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AN ASSESSMENT OF RAW MATERIALS FOR EARTH CONSTRUCTION IN COUNTY OFFALY, IRELAND.

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ABSTRACT

This paper investigates the suitability of Irish soil for earth construction in Rhode, Co. Offaly, in an effort to provide sustainable construction alternatives to a currently unsustainable building sector of high energy demand and increasing CO_2 and pollutant emission. The soil used to build a traditional earth farmhouse in Rhode was studied. The soil is too low in sand and too high in fines when compared to the optimal grading for soils for building. The liquid and plastic limits and the plastic index are lower than those considered optimal for unstabilised soils for rammed earth construction. The average linear shrinkage of the soil was lower than expected given the high amount of fines, but slightly higher than the maximum permissible values reported by some building standards. However, there was no visible cracking in any of the specimens. The low plasticity index and the low shrinkage determined suggest that, even though the soil is high in fines, these are mainly inert silts and perhaps clay minerals that do not swell.
Cement stabilisation increased the shear strength and cohesion of the soil more significantly than its compressive strength. The 15% cement stabilised earth reached the highest strength followed by the control samples which consisted of earth only however, the strength increase wasn't significant. The lime stabilisation, along with the 5% cement stabilisation caused strength loss. The drop in compressive strength and the low strength increase by the highest stabilisation are likely due to the high fine content of the soil raising the water demand and, consequently, not enough mixing water being present for hydration in the cement samples and carbonation in the lime earth soils during curing.

INTRODUCTION

With raising energy demand, CO_2 and pollutant emission and material cost in the building sector, the time has come to favour sustainable materials in construction. Earth is a low emissions material, neither CO_2 nor other gases or chemicals are released in the atmosphere as a result of earth construction. Earth is renewable as it is constantly being created through the weathering of rocks. It is also universally available and fully recyclable with no energy use. Every year, thousands of tonnes of earth, some of which can be used for building, are removed from building sites, transported at high economic and environmental expense and dumped in landfills. Several authors state that earth construction has clear competitive advantages over conventional construction which assure a promising future in years to come [1].

Earth as a building material has outstanding environmental credentials. It has a high thermal mass that allows the material to store heat and release it slowly when the heat source is removed. As a result, it can be used to build high thermal mass external walls in domestic buildings which are considered more energy efficient than walls of lightweight construction. Morel et al. [2] state that a reduction of up to 85% of energy consumed can be reached by using earth construction compared to a typical concrete house. In addition, it is well known that the embodied energy of earth (5-10 KWh/m^3) is tiny when compared to other traditional building walls such as concrete block (600-800 KWh/m^3); cement (2640) or fired brick (590-1140) [3].

Furthermore, earth walls are naturally fire proof and their large thickness (generally between 200m and 600m and density) provides great acoustic insulation. Earth is able to absorb and desorb humidity faster than any other building material therefore it balances indoor climate [4] by providing a healthy relative humidity (RH). Experiments at the FEB, University of Kassel, demonstrated that when the RH in a room was raised from 50 to 80%, earth bricks absorbed 30 times more humidity than burnt clay bricks in a period of 2 days [4].

It is estimated that 30% of the world´s population live in houses built of raw earth; and archaeological evidence suggests that earth has been used for building for about 10,000 years [3]. Buildings made with mud bricks have been found in the Russian Turkestan dating between 8000 and 6000 years BC [5]. Earth buildings exist in every continent and are abundant in Europe. Most earth buildings in Ireland were modest in scale and were built in rural areas either as dwellings or for agricultural use. Documentary evidence suggests that earth building was once wide spread throughout the country including urban areas however, few have survived. In Ireland, the majority of surviving examples can be classified as cob or mudwall. Most were built between the 15th and the 19th centuries and the most outstanding surviving example is probably Mayglass Cottage in Co. Wexford. Most surviving examples in Ireland were built with unshuttered walling but shuttered examples also survive.

Abundant work on earth stabilization has been undertaken in the last decade. When Portland cement is added to the earth, it reacts in two different ways. Firstly, the cement clinkers hydrate forming cementing hydrates (CSH) and releasing lime ($Ca\ (OH)_2$) thus producing a mortar with the sandy particles in the clay. Secondly, the clinkers may react with the clay and lime in the soil forming further cementing hydrates. The structure of the soil and its grain size distribution determine the optimal percentage of cement [6]; and the denser the soil the lower the cement needed to reach a given strength [7]. Minke [8], found that small percentages of cement stabilisation (< 2%) resulted in a reduction in strength of the soil probably due to the cement interfering with the inter-particle bonding of the clay. Bhatnagar [9] states that 3%-12% cement content is optimal for stabilization. In this project, 5 and 15% blends were chosen.

Studies have shown that lime stabilization improves the strength, stiffness, workability and water adsorption of soil for rammed earth construction [10, 11, 12]. Ciancio et al. [13] determined the optimum hydrated lime content for stabilised rammed earth at 4% (highest compressive strength). However, Ngowi [6] found strength to increase with lime addition between 5 and 15%, with the 15% stabilisation achieving the greatest strength. Due to these conflicting reports 5% and 15% lime contents were used in this project. Lime reacts with earth in a number ways including cation exchange, pozzolanic reaction and carbonation [13]. Lime increases the pH of the soil, encouraging the solubility of both silica and alumina present the soil which can then react to form calcium silicate and aluminate hydrates [13].

MATERIALS AND METHODS

1.1 The building

The building is located on a farm in Rhode, Co. Offaly. It is single story and rectangular in plan; probably dating from the 1800s. It was probably built as a dwelling and later converted for agricultural use. The earth walls are approximately 0.3m thick. They were constructed on top of a stone footing which is approximately 0.5 metres in height (Figure 1). Stone work was also used in the corners. Here the stone was interlocked with earth to increase the overall strength of a vulnerable area. Stonework was used around the door and window openings. Currently the building is roofed in galvanised sheeting but the original roof was probably thatched. Significant pebbles sized from 20mm downwards and small traces of straw are evident. Structural cracks across the earth wall are clearly visible (Figure 2). The raw material was probably sourced from an adjacent field (A in Figure 1) next to the building (B). C marks the site where the soil was taken for testing.

1.2 Sampling and grading

Raw earth from the site as well as material from the building were gathered. Approximately 0.3m topsoil was removed, traces of organic matter were still visible at this depth therefore, the soil was further excavated at a depth of 1m, divided into samples and labelled. A wet sieve analysis was carried (BS 1377-2:1990 [14]) to determine the clay, sand and gravel content. In addition, samples (300 x 300 mm cubes) were taken from the top of a gable wall.

Figure 1: Right- Traditional earth building at Rhode, County Offaly. Left- Building location (B) with respect to earth pits both original (A) and current (C).

Figure 2: Staggered fractures across the wall.

1.3 Mixing, compaction and curing

The soil was placed in a sorting tray and any stones above 20 mm removed. Screening to remove the fraction between 10-20mm [15] is generally recommended to avoid short-term damage. The soil had a moisture content of 21% before any stabilizer or water was added. The soil and stabilizer were mixed with water in a concrete mixer for 10 minutes. The mix composition is set out in Table 1. The mixes were placed in 100 mm cubic moulds which were filled in two layers and tamped in accordance with (EN 12390-2) [16]. They were wrapped in clear film for curing. The straw failed to mix through the soil in the mixer and had to be hand mixed. After three days the soil and cement specimens were removed from the moulds and the lime specimens left in moulds for three weeks. They were then wrapped in clear film and placed at 20°C and 60-70% relative humidity (28 and 56 days curing for cement and lime stabilised respectively).

Table 1: Mix composition of stabilized earth specimens.

mix	soil (kg)	cement (kg)	hydrated lime (kg)	straw (kg)	water (l)
15% cement	10	1.5	0	0	0.8
5% cement	10	0.5	0	0	0.26
earth only (control)	10	0	0	0	0
15% lime	10	0	1.5	0	1.7
5% lime	10	0	0.5	0	0.56
15% lime + straw	10	0	1.5	0.15	1.7

1.4 Optimum moisture content and maximum dry density

The compaction characteristics were determined with the standard Proctor test (BS 1377-4: 1990: 3.3) [17] which determines the optimal moisture content at which the soil will achieve its maximum density. This property is relevant as earth construction benefits from having the soil compacted to a maximum density which increases strength. Five samples were prepared, the moisture content was determined and increased in increments of approximately 2%. The soil was then placed in three equal layers in a standard cylindrical mould with a known volume (1000 cm^3) and compacted with an automatic rammer. The mould was then removed from the machine and weighed before and after the soil sample was removed, the moisture content was then calculated and plotted.

1.5 Particle Density

The dry particle density of the soil was determined using the density bottle method in accordance with (BS 1377-2: 1990: 8.3)[16] at 2.63 Mg/m^3 (mega grams per cubic meter or g/cm^3). Generally particle density of normal soils is 2.65 g/cm^3. The particle density is higher if heavy minerals are present in the soil. It slightly increases with the amount of fines and decreases with increasing organic matter. The soil strength generally escalates with rising dry density.

1.6 Compressive strength

The soil samples were tested under unconfined compression tested using the Zwick 1474 with a load rate of 50 N/s. The samples from the building could not be cut in an appropriate way in order to be tested. The load applied and the vertical displacement was automatically recorded. This data was then inputted into an excel file to create a stress strain curve. The compressive strength, strain and modulus of elasticity were calculated using the following equations:

Stress = Force/Area $\sigma = \frac{F}{A}$ (1)

Strain = Change in length/ Original length $\varepsilon = \frac{\Delta l}{l_o}$ (2)

Modulus of elasticity = Stress/Strain $E = \frac{\sigma}{\varepsilon}$ (3)

1.7 Shear Strength

The cement stabilised earth was tested in shear in accordance with BS 1377-7: 1990:4 and ASTM D3080 [18, 19] using a standard shear box apparatus. During trial tests, it was noted that a higher normal stress would be required in order to keep the sample in place while testing. Normal stresses of 100 kPa and 200 kPa were applied. The apparatus applied a horizontal force which had a displacement rate of 0.6096 mm/min. The data were recorded manually from the dials and imputed into an excel file. With the selected displacement rate, it took approximately 10 minutes to carry out each test.

$$Horizontal\ displacement\ mm = rate\ of\ displacement\ mm/\min X\ time\ mins \quad (4)$$
$$Vertical\ displacement\ mm = dial\ divs\ X\ 0.002 \quad (5)$$
$$Shear\ Stress\ (\tau) = \frac{Cr.R}{3.6} kPa \quad (6)$$

Where:

Cr = Load ring calibration (N/div)

R = Load dial reading (div)

The normal stressed used versus the maximum shear strength obtained was represented in graphs and the friction angle and a cohesion calculated. The friction angle was calculated as the inverse tangent of the slope of the (normal stressed vs maximum shear) line while the cohesion was calculated at the intersection of the line with the y-axis.

1.8 Liquid and plastic limits and plastic index

These were measured using the cone penetration method (BS 1377-2: 1990) [16]. A standardised cone penetrates the soil a number of times at different moisture contents and a graph is plotted. The liquid limit of the soil is read at a cone penetration of 20mm [20]. The liquid limit establishes the water content at which the soil begins to flow. The plastic limit establishes the lowest moisture content at which the soil remains plastic, with lower moisture content the soil cracks when molded. A standard specimen is prepared and rolled in a ball until cracks appear on the surface, then the ball is divided and a thread of approximately 6 mm diameter created. The thread is then rolled with the palm of the hand to reduce its diameter to 3mm. This process is repeated a number of times, until the 3mm thread crumbles. The crumbled threads are then gathered and the moisture content measured [20]. The difference between both values is called the plasticity (or plastic) index. The plasticity index denotes the water content increase (as % of dry weight) required for a soil to pass from a plastic to a liquid state.

1.9 Linear shrinkage

It was determined by measuring the change in length of a semi-cylindrical bar, the measurement is taken when the earth has completely dried out coming from a state where it was close to its liquid limit (BS 1377-2: 1990: 6.5)[16].

RESULTS AND DISCUSSION

2.1 Soil characteristics

The characteristics of the soil are included in Table 2. Studies carried out by Bryan , Keable and Burroughs [21-25] suggest an approximate optimal grading of earth for building as follows: 20 - 35% clay, 30 - 80% sand and 10 - 62% gravel. In addition, according to a comprehensive review of grading carried out by Maniatidis and Walker [26] for rammed earth construction, the minimum percentage of combined clay and silt should be between 20 and 25% and the maximum between 30 and 35%. Similarly, the minimum percentage of sand should be between 50 and 55% and the maximum between 70 and 75%. Therefore, according to all of the above, the soil in this paper is too low in sand and too high in fines (clay and silt).

Table 2: Properties of the earth. OMC-Optimum moisture content; PI- plastic index.

Grading %	OMC (%)	Maximum dry density (Mg/m^3)	Particle density (Mg/m^3)	Liquid and plastic limits (%)	PI	Linear shrinkage (%)
31.8 gravel 26.9 sand 41.3 silt/ clay	14	1.79	2.63	22 / 8	14	3.08

The liquid and plastic limits measured and the low plastic index of the soil (14) agree with the high content in fines, indicating that the soil will soften significantly with a small increase in water content.

The liquid and plastic limits define the transitions between liquid and plastic behavior. The liquid limit of the soil (water content at which the soil begins to flow) is 22%. The plastic limit (lowest moisture content at which the soil remains plastic) is 8%. Houben & Guillaud [15] in [26] state that the optimal liquid limit for unstabilized soils should be between 25 and 50% (30-35% preferred) and the plastic limit between 10 and 25% (12-22% preferred). According to these, the limits of the soil studied are low.

The plasticity index is an indication of the clay content and characteristics of the soil. Often, a higher plasticity index is indicative of higher clay content and/or active clay mineral and suggests that higher shrinkage will occur when the earth dries. The low plasticity index of the soil studied agrees with the low shrinkage determined (Table 2). These suggest that, even though the soil is high in fines, these are mainly inert silts and perhaps clay minerals that do not swell.
The material has some similarities with the boulder clays of Dublin studied by Farrel and Wall [27], in particular with the Dublin brown boulder clay, a stiff sandy gravelly clay of low plasticity with a percentage of fines around 35% (25-40%) and a low plastic index of 10 to 15% indicating that the soil with soften significantly with a small increase in water content.

According to Little and Morton (2001) in Foster et al. [28], this soil would be suited for mudwall construction but not for rammed earth techniques on account of the low sand and high clay proportions. According to these authors, rammed earth techniques are most suited to soils that have lower proportions of clay (less than 10%) and higher proportions of sand and gravel, while mudwall can be carried out with heavier soils, which contain higher proportions of clay (15-40%).

The average linear shrinkage of the soil (3.08%) was lower than expected given the high amount of fines. Excessive linear shrinkage can lead to different problems such as structural defects and surface cracking. The 3.08% value is relatively high according to the Austrian standards that have a maximum permissible linear shrinkage of less than 2.5% [29]. Similarly, Keable [23] and Little [30] give values of 2% and 3% for allowable linear shrinkage. However, there was no visible cracking or warping on any of the specimens.

Burroughs [25] (using treatments ranging from 4–8% total cement and/or lime) identifies “favorable” soils, with stabilization success rates over 80%, as those with linear shrinkage under 6.0% and PI under 15%; and linear shrinkage ranging from 6.0 to 11.0% and PI 15–30% and sand content under 64%. The author identified “unfavorable” soils, with stabilization success rates under 60% as those with shrinkage 6.0–11.0, PI 15–30, and sand content over 64%, or with shrinkage and PI greater than 11.0 and 30 respectively. According to this author, the soil at Rhode would be suitable for stabilization however, as it can be seen below, only high cement stabilization increased the compressive and shear strengths of the soil. As discussed below, this is probably due to the low mixing water content leading to poor early carbonation and hydration in the soil. Unlike Burroughs [25], Maniatidis and Walker [26] assert that a soil suitable for cement stabilization should have a significant sand content, at least greater than 50% and preferably closer to 75%, and at the same time low clay content, typically less that 25%. Therefore, according to these authors the soil is unsuitable for cement stabilization.

The compaction curve determined with the standard Proctor appears in figure 3 which shows an optimum moisture content of 14% and a maximum dry density of 1.79 Mg/m^3. The optimal moisture content at which the soil becomes most dense and achieves its maximum dry density is 14%. This establishes the maximum practically-reachable density of the soil at 1.79 Mg/m^3.

The dry density of the soil is important in earth construction to calculate loads on structural elements. A broad range of dry density values have been reported for rammed earth, varying from 1700 kg/m^3 to 2200 kg/m^3 [29, 15]. The soil has an average particle density value of 2.63 Megagrams /m^3 (2630 kg/m^3) rating slightly over the values reported by the authors above.

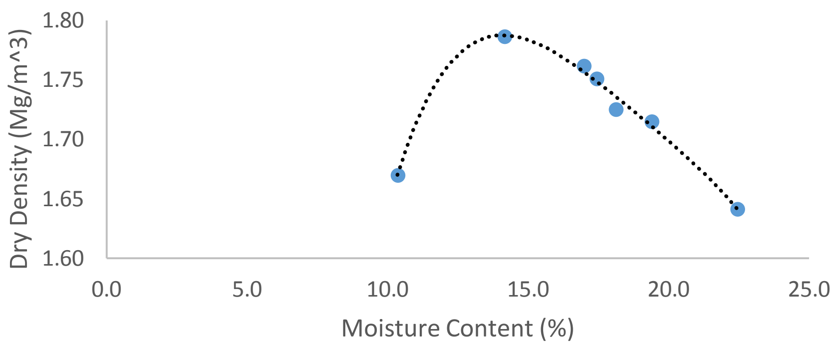

Figure 3. Compaction curve from standard proctor test.

2.2 Compressive strength of stabilised soil

The 15% cement stabilised earth reached the highest strength (1.80 N/mm^2) followed by the control samples which consisted of earth only (Figure 4). The cement addition didn't significantly raise strength and the results are lower than those reported by previous authors: Simenson [31] found a significant average compressive strength increase for a soil with 6% cement stabilization (raising from 0.44 N/mm2 to 4.85) while the 15% cement stabilization in this study only increases the strength of the soil marginally (Figure 4). The lime stabilised samples, along with the 5% cement stabilisation caused strength loss. The drop in strength is likely due to the high fine content of the soil raising the water demand and, consequently, not enough mixing water leading to a lack of moisture for hydration in the cement samples and carbonation in the lime earth soils during curing.

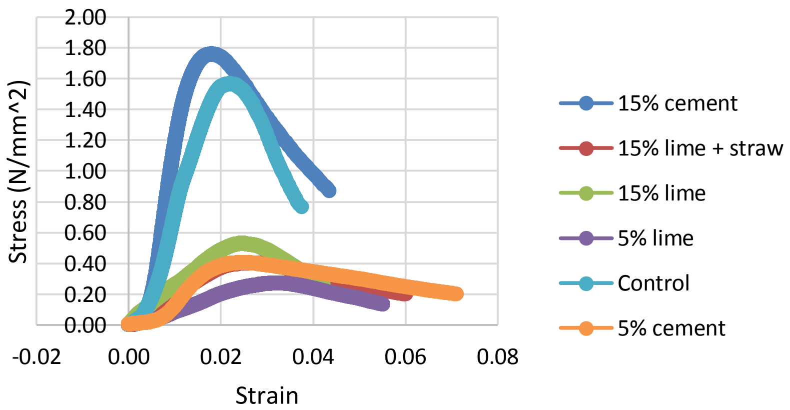

Figure 4. Deformation of specimens on stress application and peak stress of earth and stabilized earth.

Alam et al. [32], for a soil with 19 and 34% plastic and liquid limits respectively and 16% OMC also found a drop in strength with lime addition up to 7% and a slight increase (1.04 up to 1.28 N/mm^2) with 10% lime stabilization. The authors found a slight strength drop at 5% cement stabilization (1.02 N/mm^2) and strength increases at 7 and 10% cement stabilization (1.30 and 2.00 respectively). Walker [33] recommends cement contents of 5-10% by volume for soils with a plastic index under 15 to reach compressive strengths ranging between 1 and 3 N/mm^2.

The lime stabilization results agree with previous authors [13] reporting strength increase with increasing lime addition (0.28 N/mm^2 of the 5% lime vs 0.55 N/mm^2 for the 15%). However, the values are lower (e.g 1.2 N/mm^2 strength of the 5% lime vs 0.28 N/mm^2 in this study). As aforementioned, not enough moisture was present for carbonation to take place and this undermined strength.

The cement stabilised specimens failed similarly to Portland cement composites (Figure 5): considerable fracturing is evidenced on failure but a significant part of the specimen remains cohesive. In contrast, in the lime stabilised specimens, extensive cracking occurred before total collapse. The lime and straw cubes did not crumbled to the extent of the lime specimens as the straw fibres held the material.

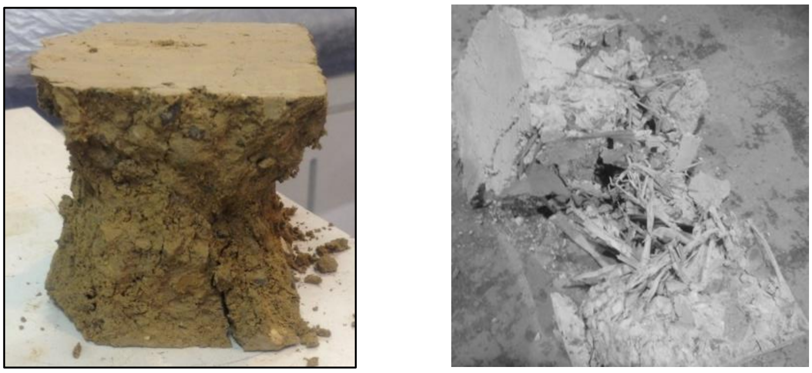

Figure 5. Failure of the 15% cement stabilized earth (left) and lime stabilized earth with straw (right).

3.3 Shear strength

As expected, the higher percentage of cement resulted in a higher shear resistance (Figure 6). It was also observed that the 15% cement sample showed a brittle behaviour, shearing soon after the peak stress. Maximum shear stress values of 768 and 782 kN/m^2 were obtained for the samples with 15% cement stabilisation (using a normal stress of 100 and 200 kPa respectively). The 5% cement stabilised samples had shear strength values of 345 and 482 kN/m^2 (at normal stresses of 100 and 200 kPa respectively). These results are generally lower than those reported by previous authors. E.g. Simenson, [31] reports an average shear stress of 1337 kN/m^2 for a soil with a 6% cement stabilisation. However, the Irish brown boulder clay is usually firm in consistency and has typical undrained shear strengths of 60 to 75 kN/m^2 [34] and a typical firm soil has a shear strength between 40 and 75 kN/m^2 [35] therefore, cement stabilisation significantly increased the shear strength of the soil. The shear resistance of soil is a result of friction and interlocking of particles as well as cementation or bonding at particle contacts. Therefore, the strength increase is likely due to cement hydrates increasing the number and strength of soil particle connections. The stabilised soil showed some residual strength after failure, which was probably owed to the roughness of the shear plane.

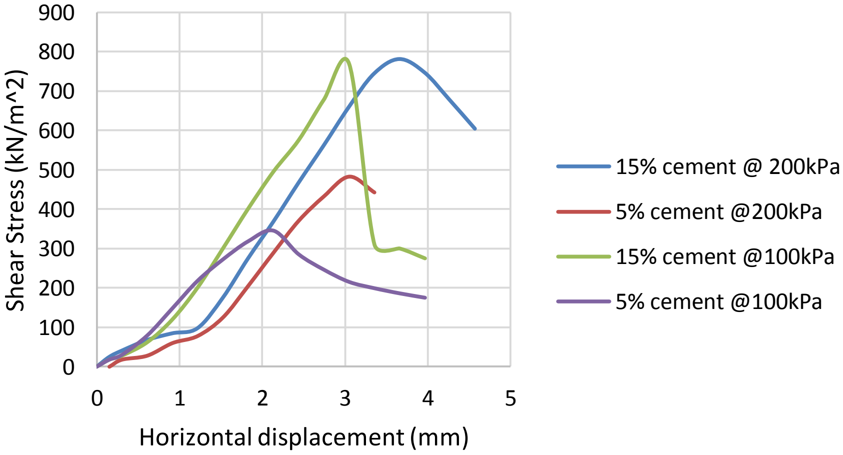

Figure 6. Shear stress v horizontal displacement.

All the specimens failed similarly, shearing in two halves with little cracking throughout the samples (Figure 7). It was noted that the soil with the higher percentage of cement resulted in one half of the shear sample been bigger.

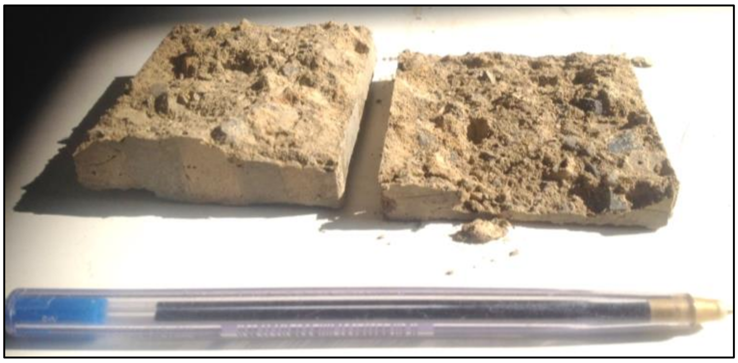

Figure 7. Shear failure of 15% cement earth specimen.

Figure 8 illustrates the normal stress applied versus the maximum shear strength obtained. From here, a friction angle of 53.9° and a cohesion of 208 kPa were calculated for the 5% cement stabilisation and a friction angle of 7.9° and a cohesion of 754 kPa for the 15% stabilisation. Cohesion ranging between 5 and 50 kPa would be expected depending on the type of soil [35] therefore, stabilisation significantly increased cohesion.

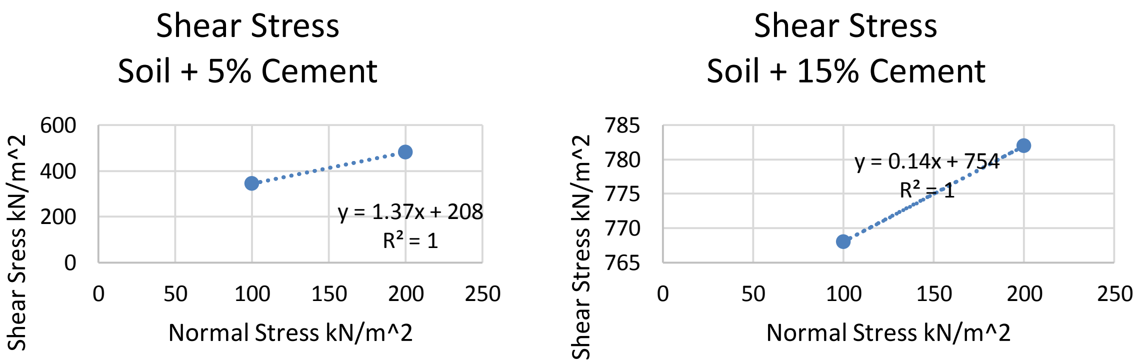

Figure 8. Maximum shear stress vs normal stress of cement stabilised earth.

CONCLUSION

The soil in this paper is too low in sand and too high in fines (clay and silt) when compared to the optimal grading for soils for building. The liquid (22%) and plastic (8%) limits and the low plastic index of the soil (14) are lower than those considered optimal for unstabilized soils for rammed earth construction. The limits agree with the high content in fines, indicating that the soil will soften significantly with a small increase in water content. The material has some similarities with the Dublin brown boulder clay, a stiff sandy gravelly clay of low plasticity with a percentage of fines around 35% (25-40%) and a low plastic index of 10 to 15%.

The average linear shrinkage of the soil (3.08%) was lower than expected given the high amount of fines but slightly higher than the maximum permissible values reported by some building standards. However, there was no visible cracking on any of the specimens. The low plasticity index and the low shrinkage determined suggest that, even though the soil is high in fines, these are mainly inert silts and perhaps clay minerals that do not swell.

The standard Proctor test established that optimal moisture content at which the soil becomes most dense and achieves its maximum dry density at 14% and the maximum practically-reachable density of the soil at 1.79 Mg/m3.

Cement stabilisation increased the shear strength of the soil to a much greater extent than its compressive strength. The 15% cement stabilised earth reached the highest strength followed by the control samples which consisted of earth only. However, the strength increase wasn't significant.

The lime stabilisation, along with the 5% cement stabilisation caused compressive strength loss. The drop in compressive strength and the low increase by the highest stabilisation are likely due to the high fine content of the soil raising the water demand and, consequently, not enough mixing water being present for hydration in the cement samples and carbonation in the lime earth soils during curing. Cement stabilisation significantly increased the shear strength and the cohesion of the soil (754 kPa and 208 kPa for the 15% and 5% cement stabilisation respectively) likely on account of the cement hydrates increasing the number and strength of the soil particles connections. The higher percentage of cement resulted in a higher shear resistance. Maximum shear stress values of 768 kN/m^2 and 782 kN/m^2 were obtained for the samples with 15% cement stabilisation while the 5% cement stabilised samples had shear strength values of 345 kN/m^2 and 482 kN/m^2.

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