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The use of gypsum mining by-product and lime on the engineering properties of compressed earth blocks

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Abstract
Disadvantages of compressed earth blocks are their poor mechanical properties and low resistance to water damage. Therefore, their use is vulnerable to deterioration and require care and maintenance, which depends on the degree of stabilization and compaction of the clay soil. Gypsum mining wastes and lime used as stabilization materials to improve the properties of these construction materials. The compressive and flexural strength, softening in water, drying shrinkage and unit weight determined. Strength values increased with both mining waste additions. Highest resistance against softening in water obtained with a 25% of mining waste. Drying shrinkage reduced with increasing mining waste content. Dry unit weight was not in the recommended standards. Results showed that gypsum mining wastes can be used as alternative materials to stabilize compressed earth blocks.

Keywords: compressed earth blocks; construction materials; gypsum mining by-product; stabilization; environmental.

El uso de residuos de minería de yeso y cal sobre las propiedades de ingeniería de los bloques de tierra comprimida

Resumen
Las desventajas de los bloques de tierra comprimida son sus bajas propiedades mecánicas y resistencia al daño al agua. Por lo tanto, su uso es vulnerable al deterioro y requiere cuidado y mantenimiento, dependiendo del grado de estabilización y compactación del suelo arcilloso. Residuos de minería del yeso y cal se utilizaron como estabilizantes para mejorar las propiedades de estos materiales de construcción. Resistencia a compresión y flexión, ablandamiento en agua, retracción por secado y peso unitario se determinaron. La resistencia aumento con la adición de residuo de minería. La resistencia al ablandamiento en agua fue mayor con 25% de residuo de minería. La contracción por secado disminuyo con el aumento del contenido de residuo de minería. El peso unitario seco no estaba en los estándares recomendados. Los resultados mostraron que los residuos de minería del yeso pueden utilizarse como materiales alternativos en la estabilización de bloques de tierra comprimida.

Palabras claves: bloques de tierra comprimida; materiales de construcción; residuos de minería del yeso; estabilización; medio ambiente.

1. Introduction

Compressed earth blocks (CEBs) play a major role in improving the environmental efficiency and sustainability of buildings and contributes to worldwide economic prosperity and infrastructural development. On the other hand, the production processes of construction materials have a considerable impact on the environment. The utilization of earth in housing construction is one of the oldest and most common methods used. CEBs are one of the oldest identifiable man-made building materials which are becoming more popular due to their simplicity and low cost, relative abundance of materials, good performance (good thermal and acoustic properties), and at the end of a building's life the clay material can easily be reused by grinding, wetting or returned to the ground without any damage to the environment [1]. However, despite their advances, further studies are needed in order to improve their durability and mechanical properties, both important quality control measures for manufacturers and builders. Many additives such as cement, lime, asphalt emulsions, bituminous materials, and natural and industrial by-products have been tested to improve the mechanical properties and to enhance the durability of the compacted blocks [1-6]. Portland cement has been by far the most used material for soil stabilization [2,5,6]. However, due to the high energy consumption necessary for its manufacture and the consequent environmental damage caused by the release of high quantities of greenhouse gases during its production, the cement industry has been highlighted as one of the major contributors of anthropogenic CO_2 emissions emitting about 5% globally [7-8]. In view of the above mentioned, several research activities are directed towards partial or total substitution of Portland cement by pozzolanic binders, e.g. lime, fly ash, and natural pozzolans among others. The worldwide development of mining produces large volumes of mining wastes and their disposal cause major challenges and serious economic and environmental problems. Mining of industrial minerals is a special case as far as mining waste generation is concerned, since they are mostly inert used directly in restoration work. The problem is the need for integrated management, including the removal and restoration, rather than the generation of hazardous materials. Gypsum is mined from Cretaceous sedimentary rocks at various locations in Colombia. However, the mining wastes produced after the extraction of gypsum is not used for restoration. Lately, researchers are making efforts to reduce the amount of waste by finding alternative uses for it. The need to conserve the traditional building materials that are facing depletion has necessitated the search for alternative materials [9]. In the 1970s and 1980s a new generation of manual, mechanical and motor-driven presses appeared, leading to the emergence today of a genuine market for the production and application of CEBs [4]. They have excellent insulating properties - reducing heating and cooling costs. The compressive strengths of the blocks depend on their densities. The compressive strength of a soil can be increased by chemical stabilization. This project was designed to prepare locally available soils, make building blocks with a block press and test them to determine the engineering properties of CEBs. The objective was to test local soils to see if they could be used for low housing construction. CEB technology offers an alternative to traditional building practices that is relatively inexpensive, uses local resources, and in some cases, has been found to last several millennia [10]. A number of standards have also developed for CEB test procedures [10-12]. However, unlike other masonry units, there is little general consensus on test procedure for CEBs. The main objective of this study is to investigate the effects of the aforementioned types of industrial residues on the properties of CEBs. Results of experimental studies are also presented. The compressive strength of blocks measured by different tests is also compared with other parameters, such as three-point bending strength.

2. Materials and methods

2.1. Materials

The materials used for the industrial trial consisted of raw clay-rich material and gypsum mining waste (Fig. 1), and lime.

2.1.1. Raw clay-rich material

The raw clay-rich material used in this study is extracted by Polypus of Colombia for the development of the housing project "Prados de Laurentia" at Floridablanca (Santander), which offers an innovative construction system. The clay soil forms part of the Quaternary Fine Member of the Bucaramanga Formation and presents characteristics suitable for the production of CEBs [13] with dimensional tolerances conform to ASTM Standards.

2.1.2. Gypsum mining by-product

Gypsum mining wastes, which are disposed after extraction of gypsum from Cretaceous sedimentary rocks of the Rosablanca Formation in several mines located around Los Santos (Santander), was used as a chemical additive to protect CEBs against moisture decomposition and stabilize them.

2.1.3 Lime

An industrial lime was also used as a stabilizer.

Figure 1. Raw materials
Source: The authors.

2.2. *Properties of materials*

Qualitative determination of major crystalline phases of the raw clay-rich material and the gypsum mining by-product was carried out by using a Siemens D500 X-Ray Diffractometer, operating in the Bragg–Brentano geometry with CuK_1 radiation (λ=1.5406 Å), at 40 kV and 30 mA, and a graphite monochromator. Data was collected in the 2-70° 2θ range (0.02° step size). The crystalline patterns were compared with the standard line patterns from the Powder Diffraction File database supplied by the International Centre for Diffraction Data (ICDD), with the help of Joint Committee on Powder Diffraction Standards (JCPDS) files for inorganic compounds. The major crystalline phases found in the clay-rich material are quartz, microcline, muscovite, anatase and kaolinite (Fig. 2a). As shown in Fig. 2b, the gypsum mining by-product is characterized by the occurrence of quartz, clinochlore, gypsum, dolomite, Mg-calcite and calcite. The chemical composition of this was investigated by X-ray fluorescence using a Shimazu EDX 800 HS XRF spectrometer to quantify the elements in the gypsum mining waste using the method of fundamental parameters (FP) with the software DXP-700E Version 1.00 Rel. 014. The chemical composition of the gypsum mining waste used in this study was 48.64% CaO, 27.31% SiO_2, 9.16% MgO, 6.13% SO_3, 4.81% Al_2O_3, 2.41% Fe_2O_3, 1.53% K_2O, 0.47 SrO%, 0.20 MnO, 0.11% BaO and 0.02% CuO.

The particle size distribution (the relative content of clay, sand and gravel) of the clay-rich material (Fig. 3) obtained by combined sieve and hydrometer analyses according to the standards ASTM C136-06 [14] and ASTM D1140-00 [15].

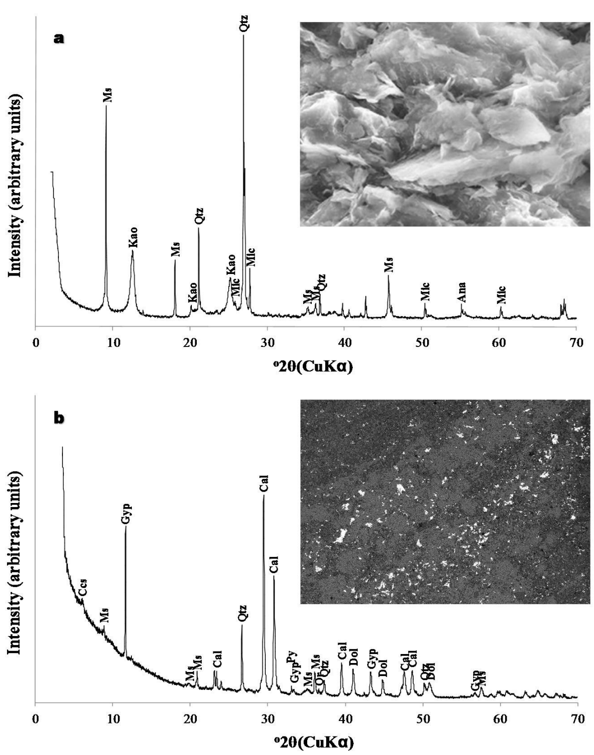

Figure 2. XRD pattern of raw clay-rich material (upper part) and and gypsum mining by-product (lower part). Ms, muscovite; Kao, kaolinite; Qtz, quartz; Mic, microcline; Ana, anatase; Ccs, clinocrysotile; Gyp, gypsum; Cal, calcite; Py, pyrite; Or, orthoclase; Dol, dolomite
Source: The authors.

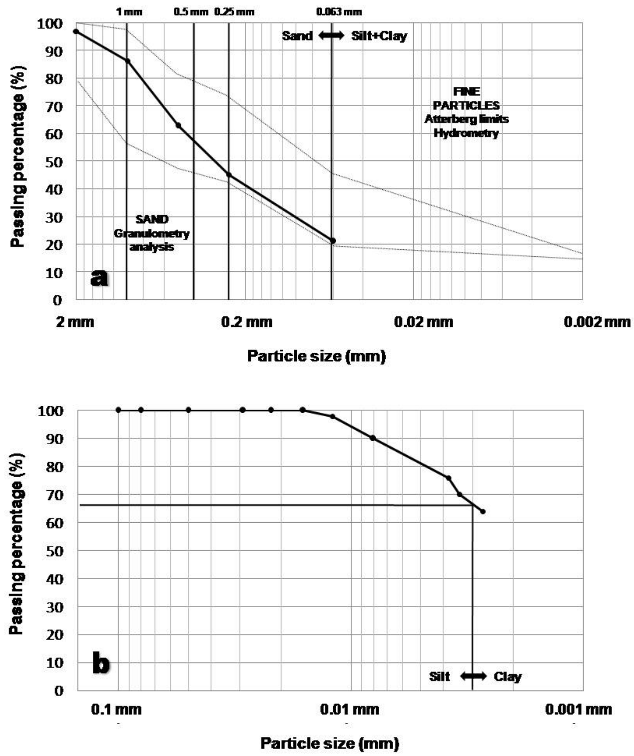

Figure 3. Particle size distribution of the clay-rich material
Source: The authors.

Fig. 3a reveals that the clay-rich material is within the recommended limits for the manufacture of CEBs, which according to Houben et al. [16], are: gravel (0-40%), sand (25-80%), silt (10-25%) and clay (8-30%). The fine grained portion (amount of soil to pass a No. 200 mesh) was 21.1%, which was used in determining the percentages of clay (13.5%) and silt (7.5%) by the hydrometry test (Fig. 3b). According to Cuéllar et al. [17], clay properties depend on the structural characteristics and particle size (< 2µm). Therefore, this test only measures the clay/silt ratio for the fine grained portion of the soil and not the entire soil itself.

The Atterberg's limits of the clay-rich material determined according to the standard ASTM D4318-10 [18], using the plasticity chart with the following results: liquid limit (LL) of 27.3%, plastic limit (PL) of 21.2% and plasticity index (PI) of 6.1%, with an acceptable correlation (R^2 = 0.739). The clay-rich material can be classified as SM-SC (silty-clayey sand with low plasticity) using the ASTM D2487-11 [19]. It corresponds to a coarse-grained (> 50% retained on No. 200 mesh) sandy (> 50% of coarse fraction is < 4.75 mm (No. 4 mesh)). Similarly, it contains > 12 % of material passing the No. 200 mesh, LL < 50%, 4 ≤ IP ≤ 7 and Atterberg's limits on or above the “A” Line.

For the purpose of sample preparation, dry density and moisture content values were established. Therefore, Proctor Compaction tests were carried out in accordance to the standard ASTM D1557-12 [20] in order to establish values of the maximum dry density and optimum moisture (Fig. 4) for the non-stabilized and stabilized CEBs. This was to guide the research on the possible range of moisture contents at which the dry unit weight of the clay-rich soil

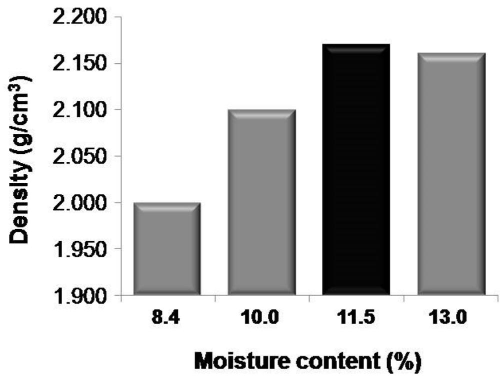

Figure 4. Results from Proctor Compaction tests
Source: The authors.

will be a maximum and to achieve the best compaction effort. The clay-rich material used in this study has a natural moisture content (optimum moisture) of 11.5%. The moisture content of the sample at the point of testing includes this natural moisture in the clay soil and the water added at the point of mixing. The clay was used at its natural moisture content because in practice, an oven drying operation will not be feasible.

2.3. Sample preparation, mix compositions and testing

Fig. 5 illustrates a block diagram showing the methodology followed in the manufacturing of the CEBs during their study. The raw clay-rich material and the gypsum mining by-product were naturally dried for three weeks under the following environmental conditions: average temperature of 24ºC and relative humidity of 83.5%. The mining waste subjected to rough crushing with a Retsch Jaw Crusher BB200 to ~ 2 mm and milling with a Retsch RM100 mortar grinder mill to clay particle size. Both raw clay-rich material and gypsum mining by-product sieved with a Ro-Tap sieve shaker (using 4, 10, 20, 40, 60, 100 and 200 mesh series). The mining waste sieved and the *particle size* below 200 mesh used. In order to evaluate the engineering properties of CEBs, with gypsum mining by-product as stabilizing agent, several mixtures were prepared for mix design of preparation of CEBs. The mix proportions were prepared based on the dry weights of the ingredients. The quantities of materials obtained from the mix design was measured with the aid of a weighing balance. CEBs were produced with a *Cinva-Ram* block making machine, a technology that offers an alternative kind of building construction which is more accessible and of high quality. For testing, 91 CEBs (13 for each mixture) were prepared. The cuboidal shape and size (290 x 100 x 140 mm) tolerances of the masonry units respected.

Fig. 6 illustrates the preparation of the CEBs. Several mixtures were loaded into the block making machine. Table 1 reports the details of the mixture compositions and the assessment of the process of manufacture of CEBs produced during the tests.

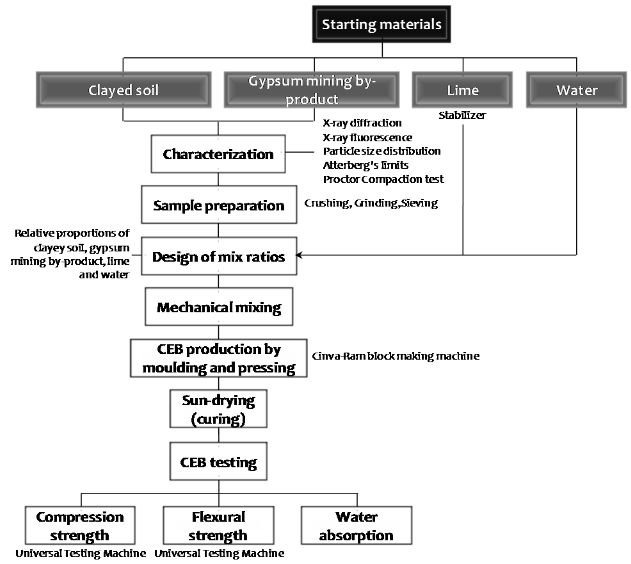

Figure 5. Methodology for manufacturing CABs
Source: The authors.

Figure 6. Stages of characterization of raw materials and preparation of CABs. (a)-(b) Combined sieve and hydrometer analyses of the clay-rich material. (c) Sieve analyses of the gypsum mining waste. (d)-(e) Test of the Atterberg's limits (limits of consistency). (f) Proctor Compaction test. (g) Mix of materials. (h) Mix in the *Cinva-Ram* block-making machine before pressing process. (i) Resultant set of CABs
Source: The authors.

Table 1.
Details of mix composition used during industrial trial.

Trial (T)	Mix code	Mix proportions (%)				CS (MPa)	*MR (MPa)*	WA (%)
		CRM	GMW	CaO	H_2O			
T1	CEB1	88.5	0	0	11.5	0.25	0.291	---
T2	CEB2	86	2.5	0	11.5	0.62	0.333	---
T3	CEB3	81.5	2.5	3	13	1.57	0.446	25.5
T4	CEB4	83.5	5	0	11.5	0.47	0.262	---
T5	CEB5	79	5	3	13	1.21	0.580	22.4
T6	CEB6	78.5	10	0	11.5	0.90	0.357	---
T7	CEB7	74	10	3	13	1.32	0.334	23.4

CEB, compressed earth block; CRM, clay-rich material; GMW, gypsum mining waste; CS, Compression strength; MR, Modulus of rupture; WA, Water absorption
Source: The authors.

To CEBs not stabilized with lime, the water content was increased by 1.5% compared to 3% lime, as suggested in Perez & Pachón [21] and given the reaction ratio of water/lime which corresponds to 0.5:1. These authors suggest minimal use of lime, as it can generate a low performance. An automated hydraulic pump, connected to a mold frame by a hydraulic hose and cylinder, was used to gradually pressurize the cylinder which in turn applied pressure to the mixture in the mold. After the pressure was applied for a few seconds, it was released and a CEB was extruded by the machine onto a conveyor belt for transfer to storage. In order to obtain comparable results, five different series of samples were prepared for the tests, a separate series for each percent material addition. CEBs were kept undisturbed under controlled environmental conditions (average temperature of 25 ºC and relative humidity of 80%) during the curing phase (28 days). No detrimental effects due to shrinking/swelling, such as cracking, were observed. Engineering tests conducted in a computerized device for mechanical assays according to the standard ASTM C67-11 [22]. A Universal Testing Machine (PINZUAR, model PC-160/116) with a maximum load of 1000kN was used in the testing procedure, taking into account its accuracy, flexibility, high performance, and innovative standard features; large test space to accommodate standard, medium and large size specimens, grips, fixtures and environmental subsystem, and environmental chamber dimension: 500 x 255 x 350 mm. Data was recorded automatically to the computer system. All CEBs were subjected to a compressive load at a crosshead speed of 0.5 mm/min. A test of compressive strength was conducted to determine the level of deformation of the material. The three-point bending flexural strength test was conducted with a crosshead speed of 0.2 mm/s and a distance between the supports of 90 mm. The test provides values for the modulus of rupture (*MR*) of the CEBs. *MR* was calculated using the following equation:

$$MR = \frac{3Pa}{2bd^2} \qquad (1)$$

Where *MR* is the flexural modulus of rupture (MPa), *P* is the maximum applied load (N), *a* is the distance between line of fracture and the nearest support (mm), *b* and *d* are the width and thickness of the specimen (mm), respectively.

The durability of the CEBs was assessed as follows: after 28 days of curing time, the CEBs were weighed; then, they were submerged in water for 24 h and then tested in compression after repeated wetting and drying on their unconfined compressive strength values. Repeated wetting and drying of the blocks can alter the soil structure and create concentrated weaknesses through cracking and the infiltration of water. The total water absorption capacity of the CEBs was established by the water absorption (*WA*) test. The water of absorption can be determined from the moist weight of specimens after submersion according to the standard ASTM C67-11 [22]. The water absorption during immersion was calculated using the following equation:

Figure 7. Compression strength test, showing experimental set up and resultant CABs after testing
Source: The authors.

$$WA = \frac{W_w - W_d}{W_d} \times 100\% \qquad (2)$$

Where W_d is the mass of the dry specimens before submersion (g) and W_w is the wet mass of the specimen after being removed from the water tank (g).

3. Test results and discussion

Table 1 shows the average values of results for the compression, flexural and water absorption tests. Each value represents the average of 5 specimens. The number and series of specimens was according to ASTM standards and depending on the number of different mixtures tested, with a minimum of five specimens per batch.

3.1. Compressive strength of the CEBs

The uniaxial compressive stress is reached when the material fails completely. The compressive strength test determines the relationship stress vs. strain of the CEBs. Fig. 7 shows a representative set of the experimental test to determine the compressive strength of the CEBs and results are depicted in Table 1.

Fig. 8 illustrates the average compressive strength of the CEBs. It also shows the influence of the gypsum mining by-product on the compressive strength of specimens obtained after 28 days of curing time under dry conditions. From trial T1, the simple compression test reached an average value for 5 units of 0.251 MPa. This value must be taken into account to compare the results with other trials. CEB1 tends to separate at the ends while the center remains consistent. From trial T2, the simple compression test reached an average value for 5 units of 0.624 MPa, higher than that obtained in the trial T1. CEBs tend to separate at the ends while the center remains consistent. From trial T3, the simple compression test reached an average value for 5 units of 1.574 MPa, higher than that obtained in trials T1 and T2. CEBs tend to separate at the ends, with some of them displaying broken side surfaces, while the front and center remain consistent. From trial T4, the simple compression test reached an average value for 5 units of 0.466 MPa, slightly higher than that obtained in the trial T1. Deep cracks were observed on the CEBs although they did not disintegrate completely. From trial T5, the simple compression test reached an average value for 5 units of 1.206 MPa, slightly lower than that obtained in the trial T3. Some CEBs displayed cracks and others tended to separate in their external surfaces while the center remains

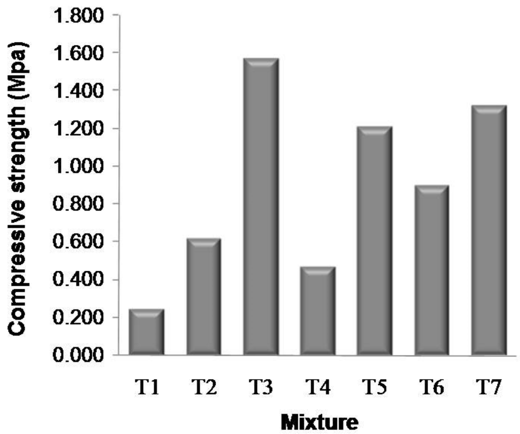

Figure 8. Average compressive strength for all CEBs
Source: The authors.

Figure 9. Flexural strength test set up, showing experimental set up and resultant CABs after testing
Source: The authors.

consistent. From trial T6, the simple compression test reached an average value for 5 units of 0.901 MPa, slightly lower than that obtained in the trial T5. Deep cracks were observed on the CEBs and they tended to separate in their external surfaces although they did not disintegrate completely. From trial T7, the simple compression test reached an average value for 5 units of 1.319 MPa, which is in the range of values obtained between the trials T3 and T5. CEBs tend to separate on the sides and front, and some of them were crossed by cracks along their front.

From Fig. 8, we observe that the behavior of unstabilized CEBs (trials T1, T2, T4 and T6), lies well below the values recommended by Colombian technical standards, which suggest a minimum value of compressive strength of 1.2 MPa. Therefore, it would not be advisable to use them for the development of individual blocks. The best performances were obtained in the mixtures stabilized with lime, obtaining the best value for the mixtures from the trial T3 containing 2.5% gypsum mining waste and 3% lime, showing an improvement of 52.7% (6 times better) with respect to CEBs obtained from the trial T1. Increasing the gypsum mining waste content above 2.5% (trials T5 and T7), promote a increase in the compressive strength but remains below the value obtained from the trial T3. Using the gypsum mining waste without the presence of lime, the results showed an improvement of between 150 and 250% (up to 3 times better). For all cases, mixtures stabilized without using lime showed compressive strength values lower than those obtained from lime stabilized CEBS.

3.2. Flexural strength characteristic of the CEBs

It is the ability of a masonry brick, beam or slab to resist failure in bending. The typical load and deflection from beam-flexural test is shown in Fig. 9 and results are depicted in Table 1.

Fig. 10 illustrates the average *MR* of the CEBs. The non-stabilized CEBs from the trial T1 have a load carrying capacity of 1133 N. This mixture achieved a MR in the range of 0.202–0.369 MPa (with an average of 0.291 MPa). The non-stabilized CEBs from the trial T2 containing clay-rich material (86%) and gypsum mining waste (2.5%) have a load carrying capacity of 1300 N. This mixture achieved a higher MR, in the range of 0.278–0.395 MPa (with an average of 0.334 MPa). The addition of gypsum mining waste helps to stabilize the clay-rich material, improving the engineering properties of CEBs. The stabilized CEBs from the trial T3 containing clay-rich material (81.5%), gypsum mining waste (2.5%) and lime (3%) have a load carrying capacity of 1767 N, which is higher than the CEBs obtained in the trials T1 and T2, increasing the stress resistance. This mixture achieved an MR in the range of 0.405–0.505 MPa (average of 0.446 MPa). The non-stabilized CEBs from the trial T4, containing clay-rich material (83.5%) and gypsum mining waste (5%), have the lower load carrying capacity of 1000 N. This mixture achieved an MR in the range of 0.233–0.316 MPa (with an average of 0.262 MPa). The stabilized CEBs from the trial T5, containing clay-rich material (79%), gypsum mining waste (5%) and lime (3%), have the higher load carrying capacity of 2233 N. The higher MR values (0.482–0.758 MPa; an average of 0.580 MPa) obtained in the mixtures with a 5% of gypsum mining waste. The non-stabilized CEBs from the trial T6, containing clay-rich material (78.5%) and gypsum mining waste (10%) have a load carrying capacity of 1433 N. This mixture achieved an MR in the range of 0.328–0.404 MPa (an average of 0.357 MPa). The stabilized CEBs from the trial T7, containing clay-rich material (74%), gypsum mining waste (10%) and lime (3%) have a load carrying capacity of 1400 N. This mixture achieved an MR in the range of 0.301–0.363 MPa (with an average of 0.334 MPa).

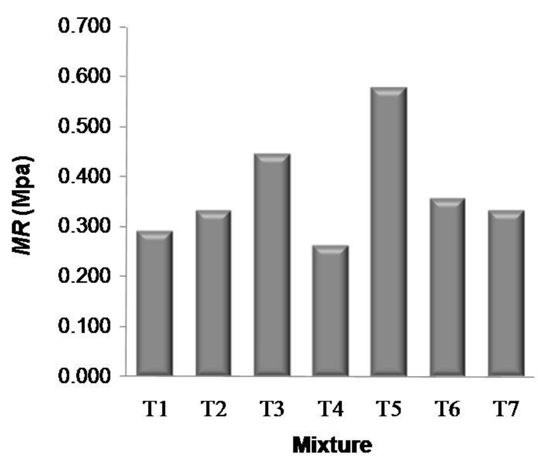

Figure 10. Average *MR* for all CEBs
Source: The authors.

These results show that although the gypsum mining waste meets the expectations and proposals for the compaction point load strength of the CEBs, doses greater than 5% strongly affect the mixture. These results confirmed the results obtained from the compressive strength test. According to the Masonry Standards Joint Committee (MSJC) [23], the allowable flexural tensile stress, or modulus of rupture, for clay and concrete masonry is 0.21 MPa. Using this as the quality standard, the allowable rupture load could be determined. The CEBs showed flexural strengths between 0.262 and 0.580 MPa, which is below the range of 0.5-2 MPa reported in previous studies [24-25], except for the MR obtained from the trial T5 (0.580 MPa). From trial T1, the population of data has a mean of 0.175 MPa and their standard deviation is 0.152. From trial T2, the population of data has a mean of 0.200 MPa and their standard deviation is 0.168. From trial T3, the population of data has a mean of 0.268 MPa and their standard deviation is 0.221. From trial T4, the population of data has a mean of 0.157 MPa and their standard deviation is 0.132. From trial T5, the population of data has a mean of 0.348 MPa and their standard deviation is 0.300. From trial T6, the population of data has a mean of 0.214 MPa and their standard deviation is 0.177. From trial T7, the population of data has a mean of 0.201 MPa and their standard deviation is 0.165. The fourth population has the smaller standard deviation than the other populations because its values are mostly close to 0.132. After performing durability and strength tests on the CEBs, results show that most of them perform at an acceptable level in all tests. However, gypsum mining waste doses of 10% or more will reduce workability of the CEBs.

3.3. Durability testing of the CEBs

The durability of the CEBs assessed by determining the effect of wetting and drying on their compressive strength values, although without the number of saturation cycles suggested by Krosnowski [25], which can alter the soil structure and create concentrated weaknesses through cracking and the infiltration of water. Results obtained from the water absorption test give a general idea to assess the behavior of the CEBs under extreme conditions. In the case of Bucaramanga and its metropolitan area, one of these extreme conditions is the possibility of a flood, particularly affecting the CEBs that form the base of a wall, which are more likely to be submerged completely and should bear the burden of the entire wall. As the density of soil is increased, its porosity reduced and less water can penetrate it [26]. Water absorption is used as an indicator for the specimen's resistance to immersion. Table 1 and Fig. 11 present results from the durability test. During the saturation, each CEB was carefully examined for any observable cracking or degradation effects.

Fig. 12 shows CEBs soaked in water and the detrimental effects of saturation. The non-stabilized CEBs from the trial T1 showed a loss of consistency, disintegrating completely, and developing a silty sand mixture. The non-stabilized CEBs from the trial T2 containing clay-rich material (86%) and gypsum mining waste (2.5%), showed a loss of consistency, disintegrating completely, and developing a silty sand mixture, in which the gypsum mining waste separated and was easily differentiated from the mixture. The stabilized CEBs from the trial T3 containing clay-rich material (81.5%), gypsum mining waste (2.5%) and lime (3%), retained their shape but their size increased from 5 to 10 mm, and deformation was observed at their edges and corners. The average water absorption was 25.502%, being the highest from the CEBs that retained their shape. The compressive strength after water absorption showed an average value of 0.580 MPa. The non-stabilized CEBs from the trial T4, containing clay-rich material (83.5%) and gypsum mining waste (5%), showed a similar behavior to that observed in the trial T2, with CEBs losing consistency, disintegrating completely, and developing a silty sand mixture, in which the gypsum mining waste separated and was easily differentiated from the mixture. The stabilized CEBs from the trial T5, containing clay-rich material (79%), gypsum mining waste (5%) and lime (3%), retained their shape but their size increased by up to 5 mm, and deformation was observed at their edges and corners. The average water absorption was 22.378%, being the lowest from CEBs that retained their shape. The compressive strength after water absorption showed an average value of 0.860 Mpa, which is higher when compared with that observed in the trial T3. The non-stabilized CEBs from the trial T6, containing clay-rich material (78.5%) and gypsum mining waste (10%), showed a similar behavior to that observed in trials T2 and T4, with CEBs losing consistency, disintegrating completely, and developing a silty sand mixture, in which the gypsum mining waste separated and was easily differentiated from the mixture. The stabilized CEBs from the trial T7, containing clay-rich material (74%), gypsum mining waste (10%) and lime (3%), showed a great loss of material to the edges and corners, which took a rounded shape. The average water absorption was 23.360%, although this percentage is not representative because possibly could correspond to the loss of material and not to the degree of water absorption. Therefore, the compressive strength test after water absorption was not performed for this trial. The water absorption tests reveal that stabilizing the mixtures with lime ensures better structural consistency. According to Fig. 11, the results obtained were not

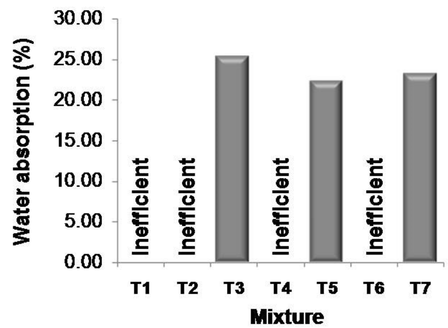

Figure 11. Durability test of the CEBs
Source: The authors.

satisfactory regarding CEBS from trials T1, T2, T4 and T6 prepared in the absence of lime, which showed results losing consistency, disintegrating completely, and developing a silty sand mixture, in which the gypsum mining waste separated and easily differentiated from the mixture. Therefore, these mixtures are described as inefficient and their behavior can be explained due to the presence of sulphates in the gypsum mining waste that are sensitive to water so that when wetted they may become easily detached. CEBs from trials T3, T5 and T7 containing 3% lime, kept in shape, showing deviation in their lengths (~ 5-10 mm) and disintegration at their edges and corners. Although CEBs from trial T3 holds its shape, CEBs from trial T5 showed the best consistency, keeping their shape better. CEBs from trial T7 suffered further disintegration, showing a great loss of material to the edges and corners, which took a rounded shape. Regarding the percentage of moisture in weight, CEBs from trials T3 and T5 showed values of 25.502% and 22.378%, respectively; CEBs from the trial T7 showed a percentage of moisture in weight of 23.036%, although due to the loss of material at the edges, cannot be considered as representative. These results are considered good considering the values obtained in previous studies [1,13,27-29]. After water absorption, the non-stabilized and stabilized CEBs were subjected to simple compression test to assess the degree of consistency while being subjected to excessive moisture. Results show that the mixtures have a cohesive behavior when having excess moisture, with the clay-rich material taking a plastic behavior. Compressive strength values of 0.593 MPa and 0.885 MPa for CEBs from trials T3 and T5, respectively, are still sufficient to maintain a standing wall in a building. According to Krosnowski [25], a decrease in the compressive strength values with the number of saturation cycles is expected to occur; however, the rate at which the compressive strength decreases also appears to decrease as the number of saturation cycles increases.

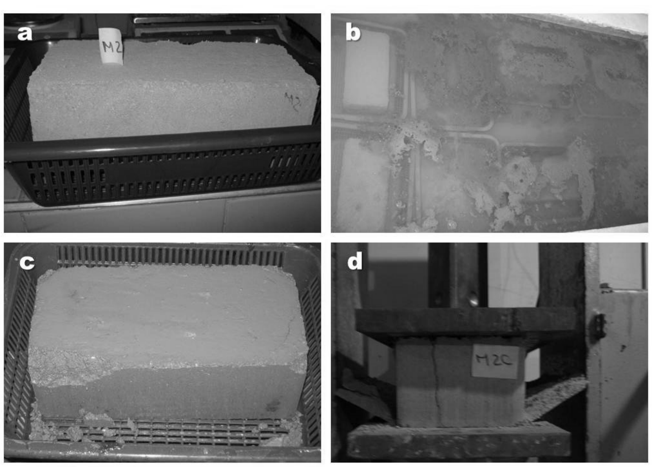

Figure 12. (a) CEB before soaking in water. (b) CEB during soaking in water. (c) CEB after soaking in water. (d) CEB during compressive strength test
Source: The authors.

4. Conclusions

A laboratory test program conducted to evaluate the potential use of gypsum mining waste to produce CEBs. The hardened properties such as compressive strength, flexural strength, and water absorption was investigated. Subordinately, test results may provide a means to reduce a waste disposal problem while providing the construction industry with a new, useful, low cost raw material. Based on the experimental tests conducted on the CEBs, the following conclusions can be drawn:

The liquid and plastic limits of the clay-rich material are appropriated for the production of CEBs, although it is advisable to test a number of natural fibers to increase compressive and flexural strength and to avoid excessive cracking.

Clay-rich material correspond to a granular soil, with > 50% of sand and gravel size, but the soil used is a sandy soil because > 50% of the coarse fraction is < 4.75 mm (No. 4 mesh ASTM). According to this and the behavior of the fine fraction of the soil, it classified as a clayed silty sand soil, settling near the boundary line suitable for the preparation of CEBs.

The chemical composition of the gypsum mining waste reveals that the elemental content would be suitable in principle for chemical stabilization, avoiding a waste with high levels of visible gypsum as this could create adverse conditions for the development of CEBs.

Non-stabilized CEBs showed values of compressive strength up to 0.251 MPa, which are below recommended limits. However, CEBs from the trial T3 (2.5% of gypsum mining waste and 3% of lime), the compressive strength was improved by up to 500% (5 times) reaching values of 1.574 MPa, that is within the minimum range required by Colombian construction standards.

Stabilized CEBs showed much better values of modulus of rupture compared with those obtained from non-stabilized CEBs. CEBs from the trial T5(5% of gypsum mining waste and 3% of lime), showed the highest values of *MR*, achieving high levels of rigidity, although in the compressive strength test they are lower than those obtained for CEBs from the trial T3.

CEBs containing 10% gypsum mining waste showed compressive strength values lower than those obtained for CEBs containing 5 or 2.5% gypsum mining waste.

Non-stabilized CEBs from trials T2, T4 and T6, showed a slight improvement in the engineering properties with respect to Non-stabilized CEBs from trials T1, although not as pronounced as observed in lime stabilized CEBs.

A significant improvement was displayed by lime stabilized CEBs in extremely humid conditions, retaining their shape after being submerged in water 24 hours that confirms the activating ability of lime to generate reactions cementing between the clay-rich material and gypsum mining waste.

Non-stabilized CEBs, containing gypsum mining waste in several percentages, after water absorption, showed a completely unacceptable behavior; they completely disintegrated, making them unsuitable in extreme conditions.

The results of this study reveal that the engineering properties of the CEBs were not satisfactory in the criterion of authors, suggesting additional experimental work to improve the engineering properties of CEBs.

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