Eco+Rceb

Eco-efficient recycled cement compressed earth blocks

FCT Project

PTDC/ECI-CON/0704/2021

Report Eco+RCEB/R4

Preliminary study of compressed earth blocks mix design – Phase 1 of Task 1

March 2023

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Acknowledgements

The authors wish to thank the Portuguese Foundation for Science and Technology (FCT) for funding this research through project PTDC/ECI-CON/0704/2021, CERIS for supporting this research, Oficinas do Convento – Montemor-o-Novo and SECIL for supporting the experimental work and suppling the materials for the experimental campaign.

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Preface

Although it is estimated that more than 30% of the world's population still inhabit earthen dwellings, in the last two centuries earth has fallen into disuse, due to the emergence of new building materials and construction techniques. However, in line with the increasing demand of more sustainable and eco-friendly building materials, earth construction has regained interest. The low environmental impact and embodied energy, the high availability of raw material, the recyclability, the high hygrothermal comfort, the improved indoor environmental quality, with nearly zero hazardous emissions, and the advances in new construction methods and in the materials science, are some reasons that contributed to the resurgence of earth construction.

A promising approach to earth building materials is the compressed stabilised earth blocks (CSEB), increasing the processing speed and showing improved mechanical strength and durability when stabilised with cementitious materials, such as ordinary Portland cement or hydraulic lime. However, despite its adequate behaviour in real exposure conditions, this type of CSEB fails to address the sustainability issue, since it requires a considerable amount of non-eco-friendly stabilisers.

Alternative more sustainable natural stabilisers have been explored by various investigators, but they are still far from being technically viable and from providing comparable mechanical and durability performance as cementitious materials.

In this context, the low-carbon thermoactivated recycled cement is expected to be a very promising alternative for CSEB stabilisation, potentially providing adequate binding properties with reduced environmental impact. Comparing to conventional cement stabilisers, the new eco-efficient binder contributes to a lower consumption of natural resources and, potentially, over 60% reduction of CO_2 emissions, while adequately repurposing construction and demolition waste.

Therefore, the main objective of this project is the innovative production and characterisation of more eco-friendly CSEB, by using low embodied energy recycled cement from concrete waste as a more sustainable stabiliser. The idea is to also explore the incorporation of construction and demolition waste as partial earth replacement, further increasing the CSEB sustainability.

The new CSEB will be characterised in terms of their main physical, mechanical, thermal and durability properties by means of laboratory tests, as well as in-situ tests involving the long term exposure of various CSEB walls to different natural environments.

In addition, the project also aims the development and characterisation of new more eco-efficient masonry earth mortars for CSEB joints, using recycled cement.

Finally, the best compromise between the technical performance and eco-efficiency of this new CSEB product is assessed by economic and environmental life-cycle analysis.

For the accomplishment of these objectives, a comprehensive experimental program was defined involving the following six main tasks: production of compressed earth blocks stabilised with recycled cement; masonry earth mortar characterisation and CSEB wall production; physical, mechanical and microstructural characterisation of CSEB; thermal performance of CSEB; durability of CSEB; life-cycle cost and life-cycle assessment of CSEB.

1. Introduction

The present study is part of FCT research project, PTDC/ECI-CON/0704/2021, which consists on the production and characterisation of an eco-efficient compressed stabilised earth block, contributing for the resurging interest and confidence in using earth materials, towards a more eco-friendly and sustainable construction practice.

The following report details the results of an initial study regarding the mix design of compressed stabilised earth blocks (CSEB) produced with soils sourced from Montemor-o-Novo.

2. Experimental campaign

A preliminary small-scale experimental study was conducted to help in defining the composition of unstabilised compressed earth blocks (UCEB) and CSEB, using the soils from Montemor-o-Novo. Taking into account the soils' characterisation presented in Report Eco+Rceb/R1 [1], the soil *Cortiçadas de Lavre* was not considered for the production of either CSEB or UCEB. Moreover, ordinary Portland cement (OPC) was used in CSEB production, which was characterised in Report Eco+Rceb/R2 [2]. To further increase the sustainability, two types of construction and demolition waste (CDW) were added as partial soil replacement, being CDW-MIX and CDW-CONCRETE. The former mostly consists of concrete, mortar, fired clay bricks and natural stone, whereas the second is exclusively concrete. Both have a maximum diameter smaller than 8 mm. Their characterisation is presented in Report Eco+Rceb/R3 [3]. First, the soil was pulverised in a mechanical paddle mill (Figure 1) and sieved through an 8 mm square mesh rotary screen (Figure 2). Table 1 and Figure 3 display the particle size distribution obtained after this process.

Figure 1 – Mechanical paddle mill

Figure 2 – Rotary screen

Table 1 - Particle size distribution of the four studied soils

Sieve aperture (mm)	Cumulative percentage of passing material (%)			
	Baldios	Amendonça	Pinheiro	Maja
4.75	96.5	95.3	94.2	96.3
2	76.2	73.3	58.6	76.7
1	64.8	57.8	41.9	67.2
0.850	62.0	54.8	39.4	64.8
0.425	49.3	37.0	28.8	51.5
0.250	40.6	27.6	22.8	40.3
0.105	28.7	17.6	15.6	22.3
0.075	25.6	15.9	14.2	18.3
0.020	9.9	8.3	9.9	4.6

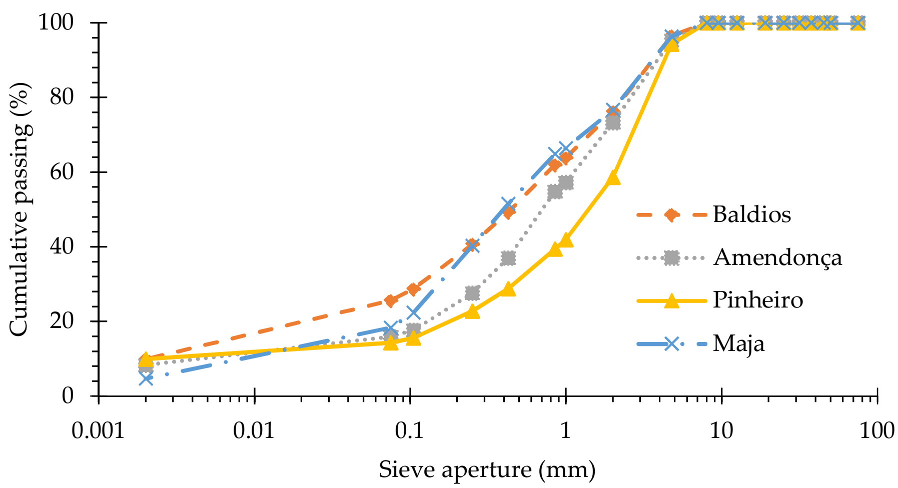

Figure 3 – Granulometric curve after 8mm sieving

To achieve maximum compactness, the Fuller reference curve (q=0.33 [4] and D_{max}=4.76mm) was employed to the mix composition of soil and CDW. As a result, various proportions of CDW were defined. In addition, 8% (by weight of soil) of OPC was incorporated in all CSEB. Table 2 outlines the sum of square deviations to the fuller's curve, per each type of soil and CDW-MIX amount. The minimum deviation values are marked in bold in Table 2. Therefore, we may conclude that the theoretical optimal content of CDW-MIX to be added to the mixture varies according to the soil type (as shown in Table 2). Moreover, incorporating 15-35% CDW would theoretically enhance the compactness for most of the soils examined. To confirm this, different CEB mixes were produced and tested with different incorporation percentages of CDW.

Table 2 – Sum of squared differences between the Fuller reference curve and the mixture curve for different contents of CDW-MIX and soils

	0% CDW	15% CDW	25% CDW	35% CDW	40% CDW	50% CDW
	Δ^2	Δ^2	Δ^2	Δ^2	Δ^2	Δ^2
Amendonça	**92**	158	221	300	345	447
Baldios	328	128	59	**42**	52	112
Maja	393	213	152	**137**	148	203
Pinheiro	837	**836**	846	864	876	906

2.1 Content and type of CDW

Three distinct mixtures were prepared using *Baldios* soil, with the only variation being the proportion of CDW-MIX used: 15%, 25%, and 35%. Once the dry mixture was homogenous, an appropriate amount of water was added. The mixing water quantity was determined based on the optimum moisture content (OMC) and adjusted through trial drop tests (HB-195 [5]). This involved squeezing a handful of moist soil together to form a ball, which was then dropped from shoulder height at arm's length onto a firm surface. The way the ball breaks upon impact is interpreted to ascertain whether the mix is at its OMC. If the mix crumbles or breaks into multiple fragments, the moisture content is deemed too low. Conversely, if it remains in one flattened piece, the moisture content is too high. It is suggested that an optimal moisture content is achieved if the ball breaks into several equally sized pieces, typically between 3 to 6 [5]. The compositions of the mixtures are enumerated in Table 3. The mixing water increased for higher CDW content, because of their higher water absorption than soil [3]. Then, plain blocks of approximately 220x105x60 mm were produced using a *Terstaram* manual press, which had a maximum pressure capacity of around 3.5 MPa (Figure 4).

Table 3 – CSEB compositions to evaluate an appropriate CDW content

Mixture	**Soil (%)**	**CDW [a] (%)**	**OPC[b] (%)**	**Water[c] (%)**
BALD15CDW	77	15	8	12.5
BALD25CDW	67	25	8	14
BALD35CDW	57	35	8	14

[a] by weight of soil + CDW; [b] by weight of soil + binder;
[c] percentage of water added via drop test

Figure 4 – *Terstaram* manual press

The curing process of blocks consisted on covering them with a plastic film and spraying with water twice a day during the first 3 days. Afterwards, the blocks were transported to the Civil Engineering Laboratory of Instituto Superior Técnico at 3 days old. Subsequently, they were cured in laboratory environment with 55-70% relative humidity (RH) until they were 7 days old, at which point they were tested in terms of compressive strength, according to EN 772-1 [6] and HB-195 [5]. The whole blocks were tested perpendicularly to the bed face, between two metal pieces (Figure 5). Three blocks per composition were tested after 7 days, employing a loading rate of roughly 0.5 KN/s. A load cell of 400 KN capacity was used owing to the low load-bearing strength of CEB. Furthermore, the apparent density of the block was determined in accordance with EN 12390-7 [7], involving the process of measuring and weighing the block.

Figure 5 – Compressive strength setup

Under laboratory conditions, the average 7-day compressive strength ($f_{c,7d}$) varied between 5.99 and 10.53 MPa, depending on the CDW-MIX content (as shown in Figure 6). The apparent density ranged between 2210 and 2389 g/cm^3 (as depicted in Figure 7). The highest compressive strength was obtained in CSEB with 25% CDW incorporation. In fact, this mixture displayed compressive strength values that were 1.8 and 1.6 times higher compared to those with 15% and 35% CDW, respectively. In fact, this mixture had the highest apparent density (2389 g/cm³) suggesting a greater compactness and a lower number of voids. According to Table 2, a greater compactness would be obtained with 35% CDW, although the difference would not be relevant for 25% CDW. Besides the fuller curve is just an approximation, the water content also affects the block compactness and density. Moreover, as CDW has lower density than other components, for the same compactness level, the mixes with higher amount of CDW will show lower density.

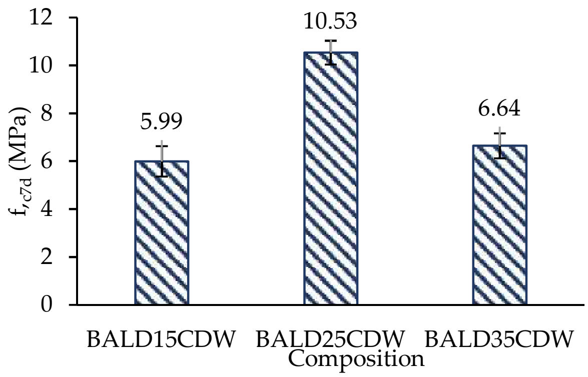

Figure 6 - Average 7-day compressive strength ($f_{c,7d}$) for the mixtures BALD15CDW, BALD25CDW and BALD35CDW

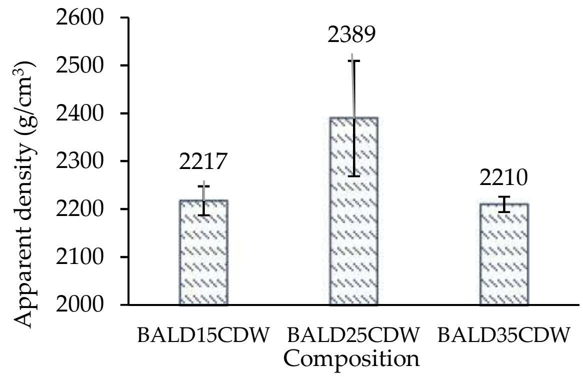

Figure 7 - Average 7-days apparent density for the mixture BALD15CDW, BALD25CDW and BALD35CDW

The influence of the type of CDW, was also assessed through the production of two compositions with 25% CDW-CONCRETE and two with 25% CDW-MIX, using *Amendonça* and *Maja* soil. The only variation was the type of CDW used. The compositions of the mixtures are listed in Table 4. Although CDW-CONCRETE exhibited higher water absorption than CDW-MIX [3], the mixtures were produced with the same water content. Therefore, the effective water in CSEB with CDW-CONCRETE was lower than that of CSEB with CDW-MIX.

Table 4 – Elaborated compositions to assess the effect of varying the CDW type

Mixture	Soil (%)	CDW [a] (%)	OPC[b] (%)	Water[c] (%)
AMEND-MIX	67	25	8	12
AMEND-CONC	67	25	8	12
MAJA-MIX	67	25	8	15
MAJA-CONC	67	25	8	15

[a] by weight of soil + CDW; [b] by weight of soil + binder;
[c] percentage of water added via drop test

Figure 8 and Figure 9 display the average $f_{c,7d}$ under laboratory conditions and the corresponding apparent density, respectively. There was a relevant reduction in compressive strength when CDW-CONCRETE was incorporated instead of CDW-MIX, regardless of the type of soil. The *Maja* soil exhibited 11.2% reduction in compressive strength, while the *Amendonça* soil displays a more significant reduction of 27.3%. This sharper decrease in compressive strength is also reflected in the apparent density, indicating a lower compactness. Nonetheless, both mixtures produced with Maja soil exhibit a similar apparent density.

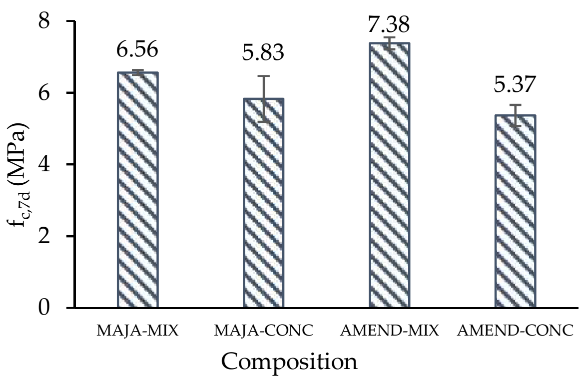

Figure 8 - Average 7-day compressive strength ($f_{c,7d}$) for the mixtures MAJA-MIX, MAJA-CONC, AMEND-MIX and AMEND-CONC

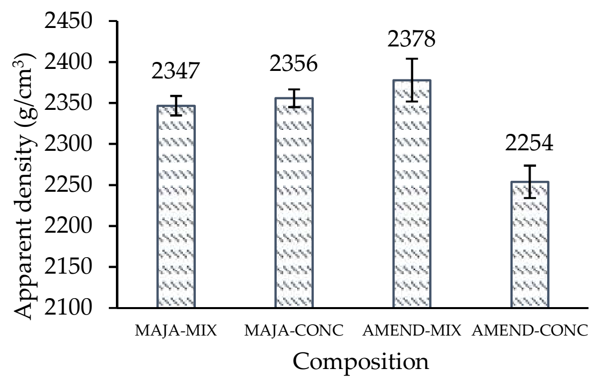

Figure 9 - Average 7-days apparent density for the mixtures MAJA-MIX, MAJA-CONC, AMEND-MIX and AMEND-CONC

2.2 Soil type

Extra mixtures were designed using soils *Amendonça*, *Maja*, and *Pinheiro* with 25% CDW-MIX content. The objective was to help in the selection of the best soil to use in the production of CEB (*Amendonça*, *Maja*, *Pinheiro or Baldios*), according to the work plan of the project. The selection criteria takes into account the results of this study and that reported in [1]. The amount of mixing water was determined using the method described in 2.1.

The compositions of the new mixtures are detailed in Table 5, as well as their 7-day apparent density. This property ranged from 2191 g/cm³ to 2347 g/cm³. The 7-days average compressive strength of the blocks ranged between 5.27 MPa and 6.56 MPa (Figure 10). These values were lower than the compressive strength obtained for the BALD25CDW mixture (2.1). Figure 11 illustrates the relative strength of these mixtures when compared to CSEB produced with the same content of CDW but with *Baldios* soil. The compressive strength varied from 50.05-62.32% of that obtained for the BALD25CDW mixture. Therefore, among the tested soils, *Baldios* showed to be the most suitable for CSEB production. This is in accordance with the optimal granulometric characteristics and fines content of this soil, as presented in Report 1 [1].

Table 5 – Compositions for the evaluation of the most suitable soil for producing CSEB

Mixture	Soil (%)	CDW [a] (%)	OPC[b] (%)	Water[c] (%)	Apparent density (g/cm³)
BALD25CDW	67	25	8	14	2389
AMEND25CDW	67	25	8	15	2299
MAJA25CDW	67	25	8	15	2347
PINH25CDW	67	25	8	15	2191

[a] by weight of soil + CDW; [b] by weight of soil + binder; [c] percentage of water added via drop test

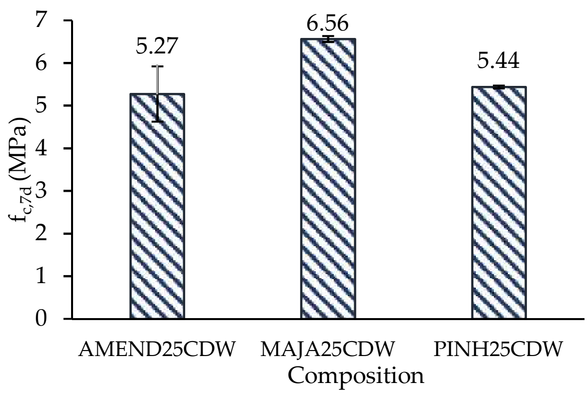

Figure 10 – Average 7-days compressive strength ($f_{c,7d}$) tested after lab curing for CSEB (different soils)

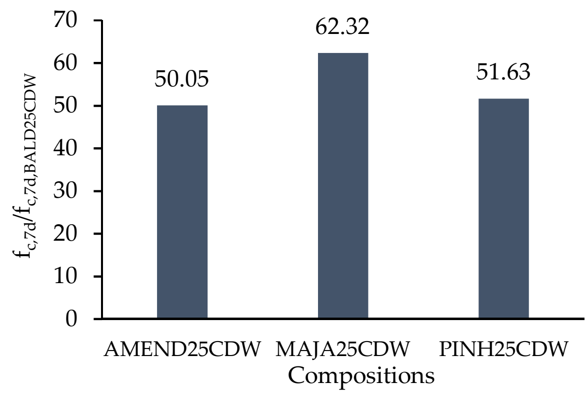

Figure 11 – Relative 7-days compressive strength ($f_{c,7d}$) against reference CSEB of equal CDW content ($f_{c,7d,BALD}$)

To determine the best soil to produce UCEB, a similar approach was taken, excluding *Baldios* soil due to its low plasticity, as indicated in Report Eco+Rceb/R1 [1]. The mixtures prepared for this part of the study are listed in Table 6, which included UCEB with *Amendonça* (UCEB-A), UCEB with *Maja* (UCEB-M), and UCEB with *Pinheiro* (UCEB-P).

Table 6 – Compositions to evaluate the best soil for the production of UCEB

Mixture	Soil (%)	CDW [a] (%)	Water (%)
UCEB-P	75	25	13
UCEB-M	75	25	15
UCEB-A	75	25	14.5

[a] by weight of soil + CDW

Figure 12 shows the average 7-day compressive strength for these mixtures that ranged between 1.24 and 1.47 MPa, significantly lower than those of CSEB, highlighting the relevance of stabilisation in these sandy soils. Despite the higher clay content of *Pinheiro* [1], the mixture made with *Amendonça* had the highest 7-day compressive strength. The

OMC for Maja was 13.3% [1], which also suggests that mixing water can be reducing, further increasing the compressive strength. Figure 13 shows the average 7-day apparent density.

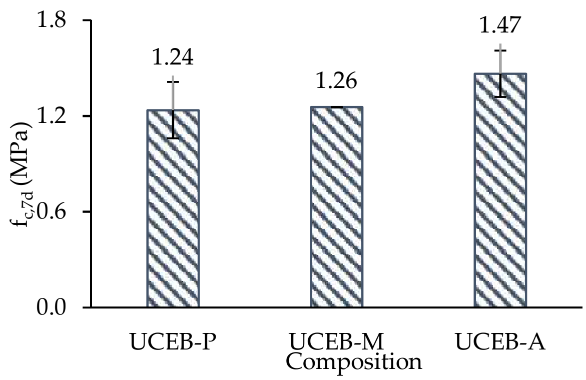

Figure 12 - Average 7-days compressive strength (fc,7d) tested after lab curing for the mixtures UCEB-P, UCEB-M and UCEB-A

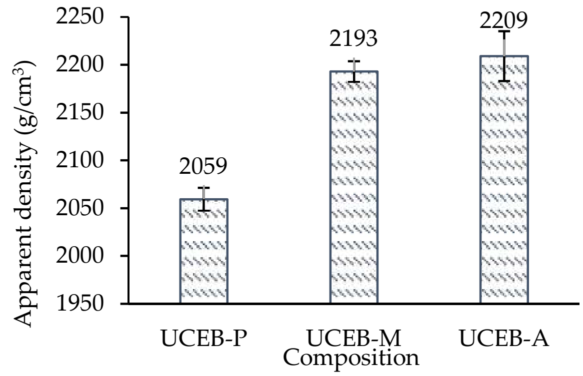

Figure 13 - Average 7-days apparent density for the mixtures UCEB-P, UCEB-M and UCEB-A

2.3 Mixing water

To assess the effect of the mixing water on CSEB and UCEB, three mixtures were produced with the *Baldios* soil, three with *Maja* soil and two with *Pinheiro* soil, only varying the mixing water content. The compositions are listed in Table 7, involving *Baldios* CSEB mixtures produced with 12% (CSEB-B-12W), 13% (CSEB-B-13W) and 15% (CSEB-B-15W) mixing water, Maja CSEB mixtures produced with 12% (CSEB-M-12W), 13% (CSEB-M-13W) and 14% (CSEB-M-14W) and UCEB mixtures produced with 12% (UCEB-P-12W) and 14% (UCEB-P-14W).

Table 7 – Compositions developed to evaluate the effect of the mixing water on CSEB

Mixture	Soil (%)	CDW [b] (%)	OPC[c] (%)	Water[d] (%)	Apparent density (g/cm^3)
CSEB-B-12W	67	25	8	12	2206
CSEB-B-13W	67	25	8	13	2333
CSEB-B-15W	67	25	8	15	2284
CSEB-M-12W	67	25	8	12	2256
CSEB-M-13W	67	25	8	13	2311
CSEB-M-14W	67	25	8	14	2161
UCEB-P-12W	75	25	0	12	2006
UCEB-P-14W	75	25	0	14	2102

[b] by weight of soil + CDW; [c] by weight of soil + binder; [d] percentage of water added via drop test

The results obtained were further compared with those of *Baldios* CSEB with 14% mixing water (BALD25CDW), Maja CSEB with 15% mixing water (MAJA25CDW) and UCEB with 13% mixing water (UCEB-P). The average 7-day apparent density is in Table 7.

The 7-day compressive strength of CSEB made with *Baldios* soil ranges from 5.47 MPa to 10.18 MPa (Figure 14). Figure 15 displays the compressive strength of the mixtures relative to CSEB produced with 14% mixing water, averaging between 51.92-96.63% of BALD25CDW. High variability suggests similarity between CSEB-B-13W and BALD25CDW, which was produced with more 1% water content. Notably, the block strength decreases with 12% mixing water, suggesting a lower compaction as demonstrated in Table 7. As the *Baldios* soil has an OMC of 10.87% [1], the incorporation of OPC in CSEB shifted the OMC to higher values, ranging from 13% to 14%. In contrast, for the new CSEB produced with *Maja* soil, the compressive strength ranges from 3.75 MPa to 5.43 MPa (Figure 16), indicating values below that obtained from the MAJA25CDW mixture (Figure 17). Similar to what was observed for the *Baldios* soil, since *Maja* soil has an OMC of 13.34% [1], the incorporation of OPC also shifted the OMC to higher values. On the one hand, this is because the OMC was tested with a smaller compaction force (Proctor test). On the other hand, the OMC was determined for the soil alone [1], without considering the 25% incorporation of CDW, of 4.3% of water absorption [3], as well as the 8% OPC incorporation.

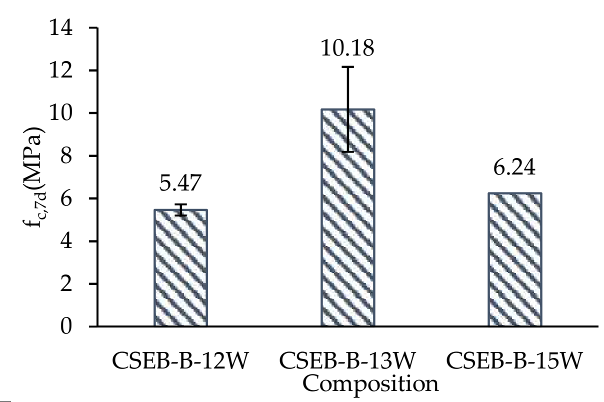

Figure 14 – Average 7-days compressive strength ($f_{c,7d}$) for the mixtures produced with soil Baldios, varying the content of mixing water

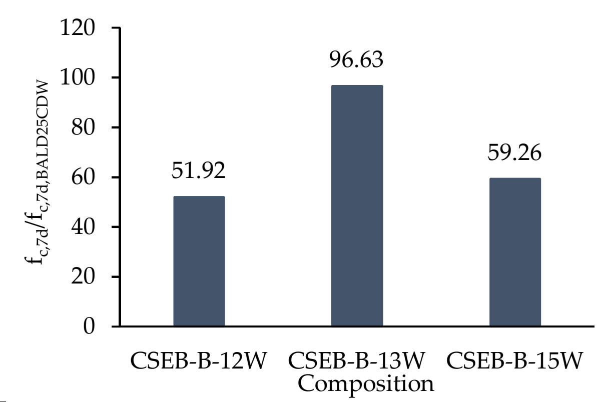

Figure 15 – Relative 7-days compressive strength (fc,7d) against reference CSEB of equal mixing water content ($f_{c,7d,BALD25CDW}$)

For UCEB, the 7-day compressive strength averaged between 0.79 MPa and 1.27 MPa (Figure 18). Figure 19 illustrates the compressive strength of the mixtures relative to UCEB produced with 13% mixing water, averaging between 63.82% and 102.92%. This indicates that reducing the mixing water from 14% to 13% and 12% lowered the compressive strength. The OMC for *Pinheiro* soil was 15.3% [1].

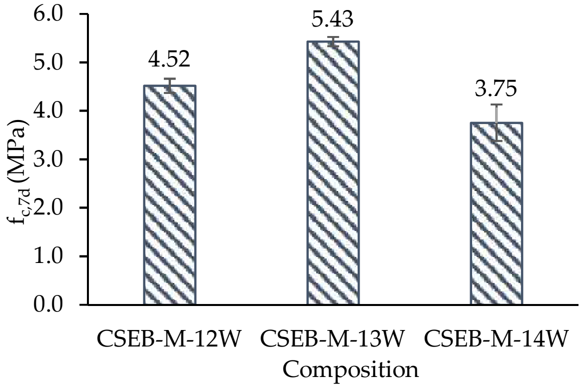

Figure 16 - Average 7-days compressive strength ($f_{c,7d}$) for the CSEB mixtures produced with soil Majas, varying the content of mixing water

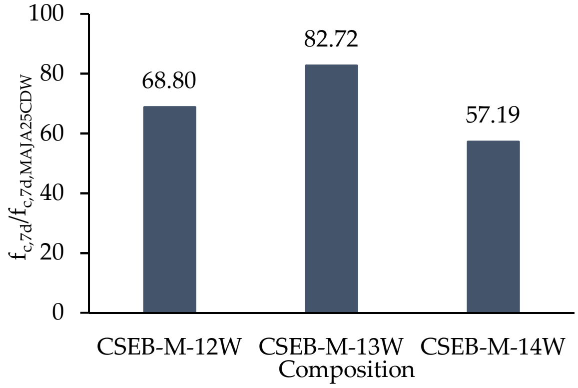

Figure 17 - Relative 7-days compressive strength ($f_{c,7d}$) against reference CSEB of equal mixing water content ($f_{c,7d,MAJA25CDW}$)

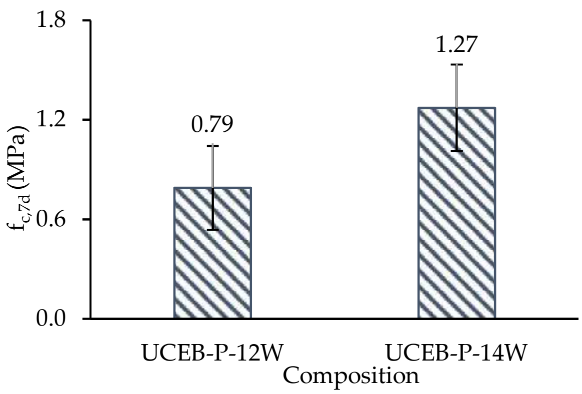

Figure 18 – Average 7-days compressive strength (fc,7d) for the mixtures produced with soil Pinheiro, varying the content of mixing water

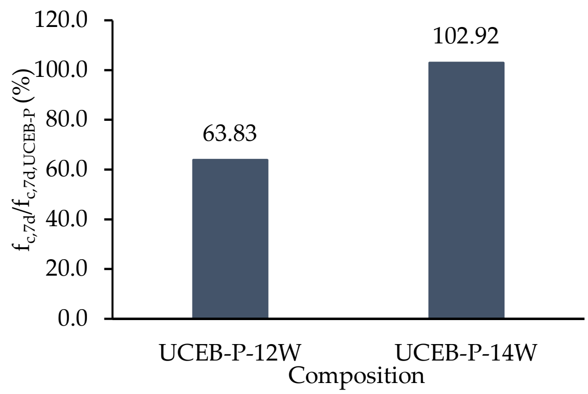

Figure 19 - Relative 7-days compressive strength ($f_{c,7d}$) against reference CSEB of equal mixing water content ($f_{c,7d,UCEB-P}$)

3. Conclusions

While building with earth is not complicated; practical experience and understating of raw materials are important to build high-quality earthen structures. Regarding a dual contribution to climate change and housing shortage, earthen construction should be affordable, breathable, climate adaptive, desirable, and most importantly, durable. Therefore, the selection of an adequate soil to produce unstabilized and stabilized CEB is crucial. This report presented the main conclusions reached in a preliminary study regarding the CEB mix design, involving unstabilized and stabilized mixes with OPC and the incorporation of construction and demolition waste. The blocks were characterized in terms of their average 7-days compressive strength and apparent density. The following main conclusions were drawn:

- The best composition was attained with 25% mixed CDW, consisting of concrete, unbounded natural aggregates and fired clay bricks. For this CDW content, the highest apparent density and compressive strength were achieved, indicating a greater compactness and a lower number of voids. Therefore, it can be concluded that incorporating CDW as earth replacement is technically advantageous, also increasing the sustainability of CEB.
- The average compressive strength reduced with the replacement of mix CDW with CDW exclusively obtained from concrete waste. This was also reflected in the apparent density, indicating a lower compactness of the mixtures produced with CDW from concrete waste.
- *Baldios* demonstrated the best potential for producing CSEB. The 7-day compressive strength was 10.5 MPa, which was nearly twice that of CSEB produced with *Amendonça* and *Pinheiro* and 1.6 times higher than that of CSEB with *Maja* soil.
- The compressive strength of unstabilized blocks was little affected by the type of soils studied.
- The incorporation of CDW and OPC shifted the OMC to higher values, regardless of the type of soil. A slight opposite effect was observed in UCEB.

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