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COMPRESSED EARTH BLOCKS (CEB) STABILIZED WITH LIME AND CEMENT. EVALUATION OF BOTH THEIR ENVIRONMENTAL IMPACT AND COMPRESSIVE STRENGTH

BLOQUES DE TIERRA COMPRIMIDA (BTC) ESTABILIZADOS CON CAL Y CEMENTO. EVALUACIÓN DE SU IMPACTO AMBIENTAL Y SU RESISTENCIA A COMPRESIÓN

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RESUMEN

En este trabajo se presenta la evaluación del impacto ambiental y la resistencia a compresión de Bloques de Tierra Comprimida (BTC) estabilizados con cal aérea hidratada y cemento Portland. Para esa labor, se fabricaron 12 series de bloques estabilizados con diferentes proporciones de cal y cemento y se empleó la metodología del Análisis de Ciclo de Vida (ACV). Tras la realización de los ensayos y las simulaciones pudo concluirse que, usando suelos y arena característicos de la ciudad de Santa Fe (Argentina), estabilizados con determinados porcentajes de cemento Portland -comprendidos entre el 5 y el 10% en peso- pueden producirse BTC con niveles de resistencia suficientes para ser utilizados en muros de carga y, de esa forma, minimizar el impacto ambiental negativo asociado a su fabricación. Se concluye, además, que la estabilización con cal aérea no incrementa la resistencia a compresión de los BTC y aumenta, por el contrario, de manera significativa el impacto negativo de éstos sobre el medio ambiente.

Palabras clave
tierra, estabilización, resistencia de materiales, impacto ambiental

ABSTRACT

This work presents the evaluation of the environmental impact and compressive strength of Compressed Earth Blocks (CEB) stabilized with hydrated aerial lime and Portland cement. For this, 12 series of blocks stabilized with different proportions of lime and cement were manufactured and the Life Cycle Analysis (LCA) methodology was used. After conducting these assays and simulations, it could be concluded that, using earth and sand typical of the city of Santa Fe (Argentina), stabilized with certain percentages of Portland cement between 5 and 10% in weight, CEB can be produced with sufficient levels of strength for them to be used in load-bearing walls, in this way minimizing the negative environmental impact associated with their manufacturing. It is also concluded that the stabilization with aerial lime does not increase the CEB's compressive strength and, on the contrary, significantly increases their negative impact on the environment.

Keywords
earth, stabilization, material strength, environmental impact

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INTRODUCTION

Compressed Earth Block or CEB is masonry manufactured using the compression or pressing of stabilized soil inside a mechanical or hydraulic press (Neves & Borges Farías, 2011). These presses may be manual, for low production demands, or automatic, for industrialized systems (González & Cabrera, 2017). CEB technology started its development in Colombia at the beginning of the 1950s, together with the Inter-American Housing and Planning Center (CINVA), as an economic alternative of construction elements that is currently considered one of the most widespread Latin American technologies in the world (Angulo & Carreño, 2017).

CEB masonry is, in fact, an economic construction technique that has better strength and durability properties than those built with adobe, and a great potential for the industrialization of its units (Herrera Villa, 2018). In addition, these blocks have several advantages that allow them to face current energy and climate issues, on being elements manufactured with low energy materials (Bradley, Gohnert & Bulovic, 2018), compared to cooked clay bricks and sand-cement, in a way that they reduce the total energy required for construction and transportation, which is mainly due to the fact that earth is an abundant and recyclable natural resource (Ben Mansour, Ogam, Jelidi, Cherif & Ben Jabrallah, 2017; Hegyi, Dico & Catalan, 2016).

Just as with the rest of earth construction techniques, CEB have two main limitations:

- If the characteristics of the earth used for their manufacturing are not suitable, their compressive strength will not be enough to comply with structural functions (Ouedraogo, Aubert, Tribout & Escadeilas, 2020);
- Regardless of the type of earth used for their manufacturing, they show some durability issues: they degrade when facing certain atmospheric phenomena, especially water (Laborel-Préneron, Aubert, Jean-Emmanuel Magniont, Maillard & Poirier, 2016).

Both limitations can be minimized and, even, eliminated using small percentages of chemical stabilizers during their manufacturing which improve their physical-mechanical properties, increasing their strength and durability (Guzmán & Iñiguez, 2016).

Different additives have been used in the stabilization of the CEB: from natural substances like aloe vera (Aranda Jiménez & Suárez-Domínguez, 2014), casein and cellulose (Vissac, Bourges & Gandreau, 2017), to oil byproducts like natural bitumen and asphaltic emulsions (Van Damme & Houben, 2018). However, since the origins of this technology, the most used stabilizer has been Portland cement (Elahi, Shahriar, Alam & Abedin, 2020), which is the case in numerous regions of Argentina and Latin America where they are known as "Cement Earth Blocks", a lexicon that is greatly influenced by highway engineering.

Despite the good performance that CEB stabilized with cement have, it must be considered that, together with the high economic cost of this additive, their manufacturing also requires high thermal transformation processes, reaching 1,450°C, ones that release enormous amounts of CO_2 into the atmosphere. It is estimated that for each ton of Portland cement produced, 0.86 tons of CO_2 are released into the atmosphere (Guilarducci, 2018).

Another frequently used additive in the stabilization of CEB is lime, both aerial and hydraulic (Malkanthi, Balthazaar & Perera, 2020), whose environmental impact is significantly lower than Portland cement for the following reasons:

- The temperature required for its manufacturing is approximately 900°C (Maddalena, Roberts & Hamilton, 2018);
- It can be produced on a small scale and on an artisanal level (Guapi Cepeda & Yagual Flores, 2017);
- Aerial lime has the property of absorbing, during its hardening process (carbonation), a large part of the CO_2 released into the atmosphere during its manufacturing process (Qiu, 2020).

Many countries have specific technical standards for construction with earth; however, there are few that have specific testing standards for CEB published by Official Standardization Entities, among which Brazil, Colombia, France, Spain and Mexico stand out (Cabrera, González & Rotondaro, 2020).

In this context, the general objective of this research consisted in evaluating the mechanical and environmental properties of the CEB stabilized with hydrated aerial lime and contrast them with their equivalents stabilized with Portland cement. For this, the following particular objectives are proposed:

- Determining the average compressive strength of CEB stabilized with different percentages of hydrated aerial lime and Portland cement;
- Correlating the average compressive strength of CEB with the percentage and type of stabilizer used.
- Calculating the environmental impact of the CEB stabilized with different proportions of lime and cement.

Sieve		4.75 mm	0.425 mm	0.250 mm	0.150 mm	0.075 mm	0.002 mm
Undersize (%)	Earth	0.0	86.0	-	-	57.0	29.0
	Sand	100	96.2	89.3	48.7	0.6	0.0

Tabla 1. Granulometría de la materia prima. Fuente: Elaboración de los autores.

METHODOLOGY

CEB MANUFACTURING

The earth used in the manufacturing of CEB came from a quarry located in the commune of Monte Vera (Santa Fe, Argentina) classified as a low plasticity clay marl "CL-ML" with 29% clay (kaolinite and illite) and a linear contraction index of 4%. With the intention of improving the granulometric curve of earth and thus increase the compressive strength of the CEB produced (Sitton, Zeinali, Heidarian & Story, 2018), it was mixed with sand from the Paraná river, which is mainly quartz (SiO_2). The granulometric distribution of the earth and sand used in the manufacturing of the CEB can be seen in Table 1.

To determine the compressive strength of CEB stabilized with different proportions of lime and cement, 12 series of 5 CEB each were manufactured in a laboratory, keeping the earth/sand ratio fixed. Blocks of 25.0 x 12.5 x 6.25 cm were produced with two vertical 6.0 cm diameter holes, using an Eco Brava hydraulic press for this purpose, developed by the Brazilian company, "Eco Máquinas". All the series were made with 12.5% moisture, considering the dry weight of the materials. The stabilizers used were hydrated aerial lime from the "Andina" brand and CPC-40 compound Portland cement made by "Holcim". Finally, the different doses used are expressed in Table 2.

The CEB produced were cut in half, thus generating 2 CEB specimens of 12.5 x 12.5 x 6.5 cm, from which, 6 per series were chosen randomly to subject them to the compressive strength test stipulated by the Mexican standard NMX-C-508 (ONNCCE, 2015): test without heading and variable load speed (for which the test lasts between 1 and 2 minutes). All the specimens were tested dry with 28 days of age and cured for 7 days (with the exception of the series without stabilizer) at a relative humidity of 100%, then remaining for 21 days in a laboratory environment, at a relative humidity of 55% and at 24°C.

Serie		Earth (%)	Sand (%)	Lime (%)	Cement (%)
Cement	Cmt. 0%	50.0	50.0	-	0.0
	Cmt. 2.5%	48.75	48.75	-	2.5
	Cmt. 5%	47.5	47.5	-	5.0
	Cmt. 10%	45.0	45.0	-	10.0
	Cmt. 15%	42.5	42.5	-	15.0
	Cmt. 20%	40.0	40.0	-	20.0
Lime	Lime 0%	70.0	30.0	0.0	-
	Lime 2.5%	68.25	29.25	2.5	-
	Lime 5%	66.5	28.5	5.0	-
	Lime 10%	63.0	27.0	10.0	-
	Lime 15%	59.5	25.5	15.0	-
	Lime 20%	56.0	24.0	20.0	-

Table 2. Dosage in weight of the different CEB series. Source: Preparation by the authors.

In order to evaluate the results obtained and determine whether the average compressive strengths of each series were statistically different to each other, an ANOVA variance analysis and a "Tukey pairs analysis" were made, using the Mini Tab[1] statistical software.

LIFE CYCLE ANALYSIS

To determine the environmental impact of CEB stabilized with different lime and cement contents, the Life Cycle Analysis (LCA) methodology, proposed by the IRAM-ISO 14040 standard (IRAM, 2017) was used. This allows characterizing and quantifying different potential environmental impacts associated to each one of the stages of the lifespan of a product or system (Carretero-Ayuso & García-Sanz-Calcedo, 2018). To perform the inventory analysis proposed by IRAM-ISO 14040, the SimaPro9 software (Copyright Pré, 2019) was used.

1 Minitab Statistical Software. See: https://www.minitab.com/es-mx/company/

UNIT OF ANALYSIS

In this framework, individual CEB of 15 x 30 x 7.5 cm were adopted as functional units, with two 6 cm diameter holes (geometry of the CEB produced by Mobak, in Santa Fe, Argentina) and a mass of 4 kg, each one with a different lime or cement content, matching the dose of the blocks tested for compression (see Table 2).

LIMITS OF THE SYSTEM

The scope of the study was limited to the approach called "from the cradle to the gate", through which only the entry and exit flows of the stages between the extraction of the raw materials needed for the manufacturing of the blocks, until these are finished and ready to be inserted in the market, outside the production plant (Curadelli, López, Piastrellini, Arena & Civit, 2019) are considered. To quantify the impact associated to the transportation of the raw materials from their extraction or acquisition site, the following was considered:

- Production unit: The analysis model was based on the Mobak CEB Factory, located in the commune of Arroyo Leyes (Santa Fe), whose production capacity is 3,000 CEB per day.
- Earth: The earth extraction quarry is located in the commune of Monte Vera (Santa Fe), 35 km from the factory.
- Sand: The acquisition of the sand used in the manufacturing of the blocks took place in a sand pit in the city of Santa Fe, 19km from the production unit.
- Stabilizers: The use of hydrated aerial lime in 25 kg bags and Portland cement in 50 kg bags was considered. Both were bought at a yard located to the north of Santa Fe, 35 km from the factory.
- Transportation: The use of a euro3 type truck with 16-32 tn capacity was considered for the transportation of the earth and sand; while, for the stabilizers, a euro3 truck with 7.5-16 tn capacity was used. These vehicle categories were adopted following the requirements stipulated by the European Union's N5 Standard (EU, 2007).
- Raw material production and extraction: with the objective of quantifying the impact associated to the extraction and sale of earth and sand, and the production of lime and cement with their corresponding distribution to the sales centers, the Ecoinvent3 database found in the SimaPro software (Copyright Pré, 2019) was used.

FIELDWORK

For the sake of quantifying the consumption of energy and resources and the residual outtake corresponding to the manufacturing stage of this type of blocks, field visits were made to the CEB production company, "Mobak"[2], where the data required was recorded onsite.

In every visit that was made, notes were taken on the amount, proportion and origin of the raw materials used to produce the CEB, as well as the final destination of the already manufactured product, with the purpose of determining the transportation distances. The production process was documented, specifying the stages, machinery and type of energy used in each phase of the process. In addition, the name, brand, and model of the machinery used was recorded, along with its production capacity and the energy efficiency of each operation expressed in energy units. Likewise, the different means of transportation used were recorded, as well as their load capacity and the distances covered.

Figure 1 summarizes the production process applied by Mobak in the manufacturing of their CEB, where, unlike the dosages proposed for this research, two types of sand with different granulometries are added, and both lime and cement are added for the stabilization.

RESULTS

COMPRESSIVE STRENGTH

Table 3 details the results of the compressive strength tests made on each one of the series of specimens: number of specimens tested (N), average compressive strength (μ) and standard deviation (σ) of each series, the value of the statistics P, resulting from the variance analysis and the group factors of the Tukey pairs analysis. Figure 2 shows the average compressive strengths of each CEB series produced.

2 CEB factory located in the commune of Arroyo Leyes, Province of Santa Fe (Argentina).

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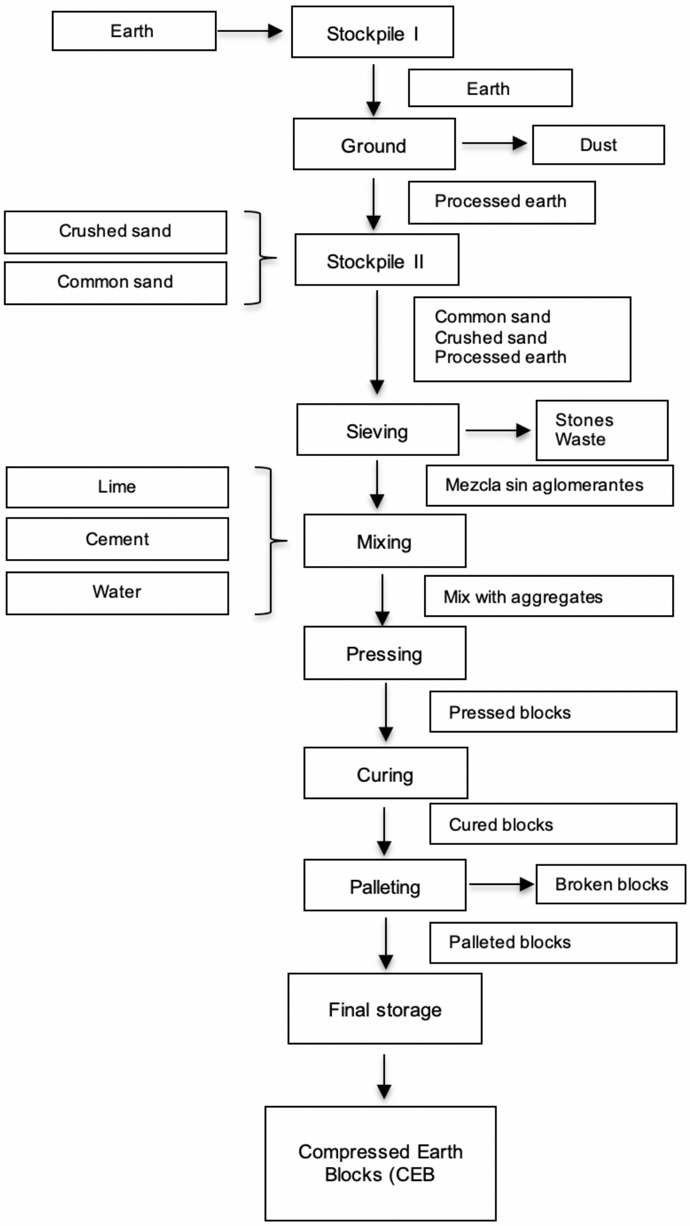

Figure 1. CEB production flow chart. Source: Preparation by the Authors.

FIELDWORK

In Table 4, the energy consumption associated to each stage of the CEB production process is seen. These consumptions were obtained after surveying Mobak's production plant: an average production of 36 batches per day, each one of these with 55 CEB. The assigning of the energy consumption per base unit (1 CEB) was made by dividing the electricity consumption of the entire batch by 55.

Series		N	μ (MPa)	σ (MPa)	ANOVA p	ANOVA Group
Cement	Cmt 0%	6	0.76	0.26	< 0.001	A
	Cmt 2.5%	6	0.81	0.14		A
	Cmt 5%	6	1.39	0.16		A
	Cmt 10%	6	5.09	0.52		B
	Cmt 15%	6	6.08	0.77		B
	Cmt 20%	6	7.426	1.34		C
Lime	Lime 0%	6	0.57	0.13	0.372	D
	Lime 2.5%	6	0.57	0.08		D
	Lime 5%	6	0.57	0.03		D
	Lime 10%	6	0.66	0.12		D
	Lime 15%	6	0.60	0.10		D
	Lime 20%	6	0.54	0.05		D

Table 3. Descriptive statistics, ANOVA variance analysis and grouping as per the Tukey analysis of the CEB series. Source: Preparation by the authors.

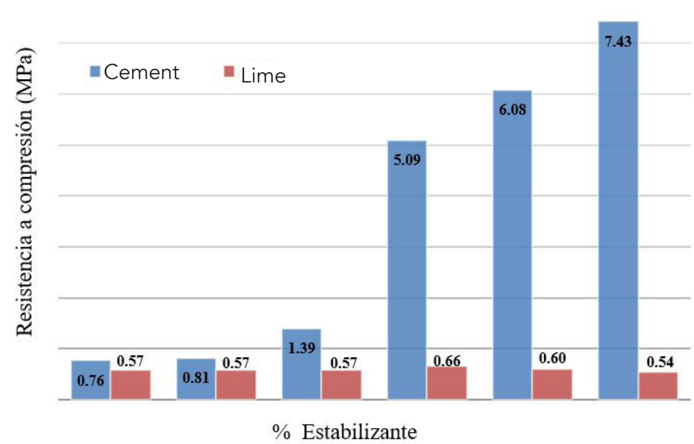

Figure 2. Compressive strength of the different CEB series. Source: Preparation by the authors.

Energy consumption per operation	Equipment's power (KW)	Use time per batch (min)	Energy consumed per batch (MJ)	Energy consumed per CEB (KJ)
Clod crusher	2.0	8.5	1.020	0.0185
Sieving machine	1.1	8.5	0.561	0.0102
Mixer	5.5	7.0	2.310	0.0420
Short conveyor belt	0.8	7.0	0.336	0.0061
Long conveyor belt	1.1	7.0	0.462	0.0084
Hydraulic press	3.0	8.5	1.530	0.0278
Curing	0.4	-	-	0.0024
			TOTAL	0.1155

Table 4. Energy consumed in each stage of the manufacturing process of 1 CEB. Source: Preparation by the Authors.

Serie	Acidification of the soil and water	Eutrophication of the water	Global warming	Photochemical oxidation	Mineral consumption	Fossil fuel consumption	Water consumption	Ozone layer deterioration
	(kg SO2 eq)	(kg PO4 eq)	(kg CO2 eq)	(kg NMVOC)	(kg Sb eq)	(MJ)	(m3 eq)	(kg CFC-11 eq)
Lime 0%	2.270E-04	4.733E-05	0.0419	2.427E-04	1.110E-07	0.6137	0.1085	5.761E-09
Lime 2.5%	3.530E-04	6.798E-05	0.1350	3.624E-04	1.242E-07	1.0708	0.1104	1.130E-08
Lime 5%	4.790E-04	8.864E-05	0.2280	4.821E-04	1.374E-07	1.5278	0.1123	1.685E-08
Lime 10%	7.311E-04	1.299E-04	0.4150	7.216E-04	1.639E-07	2.4419	0.1161	2.793E-08
Lime 15%	9.831E-04	1.713E-04	0.6010	9.610E-04	1.903E-07	3.3559	0.1198	3.902E-08
Lime 20%	1.235E-03	2,126E-04	0.7870	1.200E-03	2.167E-07	4.2700	0.1236	5.010E-08
Cmt 0%	2.489E-04	5.420E-05	0.0453	2.650E-04	1.296E-07	0.6532	0.1579	6.063E-09
Cmt 2.5%	4.515E-04	1.019E-04	0.1380	4.443E-04	1.701E-07	1.0228	0.1609	8.701E-09
Cmt 5%	6.541E-04	1.497E-04	0.2310	6.237E-04	2.105E-07	1.3924	0.1639	1.134E-08
Cmt 10%	1.059E-03	2.451E-04	0.4160	9.825E-04	2.913E-07	2.1316	0.1699	1.661E-08
Cmt 15%	1.038E-03	3.462E-04	0.4920	1.017E-03	2.575E-07	1.6293	0.1569	1.361E-08
Cmt 20%	1.870E-03	4.360E-04	0.7870	1.700E-03	4.530E-07	3.6100	0.1820	2.717E-08

Table 5. Results of the impact inventory of the different CEB series.Source: Preparation by the Authors.

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ENVIRONMENTAL IMPACT

When it comes to expressing the results of the life cycle analysis made on the 12 series of CEB using the Simapro software, the EPD 2018 (Environmental Product Declarations) method was used, which quantifies the environmental impact in 8 impact levels, which can be seen in Table 5.

DISCUSSION

COMPRESSIVE STRENGTH

The effect of the stabilizer content on the compressive strength of the different CEB series presented different behaviors depending on the type of additive used. It can be considered, with 95% confidence, that the mean compressive strength of all the series stabilized with lime, regardless of the percentage used, is statistically equal to the mean compressive strength of the CEB series without being stabilized.

On the other hand, the strength of the CEB with cement was seen to be greatly affected by the percentage of stabilizer used: the series of blocks stabilized with 2.5 and 5% of cement presented, from a statistical point of view, a mean compressive strength without a significant difference between them, and equal to that of CEB without any stabilizer (group factor A). The blocks with 10 and 15% of cement had statistically even strengths and greater than those of their homolog with low cement contents (group factor B), while the series stabilized with 20% cement had a mean compressive strength that was greater than the rest of the series (group factor C). The ratio between the lime and cement content used for the stabilization and the mean compressive strength of the CEB can be seen in Figure 3.

The results obtained match those of previous research made by the Geotechnical Laboratory of the National Technological University, Regional Faculty of Santa Fe (UTN-FRSF), where it has been shown that the compressive strength of the CEB stabilized with lime is significantly lower than those of its homologs stabilized with an equal proportion of cement (Cabrera, González & Rotondaro, 2019), which likewise coincides and reinforces the results generated by different researchers (González-López, Juárez Alvarado, Ayub Francis & Mendoza Rangel, 2018; Laguna, 2011), Ouedraogo et al., 2020).

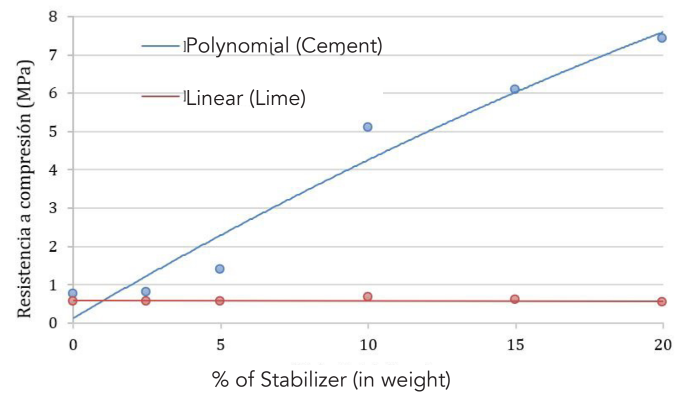

Figure 3. Interpolation curves of compressive strength vs. percentage of lime or cement used in the stabilization of the CEB. Source: Preparation by the Authors.

ENVIRONMENTAL IMPACT

Figure 4 graphically expresses the results from Table 5 and those obtained after making the inventory analysis of the CEB being studied. Regarding the acidification of the soil and water (1), the eutrophication of water (2), the photochemical oxidation (4), and the mineral consumption (5), the impact factor increases with the stabilizer content, in all cases being higher for the CEB stabilized with cement. On the contrary, the fossil fuel consumption (6) and the ozone layer deterioration (8) are significantly higher for the CEB stabilized with lime than with cement, which does not happen with the emissions of CO_2 equivalent (3) which, despite significantly increasing with the content of the stabilizer used, remain practically alike for both stabilizers.

It is interesting to highlight how the water consumption (7) is higher in the CEB stabilized with cement than those stabilized with lime. However, as can be seen in the first quadrant of Figure 4, this is not due to the type of stabilizer used, but rather, to the higher content of sand used in the manufacturing of these blocks, since its extraction demands large volumes of water compared to those required for exploitation in an earth quarry.

The comparison between energies incorporated by different researchers is no easy task since, apart from the different raw materials and manufacturing processes analyzed, each piece of research has different objectives, scopes and inventories. In Table 6, the energy incorporated by the different series of CEB analyzed in this work can be seen in detail, between 0.65 and 4.27 MJ/CEB, depending on the

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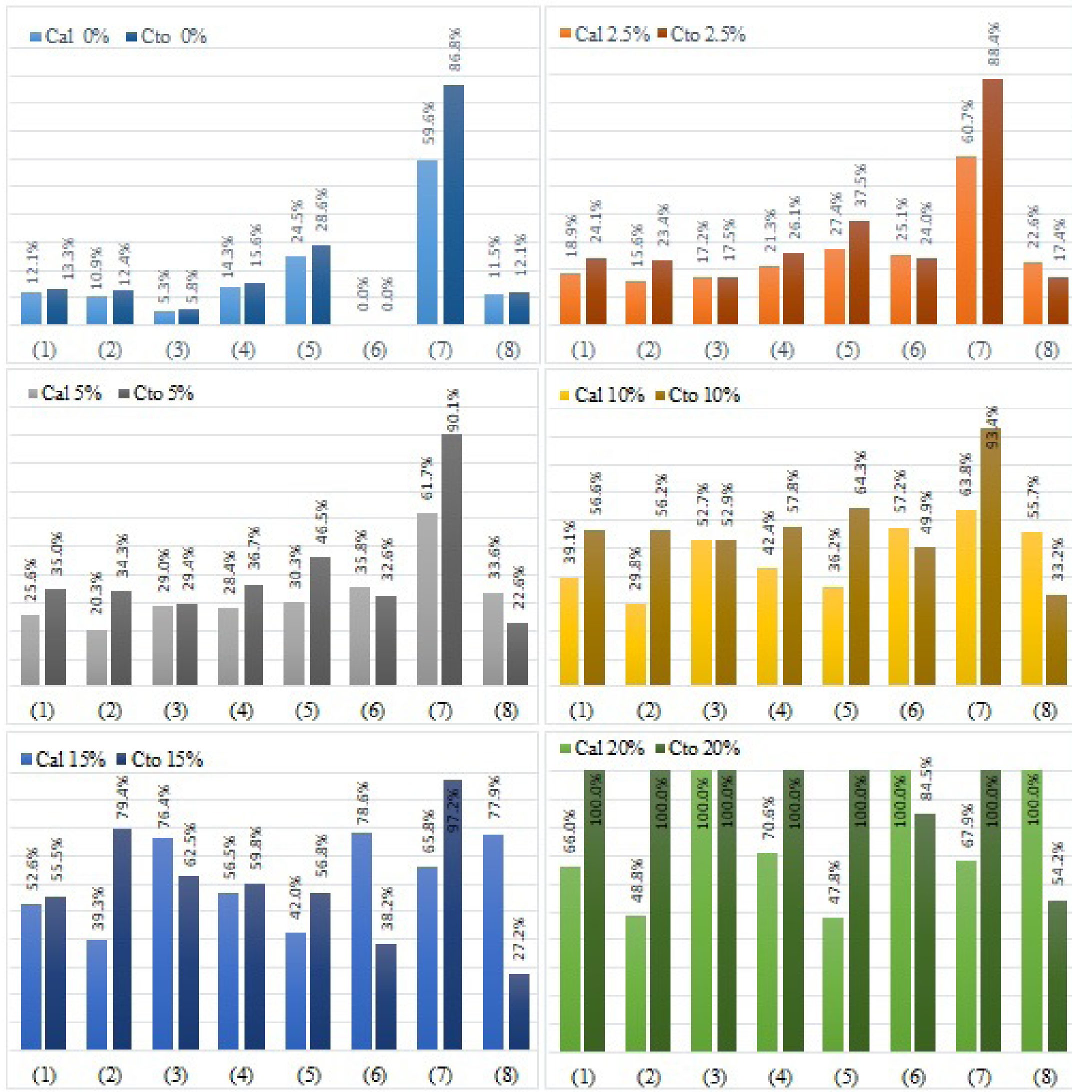

(1) Acidification of the soil and water
(2) Eutrophication of the water
(3) Global warming
(4) Photochemical oxidation
(5) Mineral consumption
(6) Fossil fuel consumption
(7) Water consumption
(8) Ozone layer deterioration

Figure 4. Comparison between the different impact factors of CEB stabilized with lime and cement in different proportions. Source: Preparation by the Authors.

Authors	Energy Incorporated (MJ/BTC)	Stabilizer used
Vázquez Espi, 2001	0.18 - 5.76	Different proportions of Portland cement
Roux Gutiérrez & Espuna Mujica, 2016	7.62	7% of hydrated aerial lime
Fernandes, Peixoto, Mateus & Gervásio, 2019the life cycle assessment of building materials is still in its infancy. So far, there is only a small number of Environmental Product Declarations (EPDs	3.94	6.5% of hydraulic lime
This research	0.65 – 4.27	Different proportions of lime and Portland cement.

Table 6. Energy incorporated during the manufacturing of a CEB published by different authors.Source: Preparation by the Authors.

amount and type of stabilizer used, and depending on the results published by the different authors, whose similarity is left clear.

CONCLUSIONS

After evaluating the results of the compressive strength tests of the different series of CEB manufactured at the Geotechnical Laboratory of UTN-FRSF and the environmental impact associated to their production, it is possible to make the following conclusions:

- The incorporation of hydrated aerial lime in the stabilization of the CEB does not improve their simple compressive strength.
- The stabilization with Portland cement significantly increases the compressive strength of the blocks, noting a considerable improvement for percentages over 5% in weight.
- The stabilization of CEB with lime or cement, even in small amounts, has the greatest responsibility for the negative environmental impact of these blocks.
- The replacement of lime by cement in the stabilization of the CEB does not significantly reduce the environmental impact associated to its production.

Finally, it can be confirmed that, using earth and sand typical of the city of Santa Fe (Argentina), stabilized between 5% and 10% in weight by Portland cement, sufficient compressive strength levels are reached for structural purposes, and the environmental impact associated to this type of masonry is minimized. It is also concluded that the stabilization with lime does not increase the compressive strength of the CEB or significantly increase the negative impact of these on the environment.

To continue with this research, the plan is to make Life Cycle Analyses of other masonry of the region, like the concrete block or the ceramic brick, comparing their environmental impact with that of the CEB stabilized with 5 and 10% cement, and their economic impact on construction. Likewise, the effect of the stabilization with hydrated aerial lime on the compressive strength in the long term and the durability of the CEB could be studied.

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BIBLIOGRAPHICAL REFERENCES

Angulo, D. E. y Carreño, K. (2017). El Bloque de Tierra Comprimido o BTC. Una alternativa de construcción para la arquitectura contemporánea. *NODO*, *12*(23), 31–37. http://revistas.uan.edu.co/index.php/nodo/article/view/655

Aranda Jiménez, Y. G. y Suárez-Domínguez, E. J. (2014). Efecto de la impermeabilidad del Mucílago de Nopal en bloques de tierra comprimidos. *Nova Scientia*, *6*(11), 331-323.

Ben Mansour, M., Ogam, E., Jelidi, A., Cherif, A. S. y Ben Jabrallah, S. (2017). Influence of compaction pressure on the mechanical and acoustic properties of compacted earth blocks: An inverse multi-parameter acoustic problem. *Applied Acoustics*, *125*, 128–135. DOI: https://doi.org/10.1016/j.apacoust.2017.04.017

Bradley, R. A., Gohnert, M. y Bulovic, I. (2018). Construction considerations for low-cost earth brick shells. *Journal of Construction in Developing Countries*, *23*(1), 43–60. Recuperado de http://web.usm.my/jcdc/vol23_1_2018/jcdc2018.23.1.3.pdf

Cabrera, S. y González, A. y Rotondaro, R. (2019). Bloques de tierra comprimida estabilizados con cal. Evaluación de dosificaciones y resistencia a la compresión. En Fundación Eco Urbano, *III Encuentro Latinoamericano y Europeo de Edificaciones y Comunidades Sostenibles (EUROelecs 2019)*, 22 a 25 de mayo de 2019, Santa Fe, Argentina (pp. 141-148). DOI: https://doi.org/10.33414/ajea.3.633.2019

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

Carretero-Ayuso, M. y García-Sanz-Calcedo, J. (2018). Comparison between building roof construction systems based on the LCA. *Revista de la Construcción*, *18*(1), 123–136. DOI: https://doi.org/10.7764/RDLC.17.1.123

Copyright Pré (2019). *SimaPro 9*. Recuperado de https://simapro.com/

Curadelli, S., López, M., Piastrellini, R., Arena, P. y Civit, B. (2019). Estudio socioambiental de la producción de ladrillos artesanales en Mendoza desde la perspectiva del análisis de ciclo de vida. Mendoza: edUTecNe. Recuperado de http://190.114.221.84/handle/20.500.12272/3719

Elahi, T. E., Shahriar, A. R., Alam, M. K. y Abedin, M. Z. (2020). Effectiveness of saw dust ash and cement for fabrication of compressed stabilized earth blocks. *Construction and Building Materials*, *259*. DOI: https://doi.org/https://doi.org/10.1016/j.conbuildmat.2020.120568

Fernandes, J., Peixoto, M., Mateus, R. y Gervásio, H. (2019). Life cycle analysis of Environmental impacts of earthen materials in the Portuguese context: Rammed earth and compressed earth blocks. *Journal of Cleaner Production*, *241*. DOI: https://doi.org/10.1016/j.jclepro.2019.118286

González, A. y Cabrera, S. (2017). Prensa electromecánica para BTC. En Neves, C, Salcedo, Z. y Borges, O. (Eds.), *XVII Seminario Iberoamericano de Arquitectura y Construcción con Tierra (SIACOT)*, (pp. 91–100). La Paz: PROTERRA. Recuperado de https://redproterra.org/wp-content/uploads/2020/06/17-SIACOT-Bolivia-2017.pdf

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

Guapi Cepeda, G. M. y Yagual Flores, K. D. (2017). *Análisis de la producción de cal de la comuna San Antonio como oferta exportable a los mercados internacionales*. Tesis de pregrado. Universidad de Guayaquil. Recuperado de http://repositorio.ug.edu.ec/handle/redug/47728

Guilarducci, A. (2018). Generación de adiciones minerales para el cemento Portland a partir de residuos de centrales termoeléctricas de lecho fluidizado. Tesis doctoral. Universidad Nacional del Litoral. Recuperado de https://bibliotecavirtual.unl.edu.ar:8443/handle/11185/1103

Guzmán, S. e Iñiguez, M. (2016). Election methodology of chemical stabilizers for earth blocks. *Estoa*, *5*(9), 151–159. DOI: https://doi.org/10.18537/est.v005.n009.12

Hegyi, A., Dico, C. y Catalan, G. (2016). Construction sustainability with adobe bricks type elements. *Urbanism. Arhitectura. Constructii*, *7*(2), 147-156. Recuperado de https://pdfs.semanticscholar.org/4296/f73ce17aad2539bda49d366ef7e2d08c93ed.pdf

Herrera Villa, J. (2018). Modelamiento numérico del comportamiento sísmico de viviendas de mampostería con bloques de tierra comprimida. Tesis de magíster. Pontificia Universidad Católica del Perú. Recuperado de http://tesis.pucp.edu.pe/repositorio/handle/20.500.12404/12059

IRAM (2017). *IRAM-ISO 14040. Gestión ambiental. Análisis del ciclo de vida. Principios y marco de referencia*. Buenos Aires.

Laborel-Préneron, A., Aubert, Jean-Emmanuel Magniont, C., Maillard, P. y Poirier, C. (2016). Effect of plant aggregates on mechanical properties of earth bricks. *Journal of Materials in Civil Engineering*, *29*(12), 719-734. DOI: https://doi.org/10.1016/j.conbuildmat.2016.02.119

Laguna, M. (2011). *Ladrillo Ecológico Como Material Sostenible para las Construcción*. Trabajo final de Carrera. Universidad Pública de Navarra. Recuperado de http://academica-e.unavarra.es/bitstream/handle/2454/4504/577656.pdf?sequence=1

Maddalena, R., Roberts, J. J. y 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. DOI: https://doi.org/https://doi.org/10.1016/j.jclepro.2018.02.138

Malkanthi, S. N., Balthazaar, N. y 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*. DOI: https://doi.org/10.1016/j.cscm.2019.e00326

Neves, C. y Borges Farías, O. (Orgs.) (2011). Técnicas de Construcción con Tierra. Bauru: FEB-UNESP / PROTERRA. Recuperado: https://redproterra.org/wp-content/uploads/2020/05/4a_PP-Tecnicas-de-construccion-con-tierra_2011.pdf

ONNCCE (2015). *NMX-C-508 Industria de la Construcción. Bloques de tierra comprimida estabilizados con cal. Especificaciones y métodos de ensayo*. México D.F.

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

Qiu, Q. (2020). A state-of-the-art review on the carbonation process in cementitious materials: Fundamentals and characterization techniques. *Construction and Building Materials*, *247*. DOI: https://doi.org/https://doi.org/10.1016/j.conbuildmat.2020.118503

Roux Gutiérrez, R. y Espuna Mujica, J. (2016). El Hidróxido de Calcio y los bloques de tierra comprimida, alternativa sostenible de construcción. *Nova Scientia*, *5*(2), 176-202. DOI: https://doi.org/10.21640/ns.v5i9.163

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

Unión Europea (UE). (2007). *Norma Euro 5*. Bruselas.

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

Vázquez Espi, M. (2001). Construcción e impacto sobre el ambiente: el caso de la tierra y otros materiales. *Informes de la Construcción*, *52*(471), 29–43. DOI: https://doi.org/10.3989/ic

Vissac, A., Bourges, A. y Gandreau, D. (2017). *Argiles & Biopolyméres. Les stabilisants naturaels pour la construction en terre*. Grenoble: CRATerre éditions. Recuperado de https://craterre.hypotheses.org/1370