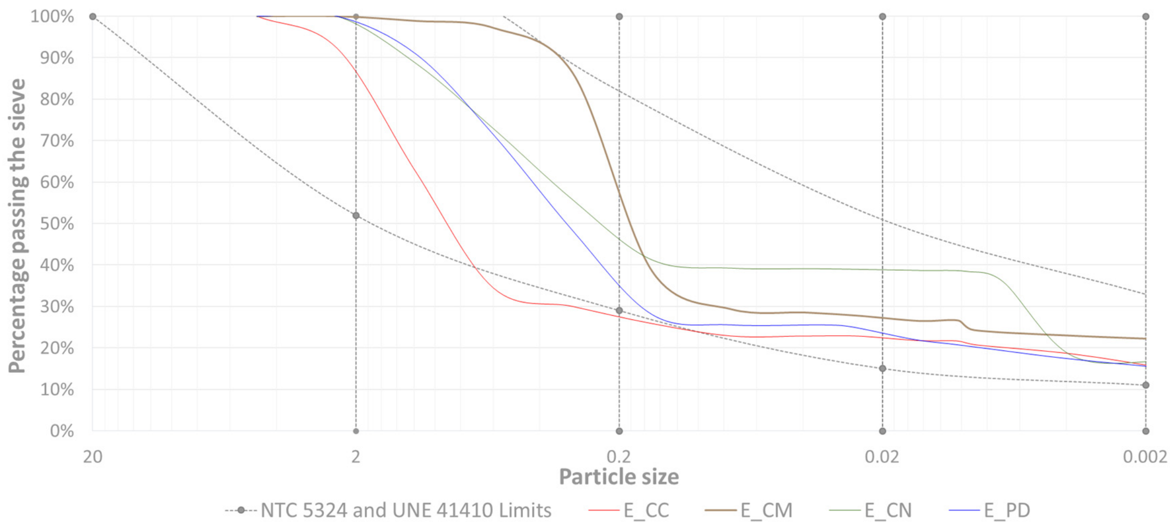


Figure 6. Granulometric curves of the samples analysed and their fit within the limits established by the regulations.

The particle size ranges shown in Figure 6 are those established by the Colombian standard NTC 5324 [40] and the Spanish standard UNE 41410 [13]. Samples E_CM, E_CN and E_PD fit in all particle sizes. Nevertheless, sample E_CC does exceed the established limits, especially in the range of the sands. Although this first test would allow this sample to be discarded, it was also subjected to other tests in order to compare it with the other samples.

Following the same standards, Figure 7 shows the plasticity ranges for the selection of earths, as well as the results for each of the samples. In this case, none of them is within the normative spectrum, so it is not possible to select or discard any of them. Nevertheless, it can be mentioned that sample E_CM is the closest to the limits.

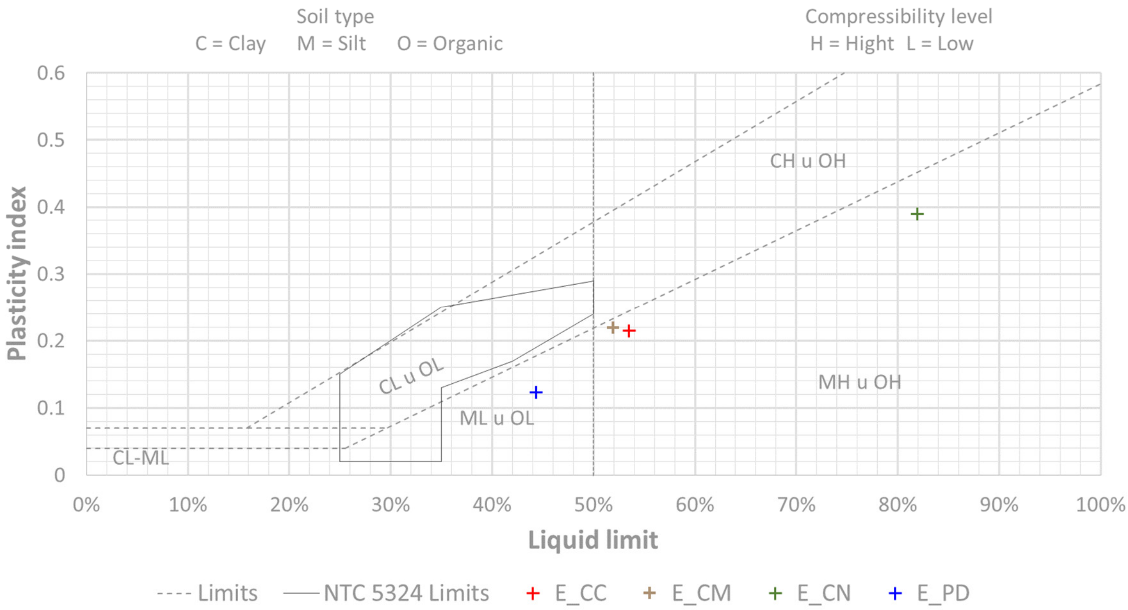


Figure 7. Diagram of the plasticity test and its fit within the limits established by the regulations.

Finally, the Proctor test allows for the evaluation of the appropriate amount of water to reach higher densities of the material with the same exerted pressure. As shown in Figure 8, sample E_PD fails to reach its maximum compaction limit due to the implication of adding a high percentage of water for this purpose; therefore, it was decided to discard this sample. On the other hand, samples E_CC, E_CM and E_CN find their compaction limit with moisture percentages lower than 30%. Among them, the one with the highest compaction, with even less water, is E_CM. This sample has a dry volumetric weight higher than 1.70 gr/cm^3 at the optimum point, while the value of the other samples is between 1.30 and 1.40 gr/cm^3. Furthermore, once the optimum point has been reached, sample E_CM loses density when the moisture content increases while the other samples remain constant. This makes it possible to determine the right amount of water to obtain higher densities at the same pressure, which is associated with higher block strength. The results of this last test agree with the greater approximation to the limits of the plasticity test of this sample, so it is reaffirmed as the best of the samples. Thus, sample E_CM is the one selected as the base earth for the manufacture of the CEBs.

3.2. Compressed Earth Blocks Properties

3.2.1. Mechanical Results

A total of 42 samples were manufactured, 3 of which were for each of the proposed dosages. The samples were cured for 7 days before being subjected to mechanical characterisation tests. In order to avoid water loss, the cement and lime samples were hydrated during the 7 days of curing, while those with fibres were only protected from the sun as required by the standards. The results of the compression tests, as well as their statistical parameters, are shown in Table 4.

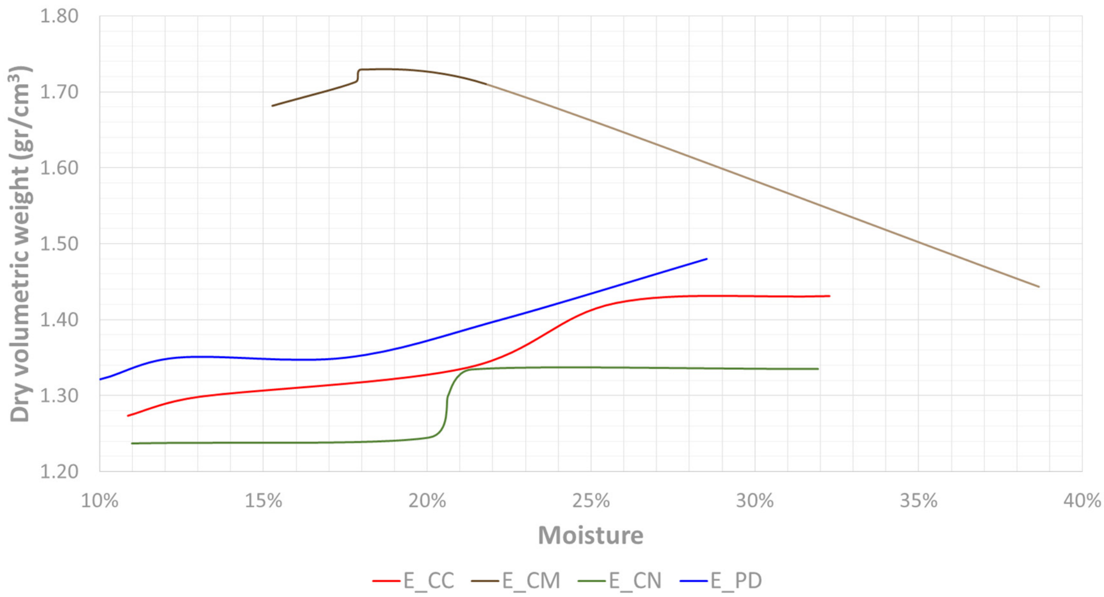


Figure 8. Density and moisture curves obtained from the Proctor test.

Table 4. Results of the compression test for CEB.

Nomenclature	Mean (MPa)	Lower Bound (MPa)	Upper Bound (MPa)	CoV (%)
PR_01	-	-	-	-
PR_02	-	-	-	-
PF_01	0.19	0.18	0.19	3.43
PF_02	0.27	0.15	0.41	48.8
PF_03	0.65	0.41	0.94	40.9
PF_04	-	-	-	-
PF_05	0.07	0.07	0.08	9.8
PC_01	0.36	0.30	0.45	20.7
PC_02	0.75	0.49	1.02	35.5
PC_03	1.61	1.41	1.78	11.7
PC_04	2.02	1.90	2.10	5.3
PC_05	2.43	1.63	3.98	42.4
PC_06	3.28	2.84	3.59	12.5
PO_01	-	-	-	-

The dehumidification process was easy in terms of PR dosages. Nevertheless, this type of specimen did not tolerate transport and placement. The samples cracked and disintegrated before loading and could not be tested.

The panels that incorporated bio-fibres (PFs) as additives were able to withstand the procedures well and could be tested, except for sample PF_04, which showed increased disintegration and broke before the application of the load. In general, the introduction of these fibres improved the stability of the panels and increased compressive strength, helping to control cracking during the drying process. Nevertheless, the strengths obtained are not sufficient to meet the minimum requirements of 2 MPa for the CEB 20 category established by the Colombian standard NTC 5324 [40].

Panels incorporating lime performed similarly to those made with fibres, although they had a very high porosity, and the strength was also not sufficient to comply with the standard.

The cement-stabilised panels performed the best. It can be seen that the higher percentage of cement added leads to an increase in strength. Despite the fact that demoulding was more difficult, the panels were much more stable and resistant to both transport and the testing process. Although all samples showed a higher compressive strength than the rest of the panels, only those with a percentage of cement equal to or higher than 15% (15%, 20% and 25%) complied with the minimum strength determined by the standards.

Finally, the panels tested with asphalt emulsion additives did not yield mechanical results. The difficulties encountered during demoulding led to lower-quality panels, which broke during transport.

In general, the behaviour of the samples that could not be tested is associated with low pressure during the manufacturing process. The lack of compaction means that when the panels are demoulded, they begin to disintegrate and cannot be subjected to compression. In addition, it should be noted that the coefficient of variation (CoV) for some of the samples was quite high. This highlights the high variability and heterogeneity of these types of materials, especially when additives are added to modify their behaviour.

3.2.2. Characterisation of the Final Solution

Although the samples showed different behaviours and not all were in accordance with the standards, it was decided to select the samples with the highest potential for further analysis. The best-performing sample corresponding to the dosage used in PC_06 was selected to represent the cementitious panels. The sample corresponding to the dosage used in PF_03 was selected to represent the panels with natural fibres, given their greater potential in terms of achieving more sustainable construction.

Three new panels for each of the dosages were subjected to more comprehensive compression tests. A 2D-DIC approach using the open source software Ncorr v1.2.2 [42] was used to obtain the displacements and strains (Figure 9a). In this process, a subset size of 20 × 20 pixels and an overlap of 65%, with a step of seven pixels, was used. Subsequently, a post-processing toolbox (Ncorr Post CSTool) was used. This tool allowed for virtual extensometers to be placed in the different areas of the specimen to analyse their behaviour and spatial influence (Figure 9b).

Due to the variability observed in the results shown above, in this case, the test with the most out-of-average behaviour was discarded. This decision was taken to ensure that the strain measurements were representative since, in some of the tests, disaggregation causes the failure mode to be inappropriate. Therefore, a full analysis of two samples of each dosage was carried out.

A total of nine virtual extensometers were placed on the surface of the specimens at three different heights to investigate the areas of greatest strain and the mode of failure. Three were placed in the central third, as required by the regulations. Three others of equal length were placed in the upper half, and three others in the lower half. The last two groups were placed in order to study the influence of the application of the load and to see the area where the greatest strain occurs. Regarding the distribution of each group, the extensometers were spaced 15 mm apart from each other. Two of them were placed in the area where the load is directly applied, while the third was placed in the outermost area where the load is not directly applied.

Maximum longitudinal strains in the state of loading before failure were extracted for each of the virtual extensometers. To analyse the heterogeneity and spatial distribution of the strains, the results were segregated into different groups, as shown in Table 5, corresponding to PF_03, and Table 6, corresponding to PC_06. On the one hand, the strain in the load zone was analysed, including the extensometers placed at the upper, middle and lower parts. On the other hand, the strain in the area where the load is not directly applied was analysed.

Regarding the results for PF_03, the previously mentioned high heterogeneity for the compression tests can be seen. In all cases, the CoV is slightly above 30%. The mean value for the peak strain in the loading area was 5.4‰, with the highest values in the lower area, although there is not much difference with respect to the rest. The mean value for the peak strain in the out-of-load area was 1.5‰, which, as expected, is significantly lower. This solution has lower strength and higher strain than the best cement-stabilised solution. Nevertheless, the values obtained can be considered acceptable for applications where a high structural character is not required, such as thin walls or partitions. In addition, the higher strain capacity of this material may be of interest for seismic applications.

Regarding the results for PC_06, despite presenting heterogeneity, it is lower than the previous case, with a CoV value below 25%. The peak strain in the out-of-load area was similar, with a value of 1.3‰. Nevertheless, for the peak strain in the loaded area, different values were obtained with respect to the previous case. In this case, the mean value was 3.0‰, with the highest values being found in the upper zone. The presence of cement as an additive causes the strains to be lower in this case. When comparing the behaviour of cement-stabilised BECs with other conventional materials such as concrete, the range of strains is very close, with values close to 2‰ being considered acceptable in most cases.

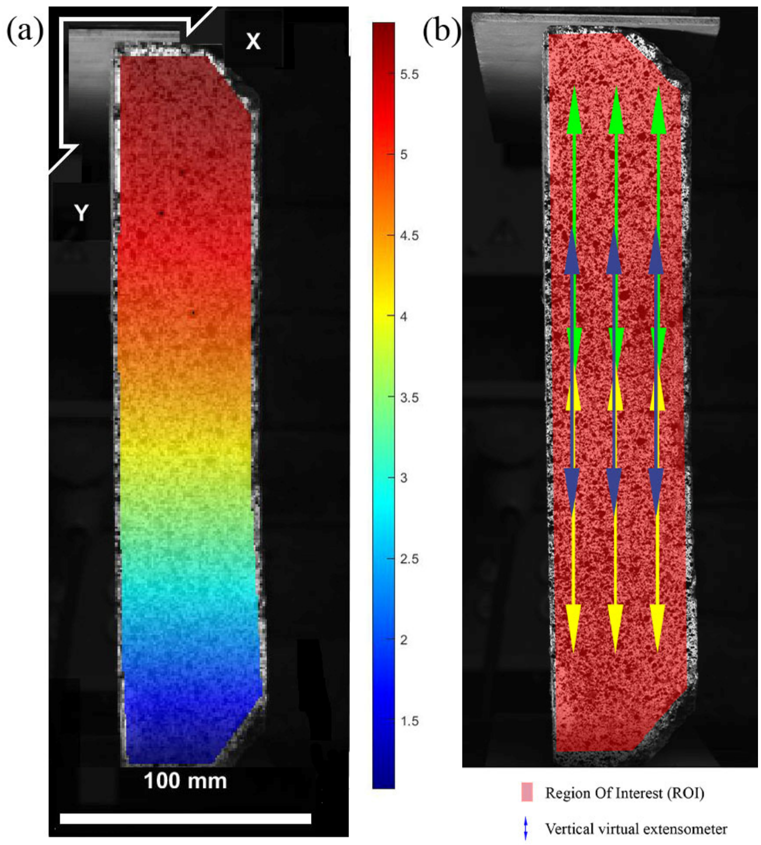


Figure 9. Results obtained during 2D-DIC analysis. (**a**) Vertical displacement before failure for PC_06; (**b**) extraction of the maximum longitudinal strain by means of the virtual extensometer.

Table 5. Results of the peak strain analysis for PF_03.

Strain Area	Mean (mm/mm)	Lower Bound (mm/mm)	Upper Bound (mm/mm)	CoV (%)
Load area	0.0054	0.0033	0.0081	30.4
Upper	0.0052	0.0033	0.0074	32.2
Middle	0.0055	0.0040	0.0072	32.3
Lower	0.0055	0.0035	0.0081	35.7
Out-of-load	0.0015	0.0010	0.0024	33.9

Table 6. Results of the peak strain analysis for PC_06.

Strain Area	Mean (mm/mm)	Lower Bound (mm/mm)	Upper Bound (mm/mm)	CoV (%)
Load area	0.0030	0.0022	0.0046	23.1
Upper	0.0035	0.0029	0.0046	22.8
Middle	0.0030	0.0023	0.0035	17.3
Lower	0.0025	0.0022	0.0032	18.9
Out-of-load	0.0013	0.0010	0.0017	21.4

In both cases and for all specimens, the peak strain value occurs at the edges. According to the results and the full field strain map obtained from DIC, it can be determined that this is the zone where the specimens begin to crack. Fracture begins in these areas, close to the contact with the compression plates, and the material begins to disintegrate until failure, while the core of the specimen remains more stable. This behaviour is typical of earthen materials and is one of the reasons why it is difficult to determine their behaviour using conventional techniques, so the DIC approach used made it possible to obtain the maximum strains in this zone.

4. Economic Analysis

To investigate the efficiency and costs of the proposed panels, an economic study of the different proposed solutions was carried out. Although only the PC_04, PC_05 and PC_06 panels complied with the standards in terms of mechanical properties, the study was carried out for all the samples. In this way, the influence on the costs of each of the additives can be verified. Furthermore, although the panels with fibre additives did not achieve good mechanical results, their incorporation did lead to an improvement, and these panels may have significant potential to be stabilised. This work can be a starting point for future research by improving and increasing some parameters, such as pressure, during the pressing process.

First of all, the costs of equipment were considered. Considering that the equipment was designed for self-manufacture, the cost was relatively low. In addition, the equipment was considered to be amortised over two years of work so that it could be used for the construction of community-level housing. The estimated cost was EUR 0.60 per CEB, considering the sifting cylinder, press and auxiliary material, such as wheelbarrows or shovels.

The labour cost to produce the panels was then considered. Although the solution is focused on self-manufacturing, the cost associated with the labour required was considered, taking into account the experience gained during laboratory manufacture. The estimated cost in this case was EUR 1.31 per CEB, considering the need for a worker and an assistant.

Finally, the material costs were considered. In this respect, water and additives were taken into account because it was considered that the earth is obtained at the same place of manufacture at no cost. In this case, the costs vary considerably for each of the panels, mainly due to the difference in additives.

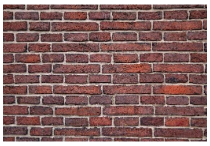
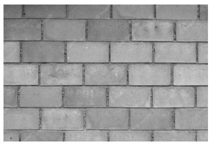
Taking into account the costs mentioned above, the unit price for each of the panels is shown in Table 7.

Panels that complied with the standard had a cost of EUR 2.50 for PC_04, EUR 2.69 for PC_05 and EUR 2.88 for PC_06. In this case, the 5% increase in cement leads to a 0.19 EUR increase. Since the PC_04 panel was the most economical, a comparison was made with other conventional house enclosure systems in Ecuador. For this purpose, the price per square metre of this solution was compared with conventional brick, masonry block and adobe (Table 8). It should be noted that the prices have been calculated according to the average costs for the year 2023 indicated by the Construction Chamber of Ecuador, so the production cost of the panels should be taken as a guideline. In this sense, in order to facilitate the comparison with other house enclosure systems, the ratio has been incorporated using the proposed solution as a reference.

Table 7. Unit price (EUR) for each panel considering equipment, labour and material costs.

Nomenclature	Equipment	Labour	Materials	Total
PR_01	0.60	1.31	0.01	1.92
PR_02	0.60	1.31	0.01	1.92
PF_01	0.60	1.31	2.74	4.65
PF_02	0.60	1.31	2.74	4.65
PF_03	0.60	1.31	2.74	4.65
PF_04	0.60	1.31	2.74	4.65
PF_05	0.60	1.31	2.74	4.65
PC_01	0.60	1.31	1.90	3.81
PC_02	0.60	1.31	0.21	2.12
PC_03	0.60	1.31	0.40	2.31
PC_04	0.60	1.31	0.59	2.50
PC_05	0.60	1.31	0.78	2.69
PC_06	0.60	1.31	0.97	2.88
PO_01	0.60	1.31	1.97	3.88

Table 8. Comparative of costs per square metre of house enclosure systems.

Material	PC_04	Brick	Masonry Block	Adobe
Image				
Price (EUR/m^2)	7.75	15.06	10.21	10.72
Ratio	1	1.94	1.32	1.38

When compared to conventional and more commonly used building materials, such as bricks, the proposed solution proves to be the most economical at half the cost. In the case of other earthen materials with similar properties, such as adobe, this solution is almost 30% cheaper. This shows that improving the properties of CEBs with this type of additive makes it possible to obtain an interesting solution from a construction, environmental and economic point of view.

5. Conclusions

This research has sought to influence basic construction materials, especially those mainly made of earth, such as compressed earth blocks. CEBs are an appropriate solution that takes advantage of local resources and contributes to environmental improvement, promoting sustainability within the self-building ecosystem in areas with limited resources. For this purpose, ad hoc equipment was manufactured to analyse types of earth from four different locations in Ecuador and to produce and characterise CEBs with stabilising additives.

- Firstly, empirical and laboratory tests were performed on the types of earth. Based on the results of the granulometry, plasticity and Proctor tests, E_CM earth from the Monay region, whose physical properties best met the standards, was selected.

- Subsequently, CEBs were made with this earth, adding additives of natural origin (bio-fibres) and others that are generally used in construction (lime or cement). Despite the fact that the pressure was not very high, the proposed methodology made it possible to manufacture and test panels of different compositions.
- The manufactured panels were mechanically characterised, obtaining the best results for the cement-stabilised panels. The addition of cement improved the compressive strength. The samples with 5% and 10% cement were the only ones that did not reach the minimum resistance of 2 MPa determined by the regulations. The samples with 15% cement reached a strength of 2.02 MPa. Subsequently, increasing the cement content to 20% improved the strength by 20%. Finally, the 25% cement reached the highest compressive strength, 35% higher than the previous ones. This solution is the most suitable from a structural engineering point of view.
- Among the rest of the non-cement samples, the one with the best results was sample PF_03, composed of 5% glue and 5% ground reed. This solution is the most interesting from an ecological point of view as it uses natural and environmentally friendly additives. This solution is interesting for architectural applications with lower load requirements, such as partitions or thin walls, and for consideration in seismic studies due to its high elongation capacity.
- Based on these results, it was decided to carry out a detailed analysis of these two samples using the digital image correlation technique. The DIC technique made it possible to analyse the displacements and strains in the full field to determine the mode of cracking, obtaining the ultimate strain at the instant prior to failure. Peak strain analysis determined a more homogeneous behaviour for the cement-stabilised samples (PF_06), with a peak strain value of 3.0‰ for a maximum load of 3.3 MPa, while for the samples stabilised with bio-fibres (PF_03), the peak strain was higher, with a value of 5.4‰ for a maximum load of 0.7 MPa.
- Finally, economic analysis was carried out to study the feasibility of manufacturing the panels and their use in housing construction. This analysis showed that CEB is an economically suitable solution, as it allows considerable savings in unit costs per m^2 of panel. The cost of a house with the Sandino construction system and this type of panel is 32% lower than the cost of using masonry blocks, 38% lower than using adobe and 94% lower than using conventional bricks.

For both of the panels that comply with the regulations and those that incorporate bio-fibres, the work yielded promising results for the earthen architecture sector, which encourages the continuation of this line of research. In particular, bio-fibre-stabilised panels are interesting from a sustainability point of view, which positions earthen materials as a strong candidate for architecture and construction in the 21st century, where better use of resources is required to support the principles of a circular economy and cleaner construction. The main challenge is to achieve a strength equal to or greater than that of cement-stabilised panels. In such a case, the high cement content could be replaced by cleaner stabilisers, such as lime. Future work will focus on improving and increasing some parameters, such as pressure, during the pressing process to ensure the stabilisation and compaction of the panels. In addition, the use of other additives to stabilise the panels and improve the compressive strength will be investigated. Finally, it is intended to investigate the behaviour of different types of earth in depth, considering the variability of behaviour due to the geographical component, so that the manufacture of CEBs can be adapted to the origin of the earth.

Author Contributions: Conceptualization, J.L.-R. and X.C.-H.; methodology, J.L.-R.; formal analysis, J.L.-R., J.P.P.-V. and K.N.-B.; investigation, J.L.-R., J.P.P.-V. and K.N.-B.; writing—original draft preparation, J.L.-R.; writing—review and editing, J.L.-R., X.C.-H., J.P.P.-V., K.N.-B. and J.P.; supervision, X.C.-H. and J.P.; funding acquisition, X.C.-H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by University of Salamanca through the ‘Programa Propio V’.

Data Availability Statement: The data presented in this study are contained within the article.

Acknowledgments: The authors want to thank the Spanish Ministry of Education, Culture and Sports for providing an FPU grant (Training Program for Academic Staff) to the first author of this paper (grant number FPU20/01376 and EST23/00460).

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Peduzzi, P. Sand, rarer than one thinks. *Environ. Dev.* **2014**, *11*, 208–218.
2. de Brito, J.; Kurda, R. The past and future of sustainable concrete: A critical review and new strategies on cement-based materials. *J. Clean. Prod.* **2021**, *281*, 123558. [CrossRef]
3. Herrmann, C.J.; Zappettini, E.O. *Recursos Minerales, Minería y Medio Ambiente*; SEGEMAR: Buenos Aires, Argentina, 2014.
4. Deboucha, S.; Hashim, R. A review on bricks and stabilized compressed earth blocks. *Sci. Res. Essays* **2011**, *6*, 499–506.
5. Costa, C.; Cerqueira, Â.; Rocha, F.; Velosa, A. The sustainability of adobe construction: Past to future. *Int. J. Archit. Herit.* **2019**, *13*, 639–647. [CrossRef]
6. Font, F.; Hidalgo, P. La tapia en España. Técnicas actuales y ejemplos. *Inf. Constr.* **2011**, *63*, 21–34. [CrossRef]
7. Rigassi, V. *Compressed Earth Blocks: Manual of Production*; GATE/BASIN: Eschborn, Germany, 1985.
8. Etzion, Y.; Saller, M. Earth construction—A review of needs and methods. *Archit. Sci. Rev.* **1987**, *30*, 43–48. [CrossRef]
9. Cid, J.; Mazarrón, F.R.; Cañas, I. Las normativas de construcción con tierra en el mundo. *Inf. Constr.* **2011**, *63*, 159–169. [CrossRef]
10. *NZS 4297*; Engineering Design of Earth Buildings. Standards New Zealand: Wellington, New Zealand, 1998.
11. *NZS 4298*; Materials and Workmanship for Earth Buildings. Standards New Zealand: Wellington, New Zealand, 1998; Volume 569, p. 570.
12. *ASTM E2392*; Standard Guide for Design of Earthen Wall Building Systems. ASTM: West Conshohocken, PA, USA, 2010.
13. *UNE 41410*; Bloques de Tierra Comprimida para Muros y Tabiques. Definiciones, Especificaciones y Métodos de Ensayo. AENOR: Madrid, Spain, 2008.
14. Sturm, T.; Ramos, L.F.; Lourenço, P.B. Characterization of dry-stack interlocking compressed earth blocks. *Mater. Struct.* **2015**, *48*, 3059–3074. [CrossRef]
15. McGregor, F.; Heath, A.; Fodde, E.; Shea, A. Conditions affecting the moisture buffering measurement performed on compressed earth blocks. *Build. Environ.* **2014**, *75*, 11–18. [CrossRef]
16. Galíndez, F. Bloques de tierra comprimida (BTC) sin adición de cemento. *Segur. Medio Ambiente* **2007**, *115*, 63–73.
17. Cid-Falceto, J.; Mazarrón, F.R.; Cañas, I. Assessment of compressed earth blocks made in Spain: International durability tests. *Constr. Build. Mater.* **2012**, *37*, 738–745. [CrossRef]
18. *IS 13827*; Improving Earthquake Resistance of Earthen Buildings—Guidelines. Bureau of Indian Standards: Delhi, India, 1993.
19. Gatti, F. *Arquitectura y Construcción en Tierra: Estudio Comparativo de las Técnicas Contemporáneas en Tierra*; Polytechnic University of Catalonia: Barcelona, Spain, 2012.
20. Ribeiro, T.; Oliveira, D.V.; Bracci, S. The use of contact sponge method to measure water absorption in earthen heritage treated with water repellents. *Int. J. Archit. Herit.* **2022**, *16*, 85–96. [CrossRef]
21. Vissac, A.; Bourgès, A.; Gandreau, D.; Anger, R.; Fontaine, L. *Argiles & Biopolymères-Les Stabilisants Naturaels Pour la Construction en Terre*; CRATerre Éditions: Villefontaine, France, 2017.
22. Losini, A.E.; Grillet, A.C.; Bellotto, M.; Woloszyn, M.; Dotelli, G. Natural additives and biopolymers for raw earth construction stabilization—A review. *Constr. Build. Mater.* **2021**, *304*, 124507. [CrossRef]
23. Teixeira, E.R.; Machado, G.; Junior, A.D.P.; Guarnier, C.; Fernandes, J.; Silva, S.M.; Mateus, R. Mechanical and thermal performance characterisation of compressed earth blocks. *Energies* **2020**, *13*, 2978. [CrossRef]
24. Borri, A.; Corradi, M.; De Maria, A. The failure of masonry walls by disaggregation and the masonry quality index. *Heritage* **2020**, *3*, 1162–1198. [CrossRef]
25. Sánchez-Aparicio, L.J.; Villarino, A.; García-Gago, J.; González-Aguilera, D. Photogrammetric, geometrical, and numerical strategies to evaluate initial and current conditions in historical constructions: A test case in the church of San Lorenzo (Zamora, Spain). *Remote Sens.* **2016**, *8*, 60. [CrossRef]
26. Callaway, P.; Gilbert, M.; Smith, C.C. Influence of Backfill on the Capacity of Masonry Arch Bridges. *Proc. Inst. Civ. Eng.-Bridge Eng.* **2012**, *165*, 147–157. [CrossRef]
27. Sutton, M.A.; Orteu, J.J.; Schreier, H.X. *Image Correlation for Shape, Motion and Deformation Measurements: Basic Concepts, Theory and Applications*; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2009.
28. Pisonero, J.; López-Rebollo, J.; García-Martín, R.; Rodríguez-Martín, M.; Sánchez-Aparicio, L.J.; Muñoz-Nieto, A.; González-Aguilera, D. A comparative study of 2D and 3D digital image correlation approaches for the characterization and numerical analysis of composite materials. *IEEE Access* **2021**, *9*, 160675–160687. [CrossRef]
29. Khan, R.M.A.; Shafighfard, T.; Ali, H.Q.; Mieloszyk, M.; Yildiz, M. Strength prediction and experimental damage investigations of plain woven CFRPs with interacting holes using multi-instrument measurements. *Polym. Compos.* **2023**, *44*, 3594–3609. [CrossRef]

30. Teijón-López-Zuazo, E.; López-Rebollo, J.; Sánchez-Aparicio, L.J.; Garcia-Martín, R.; Gonzalez-Aguilera, D. Compression and strain predictive models in non-structural recycled concretes made from construction and demolition wastes. *Materials* **2021**, *14*, 3177. [CrossRef]
31. María, R.-M.; Paula, V.-L.; Jaime, F.-G.; Jorge, L.R. Improvement of tensile properties of carbon fibre-reinforced cementitious matrix composites with coated textile and enhanced mortars. *Constr. Build. Mater.* **2023**, *369*, 130552. [CrossRef]
32. Stazi, F.; Serpilli, M.; Chiappini, G.; Pergolini, M.; Fratalocchi, E.; Lenci, S. Experimental study of the mechanical behaviour of a new extruded earth block masonry. *Constr. Build. Mater.* **2020**, *244*, 118368. [CrossRef]
33. Perić Fekete, A.; Kraus, I.; Grubišić, M.; Dokšanović, T. In-plane seismic performance of rammed earth walls: An eastern Croatia reconnaissance based study. *Bull. Earthq. Eng.* **2023**, *22*, 1359–1385. [CrossRef]
34. El Nabouch, R.; Bui, Q.-B.; Plé, O.; Perrotin, P. Rammed earth under horizontal loadings: Proposition of limit states. *Constr. Build. Mater.* **2019**, *220*, 238–244. [CrossRef]
35. Minke, G. *Manual de Construcción en Tierra: La Tierra Como Material de Construcción y su Aplicación en la Arquitectura Actual*; Nordan Comunidad: Montevideo, Uruguay, 2001.
36. *E. 080*; Diseño y Construcción Con Tierra Reforzada. Ministerio de Vivienda, Construcción y Saneamiento: Lima, Perú, 2017.
37. *ASTM D422-63*; Standard Test Method for Particle-Size Analysis of Soils. ASTM: West Conshohocken, PA, USA, 2007.
38. *INEN 692*; Mecánica de Suelos. Determinación del Límite Plástico. INEM: Quito, Ecuador, 1982.
39. *ASTM D698*; Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort. ASTM: West Conshohocken, PA, USA, 2000.
40. *NTC 5324*; Ground Blocks Cement for Walls and Divisions. Definitions. Specifications. Test Methods. Conditions of Delivery. ICONTEC: Bogotá, Colombia, 2004.
41. Pan, B.; Qian, K.; Xie, H.; Asundi, A. Two-dimensional digital image correlation for in-plane displacement and strain measurement: A review. *Meas. Sci. Technol.* **2009**, *20*, 062001. [CrossRef]
42. Blaber, J.; Adair, B.; Antoniou, A. Ncorr: Open-source 2D digital image correlation matlab software. *Exp. Mech.* **2015**, *55*, 1105–1122. [CrossRef]
43. Dong, Y.L.; Pan, B. A review of speckle pattern fabrication and assessment for digital image correlation. *Exp. Mech.* **2017**, *57*, 1161–1181. [CrossRef]
44. Pan, B.; Lu, Z.; Xie, H. Mean intensity gradient: An effective global parameter for quality assessment of the speckle patterns used in digital image correlation. *Opt. Lasers Eng.* **2010**, *48*, 469–477. [CrossRef]
45. Lecompte, D.; Sol, H.; Vantomme, J.; Habraken, A. Analysis of Speckle Patterns for Deformation Measurements by Digital Image Correlation. In *Speckle06: Speckles, from Grains to Flowers*; SPIE: Bellingham, WA, USA, 2006; Volume 6341, pp. 80–85.
46. Garcia-Martin, R.; López-Rebollo, J.; Sánchez-Aparicio, L.J.; Fueyo, J.G.; Pisonero, J.; Gonzalez-Aguilera, D. Digital image correlation and reliability-based methods for the design and repair of pressure pipes through composite solutions. *Constr. Build. Mater.* **2020**, *248*, 118625. [CrossRef]