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1 MANUSCRIPT ACCEPTED FOR PUBLICATION IN THE JOURNAL

2 “CONSTRUCTION AND BUILDING MATERIALS”

3
4 **EFFECT OF STABILISATION ON MECHANICAL PROPERTIES,**
5 **MOISTURE BUFFERING AND WATER DURABILITY OF**
6 **HYPERCOMPACTED EARTH**

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1 **ABSTRACT**

2 This paper investigates the effect of stabilisation by alkaline activation and silicon based admixture
3 on the mechanical properties, moisture buffering capacity and durability of an earthen material for
4 building construction. The stiffness and strength of both unstabilised and stabilised cylindrical
5 samples were measured, under different humidity conditions, by means of unconfined compression
6 tests. The effect of stabilisation on moisture buffering capacity was instead explored by subjecting
7 samples to cyclic variations of relative humidity at constant temperature, according to the
8 experimental procedures prescribed by the norm ISO 24353 (2008). Finally, durability against water
9 erosion was assessed by performing immersion, suction and liquid contact tests on both unstabilised
10 and stabilised samples according to the norm DIN 18945 (2013). Results from this extensive
11 experimental campaign highlighted that the chosen stabilisation methods improved the durability of
12 the material while maintaining a relatively good mechanical performance and a good to excellent
13 moisture buffering capacity.

14

15 **KEYWORDS**

16 Raw earth, compacted earth, stabilisation, alkaline activation, silane-siloxane emulsion, stiffness,
17 compressive strength, moisture buffering, water durability.

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1 ***INTRODUCTION***

2 The expression “raw earth” (translated from the French “terre crue”) describes a construction
3 material consisting of a mix of soil and water subjected to the least possible transformation before
4 being put in place. Depending on the adopted building design, the use of raw earth can reduce
5 energy consumption during construction but also during operation of buildings by cutting down air
6 conditioning. Because of its hydrophilic nature, raw earth exhibits a strong tendency to absorb or
7 release moisture, and therefore to emit or store latent heat, depending on the current levels of
8 ambient humidity. This characteristic helps to smooth out the variation of relative humidity and
9 temperature inside dwellings, thus contributing to the health and comfort of occupants (Allinson
10 and Hall, 2010; Pacheco-Torgal and Jalali, 2012; Soudani et al., 2016; Gallipoli et al., 2017;
11 Soudani et al., 2017).

12 Unfortunately, the hydrophilic nature of raw earth is also the cause of its poor resistance against
13 water infiltration. For this reason, raw earth is often chemically stabilised by addition of hydraulic
14 binders such as cement or lime (Walker, 1995; Bui et al., 2009; Reddy, 2012), which improve water
15 durability but also introduce undesirable collateral effects on stiffness, strength and moisture
16 buffering capacity. A number of studies have analysed the effect of stabilisation by hydraulic
17 binders on stiffness and strength (Walker, 1995; Jayasinghe and Kamaladasa, 2007; Morel et al.,
18 2007; Ciancio and Gibbings, 2012; Bui et al., 2014; Ciancio et al., 2014; Kariyawasam and
19 Jayasinghe, 2016; Arrigoni et al., 2017a) but also on moisture buffering capacity (Liuzzi et al.,
20 2013; McGregor et al., 2014; Arrigoni et al., 2017b). These investigations have shown that
21 stabilisation by hydraulic binders generally improves the mechanical properties of raw earth but
22 considerably reduces the ability of the material to store and release moisture.

23 Recent research has therefore focused on the development of alternative stabilisation methods that
24 do not use cement or lime and that can therefore improve the water resistance of the material while
25 preserving good mechanical and moisture capacity characteristics.

1 The present paper explores the use of some of these alternative stabilisation methods on
2 hypercompacted earth bricks (Bruno, 2016). These stabilisation methods consisted in a combination
3 of alkaline activation and silicone-based admixture.

4 Alkaline activation employs a solution of Ca(OH)_2 , NaOH or KOH to dissolve the clay minerals
5 naturally present in earthen materials so that they can reticulate again in the form of non-swelling
6 binding materials. Among the different alkaline activators, sodium hydroxide (NaOH) is selected in
7 this work because it provides the largest improvement of mechanical and durability characteristics
8 (Elert et al., 2015; Cheng and Saiyouri, 2015; Slaty et al., 2015). Instead, silicone-based admixture
9 consists in mixing the earth material with a water emulsion of silane and siloxane. This emulsion
10 reacts with the soil substrate by creating a hydrophobic nanomolecular polysiloxane film inside
11 earth capillaries, which impedes the infiltration of liquid water while largely retaining the
12 permeability to vapour (Kebao and Kagi, 2012).

13 The effects of these alternative stabilisation methods on mechanical properties have been the object
14 of very few studies mainly limited to earth plasters (Stazi et al., 2016). In this work, these studies
15 are extended to the investigation of the stiffness and strength of stabilised hypercompacted earth by
16 performing unconfined compression tests on cylindrical samples equalised at different ambient
17 conditions. Moreover, the effect on moisture capacity is equally assessed by subjecting cylindrical
18 samples to cycles of relative humidity at constant temperature to determine the Moisture Buffering
19 Value (MBV) according to the norm ISO 24353 (2008). Finally, the work investigates the water
20 durability of the material, i.e. the resistance of the material to water erosion, by performing
21 immersion tests on cylindrical samples as well as suction and contact tests on brick samples
22 according to the norm DIN 18945 (2013).

23 The purpose of this study is to identify a stabilisation method that can balance the different material
24 requirements in terms of water durability, moisture buffering capacity, stiffness and strength. The

1 effect of stabilisation method on the embodied energy of the material is not assessed in the present
2 work. Therefore, the environmental impact of the relatively small amounts of stabilising additives
3 used in this study will be the object of future research.

4 ***MATERIAL AND METHODS***

5 The soil used in the present work has been provided by a brickwork factory from the region of
6 Toulouse (France). Table 1 summarises the main properties of the tested soil. In particular, grain
7 size distribution and plasticity properties satisfy existing recommendations (e.g. MOPT, 1992;
8 CRATerre – EAG, 1998; AFNOR 2001) for raw earth construction as discussed by Bruno (2016).

Table 1. Main material properties

| Grain size distribution | | |
|--|------------------|--------|
| Gravel | > 2 mm | 0.4 % |
| Sand | 0.063 – 2 mm | 40.4 % |
| Silt | 0.002 – 0.063 mm | 42.9 % |
| Clay | < 0.002 mm | 16.3 % |
| Plasticity properties | | |
| Liquid limit, w_L (%) | | 33.0 % |
| Plastic limit, w_P (%) | | 20.1 % |
| Plasticity index, I_p (%) | | 12.9 % |
| Activity A (-) | | 0.79 |
| Other properties | | |
| Specific gravity of soil grains, G_s (-) | | 2.66 |

9

10 Clay activity, defined as the ratio between the plasticity index and the clay fraction, is equal to 0.79.
11 This classifies the clay fraction as normally active (Skempton, 1953), which is consistent with
12 mineralogy data from the soil provider that indicate a predominantly illitic material with a small
13 quantity of montmorillonite. Illite is a three-layer clay with good bonding properties and a limited
14 swelling potential upon wetting, which makes it particularly suited to raw earth construction (Dierks
15 and Ziegert, 2002).

1 Stabilised and unstabilised samples were prepared at the scale of both small cylinders (50 mm
2 diameter and 100 mm high) and bricks (200 x 100 x 50 mm³) by compaction inside stiff moulds of
3 corresponding dimensions at a relatively large pressure of 100 MPa and an optimum water content
4 of 5.2%. The optimum water content had been previously determined by compacting specimens
5 with variable moisture at the same pressure of 100 MPa as discussed by Bruno et al. (2016).

6 All samples were produced by double compaction inside a “floating” mould using two pistons at the
7 bottom and top of the sample, respectively. This minimised the heterogeneity of the compaction
8 stress caused by the friction against the mould walls and therefore maximised the homogeneity of
9 density across the material. This “hypercompaction” process resulted in a very dense material with
10 an average porosity of only 0.15 and a coefficient of variation of 0.06. Further details about the
11 adopted compaction procedure can be found in Bruno (2016). Here it is simply worth noting that,
12 even at a high pressure of 100 MPa, the energy required for the compression of the earth material
13 may be relatively small. This is because the compaction energy is calculated as the integral of the
14 applied pressure multiplied by the change of material volume. Given that the applied pressure
15 attains very high values only at the end of the compaction process, when the material is almost
16 incompressible, the above energy integral tends to be relatively small. An accurate quantification of
17 the compaction energy is however outside the scope of this work.

18 An initial evaluation of the durability of both unstabilised and stabilised cylindrical samples was
19 performed by means of water immersion tests in compliance with the German norm DIN 18945
20 (2013). Prior to immersion, all stabilised and unstabilised samples were equalised to the atmosphere
21 of the laboratory, where humidity and temperature were about 40% and 25 °C, for a minimum time
22 of two weeks until a constant mass was attained. For stabilised samples, this time also allowed
23 curing of cementing additives.

1 Immersion tests consisted in dipping samples in water for ten minutes and measuring the
2 corresponding mass loss. Unstabilised samples exhibited a large mass loss of about 70% at the end
3 of the test, which confirmed the need of stabilisation to improve water durability.

4 Immersion tests were repeated on stabilised samples where the 5.2% optimum water content of the
5 unstabilised samples was replaced with an equal amount of a stabilising liquid additive. The chosen
6 liquid additives are divided into two categories: a) a silane-siloxane emulsion diluted in water at
7 different concentrations (commercial name of the silane-siloxane emulsion is GPE50P from Tech-
8 Dry) and b) a water solution of sodium hydroxide NaOH, at molarities of 1, 2, 4 and 8 mol/l, either
9 pure or blended with the silane-siloxane emulsion. Table 2 summarises the different compositions
10 of all stabilising additives considered in this work.

11 NaOH is highly soluble in water and produces only a slight increase in viscosity of the solution
12 compared to pure water, which means a negligible change of the dry density of the compacted earth.
13 On the contrary, the silane-siloxane emulsion is not soluble in water and marginally increases liquid
14 viscosity, which results in a slight reduction of the dry density of the compacted earth. In fact,
15 silane-siloxane stabilised samples exhibited an average dry density of 2250 kg/m^3 that is about 1%
16 lower than that of unstabilised and NaOH stabilised samples.

17 After compaction, all samples were equalised to the atmosphere of the laboratory for two weeks and
18 subsequently subjected to immersion tests for evaluating the effect of the different stabilisation
19 methods on the measured mass loss. As shown in Figure 1, the erosion resistance of samples
20 stabilised with the silane-siloxane improves significantly as the concentration of the emulsion
21 increases. The addition of the NaOH solution also enhances the water resistance of the material with
22 a considerable improvement as solution molarity grows from 1 mol/l to 2 mol/l followed by a
23 deterioration as molarity increases further. The achievement of the best stabilisation properties at an
24 intermediate molarity level of 2 mol/l may be explained by the chemical interaction between the
25 saline solution and the clay minerals inside the earth material as indicated, for example, by Das and

1 Thyagaraj (2016) and Beckett et al. (2015). It is therefore possible that the optimum molarity
 2 depends on the mineralogical composition of the earth and on the amount of liquid content.

3

Table 2. Composition of stabilising liquid additives

| Silane-siloxane emulsion (% dry mass) | Water (% dry mass) | NaOH solutions at 1, 2, 4 and 8 mol/l (% dry mass) | Total liquid content (% dry mass) |
|---|------------------------------|--|---|
| 0 | 5.20 | - | 5.20 |
| 0.14 | 5.06 | - | 5.20 |
| 0.27 | 4.93 | - | 5.20 |
| 0.40 | 4.80 | - | 5.20 |
| 0.54 | 4.66 | - | 5.20 |
| 0.81 | 4.39 | - | 5.20 |
| 1.08 | 4.12 | - | 5.20 |
| 1.62 | 3.58 | - | 5.20 |
| 2.15 | 3.05 | - | 5.20 |
| 3.23 | 1.97 | - | 5.20 |
| 4.31 | 0.89 | - | 5.20 |
| 5.20 | 0 | - | 5.20 |
| 0 | - | 5.20 | 5.20 |
| 0.54 | - | 4.66 | 5.20 |
| 1.08 | - | 4.12 | 5.20 |
| 2.15 | - | 3.05 | 5.20 |
| 4.31 | - | 0.89 | 5.20 |

4

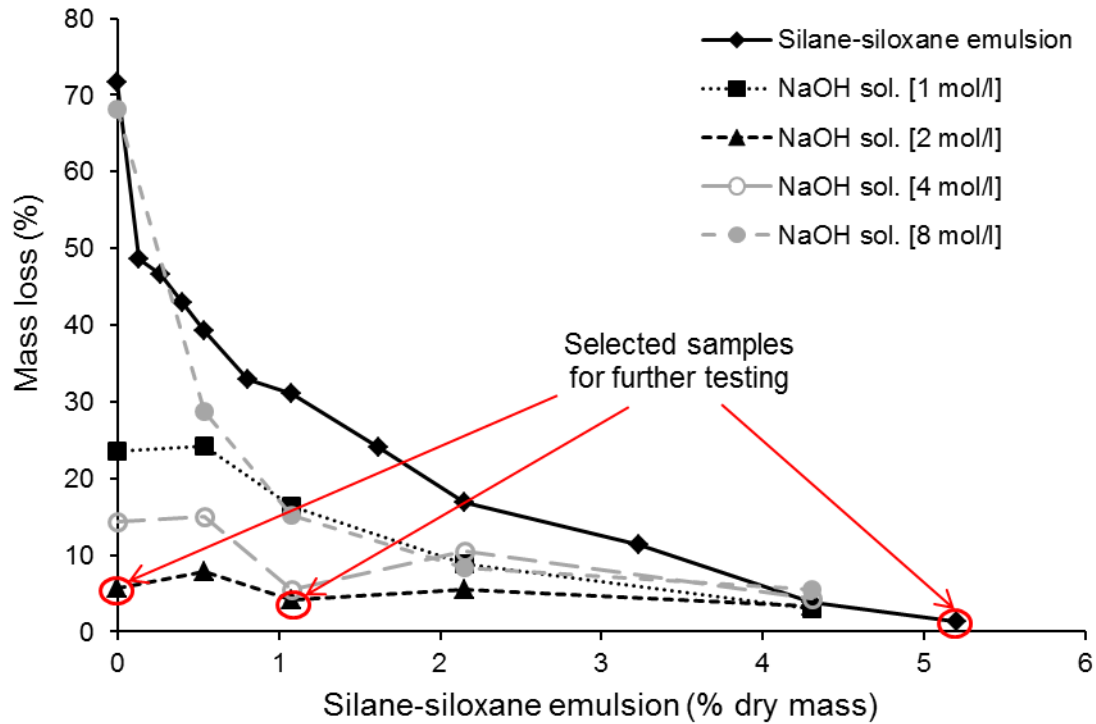


Figure 1. Results from immersion tests on stabilised hypercompacted earth samples

Based on the results of these preliminary tests, the following three stabilising liquid additives were selected for further testing because of their relatively good performance:

- 5.2% silane-siloxane emulsion (referred to as “silane-siloxane emulsion”)
- 1.08% silane-siloxane emulsion + 4.12% NaOH solution at 2 mol/l concentration (referred to as “NaOH solution+silane-siloxane emulsion”)
- 5.2% NaOH solution at 2 mol/l concentration (referred to as “NaOH solution”)

Cylindrical samples with the above compositions were tested to investigate their mechanical properties at different humidity levels and to determine their moisture buffering capacities. The water durability of brick samples was also investigated by performing suction and contact tests according to the norm DIN 18945 (2013).

EFFECT OF STABILISATION ON MECHANICAL PROPERTIES

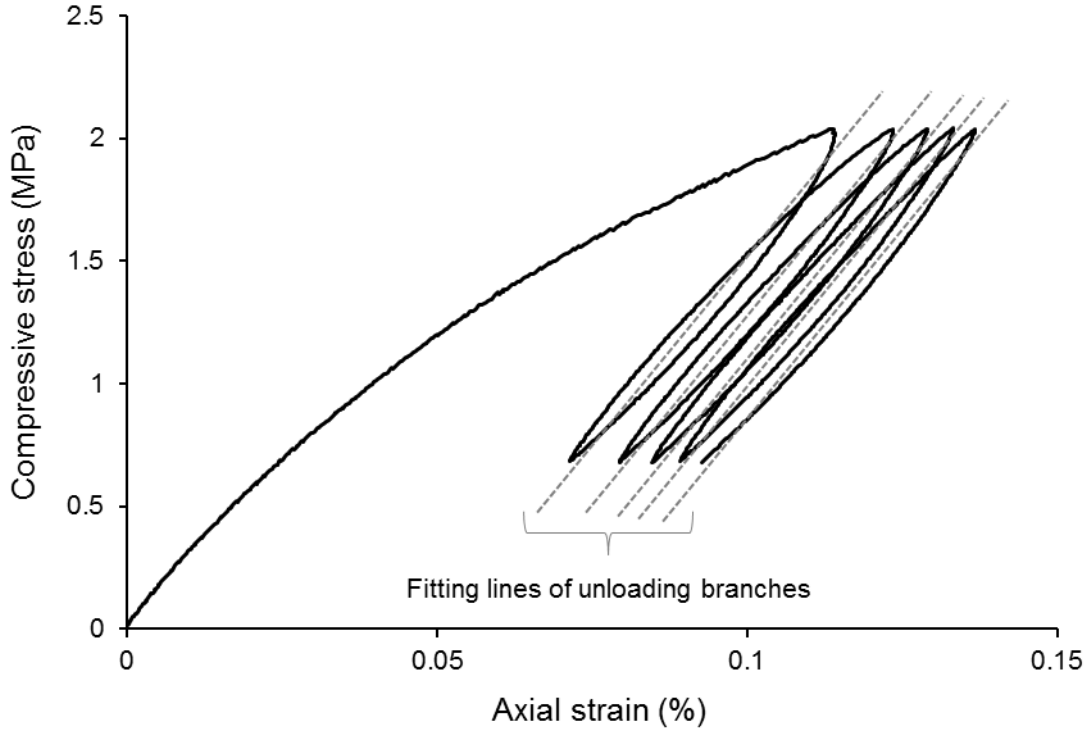
The previous campaign of immersion tests indicates that stabilisation by both alkaline activation and silane-siloxane admixture can considerably improve the durability of raw earth against water

1 erosion. It is now important to investigate the collateral effects of these stabilisation methods on the
2 mechanical behaviour of the material at different ambient humidity levels.

3 To investigate these aspects, five sets of four cylindrical samples (i.e. one unstabilised sample and
4 three stabilised samples with the chosen three liquid additives) were equalised inside a climatic
5 chamber at five relative humidity levels of 95%, 77%, 62%, 44% and 25% under a temperature of
6 25 °C. After equalisation, each sample was subjected to a sequence of five unconfined loading-
7 unloading cycles with a constant pressure rate of 5 kPa/s to determine the secant Young's modulus.
8 Cycles were performed between one ninth and one third of the compressive strength, which was
9 previously estimated as the average value from two samples equalised at a temperature of 25 °C and
10 a humidity of 62%. The adoption of a constant pressure rate, rather than a constant displacement
11 rate, is preferable during loading-unloading cycles because it avoids the application of significantly
12 different stress rates between the loading and unloading stages.

13 The observed response was prevalently elasto-plastic during loading but close to elastic during
14 unloading. Because of this, the secant Young's modulus was calculated as the average slope of the
15 fitting lines of the five unloading branches plotted in the stress-strain plane as shown in Figure 2. In
16 particular, axial strains were calculated from the relative displacement between two symmetrical
17 points separated by 50 mm along the height of the sample. This relative displacement was obtained
18 as the average reading from two extensometers placed on diametrically opposite sides of the
19 samples. The effect of end friction on measurements was reduced by applying Teflon spray on the
20 top and bottom plates of the press before these were placed in contact with the sample extremities.

21 After the loading-unloading cycles, all samples were loaded to failure with a constant displacement
22 rate of 0.001 mm/s. The change from stress- to strain-controlled loading is justified by the necessity
23 of measuring the entire deformation curve, including the post-peak portion until ultimate failure.



1

2

Figure 2. Typical stress-strain relationship during loading-unloading cycles

3

The measured values of stiffness and strength were related to the total suction, ψ inside the sample, which was calculated by means of Kelvin equation from the values of temperature, T and relative humidity, RH imposed during equalisation:

5

$$\psi = - \frac{R T}{V_m} \ln(RH) \quad (1)$$

6

where R is the universal gas constant and V_m is the molar volume of water.

8

Figure 3 shows that, as expected, all four samples exhibit growing values of secant Young's modulus as suction increases and ambient humidity reduces. The samples stabilised with the silane-siloxane emulsion and the NaOH solution + Silane-siloxane emulsion exhibit lower stiffness than unstabilised samples at all suction levels, with the silane-siloxane emulsion producing the softest samples. The samples stabilised with the NaOH solution exhibit instead higher values of secant Young's modulus than unstabilised samples but only for suctions below 65 MPa. As suction

13

1 increases beyond this value, the stiffness of the samples stabilised with the NaOH solution remains
2 approximately constant while that of the unstabilised samples continues to grow. Inspection of
3 Figure 3 also indicates that the increase of the secant Young's modulus with growing suction and
4 decreasing ambient humidity is less marked for stabilised samples than for the unstabilised ones,
5 which indicates that all three stabilisation methods reduce the sensitivity of material stiffness to
6 ambient humidity.

7 Figure 4 shows the variation of peak compressive strength for both unstabilised and stabilised
8 samples with suction and ambient humidity. Similar to the secant Young's modulus, stabilised
9 samples generally show lower values of compressive strength than unstabilised samples, with the
10 silane-siloxane emulsion producing the weakest samples. Only the samples stabilised with the
11 NaOH solution show values of strength that are comparable with those of unstabilised samples. In
12 particular, similar to the stiffness behaviour, samples stabilised with the NaOH solution are slightly
13 stronger than unstabilised samples at suctions below 65 MPa but slightly weaker at suctions above
14 this value.

15 The values of strength measured in this work for the unstabilised samples are one order of
16 magnitude higher than those reported in previous works (e.g. Ciancio et al., 2014). This is caused
17 by the hypercompaction process, which largely improves the mechanical properties of the
18 unstabilised material. Finally, inspection of Figure 4 indicates that the increase of strength with
19 growing suction and decreasing relative humidity is more marked for the unstabilised samples
20 compared to the stabilised ones, which is again consistent with the stiffness behaviour. The marked
21 improvement of the mechanical properties of the unstabilised samples with increasing suction is in
22 agreement with previous studies that have identified suction as a primary source of stiffness and
23 strength of unstabilised earthen materials (e.g. Gelard et al., 2007; Gallipoli et al., 2008; Jaquin et
24 al., 2009).

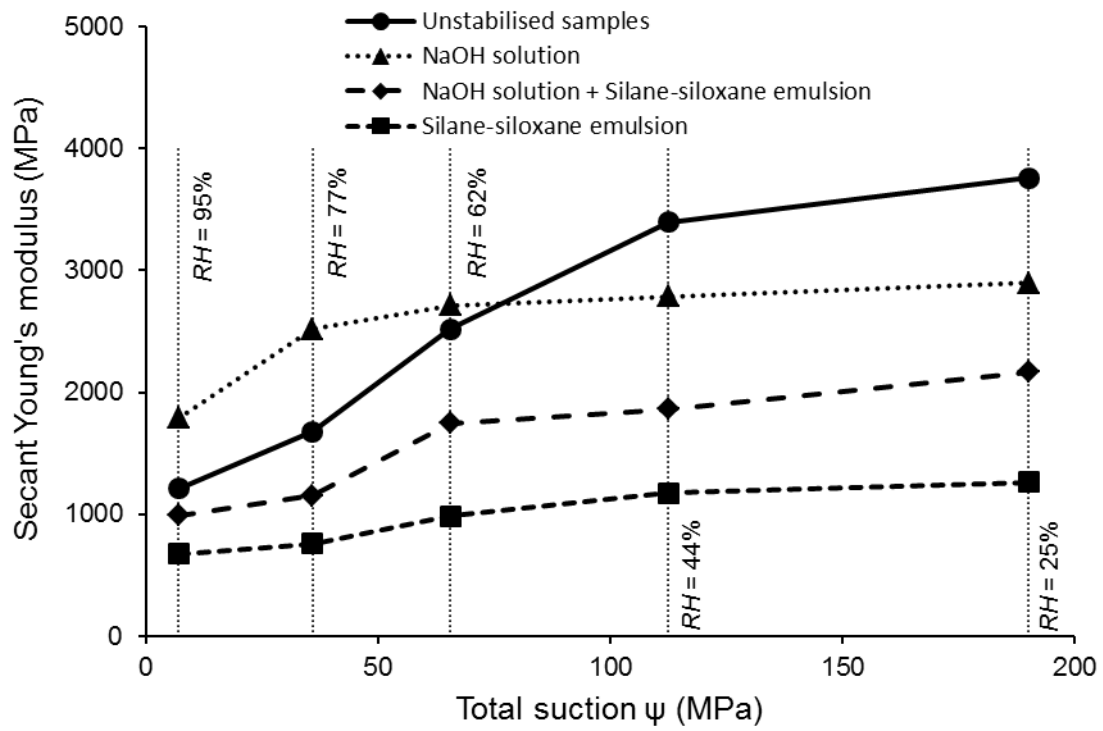


Figure 3. Variation of the secant Young's modulus with total suction: unstabilised and stabilised hypercompacted earth samples

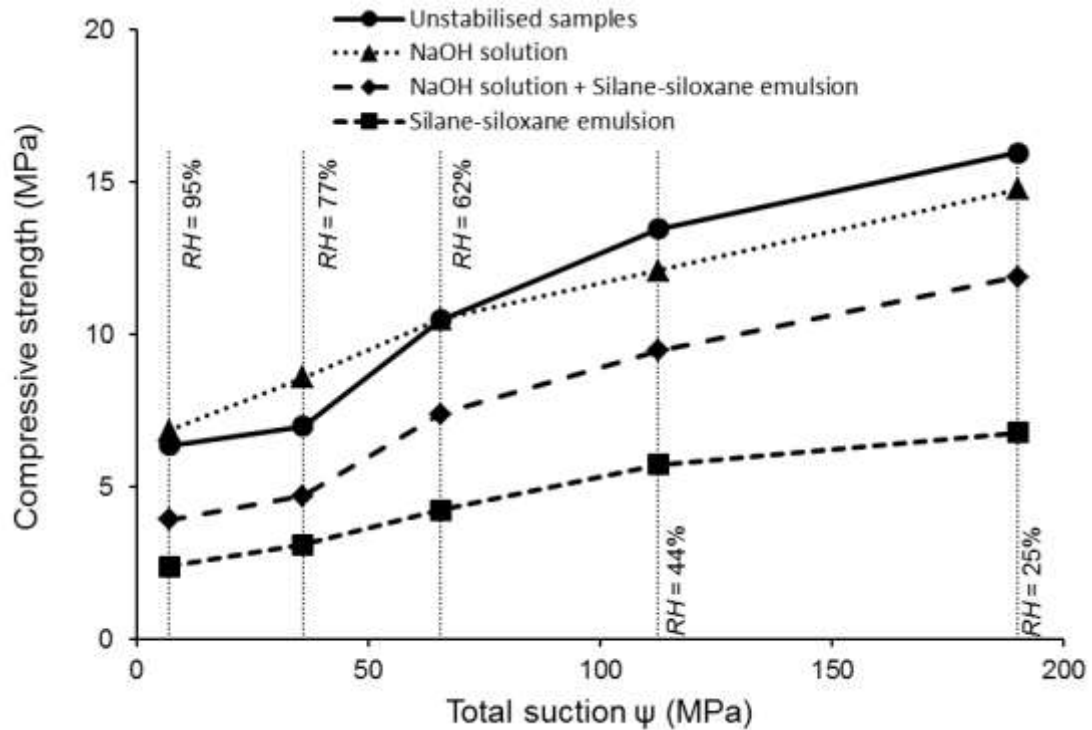


Figure 4. Variation of compressive strength with total suction: unstabilised and stabilised hypercompacted earth samples

1 Overall, the additives used in the present work appear to have a stabilising effect with respect to
2 durability during water immersion but an opposite “unstabilising” effect as far as stiffness and
3 strength are concerned. This is because the additives tend to inhibit the inter-particle bonding
4 produced by water capillarity, which is consistent with the smaller increase of stiffness and strength
5 with growing suction in stabilised samples compared to unstabilised ones. The detrimental effect of
6 stabilisation on stiffness and strength is even more evident in the two cases where the additive
7 includes the silane-siloxane emulsion. This is due to the hydrophobic nature of this emulsion, which
8 modifies the wettability of the solid grains thus disrupting the formation of stabilising capillary
9 lenses at inter-particle contacts.

10 Preliminary results from X-ray diffraction experiments currently being performed by the authors
11 (not presented in this paper) seem also to indicate the formation of a cementing zeolite fraction in
12 the samples stabilised with the NaOH solution but not in the samples stabilised with additives
13 including the silane-siloxane emulsion.

14 The reduced sensitivity of stabilised samples to variations of suction and ambient humidity is
15 further investigated in the next section in terms of their moisture buffering capacity.

16 ***EFFECT OF STABILISATION ON MOISTURE BUFFERING CAPACITY***

17 The effect of stabilisation on the ability of the material to buffer ambient humidity was explored by
18 subjecting cylindrical samples of stabilised and unstabilised hypercompacted earth to cyclic
19 variations of relative humidity inside a climatic chamber (CLIMATS Type EX2221-HA). The main
20 objective of this testing campaign was to determine the Moisture Buffering Value (MBV) of both
21 the unstabilised and stabilised material as prescribed by the norm ISO 24353 (2008). According to
22 this norm, samples were repeatedly exposed to two levels of relative humidity, corresponding to
23 75% and 53%, with each level maintained for a period of 12 hours. Temperature was fixed at 25 °C
24 throughout the cycles, which is consistent with the temperature imposed during the equalisation

1 stage of the previous mechanical tests but slightly higher than the value of 23 °C indicated by the
2 norm ISO 24353 (2008). This small difference in temperature is assumed to have a negligible
3 effect on the measured MBV.

4 Prior to the humidity cycles, all samples were equalised inside the climatic chamber at a
5 temperature of 25 °C and a relative humidity of 53% for a period of at least two weeks until a
6 constant mass was reached. Five humidity cycles were then performed, which was sufficient to
7 attain steady state conditions. Steady state conditions coincide with the measurement of three
8 identical consecutive cycles where moisture uptake at 75% humidity is equal to moisture release at
9 53% humidity. These last three cycles are referred to as the “stable cycles”, according to the norm
10 ISO 24353 (2008).

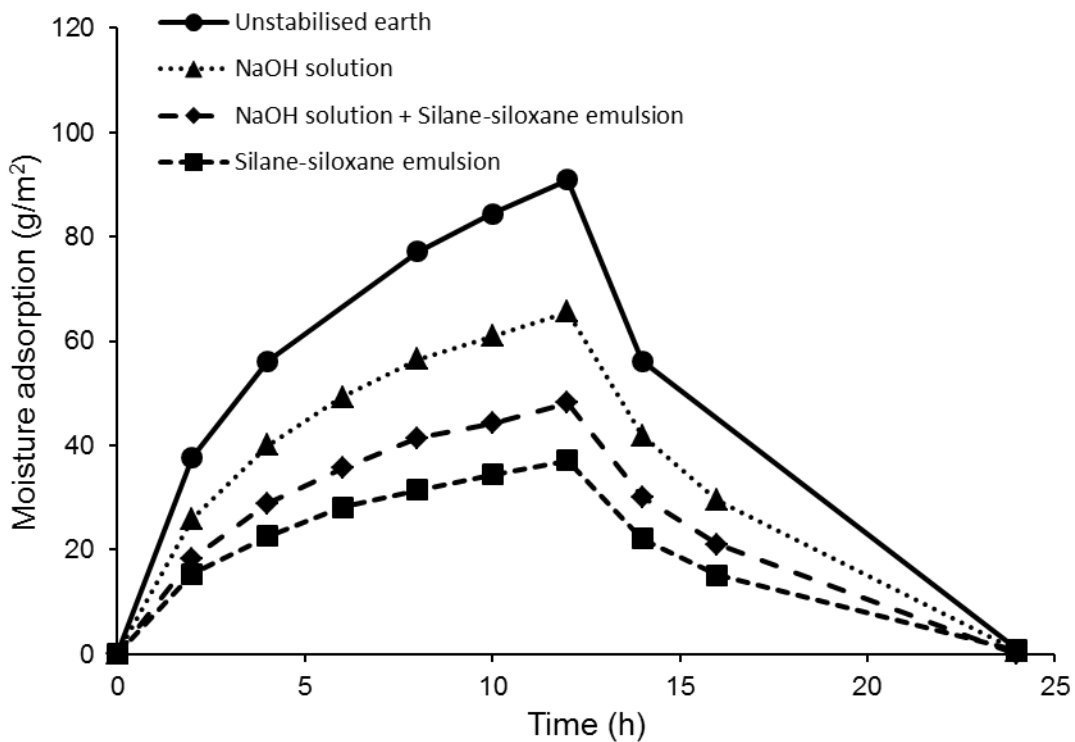
11 During tests, cylindrical samples were placed upright inside individual disposable aluminium foil
12 pans, which means that only the top and lateral surfaces of the cylinders were exposed to the
13 atmosphere of the climatic chamber. The total exposed surface was about 0.018 m², which is
14 compliant with the minimum value of 0.010 m² required by the norm ISO 24353 (2008).
15 Throughout the cycles, samples masses were periodically recorded by means of a digital scale with
16 a resolution of 0.01 grams.

17 Results are typically presented as time curves of moisture adsorption, which is defined as the ratio
18 between the change of sample mass (i.e. the difference between current and initial mass) and the
19 exposed surface. The exposed surface was calculated from the average values of samples height and
20 diameter measured both after initial equalisation (RH= 53%) and at the end of the first humidity
21 step (RH= 75%). This assures that any small change of sample dimensions owed to swelling upon
22 wetting is taken into account.

23 Figure 5 shows the final stable cycle of the moisture adsorption curves of the unstabilised and
24 stabilised samples, where each curve has been calculated as the average of three distinct

1 measurements on identical samples. Inspection of Figure 5 indicates that unstabilised samples
 2 exhibit an excellent ability to buffer moisture, probably because of the nanometric porosity of their
 3 clay fraction, as already observed by McGregor et al. (2016). Compared to unstabilised samples, all
 4 three stabilised samples exhibit a lower moisture buffering capacity, whose value depends on the
 5 type of stabiliser. Samples stabilised with the NaOH solution show a higher moisture buffering
 6 capacity than samples stabilised with the silane-siloxane emulsion, while samples stabilised with
 7 NaOH solution+silane-siloxane emulsion exhibit an intermediate behaviour between the previous
 8 two.

9 Preliminary porosimetry tests from a current experimental campaign (not presented in this paper)
 10 suggest that the reduced moisture buffering capacity of the stabilised samples might be explained by
 11 the occlusion of nanopores, which constitute the most active pore fraction in exchanging water
 12 vapour with the surrounding environment.



13

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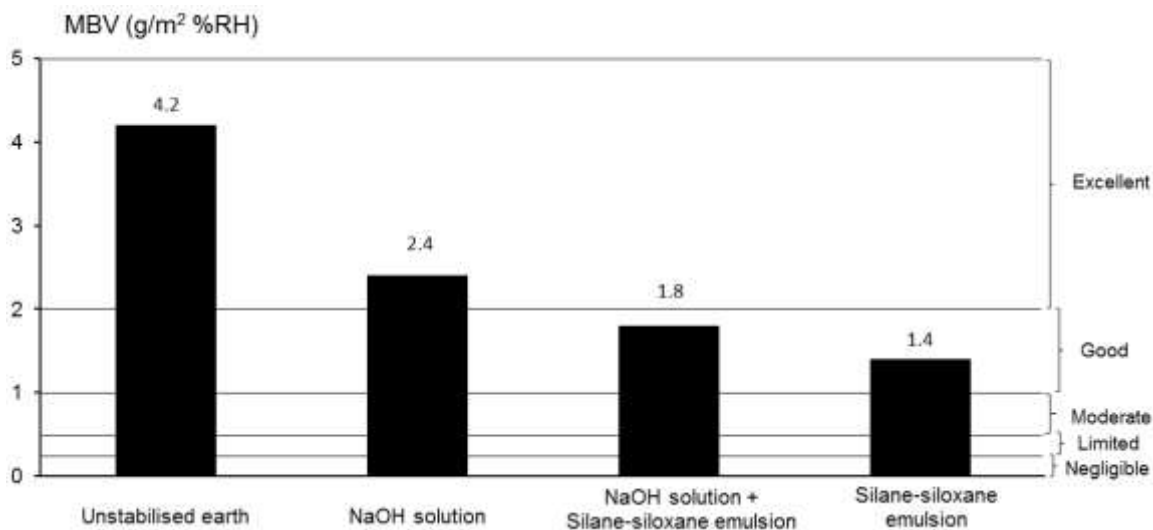
Figure 5. Last stable cycle of unstabilised and stabilised hypercompacted earth samples

1 The MBVs of the unstabilised and stabilised samples were subsequently calculated from the
2 average moisture uptakes and moisture releases of the last three stable cycles by using the
3 following equation:

$$MBV = \frac{\Delta m}{S \Delta \%RH} \quad (2)$$

4
5 where Δm is the variation of sample mass induced by the change in relative humidity, S is the
6 exposed surface and $\Delta \%RH$ is the difference between the extremes of the relative humidity cycle.

7 The calculated MBVs are plotted in Figure 6 together with the classification proposed by Rode et
8 al. (2005), which is based however on a different testing procedure where relative humidity ranges
9 between 33% and 75% with asymmetric step durations of 16h and 8h, respectively. Figure 6
10 confirms that stabilisation reduces the moisture buffering capacity of the material compared to the
11 unstabilised case. Nevertheless, the MBV of the material stabilised with the NaOH solution is still
12 classified as excellent while the MBV of the other two stabilised materials is classified as good.



13
14 *Figure 6. MBV of unstabilised and stabilised hypercompacted earth samples*

15 Overall, the stabilising additives used in the present work improve water durability at the cost of a
16 reduction of moisture buffering capacity. The choice of stabilisation method must therefore attempt

1 to balance these two requirements while also taking into account any effect on stiffness and
2 strength.

3 ***DURABILITY AGAINST WATER EROSION***

4 Durability against water erosion was further investigated by performing suction and contact tests, in
5 compliance with the norm DIN 18945 (2013), on unstabilised and stabilised hypercompacted earth
6 bricks. The stabilised earth bricks were manufactured with the same three liquid additives of the
7 stabilised cylindrical samples used in the previous testing campaigns.

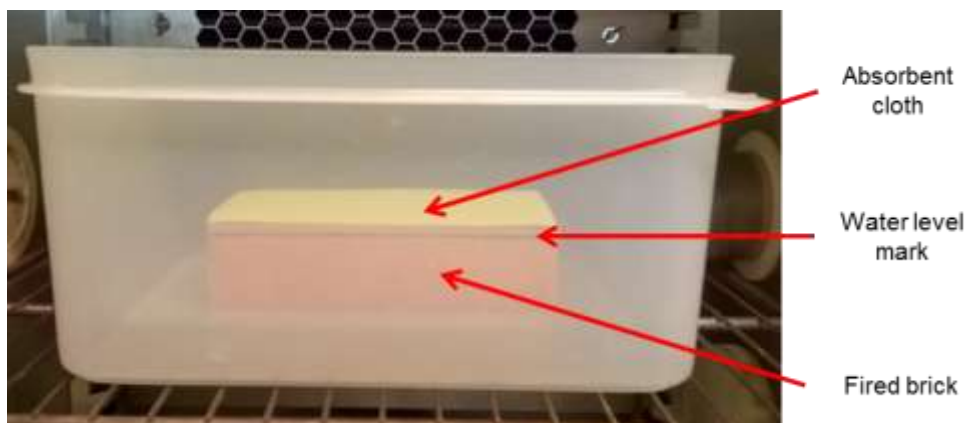
8 *Suction test*

9 Suction tests investigate the durability of earth bricks when exposed to a temporary excess of water.
10 This condition might occur, for example, in exterior timber-frame walls during driving rains with
11 water collecting between the wooden frame and the earthen infill. Also, suction tests might
12 reproduce the effect of a capillary water rise from the foundation up into the walls of a building.

13 Three identical hypercompacted bricks were tested for each stabilisation method as well as for the
14 unstabilised case. Each brick was initially equalised inside the climatic chamber at a constant
15 temperature of 23 °C and relative humidity of 50% for a period of two weeks, which was long
16 enough to attain a constant mass.

17 A support consisting of a conventional fired brick covered by an absorbent cloth was placed inside a
18 pan (Figure 7). The pan was then filled with water up to 1-5 mm below the upper edge of the fired
19 brick. After this, the compressed earth brick was placed over the absorbent cloth, which marks the
20 start of the suction test. According to the norm DIN 18945 (2013), the earth brick was visually
21 assessed at times of 30min, 3h and 24h from the beginning of the test to detect cracks and
22 permanent deformations owed to swelling.

1 Very similar results were obtained from the three bricks tested for each stabilisation method as well
2 as for the unstabilised case, which confirmed the good repeatability of the adopted experimental
3 procedure. Figure 8 shows a selection of observations for the distinct stabilisation methods at
4 different times. As expected, the unstabilised bricks exhibited the weakest response with cracks and
5 irreversible deformations already visible after only 30 minutes from the beginning of the test.
6 Instead, the earth bricks stabilised with the NaOH solution+silane-siloxane emulsion exhibited
7 greater water durability as confirmed by the appearance of cracks after 3 hours from the beginning
8 of the test. The best results were, however, obtained for the earth bricks stabilised with the NaOH
9 solution or with the silane-siloxane emulsion. These bricks showed some cracking only at the last
10 visual examination after 24 hours from the beginning of the test.



11

12

Figure 7. Set-up of suction test

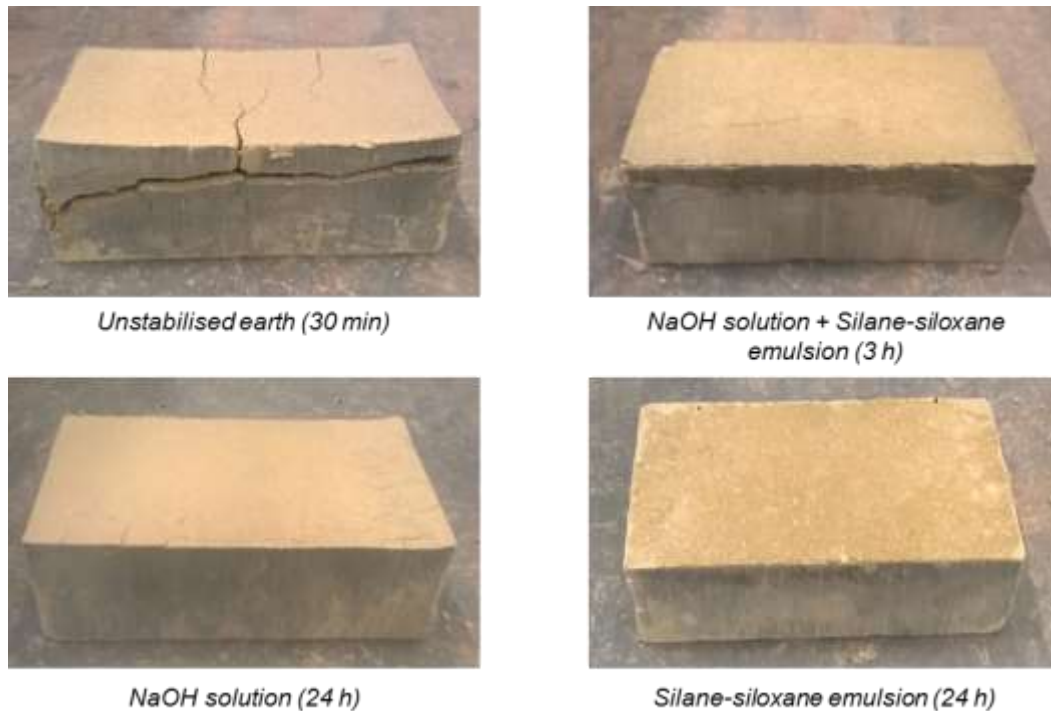


Figure 8. Results from suction tests on unstabilised and stabilised hypercompacted earth bricks

Contact test

The contact test simulates the application of a mortar joint or coating onto the bricks and assesses the response of the earth to the adsorption of moisture from the applied material (DIN 18945, 2013).

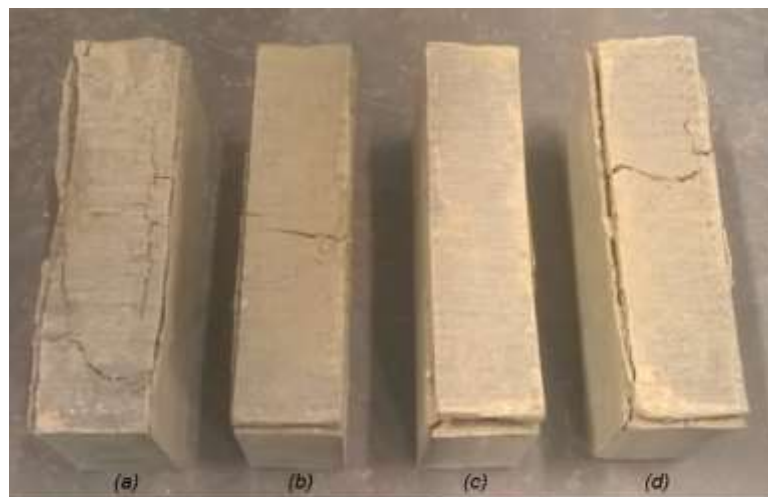
The experimental procedure consisted in placing a wet cellulose cloth on the intermediate face of the brick (Figure 9). The amount of water supplied to the brick surface by the cellulose cloth must be equal to 0.5 g/cm^2 , which reproduces the average amount of water contained in a 15 mm thick mortar layer (Schroeder, 2016). To supply the exact amount of water, the covered earth brick was placed on a balance with a resolution of 0.01 g and water was gradually added to the cloth to attain the desired weight. The earth brick with the wet cellulose cloth was then placed on two metallic supporting nuts inside a plastic container. Before sealing the container, some water was introduced at the bottom of the container with the free surface about 0.5 cm below the top of the supporting nuts. After 24 hours, the container was opened and, after removing the cellulose cloths, the bricks

1 were exposed to the atmosphere inside the laboratory for a minimum of two days. Finally, the
2 bricks were visually examined to assess the presence of cracks and the occurrence of permanent
3 deformations caused by water infiltration.

4 Unlike the suction test, only one brick was tested for each stabilisation method as well as for the
5 unstabilised case. The observations at the end of the contact tests are presented in Figure 10, which
6 shows that the bricks stabilised with the silane-siloxane emulsion exhibit less damages than the
7 other bricks. Nevertheless, all bricks showed some degree of cracking and permanent deformations.



8
9 *Figure 9. Set- up of contact test*



(a) Unstabilised earth (b) Silane-siloxane emulsion
(c) NaOH solution (d) NaOH solution + Silane-siloxane emulsion

10
11 *Figure 10. Results from contact tests on unstabilised and*
12 *stabilised hypercompacted earth bricks*

1 The norm DIN 18945 (2013) identifies different classes of compressed earth bricks based on the
 2 results from the three durability tests, i.e. immersion test, contact test and suction test. Each of these
 3 classes is suited to different applications as summarised in Table 3.

Table 3. Classes of compressed earth bricks based on durability tests (DIN 18945, 2013)

| Class | Application | Immersion test Mass loss (%) | Suction test | Contact test |
|-------|---|---------------------------------|----------------------------------|--|
| Ia | External wall exposed to natural weathering | $\leq 5\%$ | Damages observed ≥ 24 h | No cracks and no permanent swelling deformation |
| Ib | Coated external wall | $\leq 5\%$ | Damages observed ≥ 3 h | |
| II | Internal wall | $\leq 15\%$ | Damages observed ≥ 0.5 h | |
| III | Dry applications | No requirement | No requirement | No requirement |

4

5 Table 4 shows the application of the classification of Table 3 to the results from each of the three
 6 durability tests performed in this work. Note that, in Table 4, it is assumed that the immersion tests
 7 on cylindrical samples are also representative of the behaviour at the brick scale.

Table 4. Classification of earth bricks tested in the present work

| Type of stabilisation | Immersion test | Suction test | Contact test |
|---|-------------------|-----------------|-----------------|
| Unstabilised | III | III | III |
| Silane-siloxane emulsion | I | Ib | III |
| NaOH solution | II | Ib | III |
| NaOH solution+silane-siloxane emulsion | I | II | III |

8

9 As expected, the unstabilised earth bricks exhibit the worst classification and can only be employed
 10 in dry applications where they are protected from natural weathering. The best classification is
 11 instead obtained by the bricks stabilised with the silane-siloxane emulsion, which only show a small
 12 mass loss (1.36%) during immersion tests (Figure 1) and relatively limited cracking at the end of

1 suction and contact tests (Figures 8 and 10). However, compared to the other two stabilisation
2 methods, the silane-siloxane emulsion produces the largest reduction of stiffness (Figure 3),
3 strength (Figure 4) and moisture buffering capacity (Figures 5 and 6). This suggests that what is
4 gained in terms of improved water durability is lost in terms of mechanical and hygroscopic
5 characteristics.

6 Inspection of Table 4 also indicates that the norm DIN 18945 (2013) leads to different
7 classifications depending on which type of durability test is considered. The contact test appears to
8 be the most severe one leading to the conclusion that all bricks fall into the third class and are
9 therefore only suitable for dry applications.

10 ***CONCLUSIONS***

11 The present paper investigates the use of different methods for the stabilisation of hypercompacted
12 raw earth based on a combination of alkaline activation and silane-siloxane admixture. The paper
13 explores the effect of these stabilisation methods on the hygroscopic and hydromechanical
14 behaviour of the material. Results show that, in general, stabilisation significantly improve the
15 resistance of the material against water erosion. Nevertheless, the effect on strength, stiffness and
16 moisture buffering capacity is generally unfavourable, though it varies according to the chosen
17 stabilisation method. The main outcomes of the research can be summarised as follows:

- 18 • All stabilisation methods result in a reduction of stiffness and strength at different levels of
19 ambient humidity. This is due to the partial inhibition of inter-particle capillary water
20 bonding caused by the chemical stabilisers.
- 21 • The stiffness and strength of both unstabilised and stabilised samples increase as ambient
22 humidity decreases from 95% to 44% (which correspond to an increase of the total suction
23 inside the material from 7 MPa to 112 MPa). This increase of stiffness and strength is
24 however less marked for the stabilised samples than for the unstabilised ones, which

1 indicates that stabilisation makes the earth less sensitive to the variation of ambient
2 humidity.

- 3 • Stabilisation generally reduces moisture buffering capacity by an amount that depends on
4 the type of stabiliser. Samples stabilised with the NaOH solution preserve an excellent
5 ability to buffer ambient humidity while samples stabilised with the silane-siloxane
6 emulsion or with the NaOH solution+silane-siloxane emulsion exhibit only a good moisture
7 buffering capacity.
- 8 • The best resistance against water erosion is exhibited by the samples stabilised with the
9 silane-siloxane emulsion. However, even these samples show a small mass loss during
10 immersion tests and some cracks at the end of both suction and contact tests. Silane-siloxane
11 stabilisation also results in the largest deterioration of mechanical and moisture buffering
12 properties with respect to the unstabilised material.

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