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Influence of Water-Repellent Admixtures on the Water-Resistance of Unstabilized and Stabilized Compressed Earth Blocks

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Abstract: The low durability of water action has been the main issue of earth construction since ancient times. In this way, sustainable solutions are needed to improve the earthen building materials water-resistance performance without significantly changing their appearance and eco-friendly nature. This study aims at characterizing the water-resistance of compressed earth blocks (CEB) produced with or without different types of colorless water-repellent admixtures. To this end, different types of unstabilized and 8% cement-stabilized CEB were protected with two post-surface treatments, namely a silane-siloxane based surface water-repellent (SWR) and a natural linseed oil (LO), as well as one olein based integral water-repellent (IWR). Unprotected reference CEB were also considered for comparison purposes. More sustainable CEB were produced with 20% replacement of earth by recycling waste building materials. The CEB were tested in terms of compressive and flexural strength, capillary water absorption, immersion absorption, water permeability, low-pressure water absorption, and water erosion resistance from drip and spray tests. The influence of the moisture content on the compressive strength was also analysed. The cement-stabilization and water-repellent treatments were able to overcome the non-water-resistant nature of unstabilized CEB. In general, the best performance was attained with SWR, followed by IWR. The LO was less effective in reducing the long-term absorption but was able to protect unstabilized CEB from light rainfall simulated conditions. Under severe water erosion, the surface treatments were less effective, but water penetration was reduced up to near 40%. The mechanical strength, total porosity, water permeability and immersion absorption were not significantly affected by water-repellent products. Moreover, the mechanical strength reduction of stabilized CEB after saturation was about 30%, regardless of the water-repellent treatment. The main contribution of water-repellent admixtures occurred in all properties involving capillary absorption.

Keywords: compressed earth blocks; water-resistance; surface water-repellent; integral water-repellent; recycled aggregate; cement-stabilization.

1. INTRODUCTION

Earth has been used in construction since ancient times, and it is estimated that almost one-third of the world population still live in earth buildings [1-4]. However, with the industrial revolution and the subsequent emergence of new materials and robust multi-story buildings, earth was progressively discarded from construction [5,6].

Recently, following the major priority of more sustainable construction, earth resurged as a more eco-friendly building material [7-9]. The high abundance, low cost of production and raw materials, insulation properties, ability to regulate humidity in the building environment, reduced environmental impact and low embodied energy are some of the main reasons for the renewed interest in earth construction [1,7,10-13]. Moreover, some of the existing earth buildings repressent historical heritage and have to be preserved [14]. Therefore, earth construction is the focus of current research.

Compressed earth blocks (CEB), resulting from the high-pressure compaction of damp soil, aim to efficiently use unfired earth as a building material, showing improved mechanical behaviour, less variability and higher productivity than traditional adobe bricks and rammed earth [3,15]. However, like other earth building materials, the main issue of CEB is their modest mechanical strength, low integrity and, most of all, high water vulnerability [7,16]. Due to their hygroscopic and hydrophilic nature, water penetration is heightened in earth building materials and severe degradation may occur in rainy climates [17,18]. Moreover, damp walls lead to problems of staining, mold growth, cryptoflorescences, and reduction of insulation properties [12, 15,18]. This makes these materials impractical under current unsheltered, exposed conditions.

Earth stabilization is a common practice for the production of CEB with improved mechanical strength and durability [15,19]. Due to its low cost, versatility, and good bonding properties, cement is the most used stabilizer in CEB [4,10]. Other stabilizers, like bitumen, acrylic and latex emulsions are less efficient [18]. However, cement stabilization reduces the sustainability character of CEB, with a significant increase of carbon dioxide (CO_2) emissions. Alternatively, the stabilization with other more eco-friendly binders, such as granulated blast furnace slag [20] or Lime and coal ash waste blends [21] have been investigated. In addition, aiming the production of more environmentally friendly CEB, few studies have also considered the use

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of recycled aggregates (RA) as a partial earth replacement [15,22,23].

Various studies have been published concerning the mechanical and physical characterization of unstabilized and cement-stabilized CEB. The mechanical strength of CEB essentially depends on the earth composition, compaction pressure, type and content of stabilizer, and moisture conditions 25 [9-11,24]. Covering common cement contents of 4-10% by weight of dry soil, the compressive strength of stabilized CEB is reported to be over 2 times higher than that of unstabilized CEB [1,15]. However, stabilized CEB is also affected by the moisture content, showing signifycant mechanical strength reduction in direct contact with water [25]. Walker [26] verified a compressive strength reduction of about 40% between dry and saturated CEB stabilized with 5–10% cement. Based on an extensive experimental work, Bogas *et al*. [15] suggested the following compressive strength reduction coefficients for cement-stabilized CEB with more than 4% cement: 0.75 for environmental relative humidity (RH) lower than 65%; 0.65 for RH seasonally exceeding 85%; 0.35 for immersion conditions.

Despite being one of the major concerns in earth construction, fewer studies have been published regarding the durability and water-resistance of CEB [27]. Moreover, there is a lack of unified guidance tests regarding water-resistance [3,28]. These properties are usually accessed by water absorption and accelerated erosion and wearing tests, such as the most common drip and spray tests, simulating light and heavy rainfall, respectively [3,27-28]. Among accelerated tests, the spry test has been considered the most representative of natural aging [27]. However, results greatly depend on the test setup, which has not been standardized yet. Therefore, these tests should be mostly considered for comparison purposes, assessing the relative behaviour of distinct compositions.

As mentioned, one major challenge is mitigating the effect of moisture ingress and consequent decay of earth building materials properties. This is especially relevant because uncoated earth solutions are usually considered due to their recognized aesthetical value [12].

Despite the benefits of stabilization, the hydrophobic nature of cement cannot prevent water penetration and percolation within stabilized earth materials. Therefore, hydrophobic or water-repellent admixtures may play a relevant role against the water effect in earth construction. These admixtures should minimize the water movement in capillaries without affecting vapour permeability and surface appearance [14,18]. Taking this into account, the water-resistance of earth materials may be essentially improved by two approaches: protective post-surface water-repellent treatments over the hardened earth surface; incorporation of integral water-repellent admixtures (IWR) in the fresh earth mixture [14].

Non-film forming vapour-permeable surface water-repellents are commonly silicon-based products. These products with relatively small molecular sizes can effectively penetrate the capillaries and react with the substrate. In the presence of water, reactive silanes and siloxanes form a nanomolecular polysiloxane hydrophobic lining within capillaries, depressing the surface tension [18].

Conventional IWR are oil or fat-based admixtures. The hydrophobic nature is achieved by the active oil or fat molecule reacting with calcium present in the earth mixture to form insoluble calcium stearates or oleates, providing water-repellent properties [18]. The long-term performance of these products may progressively decrease due to ultraviolet (UV) radiation and natural weathering. Recent silicone-based IWR admixtures, providing strong siloxane links with capillary walls, allow a better long-term performance of these products [18].

In order to increase the water-resistance of unstabilized and stabilized earth materials, few studies have been developed considering the application of water-repellent admixtures. Some literature reports the use of natural surface treatments, essentially in Africa and South America, such as animal and vegetable oils, but without scientific studies of their ability [29-30]. Mattone [31] achieved lower water absorption in earth-gypsum plasters protected with corn oil.

Călătan *et al*. [30] studied the water absorption under wind pressure of adobe bricks protected with different surface treatments (beeswax dissolved in oil, linseed oil, animal fat). All surface treatments were effective in reducing the water penetration, but the linseed oil revealed the best performance. Moreover, the beeswax reduced the water vapour permeability and the animal fat showed low long-term durability.

The water-resistance of rammed earth walls coated with earth plasters containing three types of synthetic admixtures and three surface treatments (Silcon nanoparticles, silane-siloxane, beeswax) was analysed by Stazi *et al*. [14]. The water-resistance was measured in terms of water absorption and water erosion. The best performance was obtained for the silane-siloxane product. Similar findings were obtained by Holub *et al*. [12], taking into account four types of surface hydrophobic coatings (silane-siloxane based, transparent varnish, aqua lackspray, silicon oil spray) over rammed earth.

Akinyemi *et al*. [32] reported low water absorption, of only 3.3%, in cement-lime stabilized adobe bricks produced with termite clay and 0.05 kg/m^3 of a silane-siloxane-based powdery IWR, usually adopted in conventional concrete. About 80% reduction of water absorption in rammed earth is reported when 0.05% by weight of earth of a silicone-based IWR was added [18].

According to Luna [33], the incorporation of acrylic admixtures in earth plasters improves the abrasion resistance, but reduces the vapour water permeability and increases the capillarity absorption. Bahobail [34] reports the reduction of water permeability in adobe bricks produced with the incorporation of 0.1-0.2% soap during mixing.

To the best of the author’s knowledge, the consideration of water-repellent products in CEB has been barely explored. Cañola *et al*. [17] reported the reduction of capillary absorption in cement-stabilized CEB produced with incorporation of cold asphalt emulsion, with up to 38% reduction in the mechanical strength and no information regarding water or vapour permeability. In sum, there is still insufficient knowledge regarding the water-resistance improvement of CEB, without significantly affecting their appearance and eco-efficiency nature, and further research must be addressed.

This study aims at analysing the influence of commercially available synthetic and natural water-repellent admixtures in the water-resistance behaviour of unstabilized and cement-stabilized CEB. To this end, seven types of CEB, with or without 8% cement stabilization, were unprotected (reference) or protected with one olein based IWR and two surface treatments (silane-siloxane based admixture or linseed oil). To reduce the environmental impact, CEB were produced with partial replacement of earth by recycled fine aggregates from construction debris. The various CEB were tested in terms of their mechanical strength (compressive, flexural) and water-resistance properties (capillary absorption, immersion absorption, water permeability, low-pressure water absorption, water erosion by drip and spray tests). Moreover, the influence of the moisture content on the compressive strength was analysed. Therefore, this study contributes to improve the scientific knowledge on the water-resistance enhancement of CEB, increasing their viability and application range in the construction industry.

2. MATERIALS AND METHODS

2.1. Materials

CEB was produced with one earth collected from *Herdade da Adua in Montemor-o-novo, Portugal*. The liquid limit (w_L), plastic limit (w_p) and plasticity index (IP), determined according to NP143 [35], as well as the grain size fraction (d_i/D_i), density (ρ_d) and optimum moisture content ($w_{opt,p}$), according to the standard effort proctor test [36], are indicated in Table **1**. From literature, indicative w_L of 20-50 and w_P of 2-30 are recommended for unstabilized CEB production [37-38]. A slightly lower w_L was determined in this study.

Moreover, to reduce the depletion of natural resources and waste disposal, a more sustainable CEB was produced with the incorporation of recycled aggregates (RA) from construction debris as partial earth replacement. The main properties of RA, essentially composed of cement-based materials, fired clay bricks and natural stone, are indicated in Table **1**. For the stabilized blocks, 8% of cement type I 42.5 (EN 197-1 2011) was used by weight of dry earth, based on a previous work of the authors [15].

In order to analyse the influence of different water-repellent products in stabilized and unstabilized compressed earth blocks (CEB), the following commercially

Table 1: Earth and Recycled Aggregate Properties

Earth Composition	Grain Size Fraction, di/Di (%)				Atterberg Limits			$w_{opt,p}$ (%)	ρ_d (kg/m^3)
	Gravel (2/60)	Sand (0.075/2)	Clay/Silt (0/0.075)	Extra fine (0/0.075)	w_L	w_p	IP		
Earth	3.4	61.2	35.4	-	18	15	3	12.5	2655
RA	14.9	67.6	-	17.5	-	-	-	-	2645

available admixtures were adopted: surface water-repellent (SWR) with the commercial designation *Hydrofuge HS*; natural linseed oil water-repellent (LO); integral water-repellent (IWR) with the commercial designation *Toupydro*.

The SWR is a silane-siloxane-based admixture specified for most inorganic porous surfaces, depressing the capillary suction without significantly affecting the water-vapor permeability. Basically, this product penetrates into the capillaries and reacts with the substrate via siloxane bonding, providing water-repellent properties [12]. The recommended dosage of SWR, depending on the support porosity, is 0.12-1 l/m^2.

The IWR was tailored for cement-based materials and consists of an olein-based admixture that reacts with the calcium hydroxides in fresh cement paste by means of a saponification process, which contributes to the reduction of the capillary suction. This product was only applied in stabilized blocks since it needs the presence of alkalis from cement to react. As discussed in the introduction, better long-term behaviour may be obtained with silicone-based IWR.

Both SWR and IWR were supplied by *LaboPortugal*. The surface water-repellent SWR was sprayed at the CEB surfaces, 21 days after their production, while the waterproofing admixture IWR was directly incorporated in the fresh mix during mixing. The more ecological natural LO was applied by brush onto a clean and dry hardened surface.

2.2. Composition and Production of CEB

Following a previous study [15] and after trial tests, reference unstabilized (UCEB) and stabilized CEB (SCEB) were produced with 20% weight replacement of earth with RA. The incorporation of RA allows the reduction of the total amount of clay and silt to 28%, which is within the 20-45% range suggested in the literature [37-38].

The mixing water was 9.5% (SCEB) and 10% (SCEB with IWR and UCEB) by weight of solids (earth, RA and cement, when used). This was defined based on the Proctor test results (Table **1**) and adjusted with trial drop tests [39], which indicates the minimum water content of the dry mix to form a cohesive ball. The mixing water was near the low limit of the 10-13% range reported in the literature [40,41].

As mentioned, 8% of cement by weight of dry earth and RA was adopted in stabilized CEB, corresponding to a w/c ratio of 1.2. This is within the common range of 6-10% by weight of the dry mix reported in literature [6,8,9,15,41,42]. The incorporation of 8% cement is thus a good compromise between sustainability and durability. The same amount of stabilizer was considered in other studies [8,10,15,40].

In total, seven types of CEB were produced, taking into account non-treated and treated UCEB and SCEB with different water-repellents (Table **2**). Mixes are denominated according to their stabilized condition (“UCEB” or “SCEB”) followed by the designation of the water-repellent treatment (“LO”, “SWR”, “IWR”), when used. According to the supplier recommendation, the amount of IWR was 0.10 % by weight of cement.

The CEB were locally produced near the region of earth extraction, using a mobile *Terstaram* press with a maximum pressure capacity of about 3.6 MPa (Figure **1**). After the soil pulverization in an electric mill, the earth was first dry mixed with cement and then the water was slowly added with a hose. These compo-

Table 2: Composition of CEB

Mixture Composition	Earth	RA	Cement	Watter Repellent Product		
	(% Dry Weight of Earth + RA)			IWR	SWR	LO
UCEB	80	20	0			
UCEBSWR			0		X	
UCEBLO			0			X
SCEB			8			
SCEBSWR			8		X	
SCEBLO			8			X
SCEBIWR			8	0.1%*		

* by weight of cement.

nents were mixed for about 3 minutes in a common tilting drum mixer. The effective water content and w/c ratio were controlled from weight measurements of wet and oven-dried samples. When used, the integral water-repellent (IWR) was first dispersed in part of the mixing water and, then, sprayed to the mix after the remaining components.

Figure 1: CEB pressing and molding.

Then, the mix was poured on the press, and blocks of about 220x105x60 mm^3 were manually produced (Figure **1**). Finally, the blocks were weighted and covered with a plastic film for 7 days, during which they were sprinkled with water once a day, except those that were unstabilized. After 7 days, the CEB were transported to the lab, where they were stored until tested at variable environmental conditions (19-26 ºC and 55-75% relative humidity).

2.3. Experimental Tests

For each composition, three blocks were tested for density, compressive strength, flexural strength, immersion absorption, capillary absorption, low-pressure water absorption (Karsten pipe method) and spray test. In addition, three half blocks of about 110x105x60 mm^3 were tested for permeability and drip tests. Some tests were adapted from literature or guidance documents, because of the absence of universally well-recognized earth normalization. Before testing, some blocks were also subjected to immersion in water for 48 hours (Sat) to analyse the reduction of their mechanical properties after wetting.

2.3.1. Density and Mechanical Strength

The hardened dry and wet density were determined based on EN 772-13 [43]. The compressive strength tests were carried out according to NTC 5324 [44]. After curing, the blocks were cut in half perpendicularly to their largest dimension and then directly placed one on top of another, with the cut surfaces facing opposite ways. No mortar was applied between half blocks. The 28 days compressive strength was tested with a loading rate of about 0.05 MPa/s for different moisture content (saturated or in equilibration with lab conditions). CEB were tested perpendicularly to their batching and compaction surface (Figure **2**).

The flexural strength was carried out at 28 days according to the 3-point bending test of EN 772-6 [45], (Figure **2**). The specimens were laid over metallic cylinders 180 mm apart and tested with a loading rate of 0.1 kN/s. Depending on tested property and CEB load-bearing capacity, load cells of 100 kN and 200 kN capacity were adopted in mechanical tests.

2.3.2. Water-Resistance Characterization

The capillary absorption was tested based on EN 772-11 [46]. This test determines the water absorption along time when one CEB surface is immersed in 5 ± 1 mm of water. In order to guarantee enough water absorption height, tests were carried out through the smaller molded face, as shown in Figure **3**. The mass increase was measured at 10, 20, 30, and 60 minutes and 2, 6, 24, and 72 hours after the initial contact with water. During the test, the specimens were covered with a bell-glass in order to avoid water evaporation. The specimens were oven-dried for 28 days so that constant mass is achieved before testing. The absorp-

Figure 2: Compressive strength test from two half blocks (left) and flexural strength by the 3-point bending test (right).

Figure 3: capillary water absorption (left), water permeability (middle), and low-pressure water absorption (right) tests.

tion coefficient, $C_{abs,20m\text{-}6h}$, was calculated from the slope of the linear regression of the absorption curve, between √20 min and √6 hours.

Water absorption by immersion was tested according to NBR 8492 [47], which provides an estimation of the CEB open porosity. Blocks were first immersed for 48 hours and then oven-dried until constant weight was obtained. The water absorption corresponds to the mass of saturated CEB relative to their dry weight. Blocks were tested after capillary tests.

Water permeability was measured at 90 days according to the constant head procedure adopted by Bogas *et al*. [15] (Figure **3**). Basically, this test measures the amount of water per unit area and time that drains out of a porous material due to the imposition of a constant pressure head of 100 kPa in the top of each specimen. The permeability coefficient, K_w, is given by Eq. (1), based on Darcy's first law and assuming a laminar flow. In Eq. (1), Q is the water flow (m^3/s), l is the CEB thickness (m), A is the exposed area of water penetration (m^2) and ΔP the pressure head (mwc). The water flow through the specimen corresponds to the time needed to water-fill a known volume. Before testing, blocks were sealed with epoxy resin, except in two opposite circles of ϕ50 mm whereby the water flow was allowed. In addition, rubber rings were placed on the top and bottom to prevent any leakage of water. Unwanted capillary absorption was avoided by previously immersing each specimen for 5 days in water. Unstabilized CEBs were not tested.

$$K_w = \frac{Q.l}{A.\Delta P} \tag{1}$$

The water absorption under low-pressure was measured using the Karsten pipe method (Figure **3**) according to Rilem [48]. Basically, it determines the time required for a circular surface area (ϕ27 mm) to absorb 4 cl of water. Intermediate measurements were also recorded every 30-60 seconds. The water column in the graduated tube is 98 mm in height, exerting a low-pressure of about 961 Pa, which mimics soft raindrops hitting the wall with a static wind velocity of 140 km/h [49]. The water absorbed per unit of surface area is determined along time (g/cm^2), as well as the water absorption coefficient, $C_{abs,k,4cl}$, which corresponds to the slope of the absorption curve between 0 and the time required to absorb 4 cl of water.

Drip and spray tests were carried out at 90 days according to NZS 4298 [39], aiming to simulate light and heavy rainfall impact, respectively. At the end of these tests, first, the depth of erosion (DE) is recorded, then the blocks are sawn across the region of maximum water impact and the moisture penetration (DM) is also measured.

The drip test measures the erosion caused by the dripping of 100 ml of water drops, falling from a height of 400 mm, after 20 to 60 minutes. The exposed surface of the cut-half block, which coincides with that exposed in real conditions, is set at a 27º angle (Figure **4**). Finally, the DE and DM are determined with the aid of a caliper. For this test, CEBs are classified in NZS 4298 [39] based on the following erosion indexes (EI): 0<DE<5 (EI2); 5≤DE<10 (EI3); 10≤DE<15 (EI4); 15≤ DE (EI5). Blocks may be accepted for DE <15 mm and DM<block thickness.

The spray test measures the erosion promoted by a 50 kPa pressurized jet of water over a ϕ100 mm circular region of the exposed block surface (Figure **4**). The water jet nozzle is distanced 470 mm from the block. According to Heathcote [50] and Cid-Falceto *et al*. [3], a Fulljet GG-1550 nozzle was fitted to simulate heavy rainfall. The DE is measured every 15 minutes for one hour or until the block is eroded in all depth. The final DE and DM are recorded and the erosion rate per hour (DE/hour) is determined. Based on NZS 4298 [39] and taking into account the maximum 60 mm

Figure 4: Drip test simulating soft rain (left) and spray test simulating heavy rain (right).

thickness of CEB, the following erosion indexes (EI) were considered in spray tests: 0≤DE<10 (EI1); 10≤DE<25 (EI2); 25≤DE<45 (EI3); 45≤DE<60 (EI4); 60≤DE (EI5). Blocks should not be accepted for DE>60 mm.

3. RESULTS AND DISCUSSION

The average results of wet, ρ_w, and dry, ρ_d, density, 28 days compressive strength, $f_{cm,28d}$, 28 days flexural strength, $f_{ctm,28d}$, 2 hours (abs_{2h}) and 72 hours (abs_{72h}) capillary water absorption, coefficient of capillarity absorption, $C_{abs,20m\text{-}6h}$, long-term immersion water absorption, abs_{im}, low-pressure absorption coefficient, $C_{abs,k,4cl}$, and water permeability coefficient, K_w, are presented in Table **3**. The coefficients of variation (CV) obtained for each property are also presented in Table **3**. Compressive strength results are presented for CEB with intermediate moisture content under the laboratory environment (lab) and in saturated conditions (Sat), when applicable. The results concerning the erosion drip and spray tests are presented in 3.7 and 3.8, respectively.

3.1. Density and Total Porosity

As expected, unstabilized blocks presented the lowest wet and dry density, because the density of cement is about 15% higher than that of earth and RA. The SCEB wet density was over 2000 kg/m^3 (Table **3**), which is within the 1900-2200 kg/m^3 reported by other authors [15,24,25,41]. The difference between the 28 days dry density of UCSB and SCSB increased in relation to fresh density, because of the further contribution of cement hydration. No significant differences in density were observed between stabilized CEB with or without IWR. The marginally higher fresh and dry density of SCEBIWR should be related to the higher compactness attained in these blocks produced with slightly higher water content (see 2.2).

The total CEB porosity, P_T, may be estimated from their wet density (Table **3**) and composition (Table **2**), corresponding to the sum of the amount of air voids produced during mixing and the volume of voids left by the water not used for cement hydration, in case of stabilized CSEB. Assuming that the bounding water from hydration was about 16% (for a hydration level

Table 3: Average Results of Studied CEB from Physical and Mechanical Tests

Mixture Composition	Density		Mechanical Strength				Capilary Absorption			Immersion Absorption		Low-Pressure Absorption	Permeability	
	ρ_w (kg/m^3)	ρ_d (kg/m^3)	$f_{cm,28d}$ (MPa)	CV (%)	$f_{ctm,28d}$ (MPa)	CV (%)	abs_{2h} (g/cm^2)	abs_{72h} (g/cm^2)	$C_{abs,20m\text{-}6h}$ (g/cm^2.min$^{0.5}$)	abs_{im} (g/cm^2)	CV (%)	$C_{abs,k,4cl}$ (g/m^2.s)	K_w (x10^{-7} m^2/s)	CV (%)
UCEB	1967	1798	1.98/1.56*	2.4/13.3	0.37	13.5	2.83	-	-			232.9	-	-
UCEBSWR			1.65/1.33*	6.9/31.2	0.45	10.2	0.48	-	-			1.94	-	-
UCEBLO			-	-	-	-	1.87	5.20	0.199	12.9	7	7.76	-	-
SCEB	2035	1827	6.22/4.40*	9.9/10.5	1.80	10.2	1.29	3.69	0.080	13.3	12	11.64	2.61	3.5
SCEBSWR			6.72/4.20*	3.9/26.9	1.91	6.8	0.22	0.55	0.009	13.7	9	0.97	2.22	16.8
SCEBLO			-	-	-	-	0.65	3.39	0.058	12.3	4	7.76	-	-
SCEBIWR	2084	1897	6.77/4.96*	0.3/12.1	1.63	2.5	0.70	2.25	0.038	11.8	4	5.82	2.52	2.7

* Results for specimens tested in saturated conditions (Sat).

lower than 80%), the estimated P_T is about 33% and 25% for UCSEB and SCSEB, respectively. Gel pores of hydrated cement paste are not included in P_T. Similar P_T values of 32.7% were reported by Namango [42] for UCEB subjected to identical compaction pressure (2-4 MPa). According to Bogas *et al*. [15], the P_T is more affected by the compaction pressure than by the cement hydration and CEB composition. No significant differences of P_T were estimated for CSEB with or without IWR.

3.2. Mechanical Strength

As shown in Table **3** and Figure **5**, the stabilized CEB attained 3.1-3.4 times higher compressive strength than those unstabilized, which is in line with other results reported in literature [3,51]. This difference is much higher than that found in total porosity, showing the relevant role of cement in improving the earth consolidation. As expected, no significant differences were observed when IWR or SWR were adopted in CEB production, which indicates that these products did not affect the mechanical strength.

Contrary to SCEB, unstabilized blocks were not able to withstand the immersion conditions and totally lost their cohesion after coming in direct contact with water. The compressive strength of stabilized blocks tested in saturation conditions was about 30% lower than that in lab conditions, with no significant differrences between SCEB with and without IWR. This phenomenon may be explained by the pore water pressure and liquefaction of the unstabilized portion of clayed particles, which leads to their loss of cohesion [15,25]. Moreover, this suggests that water-repellent products had no relevant influence on earth consolidation and resistance against liquid water.

Based on an extensive experimental campaign, Bogas *et al*. [15] suggested a penalized coefficient of about 0.46 for saturated CEB stabilized with more than 4% cement when compared to the same blocks in a lab environment with RH over 65%. On the other hand, Riza *et al*. [6] reported a 35% reduction. A lower reduction was found in this study. Noteworthy is the significant increase of the coefficient of variation when CEB was saturated (Table **3**). Nevertheless, stabilized CEBs were able to meet the threshold limit of 2 MPa for saturated CEB, as recommended in NBR 8492 [47].

The difference between stabilized and unstabilized CEB was accentuated in flexural strength, in which results were up to 5 times higher in SCEB. Similar differences were obtained by Morel and Pkla [52] and Bogas *et al*. [15], also for 8% cement stabilized CEB, but with different block geometry. This underlines the great influence of stabilization in the tensile strength. Once more, no significant differences were found between SCEB with or without water-repellent admixtures. However, contrary to compressive strength, the tensile strength in SCEBIWR was slightly lower than that of SCEB. Despite the test variability, this may be explained by the possible higher water content in SCEBIWR of higher density. In fact, if higher moisture gradients are developed in SCEBIWR specimens, the global flexural strength is reduced due to the increase of the tensile stress in extreme fibers. Noteworthy is the high coefficient of variation, which is up to 14%, in unstabilized blocks of very low tensile strength.

3.3. Capillary Water Absorption

As mentioned, unstabilized CEBs are not water-resistant, and lose their cohesion properties in direct contact with water. Therefore, these samples were not

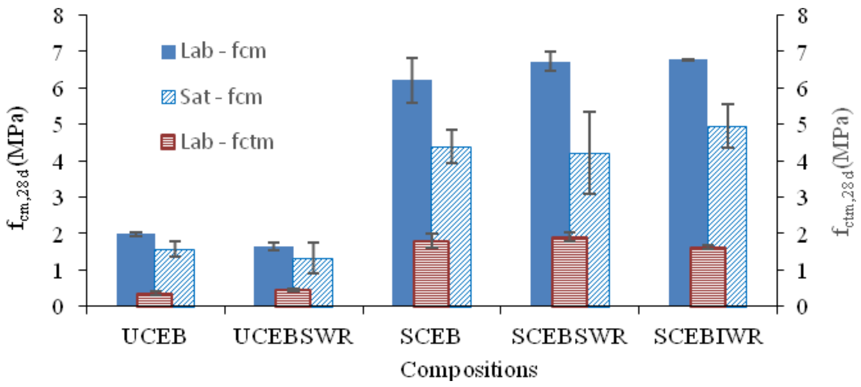

Figure 5: Compressive and flexural strength at 28 days. CEB cured and tested in a laboratory environment (lab) and CEB tested in saturated conditions (Sat).

able to finish the absorption tests. Even after lower periods of absorption, the water uptake and absorption rate were significantly higher due to their greater P_T (Table **3**) and loss of integrity.

Regarding the stabilized mixes, the water-repellent products were effective in reducing the rate of absorption (Figure **6**, Table **3**). However, these products showed different short and long-term efficiency between them.

SCEB produced with the synthetic SWR had the best performance, leading to a very low capillary coefficient and long-term 72 hours water absorption (Table **3**), only about 15% of those of SCEB. The efficiency of this water-repellent was maintained during all tests and is clearly distinguished from other products. The attained SWR penetration in CEB and its hydrophobic characteristics led to an efficient depression of the capillary action, which was almost canceled.

On the other hand, the natural linseed oil was much less efficient, especially in the long-term reduction of absorption. In fact, the 72 of hours water absorption and the coefficient of absorption up to 6 hours were only 8% and 7% lower than those of non-treated SCEB, respectively. However, this natural product was effective during the early stage of water absorption, i.e., up to about 30-60 minutes. In this case, the water absorption was 60% lower than that of SCEB, showing a performance similar to SWR. The partial destruction of the protective LO barrier and its reduced penetration depth, which was around 5 mm on average during absorption tests, may contribute to the modest reduction of long-term absorption. In fact, from cut-half blocks, it was possible to measure LO penetration depths of 5 mm and 7 mm in SCEBLO and UCEBLO, respectively.

Curiously, the LO showed great performance when applied in unstabilized blocks (UCEBLO), allowing them to complete the long-term absorption test, unlike UCEB with synthetic SWR. This may be explained by the higher LO impregnation depth attained in this more porous UCEB. Even though, the SWR showed to be more efficient than LO up to 2 hours of absorption (Table **3**).

The incorporation of IWR allowed to reduce the capillary absorption coefficient and 72 hours absorption of about 39%, compared to reference SCEB. Therefore, this product was less effective than SWR in reducing the water uptake. Since the IWR acts in all CEB volume, the shape of the absorption curve was approximately parallel to that of reference SCEB.

To conclude, when compared to UCEBLO, the earth stabilization allowed the reduction of the coefficient of absorption of at least 57% and the SWR allowed a further reduction of 85%.

3.4. Water Immersion

As found in 3.3, the UCEB and UCEBSWR lost their integrity after the first 5 minutes and 3 hours upon contact with water, respectively. Therefore, the results in Table **3** are only presented for other mixes. Once more, only the UCEB protected with LO could complete the immersion test.

All remaining compositions had very similar long-term water absorption, except that with IWR (Figure **7**). In fact, this test allows to estimate the level of water accessible porosity, which is related to the total open porosity. Since the rate of absorption is not relevant in this test and the phenomenon of imbibition prevails, the behaviour is identical between compositions.

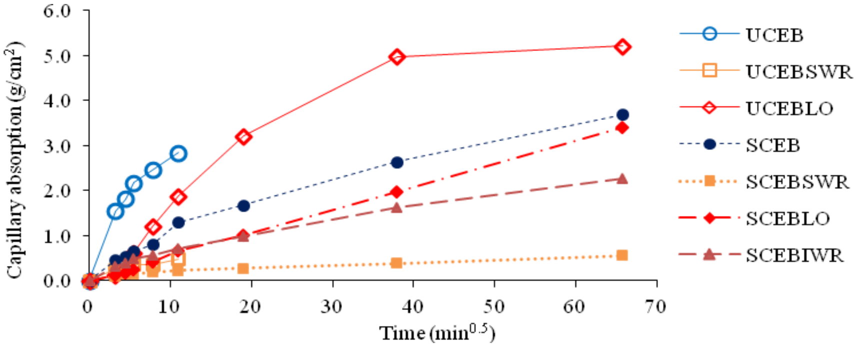

Figure 6: Capillary water absorption along time, up to 72 hours. Unstabilized CEB, with or without surface repellent, disintegrated after 2 hours absorption.

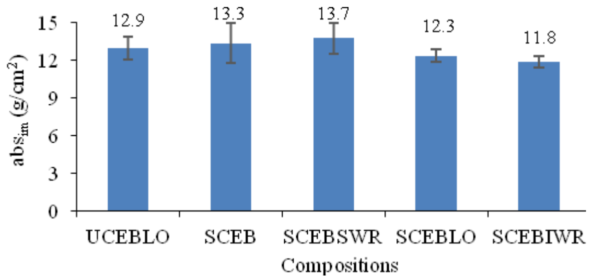

Figure 7: Water absorption by immersion.

In other words, the water-repellent products only affected the capillary suction, but not the total open porosity. Only SCEB with IWR had slightly lower absorption, which is in line with the slightly higher density estimated in 3.1. In general, the values of water absorption were around 13%, only slightly lower than that reported by Cid-Falceto *et al*. [3] for stabilized CEB (14%). This value corresponds to about 24% by volume of water absorption, which is near the total porosity estimated in 3.1.

3.5. Water Permeability

The water permeability could be only measured in SCEB because unstabilized CEBs lost their integrity on contact with water. In general, the water permeability was similar in all mixes, with small differences within the test variability range. This confirms that the water-repellent admixtures essentially affected the transport mechanisms related to capillary suction, in which the solid/liquid surface tension is relevant. Therefore, the permeability was not significantly altered, suggesting no capillary blockage. It may be thus concluded that the vapor water permeability should not be significantly affected, ensuring a healthy and comfortable indoor climate. The obtained results indicate that the CEB microstructure is not refined with the addition of IWR, as would be implied from immersion absorption tests. In fact, a gel is formed when this product interacts with cement hydration products, which reduces the surface capillary tension without affecting the CEB porosity.

The coefficients of permeability were about 3 orders of magnitude higher than those usually documented for low-quality concrete (of about 10^{-10} m/s, according to Geiker *et al* 2007). For rammed earth walls, Delgado and Guerrero [53] reported permeability coefficients of about 10^{-8} m/s, which tends to be lower than for CEB, due to their slightly higher clay content.

3.6. Low-Pressure Water Absorption

The average coefficients of absorption determined for up to 4 cl water absorption, $C_{abs,k,4cl}$ are indicated in Table **3** and the average water absorption along time is presented in Figure **8**. As expected, the unstabilized CEB had significantly worse performance than the stabilized CEB. The coefficient of absorption was as much as 18 times higher in UCEB than in SCEB. However, the application of water-repellents in unstabilized CEB led to a significant reduction of $C_{abs,k,4cl}$, over 90%, with SWR showing the best performance. Moreover, unstabilized CEB protected with SWR and LO performed similarly to stabilized CEB with the same water-repellent products.

Since this test was conducted under very low-pressure conditions, the mechanism of permeability was much less relevant than that of capillary absorption and the water-repellent products could be more effective. Only after the surface water-repellent barrier was overcome, the rate of absorption suddenly increased and the water penetration into blocks was more effective (Figure **8**). This was especially noticed in LO treated blocks.

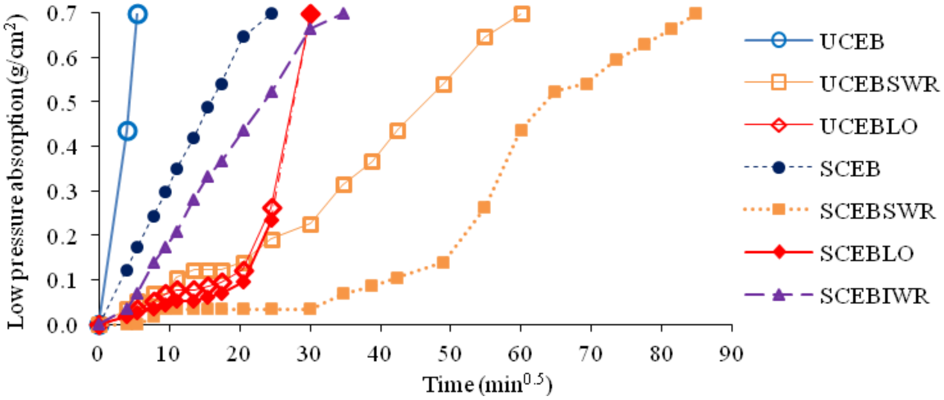

Figure 8: Low-pressure water absorption along time, up to the absorption of 4 cl water.

Once more, the CEB with IWR showed intermediate behaviour between reference stabilized CEB and those treated with surface water-repellents. This is in line with the capillary absorption results obtained in 3.3.

Note that besides the coefficient of absorption, it is also relevant to the testing time. In fact, as shown in Figure **8**, the specimens with surface water-repellent (SWR/LO) are associated with two absorption stages, in which the coefficient of absorption of the first phase is significantly lower than that of the second phase. In opposition, specimens with IWR had the same absorption curve evolution as reference SCEB (Figure **8**).

3.7. Water Erosion Resistance – Drip Test

The average penetration depths of erosion (DE) and moisture (DM) are presented in Table **4**. Only the unstabilized CEB without surface water-repellent admixtures showed significant DE, of about 10 mm (Figure **9**). Nevertheless, according to 2.3, this mixture may be considered acceptable, although with a modest erosion index (EI) of 3 (Table **4**). Other remaining mixtures were within the EI 1. It is thus clear that cement stabilization or water-repellent protection may greatly increase the CEB water-resistance against light rainfall. No significant DE in cement stabilized CEB subjected to drip tests is reported in literature [3,50].

Once more, the synthetic SWR showed the best performance, either for stabilized and unstabilized blocks. In this case, no relevant penetration depth of moisture was noticed, i.e., the SWR was highly effective against the simulated action of light rain (Figure **9**). In a second level, the natural LO reduced the moisture penetration by up to 39% compared to reference SCEB (Table **4**). Despite its lower efficiency compared to SWR, any erosion was avoided in unstabilized CEB with LO. The IWR only allowed a modest reduction of DM, of about 8%. It may be thus concluded that this product was not effective in increasing the drip resistance.

3.8. Water Erosion Resistance – Spray Test

Unstabilized blocks were severely damaged by the spray test. The full depth was eroded in less than 4 minutes, for an average erosion rate of about 916 mm/hour (Figure **10**), which is within the rejected erosion index class 5 (Table **4**). In fact, only stabilized

Table 4: Average Results of Studied CEB from Drip and Spray Tests

Mixture Composition	Drip Test			Spray Test				
	DE (mm)	DM (mm)	Class EI	DE (mm)	DM (mm)	Testing Time (min)	DE/Hour (mm/h)	Class EI
UCEB	9.7	84.7	3	56	-	3.7	916	5
UCEBSWR	0	0	1	56	-	9	137	5
UCEBLO	0	35.5	1	56	-	7	480	5
SCEB	0	58.3	1	<1	56	60	<1	1
SCEBSWR	0	0	1	<1	49	60	<1	1
SCEBLO	0	38	1	<1	35	60	<1	1
SCEBIWR	0	53.7	1	<1	47	60	<1	1

Figure 9: Drip test. Eroded unstabilized CEB (left) and very good performance of unstabilized CEB with SWR (middle) and stabilized CEB with SWR (right).

Figure 10: Spray tests. Full-depth eroded in unstabilized CEB (left) and great performance of stabilized CEB with SWR (right).

blocks were considered “accepted” according to NZS4298 (1998), with erosion rates much lower than 10 mm/hour (erosion index 1). Cid-Falcedo *et al*. [3] and Bogas *et al*. [15] also reported the total erosion of unstabilized CEB and no significant erosion when they were cement-stabilized. Taking into account both erosion tests carried out in this study, unstabilized CEB showed to be inadequate for outside elements unsheltered from rain. On the other hand, it confirmed the significant contribution of cement stabilization against heavy rainfall. Erosion rates lower than 1 mm/hour were also reported by Exelbirt [54] for stabilized blocks with 7% cement, even taking into account a maximum spray pressure of 4000 kPa, which is about 2 orders of magnitude higher than that considered in NZS 4298 [39] and in this study. As mentioned by Elenga *et al*. [55], this indicates the high water-resistance of stabilized CEB, which are able to resist more severe conditions during these accelerated tests than conditions usually affecting current CEB construction.

The application of surface water-repellent products did not avoid the erosion of unstabilized blocks. Contrary to the drip test, the heavy spray action destroyed the surface protection layer and the erosion index class could not be reduced. Nevertheless, the SWR and LO were able to reduce the erosion rate by as much as 85% and 48%, respectively. Contrary to drip tests, SCEB with LO showed the best performance in spray tests, followed by CEB with IWR or SWR. Comparing to reference SCEB, a 38% and 14% reduction of DH was observed in CEB with LO and IWR/SWR, respectively. It seems that SWR was washed away faster than LO when it was exposed to heavy rain, allowing a greater moisture penetration (Figure **10**).

4. CONCLUSIONS

In this study, the water-resistance of CEB produced with partial incorporation of recycled sand and distinct integral and surface water-repellent admixtures was analysed. The density and compactness of CEB depends on the mixing water content, affecting the total porosity and mechanical strength. The cement-stabilization of CEB was able to increase the compressive strength over 3 times. Moreover, the CEB properties were significantly affected by moisture. Unstabilized blocks lost their integrity after coming in direct contact with water, being inadequate for outside-unsheltered building solutions. Stabilized CEB reduced their mechanical strength up to 30% in saturated conditions, regardless of the application of water-repellent products.

The mechanical strength, total porosity, water permeability and imbibition absorption were not signifycantly affected by the water-repellent admixtures. As expected, these products exerted their main influence in reducing the capillary suction, and improving the CEB performance in all mechanisms affected by this property.

All tested water-repellent products were effective in reducing the capillary absorption of stabilized CEB. The SWR showed the best performance followed by IWR, reducing the absorption rate to only about 15% and 40%, respectively. The SWR also showed the best performance in drip and low-pressure absorption tests, allowing no significant water absorption rates in both situations. The application of natural LO was less effective in reducing the long-term absorption, probably because of its lower attained impregnation depth. Noteworthy was the effective behaviour of LO in unstabilized blocks, allowing them to withstand the moderate actions of dripping and low-pressure absorption, which is a representative of light rainfall.

The cement stabilization is a key condition when CEB is expected to be exposed to heavy rain. Under these severe environmental conditions, the further application of surface water-repellent may improve the water-resistance performance of stabilized CEB up to about 40%. Unstabilized blocks were severely eroded during spray tests, regardless of the application of water-repellent admixtures. The integral water-repellent always increased the water-resistance of reference cement stabilized CEB, although showing less performance than the surface water-repellent.

In sum, the unstabilized CEB showed to be inappropriate for building solutions that are directly exposed to water, and the cement-stabilization and application of water-repellent admixtures proved to significantly improve their water-resistance. Especially for low to moderate pressure conditions, surface water-repellent admixtures are effective in improving the water-resistance of stabilized CEB. The incorporation of a more sustainable natural water-repellent was less effective in improving the long-term water-resistance. Note that the water-repellent products were only tested at an early age. Future studies should be carried out concerning the long-term durability and effectiveness of these products.

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ACRONYMS

CEB = Compressed earth blocks

IWR = Integral water-repellent

LO = Linseed oil

RA = Recycled aggregate

SCEB = Stabilized CEB with 8% of cement by dry weight of earth

SWR = Surface water-repellent

UCEB = Unstabilized CEB

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