Compressed earth blocks with and without cementitious materials

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Acronyms

CEB – Compressed earth blocks

C – Stabilized CEB mixture with 8% of cement by dry soil mass

M – Stabilized CEB mixture with 4% of cement and 4% of lime by dry soil mass

N – Unstabilized CEB mixture

R – Recycled aggregate

1. Introduction

Earth is the oldest building material in the world, however it has fallen into disuse with the discovery of modern day building materials like concrete, steel and fired bricks (Barbosa, 1996; Rix, 1998; Riza et al., 2010). None the less, earth as a material, has many advantages, such as cost, thermal and acoustic insulation, minimal impact on the environment and its easy accessibility. The growing search for sustainable construction makes earth construction techniques a must. This is why, earth construction is on the rise in so called "developed" countries (Adam, 2001; Kerali, 2001; Morel et al., 2007; Pacheco-Torgal et al., 2012; Rigassi, 1985; Walker, 1995), as its production and construction techniques are viable to be industrialised. It is expected that compressed earth blocks (CEB), are the earth construction technique most likely to be accepted by modern society. This is due to the CEB technology, enabling the blocks to be standardized and greater control over the quality of its production cycle being achieved (Lourenço, 2002; Rigassi, 1985). Despite all this, and adding to the lack of normative regulation (Cid-Falceto et al., 2012), in Portugal's case, or lack of compatibility between existing normative regulation, the numerous uncertainties associated with the behaviour of CEB, are the main reasons for its dismissal as an acceptable building material.

CEB studies are on the rise (Pacheco-Torgal et al., 2012; Rigassi, 1985), mostly focusing on soil and stabilizer selection, CEB compressive strength, dry density and water absorption by submersion. Compressive strength is deemed to be the most important property (Adam, 2001; Kerali, 2001; Morel et al., 2007; Rix, 1998; Riza et al., 2010; Walker, 1995) and, as occurs with CEB dry density, is linked directly to block durability (Heathcote, 2002; Kerali, 2001; Walker, 1995). CEB durability studies are less frequent, however they normally focus on water absorption, dry and wet abrasion and resistance to water erosion.

As 80 to 90% of the volume of a CEB is soil, then soil selection is the most important part of formulating CEB mixes. Once the right soil is selected, then stabilizer and water proportions must be studied and decided on. The correct soil, stabilizer, and water proportions, and properties, have been studied by many authors (Bahar et al., 2004; Barbosa, 1996; Burroughs, 2008; Delgado et al., 2007; Morel et al., 2007; Namango, 2006; Ngowi, 1997; Pacheco-Torgal et al., 2009; Rigassi, 1985; Riza et al., 2010; Walker, 1995) however, as soil is a natural material, it's complexity creates uncertainties in any kind of established limits or percentages. All standards are really just guidelines that must be followed with common building practices.

As there are numerous studies on soil selection, two studies were considered too be the most complete, Delgado et al. (2007) compiled the existing standards on soil selection for CEB production and (Burroughs, 2008) tested over 100 different soils for rammed earth construction (soil for rammed earth is very similar to soil for CEB). Summarizing the findings in these two investigations, soil suitable for CEB production has the following composition: 0-30% of gravel; 25-70% of sand; 20-45% of silt and clay. The soils liquid limit should range from 25 to 50 and its plastic limit from 2 to 30. Water added to the dry mix in CEB production usually ranges from 10 to 13% (Bahar et al., 2004; Rigassi, 1985; Riza et al., 2010), normally determined with the Proctor test for optimum moisture content. The most common stabilizers are cement and lime (Adam, 2001; Kerali, 2001; Namango, 2006; Ngowi, 1997; Pacheco-Torgal et al., 2009; Rigassi, 1985; Riza et al., 2010; Walker, 1995. Stabilizer percentages normally depend on the type of stabilizer used but compiling the works of Adam (2001), Kerali (2001), Namango (2006), Ngowi (1997), Pacheco-Torgal et al. (2009), Rigassi (1985), Riza et al. (2010) and Walker (1995) on average, 4 to 10% of cement is added in dry weight of the soil and 6 to 12% when stabilizing with lime.

Walker's (1995) investigation of CEB mechanical strength is one of the most referenced CEB investigations throughout the CEB literature and therefore highly regarded in this report. Walker (1995) produced cement stabilized blocks with 5 to 10% of cement to dry soil mass. He reports dry compressive strengths of 3.5 to 7 MPa and 2 to 4 MPa for saturated compressive strength, seeing that water absorbed by the blocks disintegrates unstabilized clay particles. In his report he states that the tensile strength of saturated blocks, by means of the three point bending test, is inferior to 1/6 of saturated compressive strength. Namango, (2006) produce similar CEB, although increasing cement proportions to 12%, and obtained similar results for dry compression strengths (3.5 to 8 MPa). Namango (2006) reported a ratio of 1/4 in between dry tensile strength and dry compressive strength, with tensile strengths ranging from 0.8 to 2 MPa.

Bahar et al. (2004) investigated the performance of cement stabilized soils with a ratio of 5 to 10% of cement to dry soil. Bahar et al. (2004) reports water absorptions of approximately 13.7% to 16.6% and capillary absorptions of approximately 29 $g/cm^2.min^{1/2}$. Ngowi (1997) reported lower absorptions with the same amount of cement (approximately 9%), because his blocks were moulded at higher pressures (2 MPa). Kerali (2001) managed to reduce the CEB absorption even further, obtaining absorptions of 7% with just 5% cement by using a moulding pressure of 6 MPa, which is only possible through hydraulic presses. Hossain et al. (2011) reported capillary absorptions of approximately 14 g/cm^2.min$^{1/2}$, with cement stabilized soils at a ratio of 4%. The differences in between the mentioned water absorptions demonstrate the influence of cement/soil ratio and especially compaction pressure. Higher cement ratios implicate lower water absorptions as does higher compaction pressure.

CEB durability testing in general is highly criticized (Cid-Falceto et al., 2012; Cid-Falceto, 2012; Exelbirt, 2011; Heathcote, 2002), despite this CEB resistance to water erosion is measured by means of the drip test and the spray test. Few investigations were found to be compatible with this study referring to the drip test. Silva et al. (2013) investigated the erosion of unstabilized rammed earth obtaining an average erosion depth of 3 mm with drops falling at a height of 400 mm (according to NZS 4298). Galíndez (2009) reported depths of up to 8 mm on unstabilized CEB, however the height of impact was 2000 mm, and as mentioned by Heathcote, (1995) the main factor in rain bound erosion (drops of water) is drop intensity, controlled by height. Cid-Falceto, (2012) studied CEB water erosion by means of the spray test, using 50 kPa water pressure at a distance of 470 mm. Cid-Falceto, (2012) reported no erosion whatsoever on stabilized CEB and total penetration of unstabilized CEB. Exelbirt (2011) applied a much greater water pressure, 4170 kPa, at a distance of 510 mm registering small pockets of erosion of up to 1 mm.

In order to enhance the comprehension of CEB behaviour and further disseminate the use of this construction material, the present study's main objective is the characterization of its main mechanical and durability properties. In this manner, the CEB produced in this study were analysed in terms of their compressive and tensile strength, thermal conductivity, water absorption, capillary water absorption and resistance to water erosion. The influence of humidity in CEB behaviour, and the advantages of cement and lime stabilization were also studied in this report to further eliminate uncertainties associated to the CEB.

2. Experimental programme

2.1. Materials and methods

The experimental campaign involved the selection and characterization of various soils and fine aggregates, as well as, the production and characterization of stabilized and unstabilized CEB. The following types of blocks were produced: unstabilized CEB (N); stabilized CEB with 8% of cement, in weight (C); stabilized CEB with 4% of cement and lime, each, in weight (M).

All soil samples were extracted in Montemor-o-Novo (Portugal) and the recycled aggregate derived from construction debris consisting mainly of concrete, fired clay bricks, and cement mortar. In order to characterize the soils and aggregates, various tests were conducted, including: granulometric analysis (LNEC E-293, 1970) Atterberg limits (NP-143, 1969); standard Proctor test (light compaction)

(ASTM D689, 2000); dry density (NP-85, 1965). The properties of the various soils and the recycled aggregate are shown in Table 1. Note that R has no clay or silt, but particles with the same size.

Table 1 - Soil and aggregate properties

Aggregate	Granulometric analysis			Atterberg limits			Proctor	Dry density (Kg/m^3)
	Gravel (%)	Sand (%)	Clay/Silt (%)	LL	PL	PI	Optimum moisture content (%)	
Soil A	2	53.2	44.8	53	25	28	-	2550
Soil B	8.9	51.3	39.8	24	16	8	12.8	2672
Soil C	3.4	61.2	35.4	18	15	3	11.7	2665
R	14.9	67.6	17.5	-	-	-	-	2654

2.2. Mix proportions and tests

Due to the general guidelines of soil suitability for CEB production presented in 1. Soil C was considered the most suitable. A recycled aggregate (R) derived from construction debris, was added to the selected soil to better its granulometry. To achieve this goal, 15%, in weight of the dry soil, of recycled aggregate (R) was added to soil C, therefore becoming the unstabilized mixture to be used in the CEB production. The CEB compositions are indicated in Table 2.

The CEB were manually produced with a testaram press, achieving approximately 3.6 MPa of compaction pressure. The soil was pulverized by means of an electric mill before dry mixing with the rest of the components in a horizontal axis mixer. All mixtures where pressed with roughly 10% moisture content, controlled with successive drop tests while adding water to the dry mix. The CEB dimensions are 295x140x90 mm.

For the characterization of the CEB whole blocks were used as specimens for the following tests: dry density, tensile strength, water absorption and spray test. Half blocks, sawed perpendicular to their laying face (145x140x90 mm), were used as specimens for the thermal conductivity tests and drip tests. For the compressive strength test two half blocks where placed on top of each other creating a prism (145x140x180 mm). Given the lack of national regulation and the incompatibility between some of the existing regulation on CEB testing (Cid-Falceto et al., 2011) the test procedures adopted in this study required adding some alterations to the regulation followed for each test.

Table 2 - CEB compositions, water/cement ratio (w/c), average fresh block density (ρ)

Type	Acronym	Soil C (%)	Recycled aggregate (%)	Cement (%)	Lime (%)	Water (%)	w/c ratio	ρ_{fresh} (Kg/m^3)
Stabilized	C	85	15	8	-	9.5	1.35	1918.949
Stabilized	M	85	15	4	4	10	2.6	2003.088
Unstabilized	N	85	15	-	-	9.6	-	1929.222

2.3. Curing process

Once pressed, the fresh CEB were cured on pallets and covered with plastic sheeting for 7 days. The stabilized CEB mixtures, C and M, were sprayed with water during the curing process. For the next 21 days all blocks were stored under plastic sheeting to protect them from the elements. Once in the laboratory, the blocks were stored under different humidity and temperature conditions: in order to study the influence that moisture has on the block properties. Blocks were oven dried until constant mass (dry state); immersed in water for 2 hours (saturated state); stored in the laboratory, at temperatures ranging between 19ºC to 26ºC and relative humidity levels of 55% to 75%.

2.4. Mechanical strength testing

The compressive strength of the blocks was determined according to NBR 8492 (1984) and NTC 5324 (2004) at the age of 28 days. Although, contrary to the these standards the half blocks where placed on top of each other without the use of mortar due to lack of compatibility between the specimen and the mortar. The test was executed on 4 specimens, per CEB mixture, in the dry state, saturated state and laboratorial state, respectively, as described in 2.3. The compression rate was approximately 0,5 kN/s. The force at which the specimens reached failure divided by the average area of the two half blocks (composing the specimen) resulted in the compressive strength value of the CEB.

The tensile strength test was executed and determined using the three point bending model, according to NP EN 772 – 6 (2002). At the age of 28 days, 3 specimens, per CEB mixture were tested at the rate of 0,1 kN/s until failure. The span of the three point bending model was approximately 250mm long.

2.5. Thermal conductivity

The thermal conductivity of the blocks was measured using an ISOMET 2114. This device measures thermal conductivity based on a thermal impulse sent through the block by a probe placed directly on one of its faces. The thermal conductivity, at standard temperature, λ_2 (W/m.ºC), was estimated with Eq.(1), according to ISO/FDIS 10456 (2007), where λ_1 refers to the measured thermal conductivity, T_1 refers to the specimens temperature during testing, f_t refers to the temperature conversion factor, and T_2 is defined as the standard temperature. Both f_t and T_2 are defined in ISO/FDIS 1045 (2007).

$$\lambda_2 = \lambda_1 \times e^{f_t(T_2 - T_1)} \text{ [W/m.ºC]} \quad (1)$$

In total 6 specimens for each mixture were tested, obtaining 2 readings per block as the specimens are half blocks. The blocks were tested under all 3 temperature and humidity conditions mentioned in 2.3 (2 blocks per state). The specimens were wrapped in plastic, in order to avoid changes in humidity levels before and during the test.

2.6. Water absorption

Two types of tests were carried out: absorption by immersion according to to LNEC E394 (1993), and capillary absorption according to NTC 5324 (2004). In the first test blocks were submerged for 24 and 48 hours, in which water absorption is determined by the total mass of water absorbed by the blocks in percentage referring to the dry block's mass. For the second test, a coefficient of absorption, C_b is calculated with Eq. (2), in which *Md* is the blocks dry mass, *Mt* is the blocks mass after 10 minutes of contact with water at a depth of 5 mm, *t* is the time of measurement (10 minutes) and *s* is the area of the block in contact with the water.

$$C_b = \frac{100 * (Mt - Md)}{s\sqrt{t}} \ [g/cm^2 min^{1/2}] \quad (2)$$

The absorption tests were carried out on 3 whole blocks of each mixture.

2.7. Drip and spray test

In this study both drip and spray tests were conducted according to NZS 4298 (1998). These tests reproduce light and heavy rainfall impacting the CEB, respectively, and measure the depth of erosion (DE) as well as the depth of moisture penetration (DP). 3 blocks per mixture were tested in each test. The drip test consists of 100 ml of water falling as single drops on the face of a block, set at 27º angle, from a height of 400 mm. In the spray test, a circular area (140 mm diameter) of a block is sprayed by a pressurized jet of water, at 50 kPa, for one hour or until totally penetrated. The recommended distance between the block and the nozzle is 470 mm. Specific equipment was built to execute the spray test. In pursuance of mimicking heavy rainfall the nozzle used on the spray equipment was the Fulljet GG-1550 as used by Heathcote (2002) and Cid-Falceto (2012)

3. Results and discussion

The dry density ρ, compressive strength f_{cm}, structural efficiency f_{cm}/p, tensile strength f_{ctm}, tensile/compressive strength ratio f_{ctm}/f_{cm} and thermal conductivity λ for all CEB mixes and block humidity levels are listed in Table 3. Table 4 lists the CEB water absorption by submersion *A*, capillary water absorption C_b, depth of erosion *DE* and depth of moisture penetration *DP*.

Table 3 - CEB density, compressive strength, structural efficiency, tensile strength, tensile/compressive strength ratio and thermal conductivity

Mixture	Humidity	ρ (Kg/m^3)	$f_{cm,28d}$ (MPa)	$f_{cm,28d}/\rho$ (x10^{3}m)	$f_{ctm,28d}$ (MPa)	$f_{ctm,28d}/f_{cm,28d}$ (%)	λ (W/mºC)
C	Dry	1807.4	5.37	3.0	1.19	28	0.65
	Laboratory	1928.2	4.18	2.2			0.87
	Saturated	2001.7	2.24	1.1			1.34
M	Dry	1745.2	3.14	1.8	0.68	29	0.61
	Laboratory	1809.1	2.34	1.3			0.72
	Saturated	1986.8	1.05	0.5			1.47
N	Dry	1739.4	2.37	1.4	0.25	19	0.58
	Laboratory	1801.1	1.34	0.7			0.65

Table 4 - CEB water absorption by submersion, capillary water absorption, depth of erosion and depth of moisture penetration

Mixture	Water absorption A_{24h} (%)	A_{48h} (%)	C_b ($g/cm^2.min^{1/2}$)	Drip test DE (mm)	DP (mm)	Spray test DE (mm)	DP (mm)
C	13.59	13.94	20.84	0	-	0	4.0
M	16.49	16.74	29.82	0	-	0	5.7
N	-	-	-	4.3	57.7	fully eroded	-

3.1. CEB density

In their hardened state the CEB density varied in between 1740 and 2000 Kg/m^3, (Table 3) depending on the type and proportion of stabilizer added and their internal humidity. Seeing that no measurable dimension changes were registered for all CEB mixes, the increase in CEB density resulted solely due to the increase of humidity absorbed by the blocks. On average, the stabilized CEB mixes' (C and M) density increased 11 to 13% from their dry state to their saturated state. Increases of this magnitude should be accounted for when designing earth buildings.

3.2. Compressive strength

As expected, the stabilized CEBs' compressive strength was superior to the unstabilized CEB mix, as indicated in Table 3. In their dry state, the compressive strength of mixture C was 56% higher than that of the unstabilized mixture N. Ngowi (1997) reported a maximum gain of 70% in compressive strength with the addition of 5 to 10% of cement in CEB. The compressive strength of mixture M was only 24% higher than that of mixture N, demonstrating the lower increase in CEB strength associated to lime stabilization, even though mixed with cement in mixture M. Mixture C's compressive strength was roughly 42% higher than that of mixture M, thus cement was considered as a more suitable CEB stabilizer than lime especially for earlier stages of CEB strength development. Greater emphasis was given to the compressive strength test results of blocks in their dry state and blocks stored in the laboratory ("laboratorial state") as CEB are most commonly used in construction under dry conditions (Morel et al., 2007).

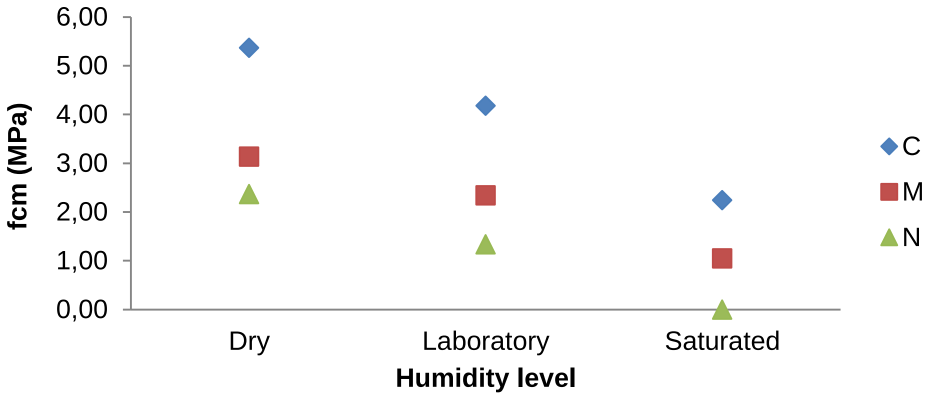

Figure 1 - Influence of block humidity on CEB compressive strength

Taking into account Figure 1, CEB compressive strength is negatively affected by humidity. Mixture N disintegrated in contact with water, therefore it was impossible to measure its saturated compressive strength. On the other hand, the stabilized mixtures remained intact for at least 48 hours (blocks were tested after 2 hours of submersion), and were physically handled without causing any superficial damage. Due to saturation of the blocks, mixture C's compressive strength reduced 58% in regards to its dry compressive strength. Mixture M suffered a reduction of 67% in the same conditions and, as mentioned before, mixture N disintegrated. Considering the increase of block humidity between dry blocks and blocks stored in the laboratory, the compressive strength of mixture N decreased 43%, whereas, for mixtures C and M, the decrease in strength was only 22% and 25%, respectively. It was established that as block humidity increases, so does the reduction in compressive strength in between CEB mixtures. This is due to the mixtures with hydraulic binders being less affected by increases of humidity.

Considering the saturated compressive strengths indicated in Table 3, the CEB mixtures C, M and N would be classified as BSC P 40 H, BSC P 20 H e BSC O 20 S, respectively according to NTC 5324 (2004). The only CEB mixture that would be accepted by the NBR 8492 (1984) standards is mixture C. Despite this, the gain in compressive strength and the capacity to maintain cohesion when submerged in water are two of the main advantages of CEB stabilization.

In light of the superior compressive strength registered in between the mixes with 4 and 8% of cement, regardless of block humidity, and considering structural efficiency (compressive strength vs. density) as the main criteria, then using higher proportions of cement in CEB mixes may be justifiable. As mentioned earlier an increase in block humidity lead to an increase in block density and a reduction in block strength. However the reduction in block strength was 10 times larger than the increase in block density. On average, block density increased approximately 7% in between dry blocks and blocks stored in the laboratory whereas compressive strength decreased approximately 67% under the same conditions. The large variation in compressive strength due to changes in block humidity, even verified in stabilized CEB, deems it necessary to consider penalizing coefficients for bock strength in CEB construction designs. The results obtained in this study suggest coefficients of 0.55 and 0.44 for mixtures similar to mixture C and M, respectively.

In this study, the ratio between CEB saturated compressive strength and dry compressive was determined in order to evaluate block durability as suggested by Heathcote (1995). Heathcote (1995) suggests a range of values between 0.33 and 0.5 as the acceptable range for this ratio, corresponding to suitable block durability. Mixtures C and M were deemed as acceptable considering the suggested range and mixture N failed as it is impossible to measure its saturated strength. The results obtained from all durability tests executed in this study confirm that the interval suggested by Heathcote (1995) is indicative of CEB durability and that the compressive strength ratio is a means to avoid durability testing in CEB.

3.3. Tensile strength

The CEB tensile testing resulted in very low tensile strengths, especially for the unstabilized mixture N (Table 3). As the tensile strengths were so low, the precision of the test results was poor, which in turn created some in uncertainties during their analysis. None the less, the same tendencies in regards to block composition and humidity level were registered in the tensile strength results as with the compressive strength mentioned above. The tensile strength of mixtures C, M and N were approximately 28%, 29% and 18% of the compressive strength of the mixtures, referring to blocks stored in the laboratory. Krosnowsk (2011), Namango (2006) and Walker (1995) reported similar ratios, 17%, 25% and 14% respectively. Krosnowski (2011) and Walker (1995) determined these ratios in saturated blocks whereas Namango (2006) determined the ratio in dry blocks. As expected, this ratio diminishes with an increase in block humidity as higher humidity levels have greater effect on CEB tensile strength than on compressive strength. Seeing that the three point bending test is simpler to execute on-site than compressive strength tests and by considering that CEB tensile strength is roughly 1/4 of its compressive strength, this test mat be used to estimate CEB mechanical strength.

3.4. Thermal conductibility

As indicated in Table 3 CEB thermal conductivity is influenced by the composition of the block and especially by the block's internal humidity. In fact, saturated blocks demonstrated 2 to 2.5 times higher thermal conductivity than dry blocks. Block composition had less impact on CEB thermal conductivity, as demonstrated by the dry thermal conductivity values in Table 3. In their dry state, the thermal conductivity of the stabilized mixture, N, was on average 8% lower than that of the stabilized mixtures, C and M, and 18% lower in blocks stored under lab conditions. Unstabilized blocks were considered a better thermal insulation solution as they had the lowest thermal conductivity regardless of the block humidity level. However these blocks should only be used in conditions where little to no water exposure is expected. Blocks of mixture C exhibited higher thermal conductivity than mixture M when dry or stored under laboratory conditions but lower thermal conductivity when saturated. Water has a thermal conductivity value 25 times superior to that of earth (Ashworth, 1991), therefore the mixture M exhibited higher thermal conductivity when saturated due to its higher porosity. Mixture M has a higher porosity than mixture C due to its higher water/cement ratio. It is well documented in concrete literature that the higher the water/cement ratio, the more porous the concrete is (Mehta et al., 2006; Neville, 1995).

3.5. Water absorption

As mentioned earlier, the unstabilized mixture, N, disintegrated when submerged in water. Partial disintegration also occurred during the capillary absorption tests hence it was not possible to determine the unstabilized mixture's water absorption, as indicated in Table 4. On the other hand, the stabilized mixtures remained intact for at least 48 hours, whereby CEB stabilization is essential when the blocks are expected to come into contact with water.

The results of the absorption tests reveal that mixture M is more porous than mixture C as both absorption test results were higher than those of mixture C (Table 4). The absorption by submersion test indicates that the CEB blocks for both mixtures are practically totally saturated in the first 24 hours of submersion, as the increase in water mass was very low during the next 24 hours of testing. Mixture C absorbed more water than mixture M after the 24 hour mark, implying that mixture M's porous structure is more interconnected than that of mixture C. According to NBR 8492 (1984) both stabilized mixtures, C and M, are suitable to be used in wet conditions and mixture N is only suitable for dry conditions.

The same tendencies were detected with the capillary water absorption tests as with the absorption by submersion, seeing that the coefficient of capillary absorption was higher in mixture M than in mixture C. According to NTC 5324 (2004) mixtures C and M can be classified as having "very low capillary absorption" and "low capillary absorption", respectively.

During capillary absorption testing, a trial was conducted in which blocks were left for 72 hours absorbing water at a depth of 5 mm rather than the 10 minutes recommended by NTC 5324 (2004). Mixture M absorbed water at a much faster rate than that of mixture C and the height of water migration followed this tendency. As CEB water absorption is indicative of CEB durability(Cid-Falceto, 2012; Kerali, 2001), the results in this study indicate that capillary absorption testing, although a bit more complex to execute, translates to a greater extent the difference in between CEB durability than that of absorption by submersion testing.

3.6. Resistance to water erosion

Referring to the drip test, neither stabilized mixtures, C and M, showed any sign of erosion and hardly any moisture penetration. Therefore this test was considered to be unsuitable for stabilized CEB testing as mentioned by Heathcote (Heathcote, 2002). According to NZS 4298 (1998) mixtures C and M would be suitable for construction, the unstabilized mixture, N, was also deemed suitable as its average DE and DP were 4,3 mm and 57,7 mm, respectively, implicating that it has an erodibility index of 2. During the execution of the drip test on the unstabilized mixture, N, due to run off water, the area below the point of drop impact became very susceptible to damage. The task of breaking apart the block to measure its DP could be executed with very little force therefore the blocks would not be suitable to bear any kind of load. Taking this into account, once again the unstabilized mixture, N, was considered absolutely unfit to be used in circumstances where any contact with water may be possible. In this context, the criteria recommended by NZS 4298 (1998) for the drip test was considered as inadequate in the evaluation of CEB durability.

When exposed to the spray test, all of the unstabilized mixture blocks were destroyed in a matter of minutes. This is, the lengths of the blocks were fully penetrated, and in less than 4 minutes. This was as expected due to the behaviour of the unstabilized mixture in contact with water. None of the stabilized mixtures suffered discernible damage, resulting in erosion depths too shallow to accurately measure. The only noticeable effect was a loss of superficial particles with diameters smaller than 1 mm, resulting in a rougher block surface than before the test. The DP in both stabilized mixtures was very low (Table 4) and no cause for concern according to NZS 4298 (1998). The only differences reported in between mixtures C and M during the tests were that, mixture M began losing particles before mixture C (first 15 minutes) and mixture M registered slightly larger depths of moisture penetration. Therefore, according to NZS 4298 (1998) the unstabilized mixture, N, has no resistance whatsoever to heavy rainfall and the stabilized mixtures C and M have erodibility indexes of 1, and thus demonstrating great resistance to heavy rainfall.

A trial was conducted during the spray test in order to enhance the notion of CEB water erosion as done by Exelbirt (2011). The spray test equipment was adjusted to deliver a water pressure of 300 kPa rather than 50 kPa, specified by NZS 4298 (1998). Even with such a large increase in water pressure, the stabilized blocks were hardly damaged. Heathcote and Elenga (Elenga, 2011; Heathcote, 2002) emphasise that CEB durability tests are mostly inadequate as they impose far more aggressive conditions on blocks than those encountered in CEB constructions. This demonstrates that the stabilized mixtures C and M have outstanding resistance to heavy rainfall and therefore much better durability than that commonly associated to earthen construction techniques.

4. Conclusions

The following main conclusions can be drawn from this study:

1. The selection of an adequate soil for CEB production is crucial for their overall quality, especially the soils behaviour in contact with water

2. It is possible to incorporate construction debris consisting of concrete, fired clay bricks, and cement paste as an aggregate in CEB, as long as particle sizes are minimal (smaller than 2mm in this study). This contributes to the sustainability of the construction industry

3. Stabilization of CEB is a major advantage in terms of mechanical strength and is essential for guaranteeing adequate CEB durability. Unstabilized blocks disintegrated in contact with water.

4. CEB stabilization with 8% of cement to dry soil mass enhances unstabilized CEB compressive strength up to 60% referring to blocks in their dry state.

5. As a stabilizer cement is considerably better than lime, for all studied properties, and may be used in proportions as low as 8% of the dry soil mass.

6. Although cement stabilization permits greater mechanical strength (up to 40% when dry) than lime stabilization, a mix of 4% cement and 4% lime guarantees just as much resistance to water erosion.

7. Humidity significantly influences CEB behaviour, even in stabilized CEB. Saturation of the blocks increased block density up to 13% and decreased compressive strength up to 70% (without considering cases where blocks suffered total disintegration). Coefficients of up to

0.55 should be used on CEB compressive strength when designing with CEB, due to possible humidity variations.

8. Unstabilized CEB were considered a better thermal insulation solution, permitting up to 18% lower thermal conductivity values at room temperature than stabilized CEB. However these blocks should only be used in conditions where little to no water exposure is expected

9. The three point bending test may be used as a means to estimate CEB mechanical strength on-site as CEB tensile strength is roughly 1/4 of its compressive strength

10. When measuring CEB water absorption, capillary absorption tests are better suited to demonstrate the differences in between stabilized mixtures than water absorption by submersion tests.

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