ESCUELA DE CONSTRUCCIÓN CIVIL
FACULTAD DE INGENIERÍA
Revista de la Construcción
Journal of Construction

Research Article

The effect of local pozzolans and lime additions on the mineralogical, physical and mechanical properties of compressed earth blocks in Argentina

Santiago Cabrera[1]*, Kerstin Elert[2], Anabela Guilarducci[3], Andrea Margasin[4]

1 Grupo de Investigación y Desarrollo en Técnicas de Construcción con Tierra, Universidad Tecnológica Nacional, Facultad Regional Santa Fe (Argentina), spcabrera@outlook.com
2 Departamento de Mineralogía y Petrología, Facultad de Ciencias, Universidad de Granada (España), kelert@ugr.es
3 Centro de Investigación y Desarrollo para la Construcción y la Vivienda, Universidad Tecnológica Nacional, Facultad Regional Santa Fe (Argentina), aguilarducci@frsf.utn.edu.ar
4 Grupo de Investigación y Desarrollo en Técnicas de Construcción con Tierra, Universidad Tecnológica Nacional, Facultad Regional Santa Fe (Argentina), amargasin@frsf.utn.edu.ar
*Correspondence: spcabrera@outlook.com

Received: 07.12.2021; **Accepted:** 10.08.2022; **Published:** 30.08.2022

Citation: Cabrera, S., Elert, K., Guilarducci, A. and Margasin, A. (2022). The effect of local pozzolans and lime additions on the mineralogical, physical and mechanical properties of compressed earth blocks in Argentina. Revista de la Construcción. Journal of Construction, 21(2), 248-263. https://doi.org/10.7764/RDLC.21.2.248.

Abstract: The purpose of this research is to evaluate the mineralogical, physical and mechanical properties of compressed earth blocks (CEBs) stabilized with lime and mineral admixtures easily obtained in Argentina: natural pozzolans and brick powder. The mineralogical composition and pozzolanic potential of the admixtures were determined, as well as the development of hydraulic phases upon reaction with calcium hydroxide (lime), adding emphasis on the formation of hydrated cementing compounds. Samples with different percentages of lime and mineral additions were prepared to assess their compressive strength, wet erosion resistance and water absorption, and the results were contrasted with those of their counterparts, stabilized exclusively with lime or cement. The results obtained imply that both the brick powder and pozzolans used have pozzolanic properties and that, in combination with calcium hydroxide, they form amorphous phases of C-(A)-S-H. However, the use of small amounts of both additions in combination with hydrated air lime in the manufacture of CEBs adversely affected their physical and mechanical properties, compared to CEB samples stabilized only with hydrated air lime.

Keywords: CEB, lime, pozzolan, durability, compressive strength.

1. Introduction

For millennia, mankind has used soil as a building material for earth construction in several forms: mixed with straw to build walls, either alone (cob) or in combination with wooden structures (wattle and daub); compacted by means of wooden formworks (rammed earth or "tapia"), or in the form of masonry blocks (adobes), usually hand-molded and sun-dried (Aubert et al., 2013). In general, most earthen structures were built in an artisanal manner, and the adaptation of modern production and construction techniques to earthen materials has been a challenge.

However, said adaptation could be feasible if production and construction processes for earthen structures were standardized and adapted to industrial production methods (González López et al., 2018). From this perspective, compressed earth blocks (CEBs) represent an evolution over traditional earth construction techniques, contributing to modernization by offering high-performance, economic construction materials (Dethier & Cohen, 2019).

CEBs are produced by mixing soil and additives, usually lime or cement. The mixture thus obtained is then compressed using specially designed machines which provide a molding pressure of about 20 kgf/cm^2 (Van Damme & Houben, 2018). Although soil is the base material for these blocks, its characteristics are usually far from ideal for CEB production, and stabilizers need to be added in order to enhance the physical properties of the CEBs, i.e., improving their mechanical strength and weathering resistance, as well as reducing clay contraction (Lima et al., 2012). In terms of improving the mechanical strength of CEBs, as with traditional adobes, many additives have been used for stabilization (Concha-Riedel et al., 2021; Rodríguez Cuervo, 2020), ranging from natural substances such as mucilage aloe, casein and cellulose (Vissac et al., 2017) to petroleum products such as bitumen emulsions (Arteaga Paucar & Loja Saula, 2018). However, Portland cement has always been the most typical stabilizer (Malkanthi et al., 2020). In several regions of Argentina and Latin America, they are often termed as "soil-cement blocks" due to the influence of civil engineering.

Despite the good performance of cement-stabilized CEBs, their fabrication involves high economic costs. Besides, binder production requires high-temperature transformation processes and clinker grinding (Maddalena et al., 2018), both processes contributing to a large carbon footprint. Indeed, the production of each ton of Portland cement implies the release of about 0.86 tons of CO_2 (Miller et al., 2018).

Lime production requires limestone to be calcined at ~900 °C; ~50% less CO_2 is released in comparison to Portland cement (Maddalena et al., 2018). Upon carbonation, lime incorporates a large part of the CO_2 released to the atmosphere during calcination. These characteristics turn lime into a more environmentally friendly alternative to Portland cement, widely used in CEB stabilization in several countries to improve resistance and durability (Ouedraogo et al., 2020).

The use of lime for CEB stabilization is not new (Hays et al., 1979): it is well known that the addition of lime improves weathering resistance, especially the resistance to rain erosion. However, the compressive strength of CEBs stabilized with lime is significantly lower than that of their counterparts stabilized with the same proportion of cement, as shown by the results obtained in different studies (González López et al., 2018; Malkanthi et al., 2020).

In order to reduce said difference in resistance between soil-lime CEBs and cement-stabilized CEBs, lime can be partially replaced by materials with pozzolanic properties (James & Pandian, 2018). These materials have no significant cementing capacity by themselves but, when finely ground, they can react with calcium hydroxide in the presence of water and thus generate hydraulic phases. Natural or artificial pozzolans are siliceous or silicoaluminous materials with small amounts of calcium, magnesium, iron, potassium and sodium which, after reacting with $Ca(OH)_2$, form hydrated dicalcium silicates and/or hydrated dicalcium aluminates, responsible for most of the physical, chemical and mechanical properties of cementitious mortars (Raggioti et al., 2015).

Partial replacement of lime by mineral pozzolanic additions could lead to more resistant products with environmental advantages: the incorporation of waste material with pozzolanic properties and the resulting reduction in lime content would lead to a reduction in CO_2 emissions. The main goal of this research is to evaluate the chemical and physical-mechanical properties of compressed earth blocks stabilized with materials easily obtained in Argentina, such as lime and local mineral additions with pozzolanic properties. The following are the specific objectives:

- To study the mineralogical composition and pozzolanic activity of two mineral additions easily obtained in the province of Santa Fe, Argentina: brick powder from Santa Fe, and a natural pozzolan from the province of Mendoza (Argentina).
- To evaluate the effect of the replacement of calcium hydroxide by different mineral additions, in particular the development of pozzolanic reactions and the formation of cementitious compounds.

- To evaluate compressive strength, resistance to pressurized water spraying, and water absorption for CEBs stabilized with lime and mineral additions, and to contrast the results with those of their counterparts stabilized exclusively with lime or cement.

2. Materials and methods

2.1. *Materials*

The soil used for CEB production in this study comes from a local quarry in Monte Vera (Santa Fe province, Argentina) dedicated to soil extraction for road works. It is classified as low plasticity clay silt CL-ML (ASTM, 2017). Because of the low content of coarse material, a granulometric correction for CEB production was made by adding fine sand from the lower basin of the Parana River.

Samples were stabilized with hydrated air lime manufactured in San Juan, Argentina, mixed in different proportions with the pozzolan and brick powder. The brick powder was manufactured by crushing discarded bricks (either broken or poorly cooked) provided by brick makers near Santa Fe. The pozzolan used is extracted from quarries close to the village of Pareditas (Mendoza, Argentina), near the Andes Mountains. For comparison purposes, other samples were prepared, stabilized with Portland cement type CPC 40 (IRAM, 2019) produced in Mendoza, Argentina.

2.2. *Sample preparation*

Cylindrical test samples (12 specimens for each sample type), 5 cm in diameter and 7 cm in height, were prepared using the following parameters: 20 kgf/cm^2 compaction pressure, 35% compression ratio, and 1.600 kg/cm^3 final density. These parameters were chosen based on the characteristics typically used to produce CEBs in a hydraulic press type ECO BRAVA (Eco Máquinas, Navegantes, Brazil), a model frequently used in this region. The optimum moisture content (13%) was determined by means of a Proctor compaction test type I (Ciancio et al., 2014; DNV, 1993) applied to the dosages used in the control series. Given the high influence of the final dry density on the mechanical properties of CEBs and their intrinsic connection to molding moisture (González López et al., 2018), the choice was to keep this variable constant for all the series.

The dosages used are listed in Table 1. It can be seen that the total content of stabilizers used in each series (except for the control series) is 10% in weight referred to the dry material total, which is the same proportion typically added by CEB manufacturers in Argentina (Cabrera et al., 2021) and the one most used by other authors in their research works (Arias & Alderete, 2017; Barbero-Barrera et al., 2020; Galíndez, 2007; González López et al., 2018; Lima et al., 2012; Sitton et al., 2018). In the series stabilized with lime and mineral additions, instead of keeping the lime percentage fixed and adding variable amounts of mineral additions, a choice was made to replace part of the lime by mineral additions, while keeping the total stabilizer percentage constant (lime + mineral additions); this methodology was applied by one of the authors in her PhD thesis (Guilarducci, 2018). Moreover, in previous research works (Cabrera, Aranda Jiménez, et al., 2020), using a methodology similar to the one applied by Ciancio et al. (2014), the effect of hydrated air lime content was assessed in the stabilization of CEBs manufactured using the same materials as in this research. From the results, a 10% lime percentage was adopted as a comparison reference to appreciate the effects of partial replacements of lime by the mineral additions being studied.

For the preparation of the series with mineral additions, both the brick powder and the pozzolan were ground manually until they passed through a #200 (75 µm) sieve, which was also the size of the lime and cement particles as confirmed by sieving.

The following procedure was used for the preparation of the cylindrical test samples: the different components were first dry-mixed manually, then water was added until the optimum moisture content of 13 wt% was obtained. Afterwards, the cylindrical molds were filled with an adequate amount of the wet mixture (264.2 g) to obtain the preestablished density. The material was compressed with the help of a hydraulic piston, reducing the initial sample height from 11.0 cm to 7.1 cm and thus achieving a 20 kgf/cm^2 compression pressure. Finally, the test samples were demolded using the same piston, and their weight, diameter and height were recorded. Curing of all samples, except for the control series (without stabilizers), was carried out by humidifying them with water and keeping them wrapped in a polyethylene film for seven days, the minimum time recommended by specialized CEB production manuals (Neves & Borges Farías, 2011; Rigassi, 1985).

Table 1. Composition (g) of the different soil mixtures.

Series	Soil	Sand	Lime	Cement	Pozzolan	Brick powder	Water
Control	2258.56	967.95	-	-	-	-	419.45
Cem. 10%	2032.70	871.16	-	322.65	-	-	419.45
Lime 10%	2032.70	871.16	322.65	-	-	-	419.45
Pozz. 3%	2032.70	871.16	225.86	-	96.80	-	419.45
Pozz. 5%	2032.70	871.16	161.33	-	161.33	-	419.45
Brick p. 3%	2032.70	871.16	225.86	-	-	96.80	419.45
Brick p. 5%	2032.70	871.16	161.33	-	-	161.33	419.45

2.3. *Analytical methods*

Nitrogen sorption based on the application of a BET method was used to determine specific surface area for the materials (TriStar 3000 analyzer, Micrometrics, Norcross, US). Before performing any analyses, degassing at 120 °C for 24 h was performed with a VacPrep 061 sample degassing system (Micrometrics, Norcross, US). Additionally, a physical characterization of the earth was performed, determining its Atterberg limits (IRAM, 2007), linear shrinkage index (ASTM, 1995), soluble salt content VN-E18-89 (DNV, 1989), and granulometric distribution (IRAM, 1977, 1986). The latter was also determined for the case of the sand. The apparent (dry) density was determined for all the materials according to the procedure described in IRAM 1520 standard (IRAM, 2002).

The mineralogical characteristics of the raw materials and the mixtures, as well as the formation of new mineral phases upon curing, were assessed using an X'Pert Pro X-ray diffractometer (Malvern Panalytical Ltd., The Netherlands). Samples were either analyzed as powders or, in the case of the clay fraction, as oriented aggregates. Oriented aggregates were air-dried, treated with ethylene glycol, or calcined at 550 °C (Do Campo & Collo, 2018). The equipment settings were CuKα radiation, 45 kV, 40 mA; scan range 2Θ 3 - 60°; and 0.05° 2θ s^{-1} goniometer speed. HighScore Plus software and the PDF 2014 database (ICDD, 2004) were used for mineral phase identification. A semiquantitative XRD analysis of minerals was performed following correction of raw intensity values with reference intensity ratios (RIR) determined using the internal standard method (Klug & Alexander, 1967) by means of the XPowder 12 software.

Changes in morphology and microstructure, as well as in chemical composition, were determined with a field emission scanning electron microscope (FESEM, AURIGA, Carl Zeiss SMT) equipped with an EDS X-ray energy emitter (INCA-200, Oxford). Samples were carbon-coated before analysis. Images, selected area electron diffraction (SAED) patterns, and elemental maps of hydrated phases formed in samples containing natural pozzolan or brick powder were obtained using a transmission electronic microscope Titan (FEI, US) with an XFEG emission gun; a sphericity corrector, and a High-Angle Annular Dark-Field (HAADF) detector operating at 300 kV. Quantitative chemical analyses (TEM-AEM) were performed using a SuperX detector in STEM mode. Powder samples were dispersed in ethanol using ultrasound and placed on copper grids (Elert et al., 2018).

The pozzolanic capacity of the pozzolan and the brick powder was evaluated by means of the "saturated lime test” method, based on Ca^{2+} consumption using a saturated $Ca(OH)_2$ solution (Donatello et al., 2010). To this end, 4 g of pozzolan were added to 300 mL of a saturated $Ca(OH)_2$ solution under N_2 to prevent carbonation. Sealed containers were stored at 40 °C (Guilarducci, 2018), and the Ca^{2+} content was determined after 7 hours, 1, 5, 8 and 16 days using a potentiometric autotitrator (Methrom Titrando 905, Madrid, Spain). For comparison purposes, pozzolanic capacity was evaluated for pure soil and Metapor® (Dennert Poraver GmbH, Germany), a product containing glass powder and metakaolin with known high pozzolanic activity. To perform this test, all the materials were passed through a #200 sieve, thus guaranteeing a particle size < 75 μm.

2.4. *Physical-mechanical tests*

Compressive strength testing was carried out after 28 days of curing on dry (5 specimens) and water-saturated (4 specimens) samples according to UNE-EN 772-1 (AENOR, 2016), applying 100 kgf/sec. The second set of samples was kept submerged in water for 24 hours before testing, in order to obtain complete water saturation.

Water absorption by immersion was determined by weighing samples (4 specimens) before and after a 24-hour-immersion, according to a Brazilian standard (ABNT, 2012). Water absorption by capillarity was determined following UNE 41410 (AENOR, 2008) standard procedure, by calculating the weight gain after the bottom face of each test sample was submerged (5-mm depth) for 10 minutes.

Finally, in order to evaluate wet erosion resistance in the samples, an adaptation of a standard pressurized water spray test NZS 4298 (SNZ, 1998) and IS 1725 (IS, 2013) was used. Samples (3 specimens) were exposed for 60 minutes to a water jet set at a 20 cm distance and at 1 bar. Samples were dried in an oven at 105 °C until constant mass values were obtained, and they were weighed before and after this test to calculate weight loss.

3. Results and discussion

3.1. *Raw material characterization*

Table 2 shows the results of the physical characterization of the soil samples, and Table 3 shows densities, specific surface areas and average pore size for the raw materials. Finally, Table 4 summarizes the mineralogical composition of all the raw materials. Note that the considerable number of amorphous phases made it impossible to reach a reasonable quantification in the case of the natural pozzolan; moreover, it contained large amounts of quartz and illite, and small or trace amounts of feldspar and calcite. In Table 4, high calcite contents can be observed for the lime used in the preparation of the specimens, which suggests deficient quality in the commercially available air limes in the area.

Figure 1 shows the granulometric distribution for the soil and the sand used in the preparation of the specimens, together with the granulometric range limits as recommended by international standards on CEB manufacturing (AENOR, 2008; AFNOR, 2017). By combining both materials in a 7:3 soil-sand ratio (the same ratio used for the preparation of all the specimens), the granulometric distribution for the mixture falls within the recommended ranges. However, it is clear that there are no particles of sizes above 0.25 mm (coarse sand), since the size distribution for the sand used for granulometric adjustment is extremely uniform: over 90% of its particles are between 0.5 mm and 0.1 mm in size.

Table 2. Physical characteristics of the soil.

Liquid limit (LL)	27	100.0%
Plastic limit (PL)	16	100.0%
Plasticity index (PI)	11	99.8%
Lineal shrinkage	4.3%	95.9%
USCS(1)/HRB(2) classification	CL/A-6 (7)	89.0%
Fine sand content	14.5%	60.6%
Slime content	53.6%	23.8%
Clay content	31.9%	0.9%
Soluble salt content	< 0.10%	< 0.10%

(1) Unified Soil Classification System; (2) Health Research Board.

Table 3. Density, specific surface area and pore characteristics based on nitrogen sorption data for all the raw materials used in this study.

Property	Sand	Soil	Pozzolan	Brick powder	Lime
Apparent density (g/cm^3)	1.555	1.161	0.769	1.157	0.597
Specific surface area (m^2/g)	-	15.154	2.198	6.856	6.884
Pore volume (cm^3/g)	-	0.0260	0.0022	0.0086	0.0130
Pore size (Å)	-	101.60	48.10	56.80	68.90

Table 4. Mineralogical composition based on XRD analysis for all the raw materials used in this study.

Mineral	Sand (%)	Soil (%)	Brick powder (%)	Lime (%)
Calcite	-	-	-	30
Portlandite	-	-	-	65
Quartz	95	65	55	<5
Dolomite	trace	trace	-	-
Hematite	-	-	5	-
Clays	trace	25	30	-
Feldspars	<5	10	10	-

*Trace: concentration < 0.1%

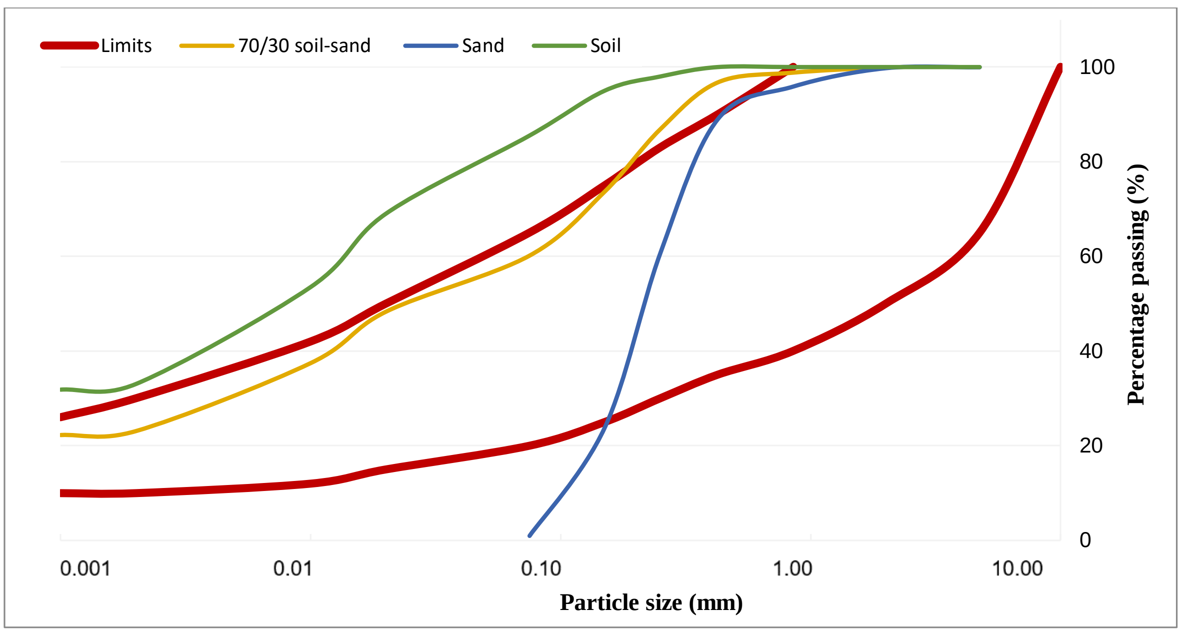


Figure 1. Granulometric distribution for the soil, the sand, and the mixture of them (70% soil, 30% sand) used for the preparation of the different specimen series. Besides, granulometric range limits are shown as per Spanish UNE 41410 (2008) and French XP P 13-901 (2017) standards.

Figure 2 shows the surface morphology for the pozzolan (images a, b, and c) and the brick powder (images d, e, and f) used in the manufacture of the corresponding series. FESEM images are coherent with surface area measurements (Table 3), showing lower porosity and larger particle size for the pozzolan compared to the brick powder. As shown in Figure 2.a and 2.d, the average particle size in the brick powder (approximately 20 µm) is lower than that for the pozzolan (between 25 µm and 100 µm). This is highly relevant, since the reactivity of a pozzolanic material does not only depend on its chemical composition, but also on the size of its particles and its specific surface area. Smaller particles feature higher specific surface areas and, consequently, higher reactivity.

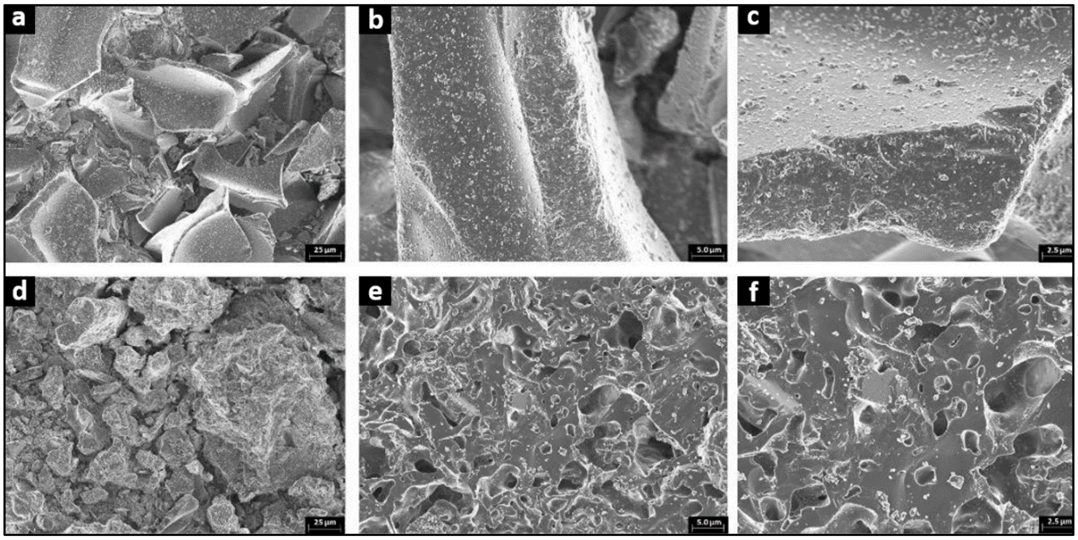


Figure 2. FESEM images of pozzolan (a, b, and c) and brick powder samples (d, e, and f) with different magnifications.

Figure 3.a shows the results of the X-ray diffraction (XRD) analyses for powder samples of the raw materials used in the preparation of the specimens, except for Portland cement, whose mineralogical composition was supplied by the manufacturer: dicalcium and tricalcium silicate, tricalcium aluminate, tetracalcium aluminoferrite, calcium sulfate hemihydrate and calcite (cement with the addition of a calcareous filler). This figure shows that the sand contained mainly quartz and a small amount of feldspar (albite), and the preponderant mineral phases in the soil were quartz, feldspars (albite and microcline) and small amounts of clay (illite); the brick powder contained quartz, feldspars (orthoclase and anorthite) and small amounts of illite and hematite. The "hump" between 20° and 33° in the diffractogram for the pozzolan indicates the presence of a considerable number of amorphous phases apart from illite, quartz, cristobalite and small amounts of feldspar (albite). Finally, the lime contained a significant amount of calcite (~30 wt%) and some quartz, apart from portlandite, indicating a low degree of purity.

Diffractograms of the oriented aggregates of the clay fraction in the soil (Figure 3.b) indicate that the phyllosilicates present in the soil were illite, kaolinite and smectite, the latter showing an increase in the 001 Bragg peak (shoulder) from ~15 Å in the air-dried sample to ~17 Å in the EG-treated sample, collapsed to 10 Å upon heat treatment. The Bragg peak at 7.15 Å shifted to 10 Å upon heat treatment, which is indicative of the presence of kaolinite and the absence of chlorite (Do Campo & Collo, 2018).

The tests performed to determine the pozzolanic potential of the two admixtures indicate that both had a similar pozzolanic capacity, brick powder and pozzolan consuming 55% and 59% of the available Ca^{2+}, respectively, after 16 days of testing. Figure 4 shows that their pozzolanic capacities were significantly lower than that of the commercial product Metapor®, of proven high pozzolanic capacity (Schmidt et al., 2012), which consumed 89.2% of the available Ca^{2+} after 16 days. Furthermore, the pozzolanic capacity of the soil was assessed and it was observed that the soil readily reacted with the Ca^{2+} in solution, but Ca^{2+} consumption increased at a lower rate than in the case of the pozzolanic admixtures under study. Initial rapid consumption might in part be attributed to cation exchange between Ca^{2+} in solution and Na^+ in the interlayer of smectite (Elert et al., 2015; Schmidt et al., 2012).

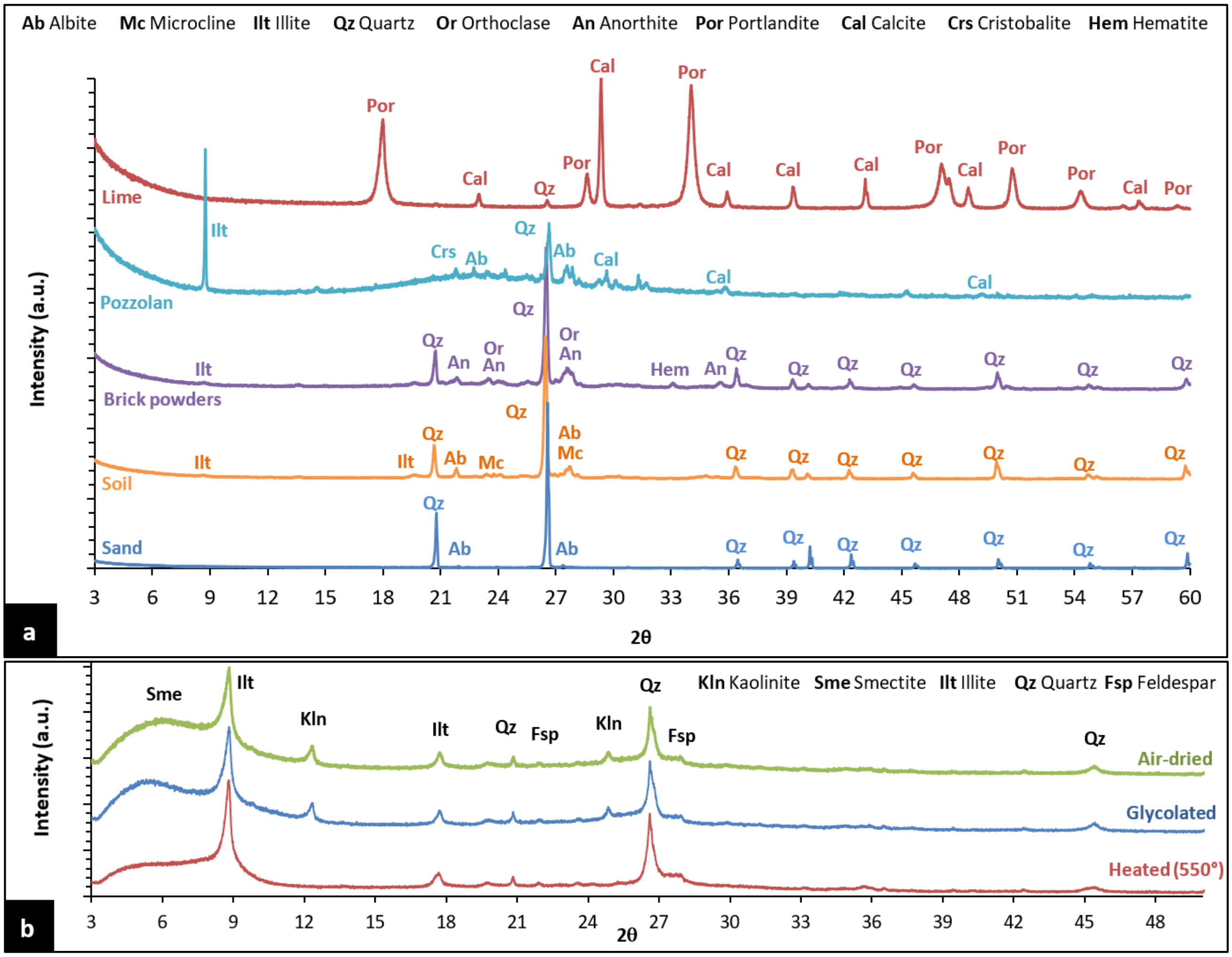
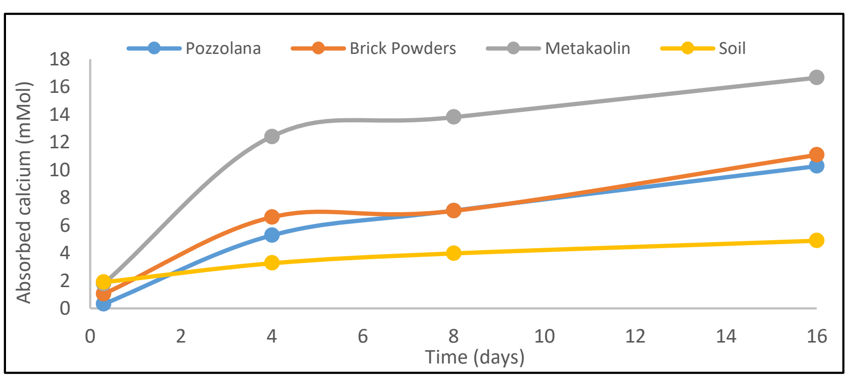


Figure 3. Diffractograms of (a) non-oriented powder of all the raw materials used in this study, and (b) oriented aggregates of the clay fraction in the soil, air-dried, treated with ethylene glycol, and calcined at 550 °C.



Material	Ca^{+2} consumption (%)				
	0 days	0.3 days	4 days	8 days	16 days
Pozzolan	0.47	1.7	28.4	39.8	54.9
Brick powder	0.43	6.0	35.6	39.8	59.4
Metapor®	7.63	10.0	67.0	78.0	89.2
Soil	8.12	10.8	17.6	22.4	26.1

Figure 4. Calcium consumption versus time and % calcium in solution (right) determined by the "saturated lime test" method.

3.2. *Characterization of cured CEBs*

In the FESEM images of the soil samples stabilized with cement, pozzolan and brick powder, the presence of ettringite is observed in the form of needles a few micrometers in size (Figure 5). XRF tests carried out in previous research works (Cabrera, 2021) confirmed the presence of sulfur in the brick powder and the pozzolan used in this work, which allows for this mineral to be formed in the series stabilized with lime and minerals additives. The formation of ettringite is reportedly very rapid, as was confirmed here in the case of samples containing brick powder or pozzolan which were cured for only 5 h (Figure 5.a and 5.b). Apparently, the ettringite content increased over time (Figure 5.c and 5.d). Substantial amounts of this phase were detected in samples cured for 28 days containing Portland cement (Figure 5.e), while samples containing lime showed calcite crystals with the typical scalenohedral morphology (Figure 5.f).

TEM images of CEB samples stabilized with 3% brick powder and 3% pozzolan, cured for 28 days, show phases with morphological features and composition in accordance with the presence of poorly crystalline C-(A)-S-H, often located on the outer edges of soil particles (Figure 6). However, as a result of the generally small amount of these poorly crystalline phases (Elert et al., 2018), they were only detected with XRD in the case of the sample containing 10 wt% Portland cement and cured for 28 days where CSH was identified.

The TEM-AEM and SAED patterns corroborated that the "rods" present in the samples stabilized with lime and pozzolan corresponded indeed to ettringite (insets in Figure 6.a), although the contents of this phase were below the detection limit for the XRD analysis. Note that ettringite seems to have suffered amorphization upon electron beam impact (Figure 6.a).

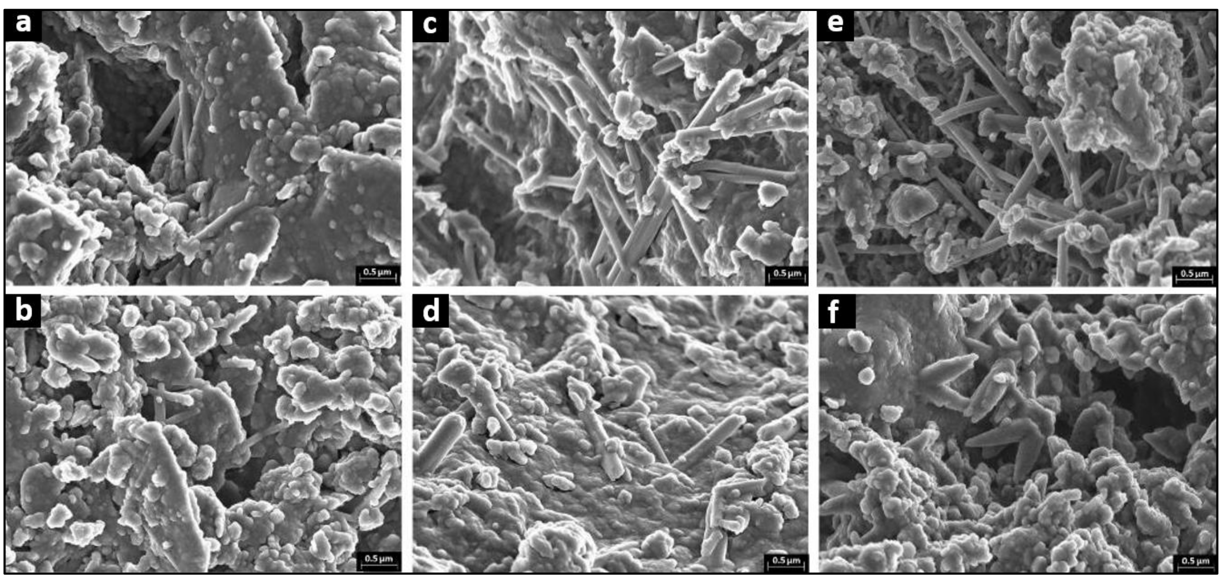


Figure 5. FESEM images of the samples stabilized with a) 3% pozzolan and 7% lime for 5 hours; b) 3% brick powder and 7% lime for 5 hours; c) 3% pozzolan and 7% lime for 28 days; d) 3% brick powder and 7% lime for 28 days; e) 10% cement for 28 days; and f) 10% lime for 28 days.

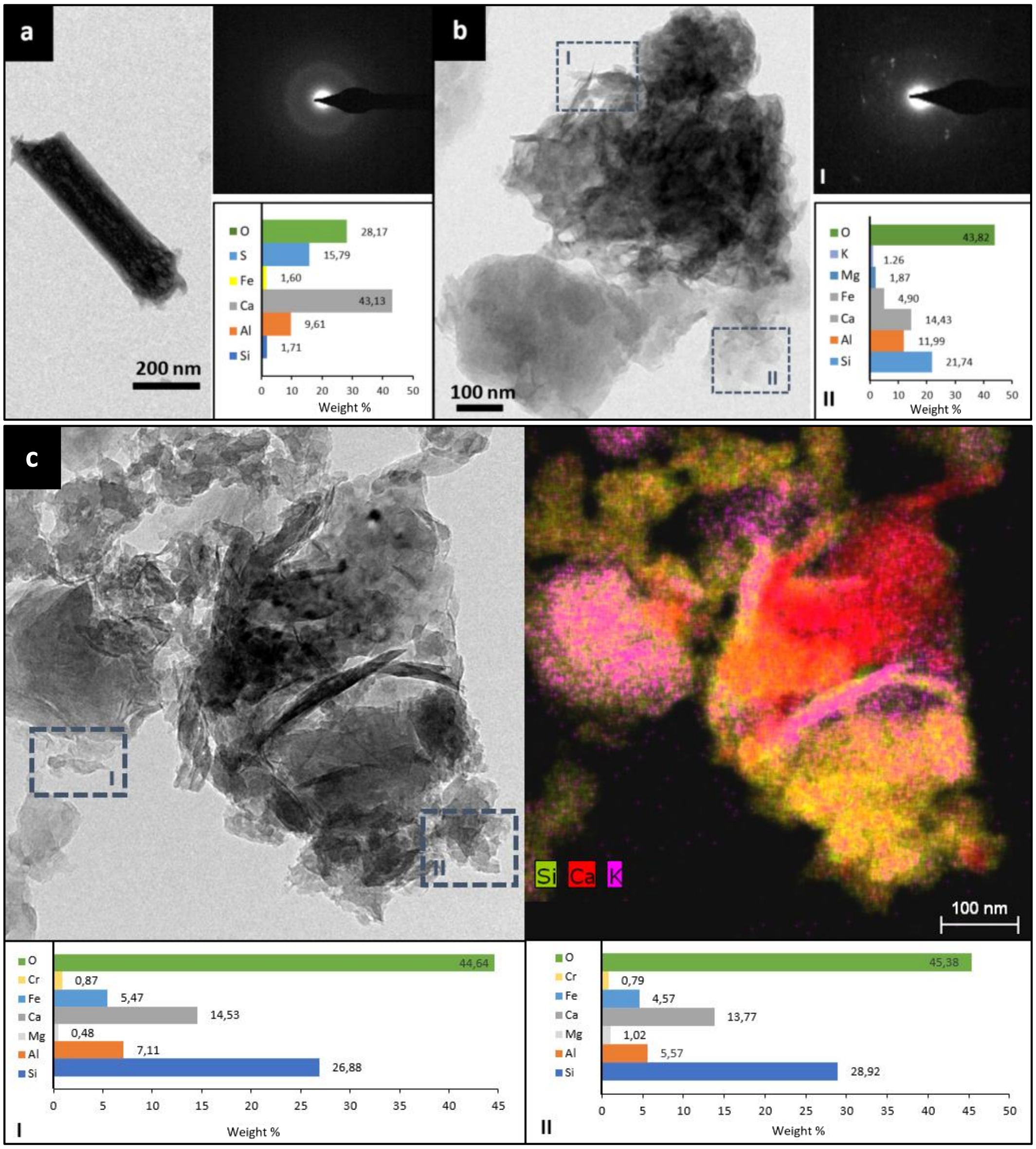


Figure 6. TEM images for the sample stabilized with 3% pozzolan and cured for 28 days. a) Isolated ettringite rod (SAED and TEM-AEM in insets); b) formation of C-(A)-S-H on the outer edges of soil particles (SAED and TEM-AEM of C-(A)-S-H in insets); c) TEM image, EDX spectra and element map of a sample stabilized with 3% brick powder. Blue squares indicate the location of the corresponding EDX analysis.

3.3. *Physical-mechanical properties*

Figure 7 shows dry densities (7.a) and average compressive strengths for dry and water-saturated samples (7.b). Both values are lower for samples stabilized with lime and mineral additions as compared to those stabilized with Portland cement. It is also evident that the compressive strength for samples stabilized with 10% Portland cement exceeds by more than six (6) times the value for the control series. In addition, regarding average dry compression resistance, it can be observed that no statistical differences are found among samples stabilized with lime and mineral additions, and the value is lower than the average resistance to compression for the control sample. Finally, experimental results revealed that lime additions significantly improved the compressive strength of water-saturated samples when compared to unstabilized soil samples, the ratio of dry and saturated compressive strength generally being lower than 0.5 (except for the sample stabilized with Portland cement). Mineral additions, however, did not result in any further improvements. It must be noted that the compressive strength of the saturated unstabilized soil sample could not be determined as it disintegrated upon testing.

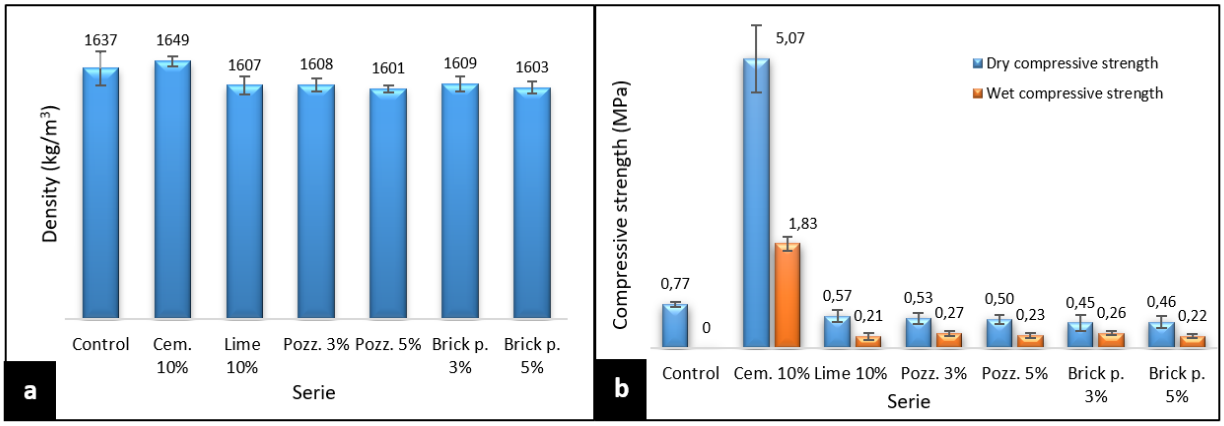


Figure 7. Density (a), and dry and saturated compression resistance (b) for the different sample series.

The decrease in resistance in CEBs stabilized with lime and mineral additions compared to the control samples can be attributed to the lower dry density with respect to control samples, since this property directly affects the dry compression resistance of stabilized soil (Ouedraogo et al., 2020). Considering that water is required to facilitate pozzolanic reactions and the formation of C(A)SH, it seems very likely that the low original water content (13 wt%) of the samples in this study was responsible for the very limited formation of hydraulic phases and consequently low strength of the samples containing lime and mineral additions, adding to the fact that the additions applied do not feature a high pozzolanic activity. In addition, the large amount of calcium carbonate in the lime used in this study most likely behaved as an inert material and did not contribute to the cementation of soil particles and the formation of a coherent matrix (Khemissa & Mahamedi, 2014). However, it should be noted that lime and mineral additions were able to stabilize the CEBs and improved their water resistance, even though their dry compressive strength did not increase. This might be due in part to cation exchange in the case of Na-smectite as well as flocculation in the presence of an electrolyte (Elert et al., 2018; Khemissa & Mahamedi, 2014).

¡Error! No se encuentra el origen de la referencia. is a summary of CEB dry and saturated compression strengths determined and published by different researchers. Considering the different specimen series prepared and tested in this work, and comparing their strengths with the values in said Table, it can be confirmed that the strength of specimens stabilized with lime and mineral additions is considerably low, even falling below the lowest strength in **¡Error! No se encuentra el origen de la referencia.**, reported by Lima et al (2012), and that it is also lower than the strength required for adobes, around 1.0 MPa, 1.2 MPa, or 1.5 MPa, depending on the reference standard (ABNT, 2020; OSARTEC, 2014; Red Protierra Argentina, 2020). From this point of view, taking into account that there still seem to be no Argentinian standards regulating minimum CEB performance, only blocks and specimens stabilized with 10% Portland cement feature values according to the requirements of Argentinian bearing wall construction standards, between 4.0 MPa and 5.0 MPa (INTI-CIRSOC, 2007; IRAM, 2005), which are similar to some of the values published by other authors (Barbero-Barrera et al., 2020; Cabrera, González, et al., 2020; Galíndez, 2007; Ouedraogo et al., 2020).

Regarding water absorption by capillarity (Table 6), no statistical difference was observed between the average percentages of water absorption for the different series tested, being all of them lower than 15%, the limit stipulated in the Indian standard IS 1725 (IS, 2013), the strictest one in this respect. Finally, the results obtained after assessing wet erosion resistance upon pressurized water spraying (see Table 7) indicated that the series stabilized only with lime or cement did not experience significant deterioration due to the action of water, while the series stabilized with different percentages of brick powder and pozzolan reached significant erosion levels.

The difference in water absorption by capillarity and resistance to wet erosion between samples stabilized only with lime and those with different percentages of pozzolan or brick powder additions indicates that the development of pozzolanic reactions and the formation of C-(A)-S-H was scarce. Similarly, mineral additions with limited pozzolanic activity behaved mostly as inert materials, absorbing part of the water in the original mixture and hindering the formation of C-(A)-S-H phases and carbonation of portlandite. Consequently, resistance to wet erosion was lower than in lime-stabilized samples.

Table 5. Dry and saturated CEB compressive strengths as determined by different researchers.

Reference	Binder	Compressive strength (MPa)
(Ouedraogo et al., 2020)	2% cement	4.8
	4% cement	5.8
	2% lime	3.4
	4% lime	3.3
(Cabrera, González, et al., 2020)	8% cement + 4% lime	1.1
	10% cement + 5% lime	3.4
	10% cement + 0% lime	3.9
(Barbero-Barrera et al., 2020)	3% lime	3.5
	6% lime	4.4
	9% lime	4.0
	12% lime	4.6
(Sitton et al., 2018)	9% cement	14.3
	11% cement	15.1
(González López et al., 2018)	15% cement	11.8
	15% lime	2.0
(Burgos, 2020)	20% cement 10% lime	3.8
(Ruiz et al., 2018)	6% cement	9.7
(Arias & Alderete, 2017)	11% cement	10.0
(Nagaraj & Shreyasvi, 2017)	6% cement + 2% lime	4.4 (saturated)
	8% cement + 2% lime	5.8 (saturated)
(Nagaraj et al., 2014)	8% cement	7.2 (saturated)
	6% cement + 2% lime	4.3 (saturated)
	4% cement + 4% lime	4.9 (saturated)
(Roux Gutierrez et al., 2014)	8% cement	7.8
	7% lime	7.4
(Lima et al., 2012)	6% cement	7.0
	6% cement + 8% fly ash	1.5
	12% cement	3.1
	12% cement + 8% fly ash	2.9
(Laguna, 2011)	5% lime + 8% fly ash	5.8
	5% cement + 8% fly ash	9.9
(Galíndez, 2007)	10% cement	3.8

Table 6. Water absorption by immersion and capillarity.

Test	Immersion absorption (24 h)		Capillarity absorption (10 min)	
Series	Abs. (wt %)	SD (%)	Abs. (wt %)	SD (%)
Cem. 10%	17.39	0.86	8.78	1.24
Lime 10%	19.29	1.25	9.16	3.99
Pozz. 3%	19.63	0.28	5.08	0.48
Pozz. 5%	19.38	0.39	9.82	2.83
Brick p. 3%	19.23	0.49	11.46	0.69
Brick p. 5%	19.55	0.23	10.68	2.68

Table 7. Resistance to wet erosion by pressurized water spray.

	Cem. 10%	Lime 10%	Pozz. 3%	Pozz. 5%	Brick p. 3%	Brick p. 5%
Sample						
Mass loss (%)	0.87	0.05	1.31	18.37	7.41	7.16
Depth (mm)	1.20	1.6	9.9	20.6	23.5	16.4

4. Conclusion

The findings of this investigation confirm that both the brick powder and the pozzolan used in this study had limited pozzolanic activity and that, in combination with calcium hydroxide, they formed small amounts of amorphous phases of C-(A)-S-H. However, compared with CEB samples stabilized only with hydrated air lime, the use of small amounts of both mineral additions in the manufacture of CEBs, in combination with hydrated air lime, did not improve their physical or mechanical properties. This behavior can be attributed to several factors:

1. Low pozzolanic activity of the mineral additions used: after 16 days in contact with a saturated solution of $Ca(OH)_2$ under ideal conditions for the formation of pozzolanic phases, less than 60% of the available Ca^{+2} was consumed by the mineral additions. Furthermore, part of the Ca^{+2} might have been consumed by competing cation exchange reactions involving clay minerals;
2. The low degree of lime purity (calcium hydroxide content lower than 67%) limited mineral dissolution and the development of pozzolanic phases. This was even more evident in samples where part of the lime was replaced with mineral additions. The available lime content might be further reduced by competing carbonation reactions;
3. The curing time and the relatively low amount of water used in the manufacture of the samples (13 wt%) might be responsible in part for the limited amount of pozzolanic phases formed upon curing. Future research should explore whether a higher water content and curing at high RH would lead to improved strength and weathering resistance in mixtures with lime and mineral additions.

Finally, a significant difference in compressive strength (dry and saturated) was observed between CEBs stabilized with lime and Portland cement, the latter reaching values greater than 5 MPa, which validates their use in bearing wall construction. Even when compared to unstabilized CEBs, the addition of lime had a negative effect on the dry compressive strength. However, the incorporation of lime as a stabilizer significantly improved the resistance of the specimens to the damaging effects of water (wet erosion and water absorption by immersion and capillarity), presenting even better results than Portland cement regarding water erosion. These findings suggest that lime-stabilized CEBs could be used for external enclosure walls that are not required to withstand axial loads.

Future research will focus on the study of the chemical interaction between the regional soil used in this study and calcium hydroxide (assessing, for example, the cation exchange capacity of the soil), in order to elucidate the reasons for the decrease in compressive strength of the samples stabilized with lime as compared to the non-stabilized control samples. In addition, the optimization of the curing conditions for CEBs will be investigated in order to facilitate the development of pozzolanic reactions between mineral additions and hydrated air lime. This would imply greater possibilities to obtain sustainable building materials of improved mechanical and weathering resistance.

Author contributions: S. Cabrera: Conceptualization, methodology, experimental investigation, drafting, review and supervision and enhancement of manuscript. K. Elert: Methodology, experimental investigation, review and supervision, enhancement of manuscript. A. Guilarducci: Methodology, review and supervision, enhancement of manuscript. *A.* Margasin: experimental investigation, review and supervision, enhancement of manuscript. All authors have read and agreed to the final version of the manuscript.

Funding: This research, carried out in the laboratories of the Universidad Tecnológica Nacional, Facultad Regional Santa Fe (Argentina) and the Department of Mineralogy and Petrology of the University of Granada (Spain), was possible thanks to funding granted by the Ministry of Education of the Argentine Republic through BECAR 2020 program, by the Spanish Service for the Internalization of Education (SEPIE), and by the National Scientific and Technical Research Council (CONICET) of Argentina.

Conflicts of interest: The authors declare no conflict of interest.

References

ABNT. (2012). NBR 8492: Tijolo de solo-cimento. Análise dimensional, determinação da resistência à compressão e da absorção de água. Método de ensaio.

ABNT. (2020). NBR 16814. Adobe. Requisitos e métodos de ensaio.

AENOR. (2008). UNE 41410. Bloques de tierra comprimida para muros y tabiques. Definiciones, especificaciones y métodos de ensayo.

AENOR. (2016). UNE-EN 772-1:2011+A1:2016. Método de ensayo de piezas de fábrica de albañilería. Parte 1: Determinación de la resistencia a comrpresión.

AFNOR. (2017). XP P13-901: Blocs de terre comprimée pour murs et cloisons : définitions - Spécifications - Méthodes d'essais - Conditions de réception.

Arias, L., & Alderete, C. (2017). Variación de la resistencia a compresión del BTC en función de la energía de compactación. Seminario "Somos Tierra Que Camina."

Arteaga Paucar, J., & Loja Saula, L. (2018). Diseño de adobes estabilizados con emulsión asfáltica. Universidad de Cuenca.

ASTM. (1995). ASTM D 4318-a: Standard test methods for liquid limit, plastic limit and plasticity index of soils.

ASTM. (2017). ASTM D2487 - 17: Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System).

Aubert, J. E., Fabbri, A., Morel, J. C., & Maillard, P. (2013). An earth block with a compressive strength higher than 45 MPa! Construction and Building Materials, 47, 366–369. https://doi.org/10.1016/j.conbuildmat.2013.05.068

Barbero-Barrera, M. M., Jové-Sandoval, F., & González Iglesias, S. (2020). Assessment of the effect of natural hydraulic lime on the stabilisation of compressed earth blocks. Construction and Building Materials, 260, 119877. https://doi.org/10.1016/j.conbuildmat.2020.119877

Burgos, L. R. (2020). Mechanical Characterization of Raw-Perlite Solid Bricks for use in Construction. Revista de La Construccion, 19(1), 170–179. https://doi.org/10.7764/RDLC.19.1.170-179

Cabrera, S. (2021). Estudio de las características físicas, químicas y mecánicas del Bloque de Tierra Comprimida (BTC) con suelo-cal y adiciones minerales. Aportes al conocimiento del BTC para su desarrollo en Santa Fe, Argentina. Universidad Tecnológica Nacional.

Cabrera, S., Aranda Jiménez, Y., Suárez Domínguez, E., & Rotondaro, R. (2020). Bloques de Tierra Comprimida (BTC) estabilizados con cal y cemento. Evaluación de su impacto ambiental y su resistencia a compresión. Hábitat Sustentable, 10(2), 70–81. https://doi.org/Bloques de Tierra Comprimida (BTC) estabilizados con cal y cemento. Evaluación de su impacto ambiental y su resistencia a compresión

Cabrera, S., González, A., & Noguera, S. (2021). El mapeo como herramienta para la difusión e intercambio de datos del BTC en Argentina. IV Encontro Latino-Americano e Europeu Sobre Edificações e Comunidades Sustentáveis.

Cabrera, S., González, A., & Rotondaro, R. (2020). Resistencia a compresión en Bloques de Tierra Comprimida. Comparación entre diferentes métodos de ensayo. Informes de La Construcción, 72(560). https://doi.org/https://doi.org/10.3989/ic.70462

Ciancio, D., Beckett, C. T. S., & Carraro, J. A. H. (2014). Optimum lime content identification for lime-stabilised rammed earth. Construction and Building Materials, 53, 59–65. https://doi.org/10.1016/j.conbuildmat.2013.11.077

Concha-Riedel, J., Antico, F. C., & López-Querol, S. (2021). Mechanical strength, mass loss and volumetric changes of drying adobe matrices combined with kaolin and fine soil particles. Construction and Building Materials, 312(April). https://doi.org/10.1016/j.conbuildmat.2021.125246

Dethier, J., & Cohen, J. (2019). Arquitecturas de tierra: El arte de construir con tierra. Pasado, presente y porvenir. BLUME.

DNV. (1989). VN-E18-89: Método de campaña para la determinación de sales solubles y sulfatos en suelos, estabilizados y suelos granulares.

DNV. (1993). VN-E5-93: Compactación de Suelos.

Do Campo, M., & Collo, G. (2018). Mineralogía y Geología de arcillas. Universidad Nacional de Córdoba.

Donatello, S., Tyrer, M., & Cheeseman, C. R. (2010). Comparison of test methods to assess pozzolanic activity. Cement and Concrete Composites, 32(2), 121–127. https://doi.org/10.1016/j.cemconcomp.2009.10.008

Elert, K., Azañón, J., & Nieto, F. (2018). Smectite formation upon lime stabilization of expansive marls. Applied Clay Science, 158(March), 29–36.

Elert, K., Pardo, E., & Rodriguez Navarro, C. (2015). Alkaline activation as an alternative method for the consolidation of earthen architecture. Journal of Cultural Heritage, 16(4), 461–469. https://doi.org/10.1016/j.culher.2014.09.012

Galíndez, F. (2007). Aportes de la tecnología para la fabricación del BTC. In Repositorio de la Universdad Católica de Salta.

González López, J., Juárez Alvarado, C., Ayub Francis, B., & Mendoza Rangel, J. (2018). Compaction effect on the compressive strength and durability of stabilized earth blocks. Construction and Building Materials, 163, 179–188. https://doi.org/10.1016/j.conbuildmat.2017.12.074

Guilarducci, A. (2018). Generación de Adiciones Minerales para el Cemento Portland a Partir de Residuos de Centrales Termoeléctricas de Lecho Fluidizado. Universidad Nacional del Litoral.

Hays, A., Doat, P., Houben, H., Matuk, S., & Vitoux, F. (1979). Construire en terre. Craterre.

ICDD. (2004). Power diffraction file (PDF) (p. http://www.icdd.com/pdfsearch/).

INTI-CIRSOC. (2007). CIRSOC 501. Reglamento Argentino de estructuras de mampostería.

IRAM. (1977). Norma IRAM 10512: Mecánica de suelos. Método de análisis granulométrico.

IRAM. (1986). Norma IRAM 10507: Mecánica de suelos. Método de determinación de la granulometría mediante tamizado por vía húmeda.

IRAM. (2002). Norma IRAM 1520: Agregados finos. Métodos de laboratorio para la determinación de la densidad relativa real, de la densidad relativa aparente y de la absorción de agua.

IRAM. (2005). Norma IRAM 12566-1: Ladrillos y bloques cerámicos para la construcción de tabiques y muros. Parte 1: Macizos.

IRAM. (2007). Norma IRAM 10501: Geotecnia. Método de determinación del límite líquido y del límite plástico de una muestra de suelo. Índice de fluidez e índice de plasticidad.

IRAM. (2019). IRAM 50000: Cementos. Cementos para uso general. Composición y requisitos.

IS. (2013). Standard IS 1725:2013. Specification for soil based blocks used in general building construction.

James, J., & Pandian, P. K. (2018). Strength and microstructure of micro ceramic dust admixed lime stabilized soil. Revista de La Construcción, 17(1), 5–22. https://doi.org/10.7764/RDLC.17.1.5

Khemissa, M., & Mahamedi, A. (2014). Cement and lime mixture stabilization of an expansive overconsolidated clay. Applied Clay Science, 95, 104–110. https://doi.org/10.1016/j.clay.2014.03.017

Klug, H. P., & Alexander, L. E. (1967). X-ray Diffraction Procedures for Polycrystaline and Amorphous Materials. John Wiley & Sons.

Laguna, M. (2011). Ladrillo Ecológico Como Material Sostenible para las Costrucción. In Universidad Publica De Navarra. niversidad Publica De Navarra.

Lima, S. A., Varum, H., Sales, A., & Neto, V. F. (2012). Analysis of the mechanical properties of compressed earth block masonry using the sugarcane bagasse ash. Construction and Building Materials, 35, 829–837. https://doi.org/10.1016/j.conbuildmat.2012.04.127

Maddalena, R., Roberts, J. J., & Hamilton, A. (2018). Can Portland cement be replaced by low-carbon alternative materials? A study on the thermal properties and carbon emissions of innovative cements. Journal of Cleaner Production, 186, 933–942. https://doi.org/https://doi.org/10.1016/j.jclepro.2018.02.138

Malkanthi, S. N., Balthazaar, N., & Perera, A. A. D. A. J. (2020). Lime stabilization for compressed stabilized earth blocks with reduced clay and silt. Case Studies in Construction Materials, 12.

Miller, S. A., John, V. M., Pacca, S. A., & Horvath, A. (2018). Carbon dioxide reduction potential in the global cement industry by 2050. Cement and Concrete Research, 114, 115–124. https://doi.org/10.1016/j.cemconres.2017.08.026

Nagaraj, H. B., & Shreyasvi, C. (2017). Compressed Stabilized Earth Blocks Using Iron Mine Spoil Waste - An Explorative Study. Procedia Engineering, 180, 1203–1212. https://doi.org/10.1016/j.proeng.2017.04.281

Nagaraj, H. B., Sravan, M. V., Arun, T. G., & Jagadish, K. S. (2014). Role of lime with cement in long-term strength of Compressed Stabilized Earth Blocks. International Journal of Sustainable Built Environment. https://doi.org/10.1016/j.ijsbe.2014.03.001

Neves, C., & Borges Farías, O. (2011). Técnicas de Construcción con Tierra. FEB-UNESP / PROTERRA.

OSARTEC. (2014). RTS 91.02.01. Urbanismo y construcción en lo relativo al uso del sistema constructivo de adobe para viviendas de un nivel.

Ouedraogo, K. A. J., Aubert, J.-E. E., Tribout, C., Escadeillas, G., & Escadeilas, G. (2020). Is stabilization of earth bricks using low cement or lime contents relevant? Construction and Building Materials, 236, 117578. https://doi.org/10.1016/j.conbuildmat.2019.117578

Raggioti, B. B., Positieri, M. J., Locati, F., Murra, J., & Marfil, S. (2015). Zeolite, Study of Aptitude as a Natural Pozzolan Applied to Structural Concrete. Revista de La Construcción., 14(2), 14–20. http://revistadelaconstruccion.uc.cl/index.php/RDLC/article/view/13302

Red Protierra Argentina. (2020). Protocolo de ensayos sobre elementos constructivos para la construcción con tierra. http://redprotierra.com.ar/2020/10/28/protocolos-de-ensayo-para-la-construccion-con-tierra/

Rigassi, V. (1985). Compressed Earth Blocks: Manual of Production. In Network. GATE / BASIN.

Rodríguez Cuervo, L. S. (2020). Adobe bricks with sugarcane molasses and gypsum to enhance compressive strength in the city Cogua, Colombia. Revista de La Construccion, 19(3), 358–365. https://doi.org/10.7764/RDLC.19.3.358

Roux Gutierrez, R. S., García Izaguirre, V. M., & Espuna Mujica, J. A. (2014). Los materiales alternativos estabilizados y su impacto ambiental. Revista Electrónica Nova Scientia, 7(1), 243–266.

Ruiz, G., Zhang, X., Edris, W. F., Cañas, I., & Garijo, L. (2018). A comprehensive study of mechanical properties of compressed earth blocks. Construction and Building Materials, 176, 566–572. https://doi.org/10.1016/j.conbuildmat.2018.05.077

Schmidt, M., Poellmann, H., & Egersdoerfer, A. (2012). The use of a recycled glass powder and a expanded glass containing metakaolin in different binder systems. In I. C. M. A. (ICMA) (Ed.), 34th International Conference on Cement Microscopy. Curran Associates, Inc.

Sitton, J. D., Zeinali, Y., Heidarian, W. H., & Story, B. A. (2018). Effect of mix design on compressed earth block strength. Construction and Building Materials, 158, 124–131. https://doi.org/10.1016/j.conbuildmat.2017.10.005

SNZ. (1998). NZS 4298: Materials and workmanship for earth buildings.

Van Damme, H., & Houben, H. (2018). Earth concrete. Stabilization revisited. Cement and Concrete Research, 114, 90–102. https://doi.org/https://doi.org/10.1016/j.cemconres.2017.02.035

Vissac, A., Bourges, A., & Gandreau, D. (2017). Argiles & Biopolyméres. Les stabilisants naturaels pour la construction en terre. CRATerre éditions.