Eco+RCEB

Eco-efficient recycled cement compressed earth blocks

FCT Project

PTDC/ECI-CON/0704/2021

Report Eco+RCEB/R7

Influence of recycled cement on the water resistance of compressed earth blocks produced from a manual press: Phase 1 of Task 1

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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.

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 current research is a component of the FCT research initiative, PTDC/ECI-CON/0704/2021. Its aim is to produce and analyze eco-friendly compressed stabilised earth blocks (CSEB). This research is part of a larger effort to encourage the use of earth-based materials in construction and promote more sustainable and environmentally conscious building practices. This report presents the results of the influence of recycled cement on the water resistance of CEB produced resorting to a manual press. This study takes part of the Phase 1 of Tasks 1 and 4, aiming the production and durability characterisation of CSEB.

2. Composition and production

Three materials were used in the production of CSEB: soil from Montemor-o-Nov; ordinary Portland CEM I 42.5R (PC); thermoactivated recycled cement (RC) from paste waste. The soil was analyzed and characterized according to the standards set out in Report Eco+Rceb/R1 [1]. The chosen soil was a clayey sand with 20.1% fine gravel, 48.4% sand, and 31.5% fine material (clay and silt), and had a particle density of 2.7 g/cm^3. It contained less than 1% organic matter, which is desirable. The liquid limit and the plastic limit were 30% and 22%, respectively, giving a plasticity index of 8%. The optimum moisture content (OMC) was 16% for a dry density of approximately 1800 kg/m^3. The RCP was produced using a process similar to that described in Report Eco+Rceb/R2 [2]. The paste waste was produced using a water-to-cement ratio of 0.45 and had a compressive strength of 57MPa after 28 days. The process of thermoactivation involved heating at a rate of 10°C/min up to 650°C, maintaining this temperature for 3 hours, and subsequently cooling it down to ambient temperature inside the kiln. Table 1 provides the characterization of PC and RC.

Table 1 - Stabiliser properties

Parameter	**Standard**	**Stabiliser**	
		PC	**RC**
Density (g/cm^3)		3.07a)	3.00b)
SiO_2+Al_2O_3+FeO_3 (%)		19.64+5.34+3.05	19.14+5.13+3.00
CaO+MgO (%)		62.80+1.80	60.79+1.77
Free CaO (%)		0.7	13.94
Compressive strength at 28 days (MPa)	EN 196-1[3]	57.0	-
Water demand (w/b)	EN 196-3 [4]	0.31	0.73
Initial/final setting time (mins)	EN 196-3 [4]	170/280	290/385

a) According to LNEC E 64 [5]; b) According to helium pycnometry

CSEB were manufactured using various stabilizers in varying amounts. For comparison purposes, some were also produced without any stabilizers. The compositions of these compressed earth blocks (CEB) are presented in Table 2, including the following: CEB without any stabilizer (UCEB); reference CSEB containing 10% PC (PC10); more environmentally friendly CSEB containing 10% RC (RC10); CSEB with a blended stabilizer of 10% comprising of PC replaced with 20% (RC2PC8) or 50% RC (RC5PC5). The mixing water was determined based on the OMC and adjusted through trial drop test as described in Report Eco+Rceb/R4 [6]. The soil had an in situ water content of 4%. As RC has a high-water demand, the quantity of mixing water increased in CSEB with this binder (Table 2). Blocks of 220x105x60 mm were produced following the same process as in Report Eco+RCEB/R4 [6]. The CSEB were subjected to wet curing for 7 days after production, while the UCEB underwent dry curing for the same duration but covered with a plastic film. Following this period, the CEB were air cured under laboratory conditions until the testing age.

Table 2 - Composition of CEB

Designation	**Soil$^{a)}$ (%)**	**PC$^{b)}$ (%)**	**RC$^{b)}$ (%)**	**Total water$^{b)}$ (%)**	**w/b$^{c)}$**
PC10	90	10	-	15.0	1.45
RCP10	90	-	10	16.5	1.60
RC2PC8	90	8	2	15.0	1.45
RC5PC5	90	5	5	15.5	1.50
UCEB	100	-	-	14.4	-

$^{a)}$ Soil with 4% humidity; $^{b)}$ By weight of solids (soil+stabiliser); $^{c)}$ Total w/b, including water absorbed by soil

3. Block characterisation

The earth blocks were characterized by determining their fresh and hardened density, compressive strength, water absorption through immersion, capillary water absorption, low-pressure water absorption, water permeability, and resistance to water erosion (spray test). Furthermore, to better understand the impact of RC as a stabilizer, thermogravimetric (TG) and X-ray diffraction (XRD) analyses were conducted on RC10 and PC10 compositions. The *STERAM TGA92 Thermobalance* was employed to perform these tests under a nitrogen environment. Using a conventional *PANalytical X'Pert Pro* diffractometer, the primary crystalline phases were identified via XRD. Compressive strength and density followed the same procedures presented in Report Eco+RCEB/R5 [7]. The absorption by immersion was determined based on LNEC E394 [8] and NBR 8492 [9] (Figure 1a). The capillary absorption test was carried out following the procedures described in NTC 5324 [10] and EN 772-11 [11], but with a modification of testing the blocks in a vertical position to ensure sufficient height. In this test, the side faces of the blocks were submerged to a depth of 5±1 mm (Figure 1b). The low-pressure water absorption was tested according to EN 16302 [12] (Figure 1c) and the water permeability was assessed using three half-cut blocks measuring approximately 110x105x60 mm for each composition, following the methodology established in Bogas et al. [13] (Figure 1d). Finally, the spray test method described in NZS 4298 [14] (Figure 1e) was used to evaluate the water erosion resistance. The volume of voids and the total porosity were estimated as in Report ECO+RCEB/R5 [7] and its values, as well as fresh and hardened density and compressive strength are represented in Report ECO+RCEB/R6 [15]. Overall, the RCP CSEB presented lower fresh and hardened densities, higher volume of voids and total porosity than the OPC CSEB. Also, the compressive strength exhibited an increase with the stabilizer content and a decrease with the percentage replacement of PC with RC.

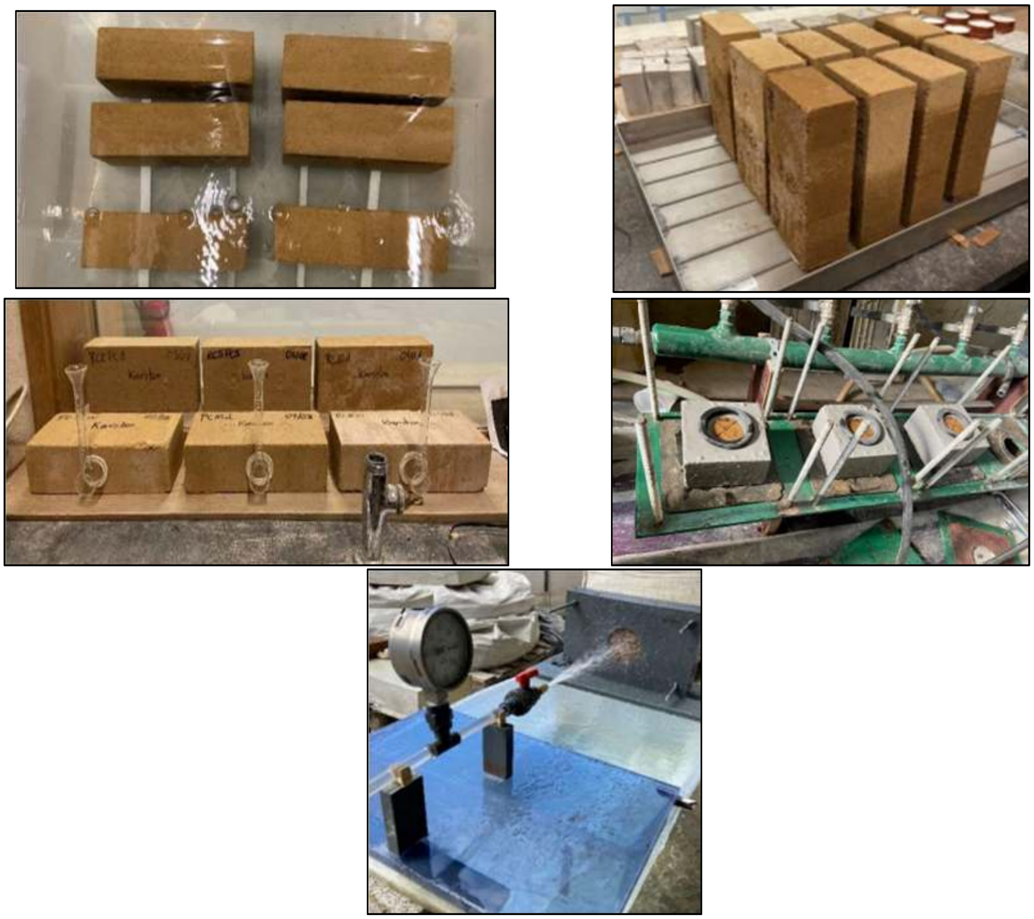

Figure 1 – Blocks characterization: a) absorption by immersion; b) absorption by capillarity; c) low-pressure water absorption; d) water permeability; e) spray test

X-ray diffraction analysis results for PC10 and RC10 compositions are illustrated in Figure 2. The minerals present in both blocks were predominantly those found in soil, including silicates such as quartz and albite. Additionally, clay minerals such as illite and nontronite, which belong to the highly expansive smectite group, were identified. The CSEB stabilized with RC exhibited a higher amount of calcite, which suggests a higher carbonation of this binder [16]. The TG curve and its derivative (DTG) for both compositions are shown in Figure 3, with mass losses primarily attributed to the presence of cementitious binder and clay minerals. The TG and DTG curves for both CSEB, whether using PC or RC, were very similar, suggesting the formation of similar phases and at a comparable hydration stage.

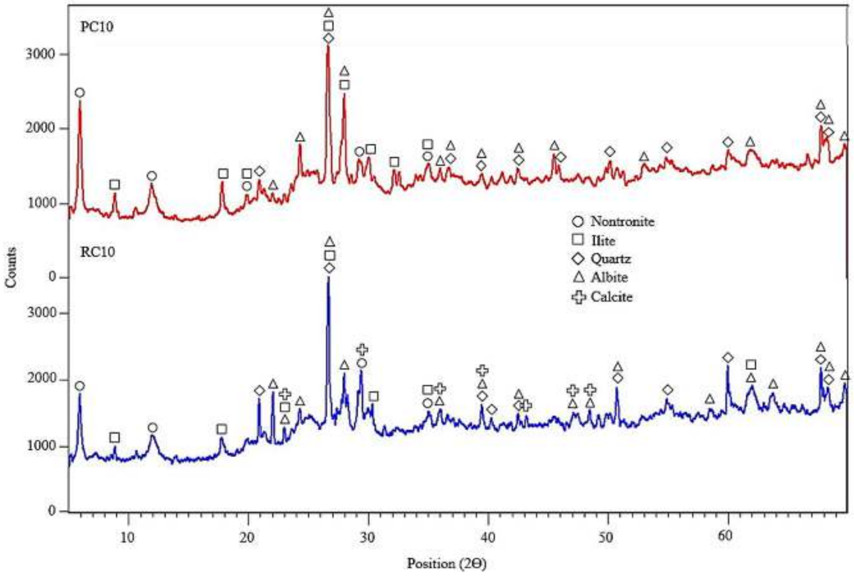

Figure 2 – PC10 and RC10 XRD analysis

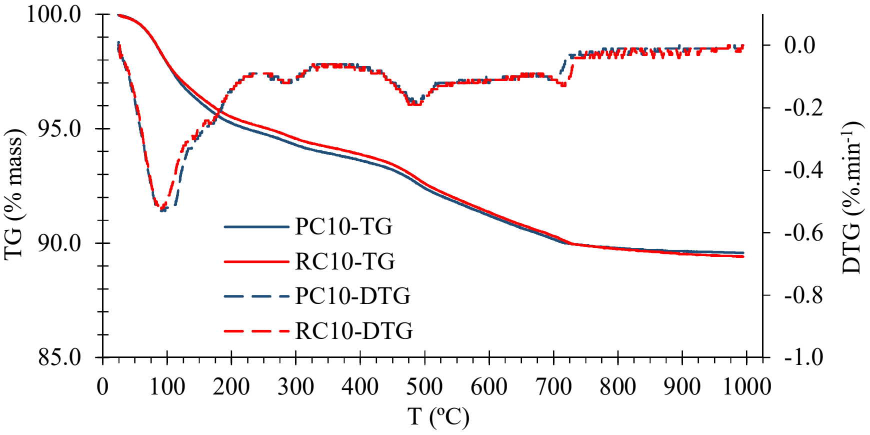

Figure 3 - TG and DTG curves for PC10 and RC10

Table 3 shows the average absorption by immersion of CSEB after 24 hours and 48 hours in terms of mass ($A_{i,m}$) and volume percentage ($A_{i,v}$), respectively. Most absorption occurred in the first 24 hours. Also, absorption of CSEB increased with RC content which is mainly attributed to its higher total porosity (see

ECO+RCEB/R6 [15]) Unstabilized blocks gradually lost their cohesion after contact with water, being fully disintegrated after some hours.

Table 3 – Average absorption by immersion

Composition	**Absorption by immersion (%)**			
	Mass		**Volume**	
	24 h	**48 h**	**24 h**	**48 h**
PC10	18.8	19.9	32.8	33.1
RC2PC8	19.2	19.9	32.9	33.9
RC5PC5	21.0	21.5	34.9	35.8
RC10	21.5	22.0	35.3	36.0

Table 4 and Figure 4 show the average capillary absorption up to 72 hours and the water absorption coefficient, C_b, over time, respectively. The capillarity results showed a consistent trend with the overall tendency of absorption by immersion. The 72-hour water absorption and the absorption rate both increased gradually as PC was replaced with RC. Specifically, RC10 exhibited a 69% higher Abs,72h compared to the reference PC10. Additionally, the absorption coefficient was 64-69% higher in RC10.

Table 4 - Average capillary absorption over time

Composition	**Capillary absorption (g/cm²)**							
	10min	**20min**	**30min**	**60min**	**120min**	**360min**	**1440min**	**4320min**
PC10	0.41	0.54	0.63	0.84	1.08	1.64	2.79	4.19
RC2PC8	0.83	0.92	1.02	1.29	1.65	2.33	3.69	5.17
RC5PC5	0.95	1.08	1.21	1.55	2.27	2.73	4.26	6.34
RC10	0.89	0.96	1.07	1.37	1.81	2.74	4.66	7.07

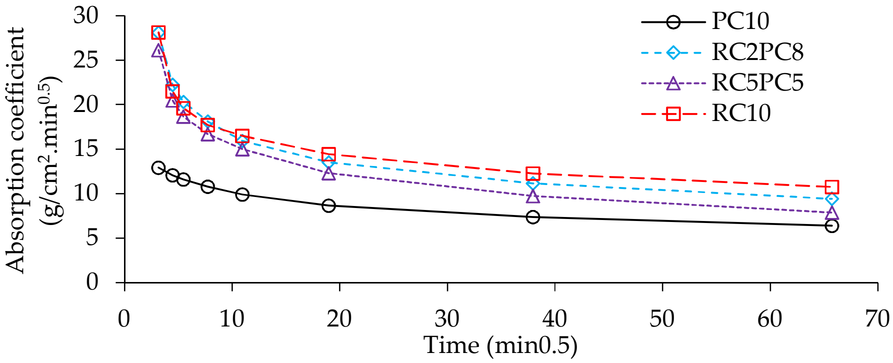

Figure 4 - Capillary absorption coefficient over time

The low-pressure absorption test allows the evaluation of the surface permeability of CEB. This property was not evaluated for the RC2PC8 mixture. The evolution of absorption over time is presented in Figure 5. In accordance with findings from other tests, PC10 exhibited the slowest absorption rate over time. In contrast, RC10 and RC5PC5 demonstrated 56% and 48% faster absorption rates, respectively, than PC10, as evidenced by the time it took to absorb 4 cm^3 of water (0.7 g/cm^2 in Figure 5). Additionally, RC10 displayed a 50% higher absorption coefficient at the 5-minute mark compared to PC10 (0.012 kg.m^{-2}.s^{-1} versus 0.008 kg.m^{-2}.s^{-1}). These results confirm that CEB produced with RC had higher absorption properties than that with OPC.

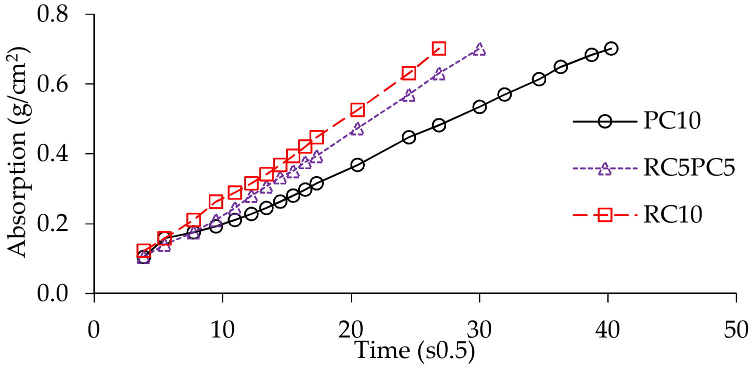

Figure 5 - Water absorption at low-pressure over time

Table 5 shows that the average permeability coefficient (K_w) varied from 2.8x10^{-7} m/s for CSEB with 10% PC to 6.1x10^{-7} m/s for CSEB with 10% RC. As observed in previous tests, permeability increased with the gradual substitution of PC with RC. Furthermore, CSEB with 10% RC displayed a K_w approximately twice as high as that of CSEB with 10% PC (Table 5). This coefficient demonstrated a strong correlation with total porosity (P_T), underscoring its crucial role in CSEB durability (Figure 6).

Table 5 – Permeability coefficient of CSEB

Composition	Permeability coefficient, K_w (m/s)
PC10	2.8
RC2PC8	4.2
RC5PC5	4.8
RC10	6.1

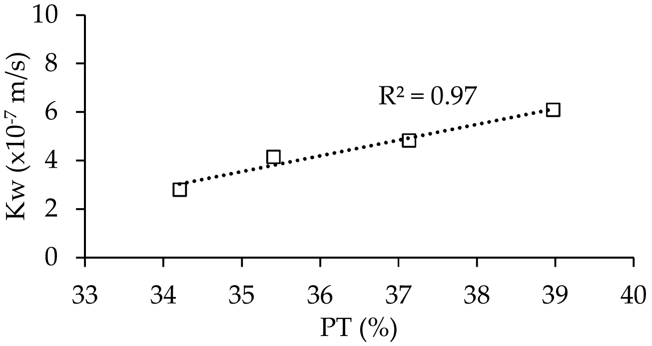

Figure 6 - Permeability coefficient (K_w) versus total porosity (P_T)

Table 6 indicates that stabilized blocks exhibited outstanding durability during the spray test, regardless of the binder type used. All specimens subjected to the NZS 4298 [74] test displayed no signs of erosion when exposed to 0.5 bar pressure, which is equivalent to heavy rain impact. Based on this standard, since the erosion depths were less than 1 mm/h, all tested blocks would be classified as class IE1. Even with a water jet pressure increase to 2.5 bar, the erosion was insignificant after 1 hour of testing (Table 6). Furthermore, after testing, the moisture penetration depth (DP) was determined by cutting the blocks perpendicular to the exposed face, and it was very similar for both stabilizers (Table 6). Unstabilized blocks were fully eroded after only 7 minutes of testing at the lowest pressure of 0.5 bar. These blocks were highly vulnerable to water erosion, and they disintegrated entirely upon contact with water. As a result, their use in outdoor applications exposed to water action without protection is not recommended. This highlights the importance of stabilization and the suitability and hydraulicity of RC.

Table 6 - Spray test results. Erosion depth (DE), moisture penetration dpth (DP) and erosion rate (DE/hour)

Mixture	Pressure (bar)	Test time (min)	DE (mm)	Erosion rate (mm/hour)	DP (mm)
PC10	2.5	60	-	< 1	38
RC5PC5	2.5	60	-	< 1	36
RC10	2.5	60	-	< 1	39
UCEB	0.5	7	60	514	N/A

4. Conclusions

The objective of this study was to evaluate the impact of partially or fully replacement of OPC with RC in terms of CSEB water resistance.

Earth blocks with RC revealed high rehydration capacity and hydration behaviour similar to PC. However, the increased water demand of RC increased the amount of mixing water and w/b ratio of the blocks while decreasing the compactness. Consequently, the density of CEBs stabilized with RC was reduced, resulting in higher total porosity. The laboratory testing revealed decrease in compressive strength when PC was replaced with 20-100% RC. This reduction was even more pronounced, under saturation conditions, indicating that RC was not as effective as PC in stabilizing CSEBs. Furthermore, an increase in both water absorption and water permeability was observed with the addition of RC. However, contrary to UCEB, that disintegrated in contact with water, RC CSEB showed insignificant water erosion, even for extreme water pressure conditions, much more severe than those found in real environment.

In short, despite its lower performance than PC, RC demonstrated itself as a highly promising substitute for cement stabilization, offering significant eco-efficiency benefits without adversely affecting the water resistance of CSEBs.

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