Extended Abstract

Compressed earth blocks stabilised with recycled cement

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ABSTRACT

Earth construction is one of the oldest construction techniques, however, it has undergone many changes due to industrial evolution and the emergence of new materials. The compressed earth block (CEB) appears as a more industrializable method and accepted by society. In the CEB's stabilization is used, predominantly, the Portland cement (PC). However, the PC is associated with a high emission of CO_2, which removes the sustainable characteristic of the BTC, therefore this work this work presents the recycled cement as a more sustainable solution in its stabilization. This work studied the CEB in order to classify its properties and characteristics with the incorporation of PC, RC and without stabilizer. We can conclude that RC improves the properties of the CEB, achieving stronger and more durable solutions than the CEB without stabilisers and, as expected, the blocks stabilised with PC show better results than those stabilised with RC. Considering the environmental benefits promoted by recycled cement, there is a huge advantage in its use in CEB stabilisation.

Keywords: Compressed earth block, recycled cement, sustainability, ecological building.

1 INTRODUCTION

1.1 EARTH CONSTRUCTION

Earth is one of the oldest building materials, whose use dates to the first agricultural societies, between 12000 and 7000 B.C. Even today, it is possible to find earthen constructions that are more than 3000 years old, contradicting the view that this type of construction is necessarily associated with reduced durability. Currently, about 30 to 50% of the world population still lives in earth dwellings [1]. Although earth is an ancient building material, after the industrial revolution this material fell into disuse being progressively replaced by new materials, more advanced building techniques and more compatible with the modern needs of the population [2, 3]. Concrete and ceramic bricks have assumed greater importance, being more versatile and associated with greater strength, durability, and easier industrialization. In this sense, compressed earth blocks, especially when stabilized, have emerged as a promising approach for earth construction, based on the increase of their mechanical properties and durability and associated to a higher productivity and easier control of their production [4, 5, 6, 7].

The biggest problem associated with earth materials is their reduced integrity and high susceptibility to water [8, 9, 10]. In addition, the high variability of earth makes its generalized use difficult [11]. In this sense, stabilization allows significantly improving the mechanical strength, water resistance and reproducibility of earth materials [11, 12]. Cement is the most efficient and most used hydraulic binder in soil stabilization, allowing increasing the mechanical strength, volumetric stability, and durability of earth materials due to the binding action that cements soil particles [9, 13, 14]. However, it fails on the sustainability issue, since it is a material, whose production is associated with high CO_2 emissions, high consumption of natural raw materials and high thermal energy needs [15].

Have been developed, in this context, several studies that consider the incorporation of natural stabilizers, such as natural resins [16], industrial by-products, such as silica fume [17, 18], fly ash [19], slag [20] and other pozzolanic materials [21, 22]. The inclusion of these products has not been very successful, failing in terms of technical and economic feasibility. Is referred the reduced water durability in BTC with natural products [23] or their excessive loss of efficiency. In this context, was initiated a research line in the department of civil engineering, architecture, and geo-resources of Instituto Superior Técnico, which aims the production and development of recycled cements obtained from hardened concrete debris.

1.2 Recycled cement

This paper presents recycled cement as a more sustainable solution that boost the circular economy in the cement production industry. The recycled cement promotes the reuse of cementitious materials present in (construction and demolition waste) CDW, it reduces the exploitation of raw materials and waste disposal in landfills and its production allows a reduction of more than 60% of GHG (greenhouse gases) emissions into the atmosphere, being also associated with a lower energy consumption compared to Portland cement [24, 25]. The concept behind recycled cement lies in the separation of the cement fraction from the other components present in construction and demolition waste, reducing it to powder and finally subjecting it to thermal treatment at high temperatures [25].

Briefly, the production of recycled cement goes through the following steps:

- The separation of concrete constituents (aggregates, sands, steel, and cement paste) is one of the main challenges in the cement recycling process, however, the civil engineering department of IST has developed a procedure that has shown to be very promising [14, 24, 25]. Because it is not yet an economically viable method, it leads many researchers to resort to analysing only the cement paste.
- Grinding starts, in many studies, from cement paste or cementitious materials taken from CDWs. This step increases the fineness and the specific surface of the particles, factors that affect the reactivity, hydration rate and development of mechanical strength in these materials [26].
- The thermal reactivation is the most important process because it is responsible for recovering the properties of the hydrated cement [27]. This treatment is composed of three stages, these being the heating ramp, residence temperature in the kiln and the cooling rate [27, 28, 29].

Recycled cements confer a high specific surface area, high porosity, and strong binder tendency, factors that lead to a higher water requirement, contributing negatively to their properties [24]. Considering the need for increasingly ecological materials, recycled cement presents itself as a strong alternative in the stabilization of compressed earth blocks.

2 Experimental campaign

The experimental campaign was divided into four phases, which involved the characterization of the soil to be used; the production and characterization of the recycled cement; the production of the blocks; CEB's characterization tests.

2.1 SOIL CHARACTERIZATION

To characterize the soil, its consistency limits were determined according to the Portuguese Standard NP - 148 (1969), which involves the identification of the liquidity limit, plasticity limit and the calculation of the plasticity index. The optimum water content (OWC) was identified from the compaction test (Proctor) according to Standard D698 (2000). The determination of the OWC makes it possible to identify, approximately, the water content to use in the production of CEB, ensuring its maximum compactness [30].

In the granulometric analysis by wet sieving, the main objective is to obtain the granulometric curve for a given soil by identifying the percentages of clay, sand, and gravel. This test was performed according to LNEC Specification E-239 (1970). The density of the soil particles was also determined and performed according to Standard NP - 83 (1965).

The soil selected to produce the CEB was a clayey sand with 20.1% fine gravel, 48.4% sand and 31.5% fine material (clay and silt). The density of the soil particles is 2.85 g/cm3. The liquidity limit is 30% and the plasticity limit is 22%, corresponding to a plasticity index of 8%. The optimum water content (OWC) was 16% for a dry density of approximately 1800 kg/m3.

2.2 CHARACTERIZATION AND PRODUCTION OF RECYCLED CEMENT

To produce the original paste subject to recycling, as well as, for the production of the reference CEBs, was considered a type I 42.5 (CP) cement whose main characteristics are presented in Table 1.

To have greater control over the variables present in the study, the recycled cement was obtained directly from laboratory-produced pastes, without aggregate contamination. Initially, a cementitious paste was produced with w/c (relation water/cement) of 0.45, which was cured for another 120 days, to simulate an old one. The cement recycling process goes through four important stages (crushing, grinding, sieving and thermo-activation) referred to in section 1.2.

Table 1 - Portland cement properties.

Parameters		**CEM I 42,5 R**
Density (g/cm^3)		3,07
Specific surface (cm^2/g)		4 437,00
Residue on the 45 μm sieve (%)		6,80
Compressive strength in mortar (MPa)	1 day	16,80
	2 days	28,80
	7 days	43,60
	28 days	57,00
Expansion (mm)		1,00
SiO_2+Al_2O_3+Fe_2O_3 (%)		19,64 + 5,34 + 3,05
CaO + MgO (%)		62,80 + 1,80
CaO + MgO livre (%)		0,7 + 0,9
Setting time (min)	Initial	170
	Final	280

In the characterization of the recycled cement produced, were evaluated its physical and mechanical properties in the fresh and hardened state from the production and testing of recycled cement mortars. Were evaluated the setting time, density, spreading, flexural strength and compressive strength. The w/c ratio obtained for the normal consistency of the mortar was 0.73, and this value was used to produce the mortar to be tested. The specimens were produced according to the EN 1015-2 standard (1998). After the production of the mortar, the setting time, its density, spread and resistance were evaluated according to EN 196-3 (2017), EN 1015-6 (1998) and EN-1015-3 (2004), respectively.

As mentioned, the binders used for soil stabilization were recycled cement (RC) and cement Type I 42.5 (PC). Table 2 summarises the results concerning the characterisation of the recycled cement, namely regarding its chemical composition, density, mechanical strength, water requirement and setting time.

Table 2 – Properties of recycled cement (RC).

Parameters		Standards	RC
Absolute density [a] (g/cm3)			3,00
Compressive strength in mortars of normal consistency (MPa)	3 days	EN 196-1	9,8
	7 days		13,7
	28 days		17,3
Resistance to bending in mortars of normal consistency (MPa)	3 days	EN 196-1	0,96
	7 days		1,17
	28 days		1,22
SiO_2+Al_2O_3+Fe_2O_3 (%)		EN 196-2	19,14 + 5,13 + 3,00
CaO + MgO (%)		EN 196-2	60,79 + 1,77
CaO livre (%)		EN 451-1	13,94
Water requirement (w/c)		EN 196-3	0,73
Setting time (min)	Initial	EN 196-3	290
	Final		385

[a] Through helium pycnometer measurement

2.3 PRODUCTION OF CEB

For the characterisation of the blocks, were produced CEBs with dimensions of 220x105x60 mm. For the production of approximately 300 blocks, it was necessary about 1.4 m^3 of soil, 50 kg of Portland cement and 42 kg of recycled cement. Table 3 shows the amounts of soil, cement and water used for each composition.

Table 3 –Composition of the blocks produced.

Compositions	Soil [a] (%)	PC [b] (%)	CR [b] (%)	Water (%)	w/c
PC10	90	10	-	11,0	1,10
RC10	90	-	10	12,5	1,25
PC5	95	5	-	11,0	2,20
RC5	95	-	5	12,5	2,50
RC2PC8	90	2	8	11,0	1,10
RC5PC5	90	5	5	11,5	1,20
T	100	-	-	10,0	-

[a] percentage by mass of soil with 4% humidity; [b] percentage by dry weight of stabilizer

2.4 TESTS FOR CHARACTERIZATION OF CEB

The CEBs were characterized according to their mechanical strength (compressive, tensile by diametrical compression, flexural), modulus of elasticity, shrinkage, ultrasonic velocity, surface hardness, thermal conductivity, and water resistance (absorption by immersion, capillarity, at low pressure, permeability and accelerated erosion by water jet). Complementarily, the thermogravimetry and X-ray diffraction tests have been performed to assess the hydration capacity of the recycled cement when incorporated into the CEB.

CEB's density was evaluated in the fresh state (right after production) and in the hardened state, after 28 days of age. The fresh density allows indirect characterization of the compactness of the CEB, relating it with other properties in the hardened state.

The compressive strength test was based on the European standard for fired bricks EN 772-1 (2002). Specimens were tested at 3, 7, 28 and 90 days. The variation of CEB strength was also evaluated according to its water content, by testing saturated blocks, dried in an oven at 100ºC and conditioned in a laboratory environment.

In the flexural tensile strength test a punctual force was exerted at mid-span, which originates a tensile force on the lower surface of the specimen. The specimens used in this test were all conditioned in a laboratory environment and tested at 28 days.

The tensile strength by diametral compression was performed according to standard NP EN 12390-6 (2011), designed for testing concrete specimens, and adapted for CEB. The specimens were tested at 28 days conditioned in laboratory environment and in a humid chamber.

The modulus of elasticity, or Young's modulus, allows the evaluation of the stiffness of a given solid material. This test was based on an adaptation of specification E-397 (1993), designed for concrete specimens, using strain gauges. Was tested a block for each compositions with 10% incorporation of CP and RC.

The ultrasonic technique is a non-destructive test performed by means of ultrasonic waves, that allows detect possible internal defects in the materials. The test was based on the standard NP EN 12504-4 (2007), using the equipment Pundit Lab+ (Proceq). Two specimens were tested for different moisture contents at 28 days of age.

The main purpose of the pendulum sclerometer test is to measure the surface hardness of a material, based on the principle of reflection of an elastic mass, as described in ASTM C805 and EN 12504-2. Two blocks of each composition PC10, RC10, RC5PC5, RC2PC8 and T were tested.

The total shrinkage of the CEB was measured according to the procedure indicated in LNEC specification E-398 (1998). For this test three blocks of each of the PC10 and RC10 compositions were used. The variation in size was monitored for 21 days, obtaining records after 1, 2, 3, 4, 5, 6, 7, 8, 10, 13, 16, 20 days of age.

Thermal conductivity was measured based on ISO/FDIS 10456 (2007), and ISOMET 2114 (Applied Precision Enterprise) measuring equipment with a flat probe was used. Since thermal conductivity is affected by moisture content, the CEBs were tested for 3 levels of preconditioning: equilibrium with the laboratory environment; oven-dried at 100°C; saturated (immersed for more than 48 hours).

The water permeability test aims to determine the water permeability coefficient of the CEBs, which is a measure of the rate at which a given flow of water passes through an area of material. For each composition with 10% binder incorporation, three media were tested initially cured in a laboratory environment.

The immersion absorption test allows for an indirect evaluation of the blocks' open porosity, a property that is related to durability and water resistance. In this test the LNEC Specification E394 (1993) was adopted.

The capillary water absorption test was performed according to that suggested in the NTC 5324 (2004) standards. Were tested three specimens for each composition and preconditioned in laboratory environment or in a humid chamber.

The low-pressure water absorption test evaluates the permeability of the block surface when in contact with water and was performed according to EN 16302 (2013). For this test, the blocks were dried in a ventilated oven at a temperature of 100 ± 5ºC until constant mass.

The main objective of the accelerated erosion test is to determine the resistance to erosion of the CEB by means of a jet of water under pressure, simulating the action of heavy rain. Two specimens of compositions PC10, RC10, RC5PC5 and T were tested.

The thermogravimetry test was carried out with the support of the Laboratório Nacional de Engenharia Civil (LNEC) and the X-ray diffraction test was performed at the Mineralogy and Petrology Laboratory of IST.

3 Analysis and discussion of results

This chapter presents and discusses the results concerning the characterization of the compressed earth blocks (CEB).

Table 4 summarizes the average values obtained in each of the main properties analysed in this work for the various compositions studied.

3.1 Fresh state and composition of CEB

The fresh density is directly related to the degree of compaction. The compaction of the block is influenced not only by the water content of the moister, but also by the pressure exerted by the press itself. According to Rigassi (1985), the value of the ideal minimum fresh density is 1800 kg/m^3, recommending a value of 2200 kg/m^3. Table 4 also presents an estimate of the total porosity of the CEB in the hardened state, in the long term ($P_{T.mvf}$), based on the knowledge of the value of the fresh density mass. The total porosity varied between 36.4% and 41.7%, depending on the type of composition. After hydration, the lowest total porosity is reached in the mixture with 10% CP. In turn, the porosity estimation confirms the obtaining of CEB of lower compactness when CR is incorporated.

Table 4 – Summary of the average results obtained in the tests presented in chapter 3.

Properties	**PC10**	**RC10**	**RC2PC8**	**RC5PC5**	**PC5**	**RC5**	**T**
ρ_{fr} (kg/m^3)	1 991	1 871	1 954	1 870	1 950	1 879	2 026
$\rho_{se,28d}$ (kg/m^3)	1 732	1 629	1 689	1 646			1 794
$\rho_{lab,28d}$ (kg/m^3)	1 864	1 723	1 797	1 782	1 793	1 718	1 839
$\rho_{sat,28d}$ (kg/m^3)	2 080	1 913	1 973	1 950			
PT_{mvf} (%)	36,9	41,5	38,1	40,9	39,8	41,9	38,5
PT_{mvs} (%)	38,4	42,1	39,9	41,4			37,1
$f_{cm,lab,28d}$ (MPa)	5,92	4,44	5,12	4,99	3,34	2,45	2,33
$f_{cm,se,28d}$ (MPa)	7,43	6,53					
$f_{cm,sat,28d}$ (MPa)	4,32	2,45					
$f_{ctsp,lab,28d}$ (MPa)	0,51	0,44	0,44	0,56	0,36	0,20	0,25
$f_{ctmr,lab,28d}$ (MPa)	0,97	0,93	1,02	1,17	0,69	0,52	0,41
E (GPa)	2,77	2,10					
V_{us} (m/s)	1 714	1 414	1 584	1 472	1 147	1 094	1 104
ε_{cst} ($\times 10^{-6}$)	- 39	- 52					
IE_{PT}	33,5	24,3	29,5	28,8			15,5
λ_m (W/m°C)	0,57	0,42	0,51	0,42	0,44	0,39	0,56
K_w (x 10^{-7} m/s)	2,80	6,10	4,20	4,80			
$AbsI_{48h}$ (%m)	19,0	22,0	19,9	21,5			
Abs_{48h} (%v)	32,9	35,8	33,5	35,3			
$AbsC_{72h}$ (g/cm^2)	4,19	7,07	6,19	5,17			
$C_{abp,5min}$ (kg/m^2.s)	0,008	0,012	0,016	0,011			
$I_{erosão}$	Accepted	Accepted		Accepted			Rejected

Fresh density (ρ_{fr}), dry density (ρ_{se}), density in laboratory environment (ρ_{lab}), saturated density (ρ_{sat}), total porosity calculated from fresh density (PT_{mvf}), total porosity calculated from dry density (PT_{mvs}), average compressive strength (f_{cm}), average flexural tensile strength (f_{ctmr}), tensile strength by diametral compression (f_{ctsp}), modulus of elasticity (E), ultrasonic propagation velocity (V_{us}), shrinkage index (ε_{cst}), sclerometer index (IE_{PT}), average thermal conductivity (λ_m), water permeability (K_w), water absorption by immersion (AbsI), water absorption by capillarity (AbsC), coefficient of water absorption at low pressure (C_{abp}), erosion index ($I_{erosão}$).

3.2 Density in the hardened state

The density in the hardened state of CEB is a non-destructive test and allows indirectly measuring the quality and compactness of the blocks. Table 4 shows the density values obtained at 28 days (for CEB cured in laboratory environment), as well as the dry and saturated density values.

As expected, there is a reduction in density with the decrease of stabilizer in the moisture content. It was also found that in the case of non-stabilized blocks, they disintegrated after immersion in water and it was not possible to determine their saturated density. It is highlighted the importance of stabilization in the water resistance of CEB. In this sense, the CR proved to be efficient in stabilizing the CEB, demonstrating to have adequate hydraulic properties.

Considering the relationship between density in the hardened state, at 28 days, and total porosity, it confirms a high correlation between these properties (Figure 1). It was achieved the highest compactness in the block with 10% of PC.

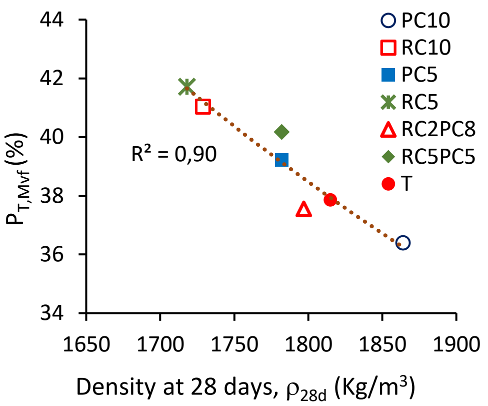

Figure 1 - Ratio between density mass at 28 days (ρ_{28d}) and total porosity, $P_{T;Mvf}$.

3.3 Thermogravimetric Analysis (TG) and X-ray Diffraction (DRX)

In the thermogravimetric analysis it is found that the curves were very similar for the two types 9 (PC10 and RC10) suggesting the presence of the same type of phases and associated with similar hydration states.

In the X-ray diffraction analysis, it is possible to identify the minerals in greater abundance in the composition. The block with CR is distinguished by the presence of higher calcite content, being in line with the higher content of carbonate products in these materials [31].

It is important to mention that during the production of the blocks there was a greater phenomenon of leaching and appearance of lime spots in the blocks with CR. This should be associated with the fact that the CR initially presents a free lime content higher than 10%, which is extinguished during the mixing process and becomes immediately available during the first moments of hydration.

3.4 Mechanical strength

This subchapter presents the characteristics of the mechanical strength of CEB, namely in terms of compressive and tensile strength.

The compressive strength, depending on the curing conditions, age of test and composition of the CEB, varied between 0.83 MPa and 7.43 MPa (Table 4), which highlights the importance of these factors.

The dry blocks show better behaviour compared to the saturated blocks. It can be observed that the stabilized blocks saw their strength reduced to values of 58% (CP) and 38% (CR) of their strength in the dry state, when they were immersed in water. It can be admitted that the higher the water content, the lower the compressive strength. It should also be noted that there is a decrease in resistance according to the amount and type of binder used, as presented in Figure 2. The CP shows a better behaviour in relation to the RC.

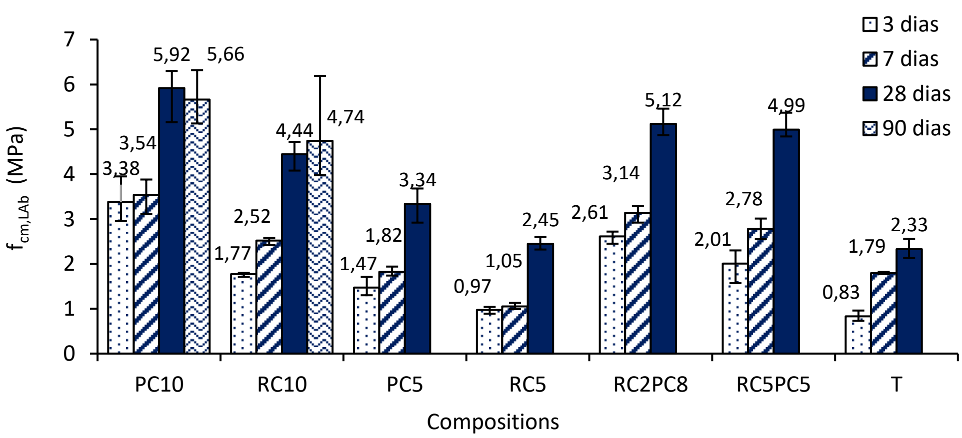

Figure 2 - Compressive strength of CEB at 3, 7, 28 and 90 days under laboratory conditions.

Table 4 shows the average values obtained for the flexural tensile and diametral compression tensile tests. As expected, and as this is a material from the ceramics group, the tensile strength was reduced, being about 8-10% and 16-23% of the compressive strength. As observed in concrete tests, flexural strength tends to be double that obtained by diametral compression, since the latter benefits from the effect of greater plasticity and stress redistribution in the tensioned region [32]. As observed for compressive strength, flexural strength was more affected by the binder content than by the type of binder. It is noteworthy the fact that for 10% binder content, there were little significant differences, less than 15% between CEB with CP and CR.

The structural efficiency relates the compressive strength to the density of a given material, aiming for solutions with higher strength associated with low density. As expected, the CEB in the dry state present the highest values of structural efficiency, since they are associated with a decrease in their density mass and a significant increase in their mechanical strength. In turn, the CEB tested in saturated conditions present significant reductions in their structural efficiency, to values below 50% of that obtained in dry conditions. This aspect is relevant and highlights the enormous sensitivity in terms of the structural behaviour of CEB, even when stabilized. Corroborating the compressive strength results, the binder content had a significant influence on the increase in structural efficiency. The influence of the binder type was most important when the CEBs were tested saturated, with little significant differences under dry conditions. Even under laboratory conditions, the slight decrease in density in CR stabilized blocks (7%) compared to CP stabilized ones, is not compensated by the greater reduction in compressive strength (25%).

3.4 Modulus of elasticity

The modulus of elasticity obtained for the PC10 and RC10 blocks was 2.77 and 2.1 GPa, respectively. The low stiffness of these materials derives mainly from the high porosity and poor consolidation between the soil particles. The CEB with CP, associated with lower total porosity and higher mechanical strength, showed a 32% higher modulus of elasticity than the BTC with CR.

3.5 Ultrasound Propagation Velocity

In this work, the ultrasound velocity varied between 1100 and 1700 m/s in the laboratory cured CEBs, reaching about 2100 m/s when saturated. In general, the ultrasonic velocity was able to distinguish the CEB of better quality, with lower V_{us} values in the CEB not stabilized or with poor dosages of binder. A high correlation between V_{us} and compressive strength is observed, since these two properties are essentially affected by porosity and bonding between particles.

3.6 Sclerometer Index

The pendulum sclerometer was also considered for non-destructive evaluation of the quality of CEBs. As with the ultrasonic velocity, there is a good correlation between the IE_{PT} and the compressive strength, despite the small number of results, with the sclerometer test efficiently allowing the distinction of CEB of different qualities.

3.7 Thermal Conductivity

The thermal conductivity in saturated CEB was more than double that obtained in the dry state, resulting in an important depreciation of its thermal insulation capacity. This factor proved to be more relevant than the changes imposed in the composition and type of stabilization of the mixtures [7, 33]. For a given type of curing, non-stabilized CEB and CP-stabilized CEB showed higher thermal conductivity than CR-stabilized blocks (13 to 36%), which should be linked with the differences in total porosity achieved in the various compositions.

3.8 Shrinkage

In the present study, shrinkage was evaluated for the BTC produced with 10% of CR or CP. The blocks were subjected to an environment with average temperatures of 28.5 °C and relative humidity of 62.5 % for 21 days. The shrinkage of PC10 and RC10 measured at 21 days corresponds to only about 0.053 and 0.039 mm/m, respectively.

3.9 Durability

The durability of CEBs was essentially evaluated in terms of their water transport properties and resistance to water. In this sense, tests for water absorption by immersion, capillarity and at low pressure, as well as permeability and resistance to erosion by water jetting were performed.

Water absorption by immersion was only measured for the stabilized CEB, since the non-stabilized blocks, after contact with water, progressively lost their cohesion. In the remaining cases, the various blocks analysed did not undergo apparent deterioration during the 48-hour period in which they were submerged. The absorption occurred essentially during the first 24 hours, with a slight increase until 48 hours. In general, an increasing trend of increasing absorption is observed with the percentage of CR incorporation. The absorption in the CEBs with CR was up to 14% higher than in the CEBs with CP only.

As observed in the immersion absorption test, in the capillary absorption (Figure 3) there is also an increase in the rate of absorption and volume of water absorbed at 72 hours in the CEB with 10% of CR, with the compositions with partial replacement of CP by CR presenting intermediate values of those of the CEB with only CP. As discussed, this should be related to the higher overall porosity of the blocks with CR (associated with higher w/c ratio and higher paste volume), as well as the higher porosity refinement of these compositions, for identical porosity level [34].

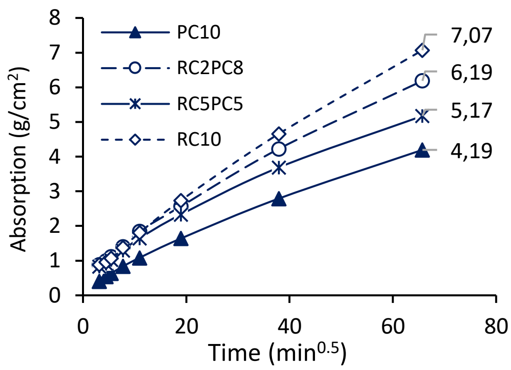

Figure 3 - Evolution of water absorption by capillarity.

In turn, after the capillary absorption test, the CEBs with 10% CP and 10% CR showed an absorption at 72 hours that, converted to mass percentage, corresponded to 59% and 92% of the immersion absorption, and converting to volume, to 52% and 81% of the total porosity. This suggests a significant reduction in absorption resistance when replacing CP with CR. Thus, it seems to be clear that BTC with CR are associated with a higher level of porosity and pore connectivity.

The permeability coefficient (K_w) obtained in this work ranged from 2.8 x 10^{-7} m/s, for blocks stabilized with 10% CPN, to 6.1 x 10^{-7} m/s for blocks stabilized with 10% CR.

Corroborating the general trend observed in the other tests, it was found that the permeability increased with increasing percentage of incorporation of CR replacing PC. In this case, the permeability coefficient was about 2 times higher in CEB with 10% CR than with only the same content of PC. Once again, the permeability results follow the trend of total porosity, demonstrating the importance of this parameter in the durability of CEBs.

The stabilized CEB showed good durability against erosion by heavy rain, regardless of the type of binder. All specimens showed negligible erosion. Even increasing the water jet pressure to double (1 bar) and then to 5 times the initial pressure (2.5 bar), the erosion was not very significant after 1 hour of testing. In turn, the non-stabilized blocks were fully eroded after only 7 minutes of testing for the lowest pressure of 0.5 bar.

4 Conclusions

This chapter presents the main conclusions archived after analysing the obtained results in this work, which had as main objective the production and characterization of compressed earth blocks (CEB) stabilized with the incorporation of recycled cement (RC).

- The high optimum water content (OWC) of the soil used (16%) stands out, with consequences on the final compactness of the CEB.
- The parallel performance of thermogravimetric and X-ray diffraction tests, on the CEB produced with recycled cement, also confirmed the adequate hydration capacity of the recycled cement, appearing as a binder or an active addition with high potential for the alternative production of more eco-efficient cementitious composition.
- The CEB produced in this work presented a fresh density mass between about 1850 and 2000 kg/m3, for total porosities of 36-42%, slightly above that reported by other authors, which suggests a lower optimization of the compositions for the soil type and compaction action used.
- The incorporation of only 5% of stabilizer, CR or CP, was not very effective, and these compositions were preferred for the remaining characterization tests. The incorporation of 10% CR was effective in increasing the strength of CEB at 28 days by about two times compared to non-stabilized CEB.
- As expected, the same trend observed in compressive strength tests was verified in tensile and flexural tests, namely regarding the influence of the type and content of stabilizer.
- The ultrasonic propagation test was able to distinguish CEB of different quality, obtaining lower values for lower binder contents and higher percentages of RC incorporation, which led to CEB of higher total porosity and lower stiffness.
- The modulus of elasticity in CEB with CP was 32% higher than in CEB with CR, reaching in both cases modulus of elasticity of the order of magnitude of that reported in current CEB.
- CEBs with CP achieved lower long-term shrinkage values than CEBs with CR, also indicating earlier stabilization of this property. This results from the larger paste volume and lower stiffness of the CR-containing CEBs.
- The thermal conductivity was significantly affected by the moisture content of the CEBs, being more than twice as high in saturated than in dry blocks. The lowest thermal conductivity was achieved in CEBs with CR, associated with lower density mass and higher total porosity, being up to 26% lower than in CEBs with equal CP content.
- In general, the immersion absorption, capillary absorption rate and low-pressure absorption increased with the percentage of CR incorporation. More than 90% of the porosity of the BTCs was accessible to water, revealing the high interconnectivity of their porous structure.
- In general, it can be concluded that, in the present study, it was possible to achieve durable solutions with incorporation of only 180 kg/m^3 of CP or CR. In the case of adopting CR, and simplistically assuming a potential reduction of more than 60% in the level of CO_2 emissions (reduction of thermal energy and avoided decarbonation), the solution achieved would be comparable to that of using only 70 kg/m^3 of cement.

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