Eco+RCEB

Eco-efficient recycled cement compressed earth blocks

FCT Project

PTDC/ECI-CON/0704/2021

Report Eco+RCEB/R5

Production and mechanical characterisation of more eco-efficient compressed stabilised earth blocks resorting to 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 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 concerns one study related to the mechanical characterisation of compressed earth blocks (CEB) stabilised with low-carbon recycled cement and produced using a manual press. This corresponds to Phase 1 of Task 1 of Eco+RCEB and involved various CEB produced with different types and amounts of stabiliser and of fine recycled aggregates. The CEB were characterised in terms of density, ultrasonic pulse velocity, compressive strength, splitting and bending tensile strength, modulus of elasticity, pendular sclerometer, abrasion, drying shrinkage and thermal conductivity. The main results obtained during this study are presented in the following sections.

2. Composition and production of CEB

Based on the results of the preliminary study (Report Eco+RCEB/R4 [1]) performed on the soils from Montemor-o-Novo, soil *Baldios* was selected to be used in the production of CEB. Moreover, thermoactivated recycled cement from paste waste (RCP and RCPF (fine RCP)) and concrete waste (RCC), ordinary Portland cement CEM I 42.5R (OPC) and Portland limestone cement CEM II/B-L 32.5N (PLC) were chosen to be used as stabilisers. Additionally, fine recycled aggregates (FRA), namely construction and demolition waste (CDW) and high quality recycled sand (HQRS), were also singled out to be used in CEB production. The characterisations of the soil, stabilisers and fine recycled aggregates are presented in Report Eco+RCEB/R1 [2], Report Eco+RCEB/R2 [3] and Report Eco+RCEB/R3 [4], respectively.

In order to analyse the influence of the composition of CEB on their physical and mechanical properties, 18 compositions were chosen, considering different types and incorporation percentages of stabiliser (0-13%), types and incorporation percentages of FRA (0-25%), as well as water contents and types of curing (air curing AC, wet curing WC). The CEB were produced as described in Report Eco+RCEB/R4 [1] and their composition is presented in Table 1. Note that one CSEB was produced with 13%RCC in order to simulate an 8%cementitous stabiliser comparable to the other CSEB compositions, accounting for the amount of inert aggregate residue present in this stabiliser.

Table 1 – Composition of CEB

Designation	Type of FRA	wt% FRA	Type of stabiliser	wt% of stabiliser	Total water (%)	Type of curing
8OPC25CDW14W	CDW	25	OPC	8	14.0	AC
8OPC25CDW13W	CDW	25	OPC	8	13.0	AC
8OPC15CDW	CDW	15	OPC	8	13.5	AC
8OPC	-	-	OPC	8	13.5	AC
8OPC25CDWWC	CDW	25	OPC	8	13.0	WC
5OPC25CDW	CDW	25	OPC	5	13.5	AC
8PLC25CDW	CDW	25	PLC	8	14.0	AC
8OPC25HQRS	HQRS	25	OPC	8	15.0	AC
8RCP25CDW	CDW	25	RCP	8	14.0	AC
8(20%RCP+80%OPC)25CDW	CDW	25	RCP/OPC	8	12.5	AC
8(50%RCP+50%OPC)25CDW	CDW	25	RCP/OPC	8	12.5	AC
8RCPF25CDW	CDW	25	RCPF	8	14.0	AC
8RCC25CDW	CDW	25	RCC	8	18.0	AC
13RCC25CDW	CDW	25	RCC	13	14.0	AC
8(20%RCC80%OPC)25CDW	CDW	25	RCC/OPC	8	17.5	AC
8(50%RCC50%OPC)25CDW	CDW	25	RCC/OPC	8	17.5	AC
UCEB	-	-	-	-	11.0	AC
UCEB25CDW	CDW	25	-	-	12.0	AC

3. Physical properties

The density of the CEB was determined according to EN 772-13 [5], whereas the total porosity was established according to EN 772-4 [6].

For the total porosity, the CEB were oven-dried at 100°C (Figure 1a), and their dry weight (M_{dry}) was determined. Then, the specimens were placed in vacuum in a dessicator for 24 hours, at which point water was introduced until the specimens were immersed, and left in vacuum for 24 hours (Figure 1b) and at atmospheric pressure for another 24 hours. Afterwards, the immersed weight (M_{im}) (Figure 1c) and the saturated surface dry weight (M_{ssd}) (Figure 1d) were measured, and the CEB were oven-dried. Subsequently, the CEB were crushed (Figure 1e) and sieved in a 100μm mesh and the density of these particles was determined through the Le Chatelier method (Figure 1f). The experimental total porosity is determined according to Eq. (1).

Additionally, the total porosity was also estimated based on the fresh density of the CEB.

Figure 1 – Total porosity test: a) oven-drying; b) saturation; c) immersed weighting; d) saturated surface dry weighting; e) particle size reduction; f) particle density

$$TP = \left(1 - \frac{Density_{CEB}}{Density_{particles}}\right) \times 100 = \left(1 - \frac{\frac{M_{dryCEB}}{\left[\frac{M_{ssd} - M_{im}}{998}\right]}}{\frac{M_{dry\ particles}}{V_{particles}}}\right) \times 100 \quad (1)$$

The fresh density ranged 1990-2200 kg/m^3, depending on the composition and water content (Table 2). In general, the fresh density was more influenced by the total water content than by the type and percentage of FRA (Figure 2) or by the type and percentage of stabiliser (

Figure 4). Nonetheless, the fresh density tended to decrease with the incorporation of FRA (Figure 2), given that the density of this component was lower than that of the replaced soil. Moreover, compared to OPC CSEB, the reduction of workability in RCP or RCC CSEB, owed to the higher water requirement of these stabilisers, resulted in higher total porosity, and therefore, in lower fresh densities (

Figure 4).

The dry density varied between 1730 and 1930 kg/m^3, depending on the composition and moisture conditions (Table 2). This property tended to increase with the incorporation of FRA, stabiliser and moisture content and decrease with the total water content (Figures 5-7). The density of the CEB was more affected by the total water content than by their composition (Figures 5-7). In fact, the total porosity tended to be higher in CEB with greater total water contents, which consequently resulted in lower density. Actually, not even the development of hydration products from the stabilisers were able to offset the effects of higher total water contents (Figure 6).

Table 2 – Physical properties of CEB

Designation	Fresh density (kg/m^3)	Dry density (kg/m^3)	Calculated total porosity (%)	Experimental total porosity (%)	UPV_{lab} (m/s)	CV_{lab} (%)	UPV_{dry} (m/s)	CV_{dry} (%)	UPV_{sat} (m/s)	CV_{sat} (%)
8OPC25CDW14W	2150	1850	27.4	-	2304	2	1776	9	2494	2
8OPC25CDW13W	2200	1900	25.0	26.0	2245	3	1657	1	2329	2
8OPC15CDW	2190	1870	25.9	25.6	2209	1	-	-	-	-
8OPC	2190	1910	26.3	26.2	2076	2	-	-	-	-
8OPC25CDWWC	2200	1900	25.0	26.3	2327	2	-	-	-	-
5OPC25CDW	2200	1850	25.8	27.7	1852	2	1429	6	1950	5
8PLC25CDW	2140	-	27.7	-	2084	1	-	-	-	-
8OPC25HQRS	2140	1920	27.8	28.9	2049	1	-	-	-	-
8RCP25CDW	2050	1840	30.9	-	1668	2	1358	2	1790	5
8(20%RCP+80%OPC)25CDW	2110	1850	27.8	-	2185	5	-	-	-	-
8(50%RCP+50%OPC)25CDW	2120	1860	27.5	-	2041	2	-	-	-	-
8RCPF25CDW	2150	1770	27.5	-	1576	2	-	-	-	-
8RCC25CDW	2100	1860	31.4	27.9	1239	4	-	-	-	-
13RCC25CDW	2080	-	28.9	32.0	1295	2	-	-	-	-
8(20%RCC80%OPC)25CDW	2130	1800	30.1	30.4	2047	6	-	-	-	-
8(50%RCC50%OPC)25CDW	2130	1780	30.1	-	1937	3	-	-	-	-
UCEB	2140	1930	27.6	-	1519	5	-	-	-	-
UCEB25CDW	2150	1850	27.3	-	1298	3	-	-	-	-

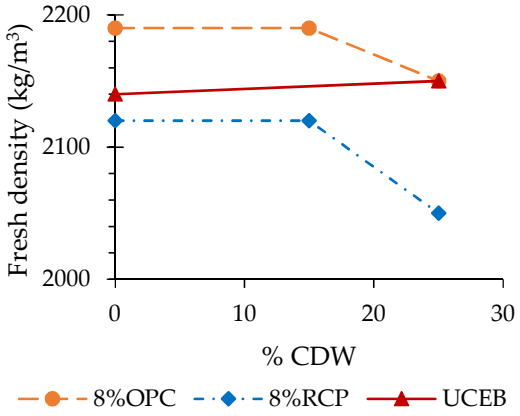

Figure 2 – Fresh density of CSEB with different incorporation percentages of CDW

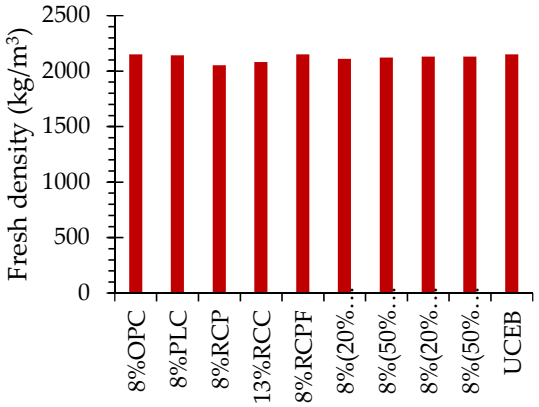

Figure 3 – Fresh density of CSEB with 8% stabiliser and of UCEB

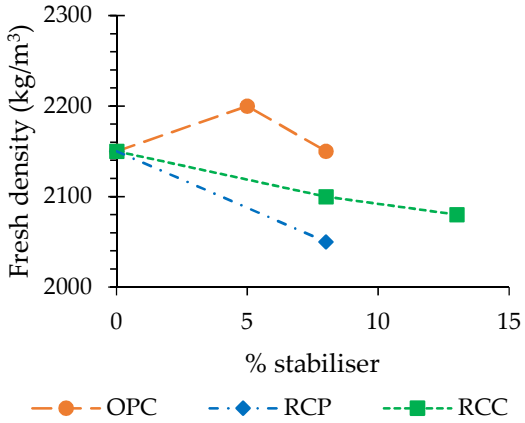

Figure 4 – Fresh density of CSEB with different incorporation percentages of stabiliser

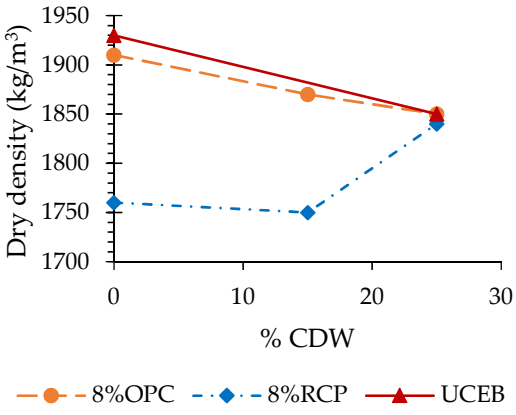

Figure 5 – Dry density of CSEB with different incorporation percentages of CDW

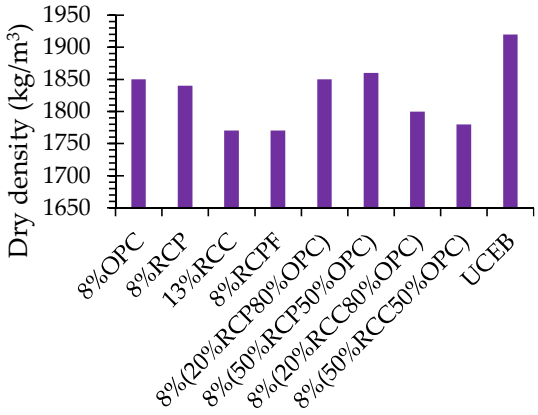

Figure 6 – Dry density of CSEB with 8% stabiliser and of UCEB

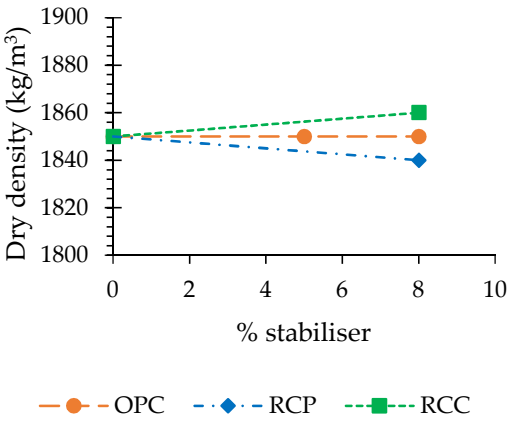

Figure 7 – Dry density of CSEB with different incorporation percentages of stabiliser

The ultrasonic pulse velocity was ascertained according to EN 12504-4 [7], resorting to a *Pundit* portable ultrasonic non-destructive tester (Figure 8). The time required for a pulse to cross through the CEB was ascertained with an accuracy up to 0.1 μs, using 54 kHz transducers positioned on two opposing CEB surfaces. The UPV corresponds to the ratio between the crossed length and the measured time.

This property ranged 1076-2494 m/s, having varied with the composition and moisture conditions (Table 2). As observed for the density, the UPV was also more affected by the total water content than by other composition parameters, such as the type and incorporation percentage of CDW and stabiliser (Figures 9-11). Furthermore, given that the CEB were mostly tested in laboratory conditions, their moisture content also varied, which also contributed to the results. This was especially clear when comparing the results of OPC CSEB subjected to air curing and wet curing. Nonetheless, the UPV tended to increase with the incorporation percentage of FRA (Figure 9) and of stabiliser (Figure 11). Besides contributing to the total porosity of the CEB, the FRA also assist in increasing their overall stiffness. Furthermore, essentially due to their higher total porosity and lower amount of hydration products, RC CSEB displayed lower UPV than OPC CSEB. Additionally, as expected, the UPV of the CEB was highest and lowest in saturated and dry conditions, respectively (Figure 12).

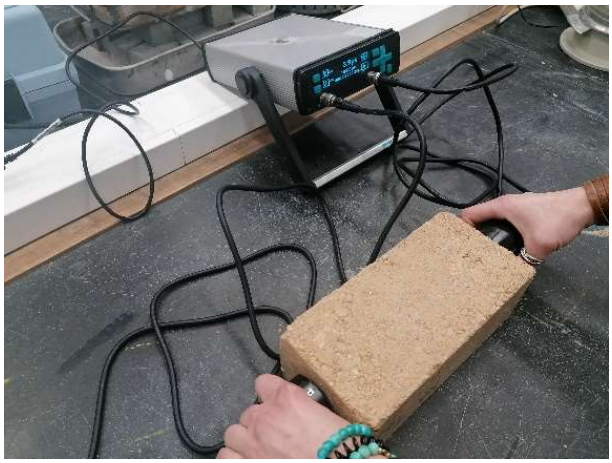

Figure 8 – Ultrasonic pulse velocity test

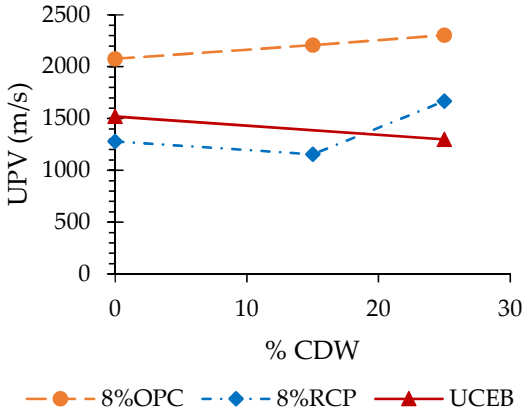

Figure 9 – Ultrasonic pulse velocity (UPV) of CSEB with different incorporation percentages of CDW in laboratory conditions

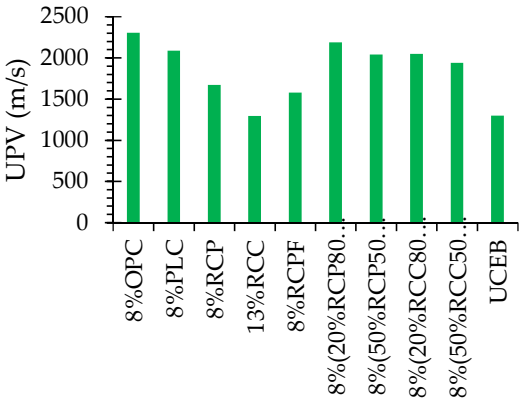

Figure 10 – Ultrasonic pulse velocity (UPV) of CSEB with 8% stabiliser and of UCEB in laboratory conditions

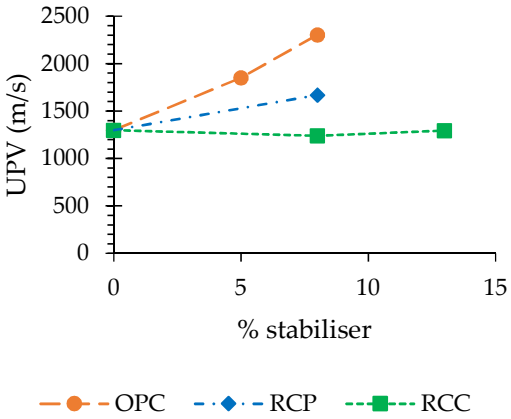

Figure 11 – Ultrasonic pulse velocity (UPV) of CSEB with different incorporation percentages of stabiliser in laboratory conditions

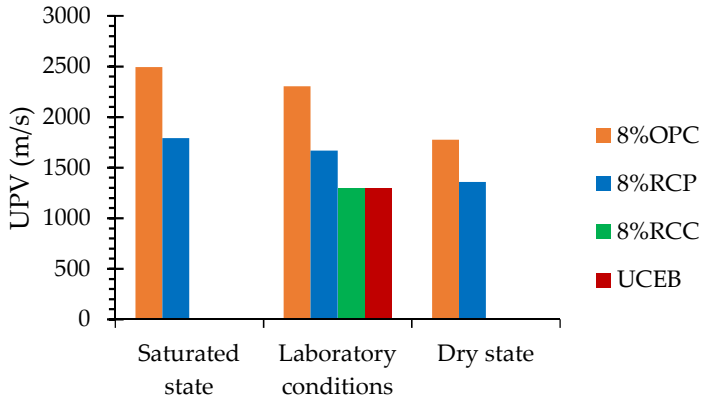

Figure 12 – Ultrasonic pulse velocity (UPV) of CSEB with 8%stabiliser and of UCEB with different moisture conditions

4. Mechanical performance and shrinkage

The compressive strength (Figure 13), splitting tensile strength (Figure 14) and bending tensile strength (Figure 15) were tested according to EN 772-1 [8], EN12390-6 [9] and EN 772-6 [10], respectively. These mechanical strength tests were performed using a *Tonipact* hydraulic press with a 3000 kN capacity and a load cell with 400 kN capacity, at a loading rate of about 0.5 kN/s. For the compressive strength test, the CEB were tested between two metal sheets on the perpendicular to the moulding surface (Figure 13). The tests were conducted at varying ages (3, 7 and 28 days) and for different moisture contents, whereas the splitting and bending tensile strengths were only tested at 28 days in laboratory conditions. The bending tensile strength test was performed by means of a three-point bending test at a constant velocity of 0.1 kN/s. The splitting tensile strength was carried out at the same velocity.

Figure 13 – Compressive strength test

Figure 14 – Splitting tensile strength test

Figure 15 – Bending tensile strength test

The compressive strength of the CEB varied between 0.41 and 19.24 MPa, depending on the composition, testing age and moisture conditions (Table 3). Overall, similarly to the other properties, the compressive strength was more affected by the total water content

than by other composition parameters (Figures 16-18). This made the analysis of the influence of the FRA incorporation percentage especially difficult, where no clear tendency was found (Figure 16). On the other hand, as expected, the compressive strength at 28 days increased with the incorporation of stabiliser, regardless of its type (Figure 18), demonstrating the potential of stabilisation of cementitious materials. Furthermore, the compressive strength of RC CSEB was lower than that of OPC or PLC CSEB, owed to their higher total porosity and lower development of hydration products, which promote cohesion between soil particles (Figure 18). This difference was more significant in RCC CSEB than in RCP CSEB, due to the fact that RCC is contaminated with inert aggregate particles from the concrete waste.

Nonetheless, the compressive strength of RC CSEB was significantly higher than that of UCEB (Figure 17), demonstrating its potential as a stabiliser for CSEB production.

Table 3 – Compressive strength (f_c) of CEB at different age and moisture contents

Designation	$f_{c3d,lab}$ (MPa)	$CV_{3d,lab}$ (%)	$fc_{7d,lab}$ (MPa)	$CV_{7d,lab}$ (%)	$f_{c28d,lab}$ (MPa)	$CV_{28d,lab}$ (%)	$f_{c28d,dry}$ (MPa)	$CV_{28d,dry}$ (%)	$f_{c28d,sat}$ (MPa)	$CV_{28d,sat}$ (%)
8OPC25CDW14W	4.46	9	5.88	16	9.04	8	18.75	12	6.19	8
8OPC25CDW13W	4.66	10	7.14	3	10.78	5	19.24	6	6.13	14
8OPC15CDW	5.73	4	-	-	9.99	6	-	-	-	-
8OPC	4.16	8	-	-	9.34	7	-	-	-	-
8OPC25CDWWC	-	-	-	-	7.67	7	-	-	-	-
5OPC25CDW	3.33	5	-	-	6.52	9	13.38	2	3.88	9
8PLC25CDW	-	-	-	-	6.79	7	-	-	-	-
8OPC25HQRS	3.65	8	7.34	8	8.73	5	-	-	-	-
8RCP25CDW	2.19	8	2.67	13	5.51	12	8.53	8	2.53	15
8(20%RCP+80%OPC)25CDW	5.49	2	-	-	10.43	17	-	-	-	-
8(50%RCP+50%OPC)25CDW	4.34	12	-	-	8.39	9	-	-	-	-
8RCPF25CDW	2.23	5	-	-	5.28	6	-	-	-	-
8RCC25CDW	1.03	11	1.25	27	2.35	37	-	-	-	-
13RCC25CDW	1.18	14	1.36	0	3.09	6	-	-	1.32	17
8(20%RCC80%OPC)25CDW	4.54	5	-	-	6.79	19	-	-	-	-
8(50%RCC50%OPC)25CDW	3.13	11	-	-	4.86	7	-	-	-	-
UCEB	0.59	18	1.27	16	2.72	9	-	-	-	-
UCEB25CDW	0.41	11	0.65	7	2.08	8	-	-	-	-

The compressive strength of CSEB and UCEB increased with the testing age (Figure 19). In the case of UCEB, this is essentially related to the drying of the specimens over time, due to their air curing. In the case of CSEB, besides the mentioned drying effect, this is also the result of hydration products development, which was higher in OPC CSEB than in RC CSEB.

Furthermore, though the compressive strength of both OPC and RC CSEB increased with the decrease of the moisture conditions, the increase rate was higher for OPC CSEB (Figure 20). Nonetheless, all CSEB complied with the minimum of 1 MPa recommended in HB 195 [11].

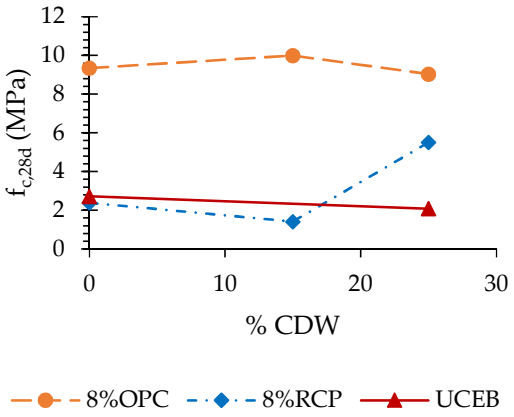

Figure 16 – Compressive strength at 28 days ($f_{c,28d}$) of CSEB with different incorporation percentages of CDW in laboratory conditions

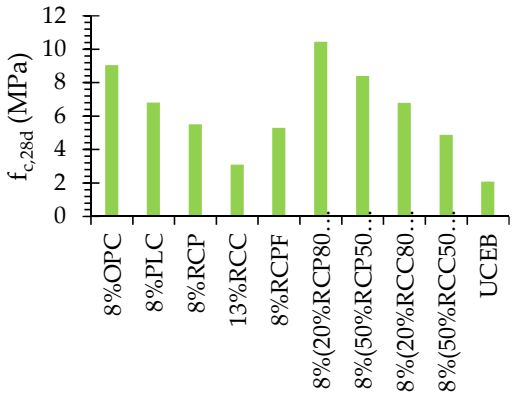

Figure 17 – Compressive strength at 28 days ($f_{c,28d}$) of CSEB with 8% stabiliser and of UCEB in laboratory conditions

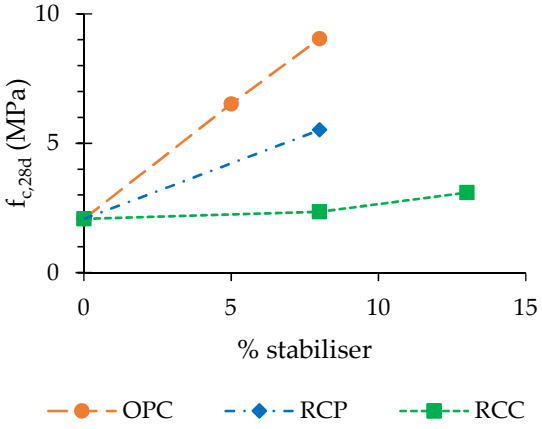

Figure 18 – Compressive strength at 28 days ($f_{c,28d}$) of CSEB with different incorporation percentages of stabiliser in laboratory conditions

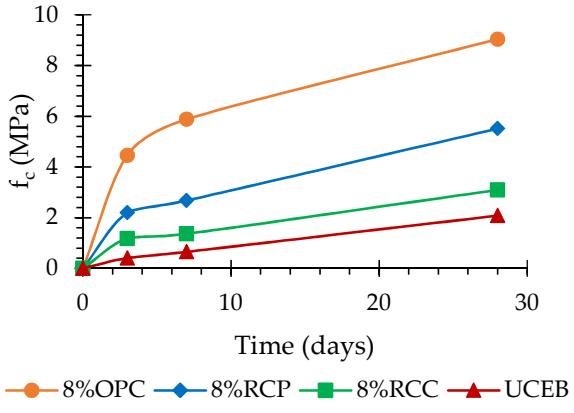

Figure 19 – Compressive strength (f_c) over time of CSEB with 8%stabiliser and of UCEB

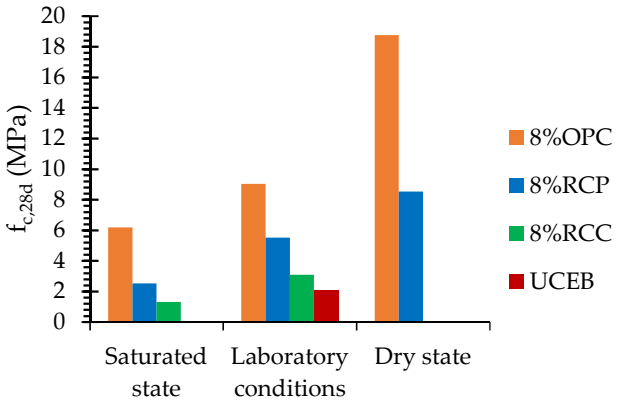

Figure 20 – Compressive strength at 28 days ($f_{c,28d}$) of CSEB with 8%stabiliser and of UCEB with different moisture conditions

The splitting and bending tensile strengths at 28 days of the CEB in laboratory conditions ranged 0.07-0.62 MPa and 0.28-1.25 MPa, respectively (Table 4). In general, these mechanical properties followed the same tendency observed for the compressive strength (Figures 21-25), having also been more influenced by the total water content than by the composition of the CEB. Consequently, the splitting tensile strength did not display a clear tendency with the incorporation of CDW (Figure 21).

Table 4 – Splitting tensile strength (f_{ctsp}), bending tensile strength (f_{ctr}) and modulus of elasticity (E_c) of CEB in laboratory conditions

Designation	f_{ctsp} (MPa)	CV_{fctsp} (%)	f_{ctr} (MPa)	CV_{fctr} (%)	E_c (GPa)	CV_{Ec} (%)
8OPC25CDW14W	0.59	8	1.16	6	4.33	7
8OPC25CDW13W	0.61	8	-	-	4.59	3
8OPC15CDW	0.51	22	-	-	-	-
8OPC	0.50	9	-	-	4.35	2
8OPC25CDWWC	0.62	13	1.53	8	-	-
5OPC25CDW	0.37	8	0.88	11	2.79	7
8PLC25CDW	-	-	1.04	9	-	-
8OPC25HQRS	0.34	6	-	-	-	-
8RCP25CDW	0.21	16	0.63	20	2.50	9
8(20%RCP+80%OPC)25CDW	0.42	11	1.25	10	-	-
8(50%RCP+50%OPC)25CDW	0.34	13	0.96	9	4.55	9
8RCPF25CDW	0.21	15	-	-	-	-
8RCC25CDW	0.07	13	0.28	3	-	-
UCEB	0.12	9	0.40	11	-	-
UCEB25CDW	0.07	4	0.29	32	0.97	4

However, these properties tended to increase with the incorporation percentage of stabiliser (Figures 23 and 25). Moreover, as expected, the splitting and bending tensile strengths of OPC and PLC CSEB were higher than those of RC CSEB, owed to their higher total porosity and lower amount of developed hydration products (Figures 22-25).

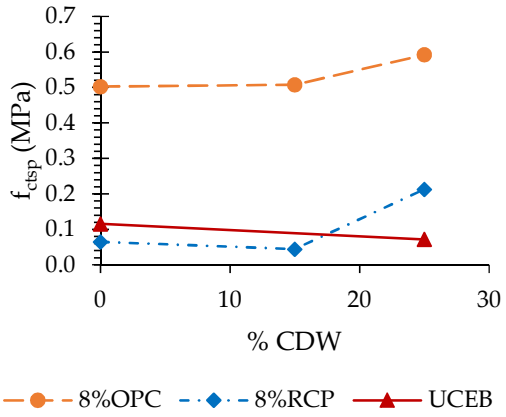

Figure 21 – Splitting tensile strength (f_{ctsp}) of CSEB with different incorporation percentages of CDW in laboratory conditions

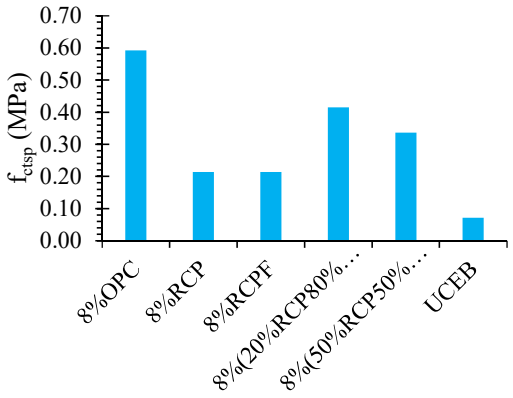

Figure 22 – Splitting tensile strength (f_{ctsp}) of CSEB with 8% stabiliser and of UCEB in laboratory conditions

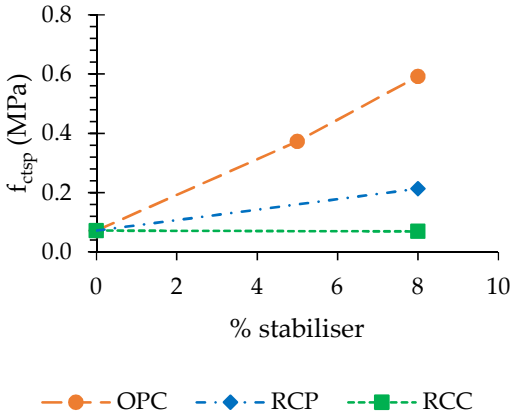

Figure 23 – Splitting tensile strength (f_{ctsp}) of CSEB with different incorporation percentages of stabiliser in laboratory conditions

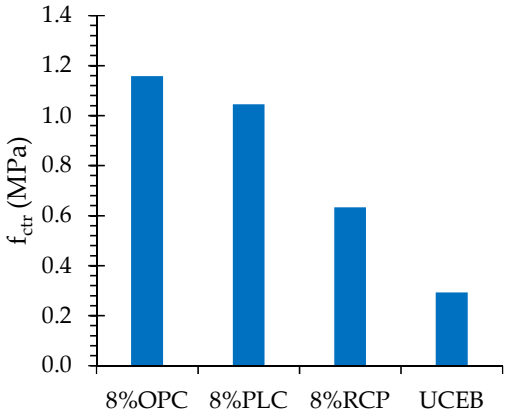

Figure 24 – Bending tensile strength (f_{ctr}) of CSEB with 8% stabiliser and of UCEB in laboratory conditions

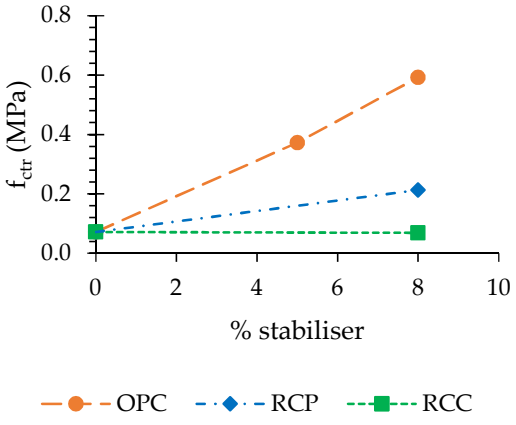

Figure 25 – Bending tensile strength (f_{ctr}) of CSEB with different incorporation percentages of stabiliser in laboratory conditions

The modulus of elasticity was determined resorting to an *Instron 5989* testing system with a 600kN load capacity and a high definition video extensometer composed of a *Sony XCG-500E* camera coupled with a *Fujifilm HF50SA-1* lens. First, the CEB were painted white and several black target points were marked on its surface at known distances (Figure 26a), for the video extensometer (Figure 26b) to be able to determine target point displacement more accurately (Figure 26c). Then, placed in the *Instron* testing system and the camera of the video extensometer adequately positioned (Figure 26b). The test comprised, at least, 8 cycles of loading (at about 0.5±0.01 MPa/s) and unloading, with an applied stress varying between 1 MPa and 1/3 of the estimated compressive strength at 28 days, until the difference between the average strain for consecutive cycles was lower than 10%.

The modulus of elasticity of the CEB varied between 0.97 and 4.55 GPa (Table 4). Overall, the RC CSEB presented lower modulus of elasticity than the OPC CSEB, which would be expected given their lower stiffness (Figures 27 and 28). On the other hand, the modulus of elasticity increased with the increase of the incorporation percentage of stabiliser (Figure 28), demonstrating the increase of rigidity of CEB with stabilisation.

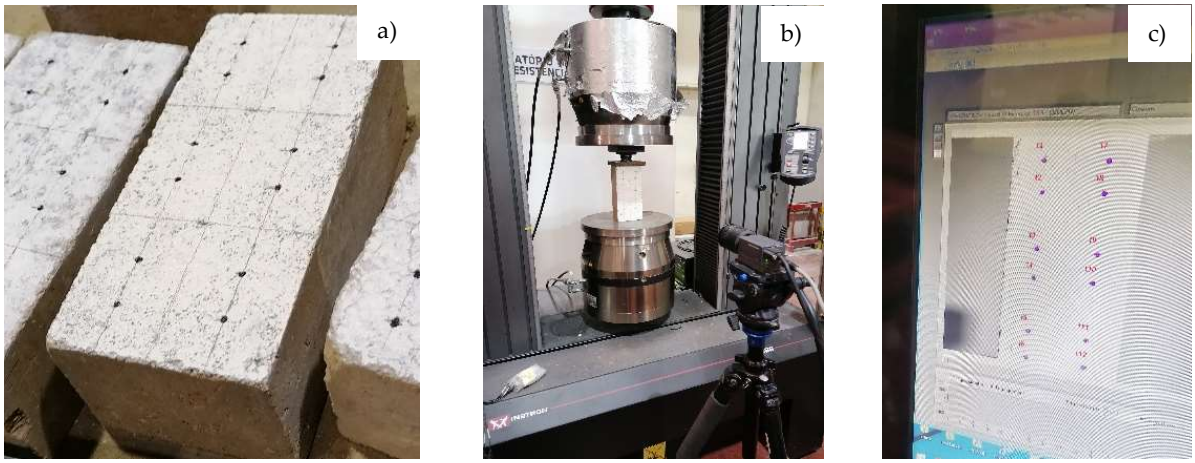

Figure 26 – Modulus of elasticity test: a) CEB preparation; b) test setup; c) digital target point identification

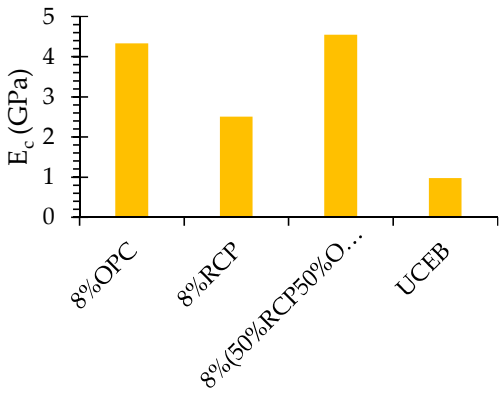

Figure 27 – Modulus of elasticity (E_c) of CSEB with 8% stabiliser and of UCEB in laboratory conditions

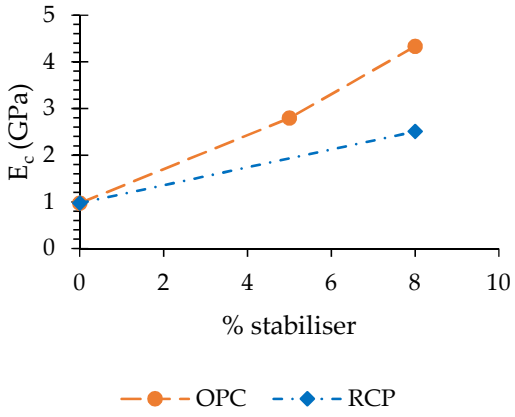

Figure 28 – Modulus of elasticity (E_c) of CSEB with different incorporation percentages of stabiliser in laboratory conditions

The pendular sclerometric test was carried out by determining the rebound number of a spring-driven steel hammer leaning against the CEB's surface (Figure 29).

The abrasion test was performed according to XP P13 901 [12] (Figure 30). First, the CEB was oven dried and weighted (M_{CEB}). Then, one of the CEB's surface (area A) was uniformly brushed with a 3kg steel brush, at a rate of one brush width per second for one minute. Afterwards, the released particles were carefully removed and the specimen was weighted (M_{ab}) and measured. The abrasion coefficient (CA) was determined through Eq. (2).

$$CA = \frac{A}{(M_{CEB} - M_{ab})} \quad (2)$$

Figure 29 – Pendular sclerometer test

Figure 30 – Abrasion test

The sclerometric index of the CEB in laboratory conditions varied between 12 and 42.5 (Table 5). Overall, this index was not relevantly influenced by the incorporation of FRA (Figure 31). On the other hand, as expected, the incorporation of RC or OPC improved the SI significantly, having increased with their incorporation percentage (Figures 32 and 33), demonstrating the contribution of stabilisers to the improvement of CSEB surface hardness.

The abrasion coefficient of the CEB in laboratory conditions ranged 2.96-38.6 cm^2/g (Table 5). In general, the incorporation of FRA did not affect the CA (Figure 34), whereas, as expected, the increase of the incorporation percentage of stabiliser led to higher CA (Figures 35 and 36), further validating the importance of stabilisers to CSEB performance.

Table 5 – Sclerometric index (SI) and abrasion coefficient (CA) of CEB in laboratory conditions

Designation	SI	CA (cm^2/g)
8OPC25CDW14W	27.5	38.6
8OPC25CDW13W	32.5	17.9
8OPC15CDW	33.0	13.6
8OPC	34.0	12.2
8OPC25CDWWC	31.5	15.4
5OPC25CDW	19.0	7.4
8OPC25HQRS	-	18.1
8RCP25CDW	27.5	15.5
8(20%RCP+80%OPC)25CDW	42.5	33.2
8(50%RCP+50%OPC)25CDW	34.5	28.9
8RCC25CDW	12.0	-
13RCC25CDW	20.3	-
8(20%RCC80%OPC)25CDW	-	6.3
8(50%RCC50%OPC)25CDW	-	11.5
UCEB	13.0	3.8
UCEB25CDW	13.0	4.3

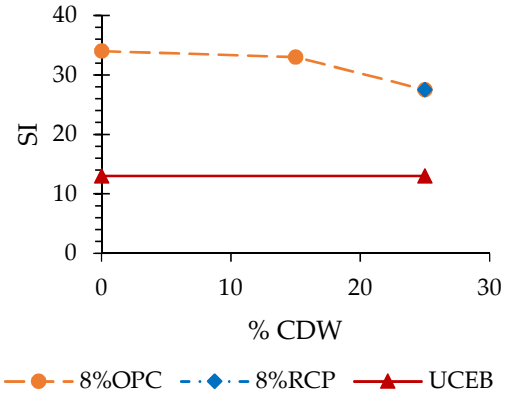

Figure 31 – Sclerometric index (SI) of CSEB with different incorporation percentages of CDW in laboratory conditions

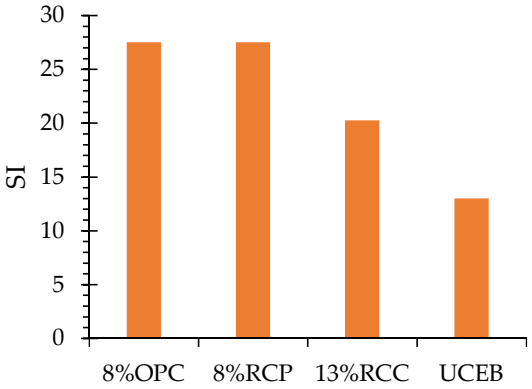

Figure 32 – Sclerometric index (SI) of CSEB with 8% stabiliser and of UCEB in laboratory conditions

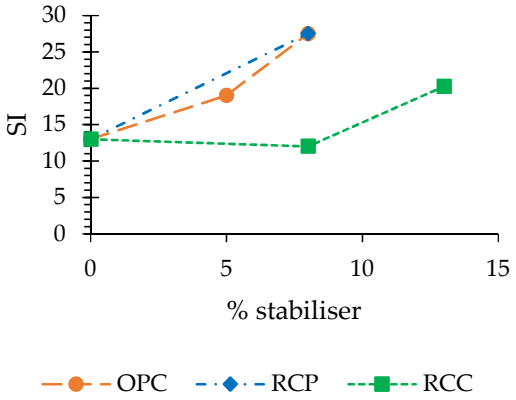

Figure 33 – Sclerometric index (SI) of CSEB with different incorporation percentages of stabiliser in laboratory conditions

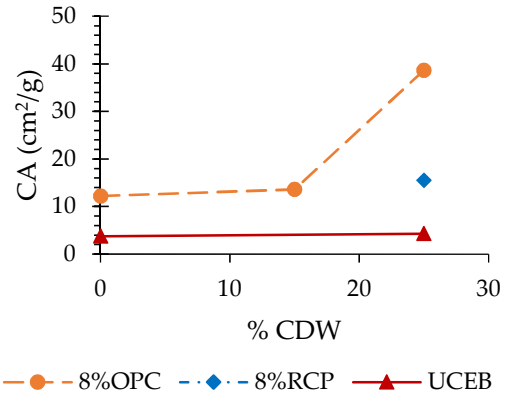

Figure 34 – Abrasion coefficient (CA) of CSEB with different incorporation percentages of CDW in laboratory conditions

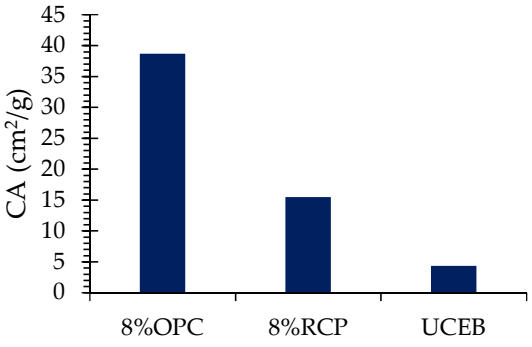

Figure 35 – Abrasion coefficient (CA) of CSEB with 8% stabiliser and of UCEB in laboratory conditions

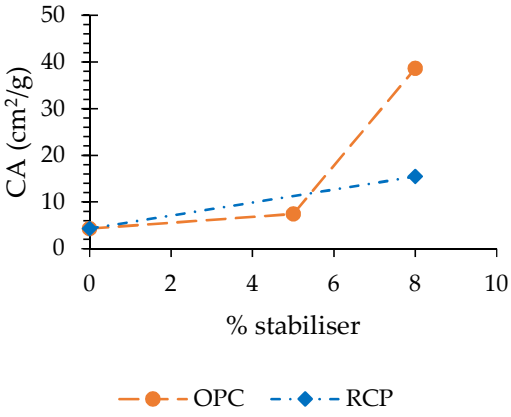

Figure 36 – Abrasion coefficient (CA) of CSEB with different incorporation percentages of stabiliser in laboratory conditions

The drying shrinkage was determined according to LNEC E 398 [13], using a *Demec* mechanical strain gauge with a precision of 1 μm and a gauge length of 5 mm (Figure 37b), over two pins 200mm apart glued to the CEB (Figure 37a). The CEB were kept in a controlled chamber with 20±2°C and 50±5% RH, over the testing period.

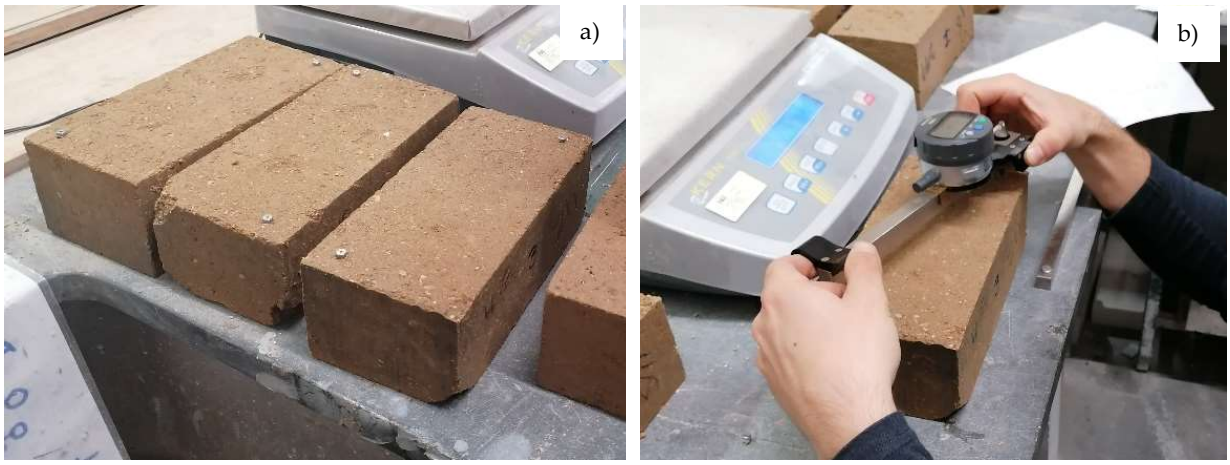

Figure 37 – Drying shrinkage test: a) CEB preparation; b) length measurement

The drying shrinkage of the CEB was measured up to 55 days (Figures 38 and 39). Both the weight loss and shrinkage seem to have stabilised before 30 days, independently of the CEB composition (Figures 38 and 39). The UCEB clearly displayed the highest weight loss and shrinkage, even though this CEB had the lowest total water content (Figures 38 and 39). Though a lower weight loss was not clear (Figure 38), the incorporation of FRA contributed to the reduction of the drying shrinkage (Figure 39), possibly due to a stiffness increase.

The drying shrinkage of RC CSEB was expected to be higher than that of OPC CSEB. However, though its weight loss was higher (Figure 38), that did not occur. In fact, when comparing CSEB with both OPC and RCP with the same total water content, the CSEB with the highest RCP content (50%) presented higher drying shrinkage than the other one (with 20%RCP) (Figure 39). This could be explained by the porous nature and lower stiffness of RC particles compared to those of OPC.

Furthermore, as expected, the increase of OPC incorporation led to the decrease of the weight loss and drying shrinkage, essentially owed to an overall stiffness increase and to a lower total porosity.

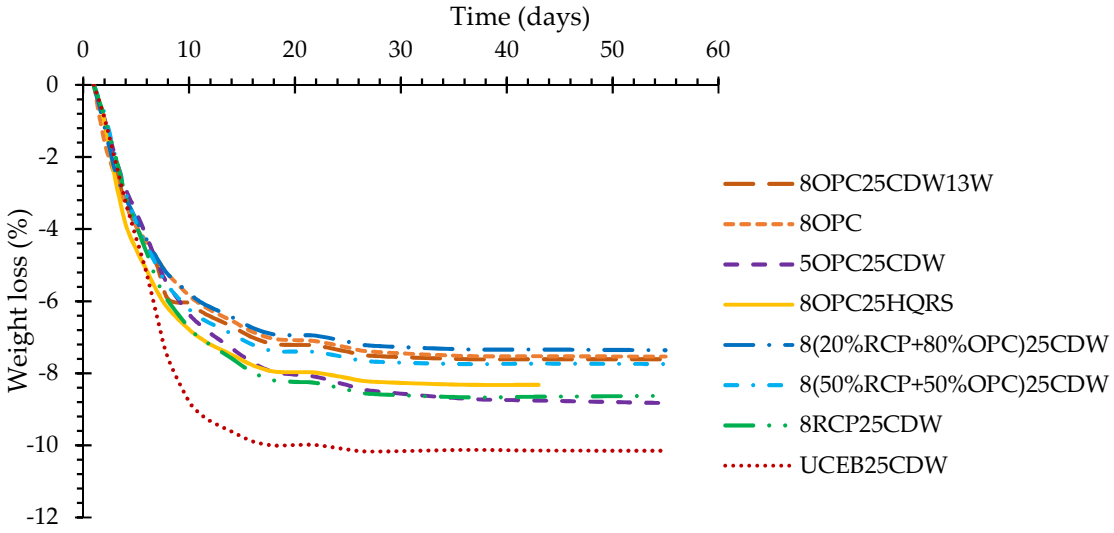

Figure 38 – Weight loss of CEB over time

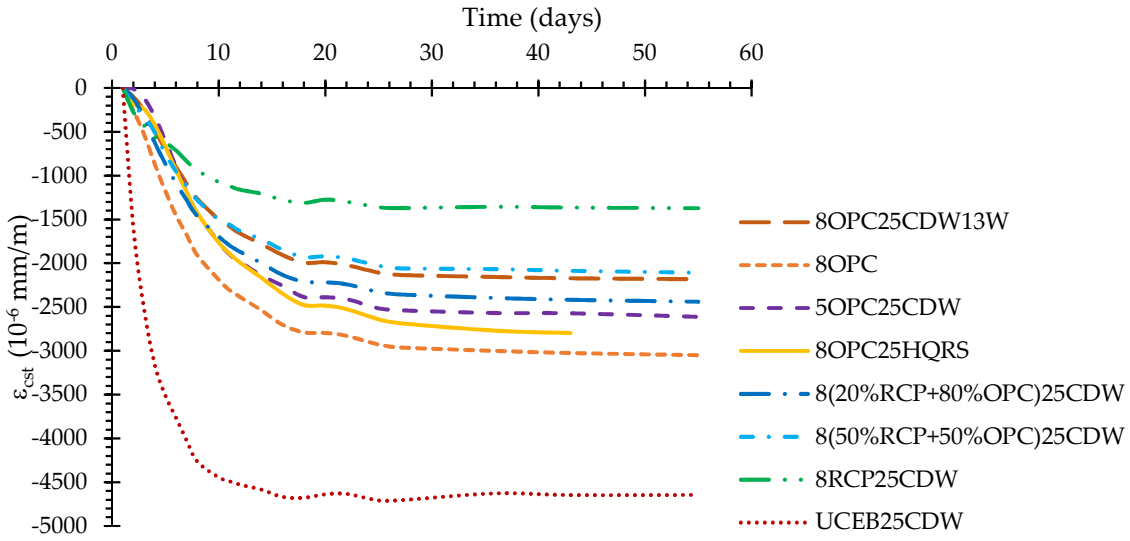

Figure 39 – Drying shrinkage of CEB over time

5. Thermal conductivity

The thermal conductivity of the CEB were determined through a modified transient pulse method (ASTM D5334 [14], ASTM D5930 [15]), resorting to an *ISOMET 2114* heat transfer analyser with a surface probe (Figure 40a), from *Applied Precision Enterprise*. The thermal conductivity results were converted to 10ºC, according to ISO/FDIS 10456 [16].

The CEB were tested under varying moisture conditions, namely in laboratory conditions and in the dry and saturated states (Figure 40b).

Figure 40 – Thermal conductivity test: a) ISOMET 2114; b) surface probe over plastic wrapped saturated surface dried CEB

The thermal conductivity of the CEB varied between 0.63 and 1.75 W/mK, depending on their composition and moisture conditions (Table 6). Regardless of the CEB composition, this property increased significantly with the moisture conditions (Figure 41), due to the fact that the thermal conductivity of water is about 25 times higher than that of air.

The dry thermal conductivity of the CEB ranged 0.63-0.8 W/mK, having depended essentially on their total porosity (Figure 42), rather than their composition.

Table 6 – Thermal conductivity at 10ºC ($\lambda_{10ºC}$) of CEB with different moisture conditions

Designation	$\lambda_{dry10ºC}$ (W/mK)	$\lambda_{lab10ºC}$ (W/mK)	$\lambda_{sat10ºC}$ (W/mK)
8OPC25CDW14W	0.69	0.87	1.55
8OPC25CDW13W	0.71	0.92	1.26
8OPC15CDW	0.76	0.93	1.69
8OPC	0.80	1.01	1.75
5OPC25CDW	0.63	0.69	1.47
8OPC25HQRS	0.64	0.75	1.48
8RCP25CDW	0.63	0.74	1.49
8(20%RCP+80%OPC)25CDW	0.75	-	1.62
8(50%RCP+50%OPC)25CDW	0.66	0.83	1.42
8RCPF25CDW	0.68	0.83	1.65
8RCC25CDW	0.66	0.71	1.69
13RCC25CDW	0.66	0.76	1.70
8(20%RCC80%OPC)25CDW	-	0.72	1.45
UCEB	0.84	1.04	-
UCEB25CDW	0.74	0.87	-

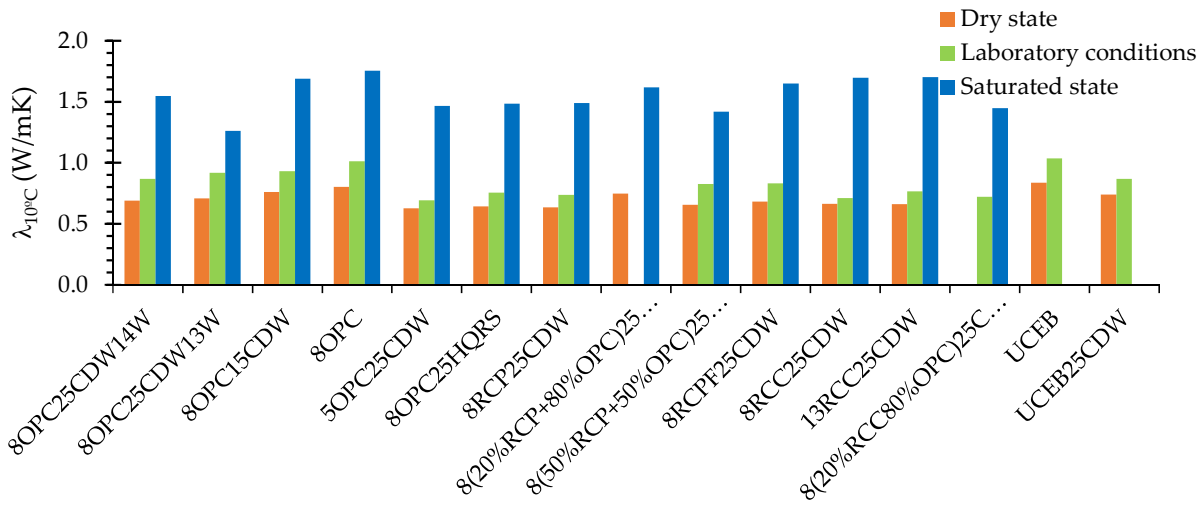

Figure 41 – Thermal conductivity at 10ºC ($\lambda_{10ºC}$) of CEB with different moisture conditions

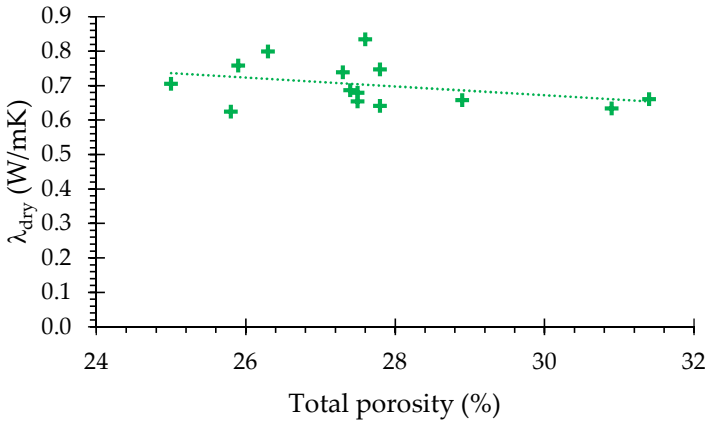

Figure 42 – Dry thermal conductivity at 10ºC (λ_{dry}) as a function of the estimated total porosity

6. Conclusions

This report showed the composition, production and physical and mechanical characterisation, shrinkage and thermal conductivity of CEB during Phase 1 of Task 1.

For this study, 18 compositions were chosen, considering different types and incorporation percentages of stabiliser (0-13%), types and incorporation percentages of FRA (0-25%), as well as water contents and types of curing (air curing, wet curing). The CEB were tested for fresh and dry density, ultrasonic pulse velocity, compressive

strength, splitting and bending tensile strength, modulus of elasticity, pendular sclerometer, abrasion, drying shrinkage and thermal conductivity.

Overall, the mechanical performance of the CEB was more influenced by the total water content than by other composition parameters. The mechanical behaviour of RC CSEB was inferior than that of OPC CSEB, especially that of RCC CSEB. Nonetheless, all properties showed a significant improvement with stabilisation, regardless of the type of stabiliser, and all CSEB complied with the minimum of 1 MPa recommended in HB 195. Additionally, the drying shrinkage also decreased with the incorporation of stabiliser. The thermal conductivity was essentially affected by the moisture content and the total porosity.

In sum, the viability of RC CSEB and its potential to be a more sustainable alterative to OPC CSEB was demonstrated.

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