Eco+RCEB

Eco-efficient recycled cement compressed earth blocks

FCT Project

PTDC/ECI-CON/0704/2021

Report Eco+RCEB/R6

Influence of recycled cement on the physical and mechanical properties of compressed earth blocks produced from a manual press: Phase 1 of Task 1

March 2023

FCT Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA CIÊNCIA E DO ENSINO SUPERIOR Portugal

Eco-efficient recycled cement compressed earth blocks

FCT Project

PTDC/ECI-CON/0704/2021

Report Eco+RCEB/R6

Influence of recycled cement on the physical and mechanical properties of compressed earth blocks produced from a manual press: Phase 1 of Task 1

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.

Written by

This report has been written by: Sofia Real, Ricardo Cruz, M. Glória Gomes and José Alexandre Bogas.

Information

Main Contractor:

Instituto Superior Técnico, Technical University of Lisbon

Department of Civil Engineering and Architecture

Av. Rovisco Pais, 1049-001 Lisbon, Portugal

Main Research Unit:

CERIS is an FCT-registered research unit, hosted by the Department of Civil Engineering, Architecture and Georesources (DECivil) of Instituto Superior Técnico (IST), University of Lisbon (ULisboa).

Table of Contents

List of Figures

List of Tables

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

This report regards a second study, within the scope of Phase 1 of Task 1 of Eco+RCEB, on the mechanical characterisation of compressed earth blocks (CEB) stabilised with low-carbon recycled cement and produced using a manual press. This work comprised the production of CEB with different types and amounts of stabiliser, as well as their characterisation in terms of density, ultrasonic pulse velocity, compressive strength, splitting and bending tensile strength, modulus of elasticity, pendular sclerometer and drying shrinkage.

2. Composition and production

For this study, one soil from Montemor-o-Novo, ordinary Portland CEM I 42.5R (OPC) and thermoactiviated recycled cement from paste waste (RCP) were used. Table 1 presents the soil characterisation, which was performed according to the same standards presented in Report Eco+RCEB/R1 [1]. The RCP was produced in a similar manner to the one presented in Report Eco+RCEB/R2 [2]. However, the paste waste was produced with a water/cement ratio of 0.45 and a compressive strength at 28 days of 57MPa. The thermal activation process consisted on heating at 10°C/min up to 650°C; remained at maximum temperature for 3 hours; cooling inside the kiln up to ambient temperature. Table 2 presents the characterisation of OPC and RCP.

For this study, 7 compositions were designed, considering different types (OPC or RCP) and percentages (5-10%) of stabiliser (Table 3). For CSEB with 10% stabiliser, OPC was gradually substituted with RCP (0, 20, 50 and 100%). Additionally, unstabilised compressed earth blocks (UCEB) were also produced for comparison purposes.

Table 1 – Soil characterisation

Particle density (g/cm^3)	Composition (%)			Organic matter content (%)	Atterberg limits (%)		
	Gravel	Sand	Silt/clay		Liquid limit	Plasticity limit	Plasticity index
2.7	20.1	48.4	31.5	<1	30	22	8

Table 2 – Stabiliser properties

Parameter	Standard	Stabiliser	
		OPC	RCP
Density (g/cm^3)		3.07[a)]	3.00[b)]
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

The production of the CEB of 220x105x60 mm followed the same manual press process presented in Report Eco+RCEB/R5 [6]. After production, the CSEB were subjected to 7 days of wet curing, whereas the UCEB underwent dry curing (7 days covered with a plastic film). After this period, the CEB were air cured under laboratory conditions up to testing age.

Table 3 – Composition of CEB

Designation	Soil[a)] (%)	OPC[b)] (%)	RCP[b)] (%)	Total water[b)] (%)	w/b[c)]
OPC10	90	10	-	15.0	1.45
RCP10	90	-	10	16.5	1.60
OPC5	95	5	-	15.2	2.93
RCP5	95	-	5	16.2	3.13
RCP2OPC8	90	8	2	15.0	1.45
RCP5OPC5	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. Physical and mechanical characterisation

The physical and mechanical characterisation of the CEB was carried out according to the fresh density, hardened density, compressive strength (Figure 1a), splitting and bending tensile strengths (Figure 1b and c), modulus of elasticity (Figure 2a), ultrasonic pulse velocity (Figure 2b), pendular sclerometer (Figure 2c) and drying shrinkage tests, which, except for the modulus of elasticity, essentially followed the same procedures presented in Report Eco+RCEB/R5 [6].

The volume of voids (Vv) and the total porosity (TP) were estimated, taking into account their composition and fresh density. The modulus of elasticity was conducted using an *Instron* press with 250 kN capacity and two *TML extensometers PFLW-30-11-3LJC* of 120 Ω, which were attached on opposite lateral surfaces of the blocks (Figure 2a).

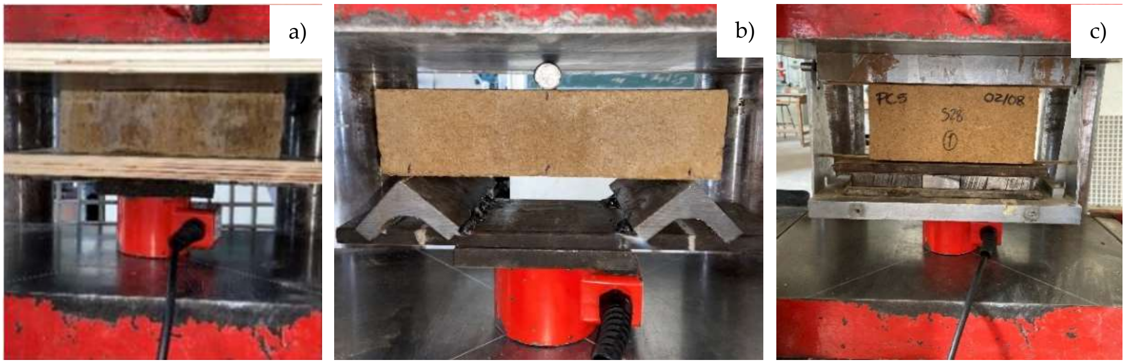

Figure 1 – Mechanical tests: a) compressive strength; b) bending tensile strength; c) splitting tensile strength

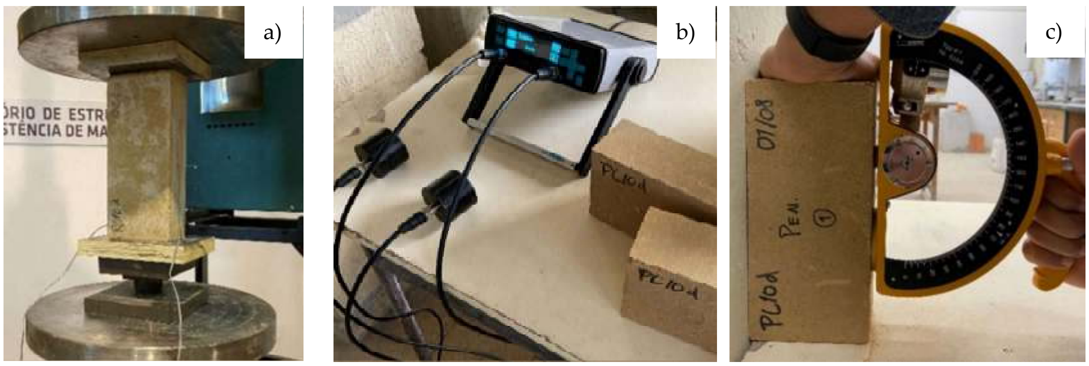

Figure 2 – Tests: a) Modulus of elasticity; b) ultrasonic pulse velocity; c) pendular sclerometer

The fresh and hardened densities of the CEB ranged 1870-2030 kg/m^3 and 1640-1750 kg/m^3, whereas the volume of voids and the total porosity varied between 8.9and14.6% and 34.2 and 39.3%, respectively (Table 4).

Table 4 – Density, volume of voids (Vv) and total porosity (TP) of CEB

Designation	Fresh density (kg/m^3)	Vv (%)	TP (%)	Density (kg/m^3)		
				lab	dry	sat
OPC10	1990	10.7	34.2	1860	1740	2080
RCP10	1870	14.6	39.0	1730	1640	1910
OPC5	1950	12.0	36.5	1790	-	-
RCP5	1880	14.2	39.3	1720	-	-
RCP2OPC8	1950	12.4	35.4	1800	1710	1970
RCP5OPC5	1910	13.9	37.1	1780	1670	1950
UCEB	2030	8.9	34.4	1820	1750	-

Overall, the RCP CSEB presented lower fresh and hardened densities than the OPC CSEB, essentially due to their higher total water content, stemming from their higher water demand and porous nature of RC particles. This also explains their higher volume of voids and total porosity. Furthermore, given that UCEB was produced with the lowest total water content, this CEB had the highest compactness, having displayed the highest fresh density and lowest volume of voids.

The compressive strength varied between 0.8 and 5.9 MPa, depending on CEB composition and testing age (Table 5). This property increased with the stabiliser content, independently of the type, demonstrating the benefits of stabilisation to the mechanical performance of CEB (Figure 3). The compressive strength of RCP CSEB was lower than that of OPC CSEB, essentially due to the higher total water content and total porosity, as well as the lower development of hydration products over time. Therefore, the substitution of OPC with RC (20 and 50%) led to the reduction of the compressive strength of the CEB (Figure 3).

Moreover, as expected, except for UCEB, the compressive strength of CEB increased over time (Figure 3), due to the development of stabiliser hydration products, which promoted cohesion between the soil particles.

Table 5 – Compressive strength (f_c) of CEB at different ages and moisture conditions

Designation	$f_{c,3d}$ (MPa)	$CV_{fc,3d}$ (%)	$f_{c,7d}$ (MPa)	$CV_{fc,7d}$ (%)	$f_{c,28d}$ (MPa)			$CV_{fc,28d}$ (%)		
	lab		lab		lab	dry	sat	lab	dry	sat
OPC10	3.38	15	3.54	11	5.92	7.43	4.32	8	34	21
RCP10	1.77	3	2.52	3	4.44	6.53	2.45	5	15	4
OPC5	1.47	15	1.82	6	3.34	-	-	9	-	-
RCP5	0.97	8	1.05	7	2.45	-	-	5	-	-
RCP2OPC8	2.61	5	3.14	6	5.12	-	-	6	-	-
RCP5OPC5	2.01	19	2.51	21	4.99	-	-	2	-	-
UCEB	0.83	14	1.79	2	2.33	4.25	-	8	8	-

Furthermore, the compressive strength of all CEB decreased with the moisture content (Figure 4). This is due to the development of water pressure within the CEB pores and liquefaction of the non-stabilised portion of the clayed soil particles. The compressive strength reduction of RCP CSEB was higher than that of OPC CSEB with the moisture content increase. Nonetheless, contrary to UCEB, the CSEB remained intact upon saturation, demonstrating the contribution of the stabiliser to the behaviour of the CEB. Finally, all CEB complied with the minimum of 1 MPa recommended in HB 195 [7].

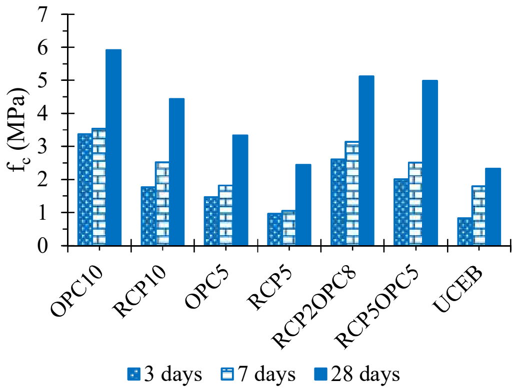

Figure 3 – Compressive strength (f_c) at different ages under laboratory conditions

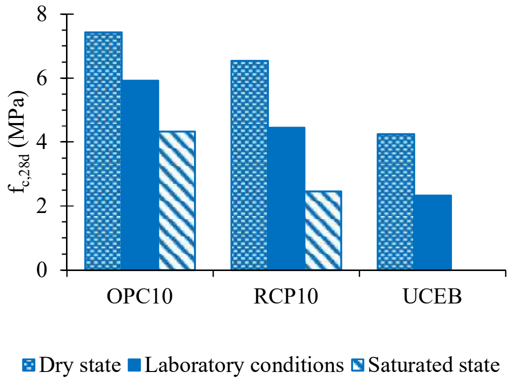

Figure 4 – Compressive strength at 28 days ($f_{c,28d}$) of CEB under varying moisture conditions

The splitting and bending tensile strengths varied between 0.25 and 0.56 MPa and 0.41 and 1.17 MPa, respectively (Table 6), depending on the composition and moisture conditions. The reduced tensile strength results and their variability made their analysis more difficult.

As for the compressive strength, the percentage of stabiliser affected the splitting and bending tensile strengths more relevantly than its type, having been little influenced by the latter in laboratory conditions (Figures 5 and 6). However, when CEB were tested in saturated conditions, the tensile strength of RCP CSEB was lower than that of OPC CSEB, demonstrating its higher sensitivity to the moisture conditions.

Table 6 – Splitting (f_{ctsp}) and bending (f_{ctr}) tensile strengths, modulus of elasticity (Ec), ultrasonic pulse velocity (UPV) and scletometric index (SI) of CEB at different moisture conditions

Designation	**$f_{ctr,28d}$ (MPa)**	**$CV_{fctr,28d}$ (%)**	**$f_{ctsp,28d}$ (MPa)**		**$CV_{fctsp,28d}$ (%)**		**$E_{c,28d}$ (GPa)**	**UPV (m/s)**			**SI**
	lab		**lab**	**sat**	**lab**	**sat**	**lab**	**lab**	**dry**	**sat**	**lab**
OPC10	0.97	9	0.51	0.45	14	25	2.77	1714	1247	2069	33.5
RCP10	0.93	15	0.44	0.33	12	33	2.10	1414	1307	1934	24.3
OPC5	0.69	7	0.36	-	11	-	-	1147	-	-	-
RCP5	0.52	13	0.20	-	12	-	-	1094	-	-	-
RCP2OPC8	1.02	3	0.44	-	7	-	-	1584	-	-	29.5
RCP5OPC5	1.17	6	0.56	-	5	-	-	1472	-	-	28.8
UCEB	0.41	12	0.25	-	20	-	-	1104	1338	-	15.5

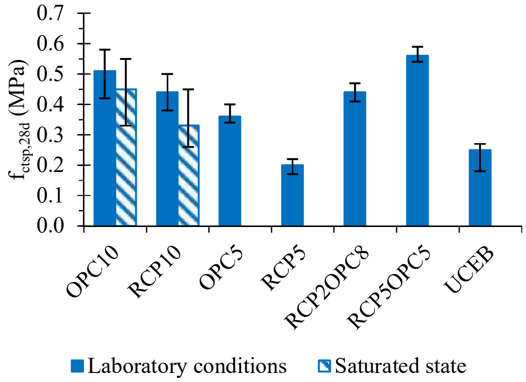

Figure 5 – Splitting tensile strength at 28 days ($f_{ctsp,28d}$) of CEB under varying moisture conditions

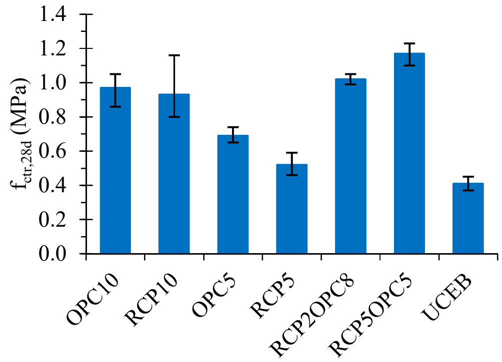

Figure 6 – Bending tensile strength at 28 days ($f_{ctr,28d}$) of CEB

The modulus of elasticity was only performed for OPC10 and RCP10, having presented 2.77 and 2.1 GPa, respectively (Table 6, Figure 7). In accordance with the total porosity and mechanical strength results, the modulus of elasticity of OPC10 was higher than that of RCP10. This can be explained by the lower stiffness and higher porosity of RCP particles, when compared with OPC particles.

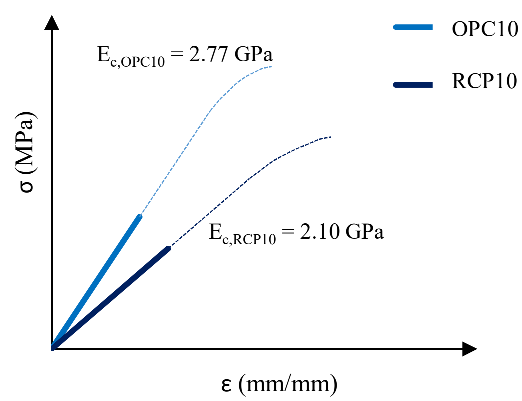

Figure 7 – Stress (σ) - strain (ε) curves of OPC10 and RCP10

The ultrasonic pulse velocity ranged 1104-2069 m/s, depending on CEB composition and moisture conditions (Table 6). The ultrasonic pulse velocity tended be lower in RCP CSEB than in OPC CSEB and to increase with the stabiliser content (Figure 8). Moreover, this property decreased with the substitution of OPC with RCP, mainly due to a stiffness reduction and total porosity increase (Table 4). Furthermore, the ultrasonic pulse velocity was especially influenced by the moisture content, having been significantly higher in the saturated state than in the dry state (Figure 8), given that waves propagate faster through water filled pores.

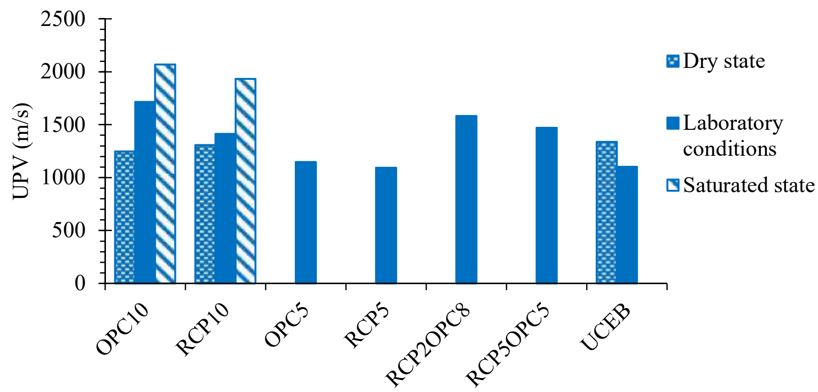

Figure 8 – Ultrasonic pulse velocity (UPV) of CEB under varying moisture conditions

The sclerometric index varied between 15.5 and 33.5 (Table 6). The sclerometric index of OPC CSEB was higher than that of RCP CSEB (Figure 9), given their greater total porosity and lower mechanical strength. Nonetheless, all CSEB presented higher surface hardness than the UCEB (Figure 9).

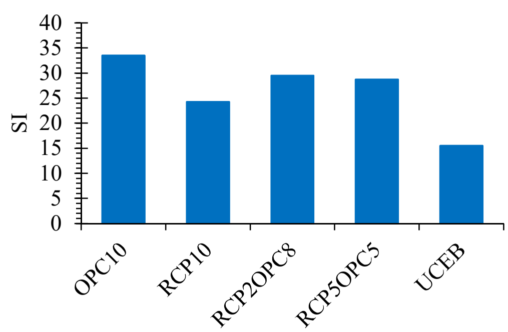

Figure 9 – Sclerometric index (SI) of CEB

The drying shrinkage of OPC10 and RCP10 was only measured up to 21 days, which was not sufficient of shrinkage stabilisation (Figure 10). Nonetheless, Figure 10 indicates that that it should occur first in OPC10 than in RCP10. The shrinkage of these CSEB was comparable until 5 days, but afterwards was higher in RCP10 than in OPC10 (Figure 10), owed to its greater total water and paste content and its higher total porosity and lower stiffness.

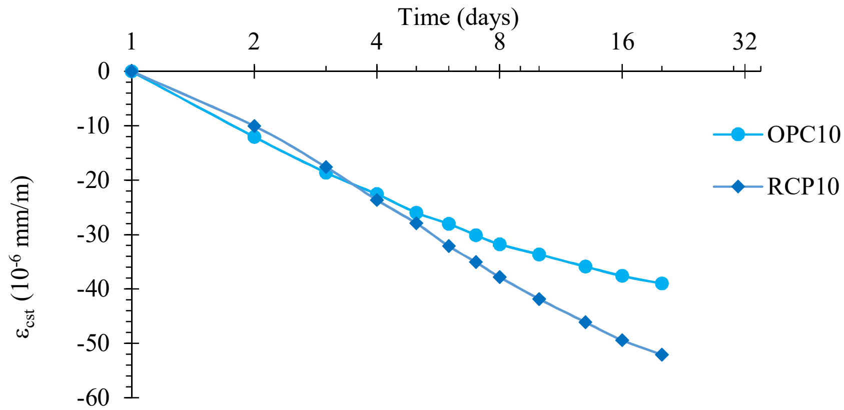

Figure 10 – Drying shrinkage (ε_{cst}) of CEB over time

4. Conclusions

In this study, more eco-efficient compressed earth blocks stabilised with thermoactivated recycled cement (RCP) were developed and characterised in terms of their main physical and mechanical properties.

RCP CSEB presented lower fresh and hardened densities and higher volume of voids and total porosity than the OPC CSEB. Furthermore, their mechanical performance was also lower than that of OPC CSEB. This can be explained by their higher total water content, stemming from their higher water demand and porous nature of RC particles, as well as by the lower development of RCP hydration products over time.

The mechanical strength was more affected by the percentage of stabiliser than by its type, having increased with this parameter, demonstrating the benefits of stabilisation to the mechanical performance of CEB. In fact, all CEB complied with the minimum of 1 MPa recommended in HB 195.

Acknowledgments

The authors wish to thank the Portuguese Foundation for Science and Technology (FCT) for funding this research through project PTDC/ECI-CON/0704/2021, and under the unit project UIDB/ECI/04625/2020 (CERIS). The authors also wish to acknowledge SECIL for providing the cement used during the experimental campaign and the collaboration of *Oficinas do convento*, Montemor-o-novo, in the production of compressed earth blocks.

References

[1] Real S, Cruz R, Balboa A, Pereira MFC, Bogas JA. Characterisation of materials: soils from Montemor-o-Novo. Report Eco+RCEB/R1, DTC nº2/2023, CERIS, Lisbon, Portugal, March 2023.

[2] Real S, Cruz R, Balboa A, Bogas JA. Characterisation of materials: cementitious stabilisers. Report Eco+RCEB/R2, DTC nº3/2023, CERIS, Lisbon, Portugal, March 2023.

[3] EN 196-1. Methods of testing cement. Determination of strength. European Standard, European Committee for Standardization (CEN), Brussels, Belgium, 2016.

[4] EN 196-3. Methods of testing cement. Determination of setting times and soundness. European Standard, European Committee for Standardization (CEN), Brussels, Belgium, 2016.

[5] LNEC E 64. Cement. Determination of density. Portuguese standard, Laboratório Nacional de Engenharia Civil (LNEC), Lisbon, Portugal, 1979.

[6] Real S, Cruz R, Bogas JA. Production and mechanical characterisation of more eco-efficient compressed stabilised earth blocks resorting to a manual press: Phase 1 of Task 1. Report Eco+RCEB/R5, DTC nº6/2023, CERIS, Lisbon, Portugal, March 2023.

[7] HB 195. The australian earth building handbook, Standards Australia, 2012.

Lisbon, 31 of March 2023

Authors

Sofia Real

Researcher
(IST)

Ricardo Cruz

PhD student
(IST)

M. Glória Gomes

Assistant Professor
(IST)

José Alexandre Bogas

Associate Professor with Habilitation
(IST)