Chapter 17
Advances in the Use of Biological Stabilisers and Hyper-compaction for Sustainable Earthen Construction Materials

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17.1 Introduction

The construction industry is one of the largest contributors to carbon emissions, and therefore, there is considerable interest in research to transform the current industry to be more sustainable, partly by developing new eco-friendly construction materials and techniques. The use of unbaked earth bricks as a building material has clear advantages in the field of sustainability over conventional construction reducing carbon emissions and energy consumption throughout the lifetime of buildings (Morel et al. 2001; Gallipoli et al. 2017). "Raw Earth" consists of a compacted mix of soil and water which is put in place with the least possible transformation (Jaquin et al. 2009) and because of its hydrophilic nature, exhibits a strong tendency to adsorb or release moisture, and therefore to emit or store latent heat, depending on current levels of ambient humidity. Two key barriers to the wider use of "Raw Earth" are poor mechanical properties and questions over durability, and both are traditionally tackled by using stabilisers. However, when the stabiliser is cement, as is most common, the material produced is really a weak concrete and has the carbon footprint approaching that material (Lax 2010). Here we present findings from two avenues of research under the TERRE project, a European Commission funded project training early stage researchers in the development of eco-friendly construction, including earthen materials. Delivering improved mechanical properties and good durability is tackled here in two ways. Firstly, the use of biopolymer stabilisers is presented

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with an emphasis on durability. Secondly, a new means of manufacture using hyper-compaction is presented where the focus is on the mechanical properties.

17.2 Durability of Earthen Construction Materials

Durability has always been a key issue to the acceptance of earthen materials. The earliest known earthen construction material was used in Mesopotamia and consisted of hand-moulded alluvial deposit mixtures (Deboucha and Hashim 2011). With time, organic compounds such as animal dung and plant extracts were added to these soil mixtures to improve their erosional resistance (Ngowi 1997). One class of modern, widely available organic products are biopolymers which are receiving attention as stabilisers for earthen materials due to their potential green credentials (Chang et al. 2016). Recent work reported in Aguilar et al. (2016) and Nakamatsu et al. (2017) has investigated the use of biopolymers (namely chitosan and carrageenan) as stabilisers and has reported that the addition of these biopolymers improved mechanical and durability performance of earthen materials. Very recently, the mechanical behaviour of earthen construction materials stabilised with the biopolymers guar gum and xanthan gum was studied by Muguda et al. (2017) which showed that the addition of these biopolymers improved compressive and tensile strengths. These biopolymers sequester CO_2 during production (Chang et al. 2016; Krishna Leela and Sharma 2000) in contrast to cement, which leads to the opposite; however, energy required in production of the gums may be much greater than for an equivalent amount of cement (e.g. see Lo et al. 1997), so it would be good to see a full life cycle assessment of these biopolymer-based stabilisers, which is not yet available. At present, durability performance of earthen construction materials is assessed via different tests as described in various international standards, all of which measure the resistance of the earthen material against the erosional action of water. For unstabilised earthen construction, the standard tests are immersion, contact, drip and suction tests, while for stabilised materials, accelerated erosion, spray and wire brush tests are conducted to assess durability. Here we examine the durability properties of the materials studied in Muguda et al. (2017).

17.3 Materials and Methods: Durability Testing

17.3.1 Materials

For this study, an engineered soil mixture comprising 20% Kaolin, 70% sharp sand and 10% gravel by mass was used. This mix complies with the requirements for earthen construction materials given in Oliver and Mesbah (1987) and Houben and Guillaud (1994) and is a combination widely investigated in earthen construction.

Table 17.1 Physical properties of the unamended soil mixture used in this study

Index property		*Atterberg limits*	
Standard compaction tests (BS 1377-2 1990; BS 1337-4 1990)		Liquid limit (%)	36
Maximum dry density (kg/m^3)	1870	Plastic limit (%)	18
Optimum moisture content (%)	9.8	Plasticity index (%)	18
Grain size distribution			
Gravel content (%)	10		
Sand content (%)	70		
Silt content (≤63 μm, %)	04		
Clay content (≤2 μm, %)	16		

Atterberg limits and compaction characteristics for the unamended soil mixture are given in Table 17.1. Commercially available guar gum and xanthan gum were chosen as biopolymer stabilisers in this study. The biopolymer stabiliser content was maintained at 2.0%.

17.3.2 Methodology

Stabilisation using biopolymers is achieved through "hydrogels" which are formed through the interaction of soil, biopolymer and water particles. Unlike cementitious bonds formed due to hydration of cement, these "hydrogels" bind soil particles through a combination of chemical bonds and soil suction (Muguda, et al. 2017). As these hydrogels become susceptible to weakening on contact with water, durability tests such as accelerated erosion tests, spray tests and wire brush tests were considered to be too vigorous and hence an alternative test was chosen, namely the "Geelong" test (NZS 4298, 1998). Samples in the form of 150 × 150 × 20-mm tiles and 38 mm diameter and 76-mm-length cylinders were tested. In both cases, the required bulk mass of the sample was placed in a mould and statically compacted. All blocks were compacted to achieve an initial dry density equivalent to the maximum dry density, i.e. 1870 kg/m^3. Once the sample was compacted, it was carefully removed from the mould and left to air cure at a relative humidity of 50% and temperature of 21 °C. The durability tests were then performed on samples cured for 7 days.

The test procedure involves the dripping of 100 ml of water for up to 60 min from a height of 400 mm on to the surface of the sample. For the tile samples, the surface was kept at an inclination of 2H:1V, while for cylindrical specimens the surface of erosion was held perpendicular (Fig. 17.1). As well as noting the final erosion at 60 min as recommended by the code, the erosion depths were also noted at intermediate 15 min intervals. The results presented herein are the average values of

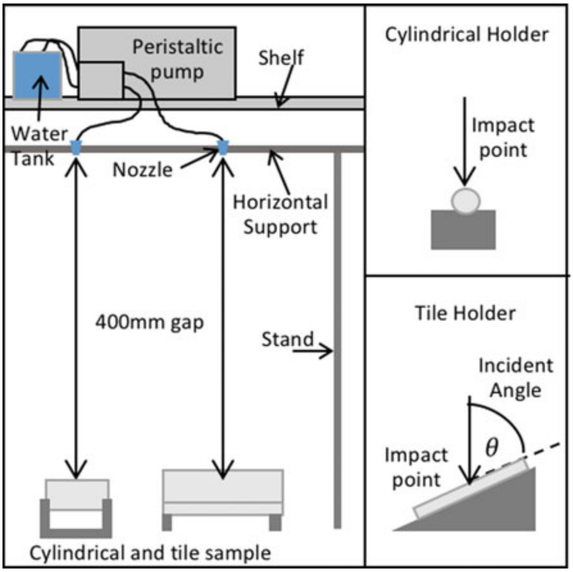

Fig. 17.1 Schematic representation of durability test set-up

five replicates. These results are compared with those of the unamended soil mixture and 8.0% cement-treated specimens.

17.4 Results and Discussion: Durability

Table 17.2 presents the final erosional depth after 60 min for both tile and cylindrical samples for unamended, cement and biopolymer-stabilised material. It can be observed from the results that unamended samples failed against the permissible limit for both tile and cylindrical samples, while cement-stabilised samples had negligible erosion. In the case of the biopolymer-treated samples, both guar- and xanthan gum-stabilised samples had erosional depths within 5 mm and passed the durability tests satisfactorily, with xanthan gum-treated samples performing better. The erosion rates for the biopolymer-treated samples are presented in Fig. 17.2. For both the biopolymers, the observed rates of erosion for tile samples are higher than for the cylindrical samples. This higher rate of erosion may be due to the sample orientation with the drip direction. It is also notable that the rate of erosion for xanthan gum-treated samples was less than guar gum-treated samples. In order to assess the time required to achieve an erosion depth of 5 mm, linear extrapolation was carried out indicating that guar gum-treated samples would require 118 and 200 min for tile and cylindrical samples, respectively, while xanthan gum samples would require 165 and 235 min.

It can be concluded from the above findings that biopolymer-treated earthen materials appear to have much improved durability properties as compared to unstabilised

Table 17.2 Final erosional depths after 60 min for both sample types (tile and cylinder)

Sample	Eroded depth (mm)		Remarks
	Tile	Cylinder	
Unamended	8.00	10.00	Permissible limit as per NZS 4298 is 5 mm
Cement treated	0.10	0.01	
Guar gum—2.0%	2.65	1.51	
Xanthan gum—2.0%	1.86	1.25	

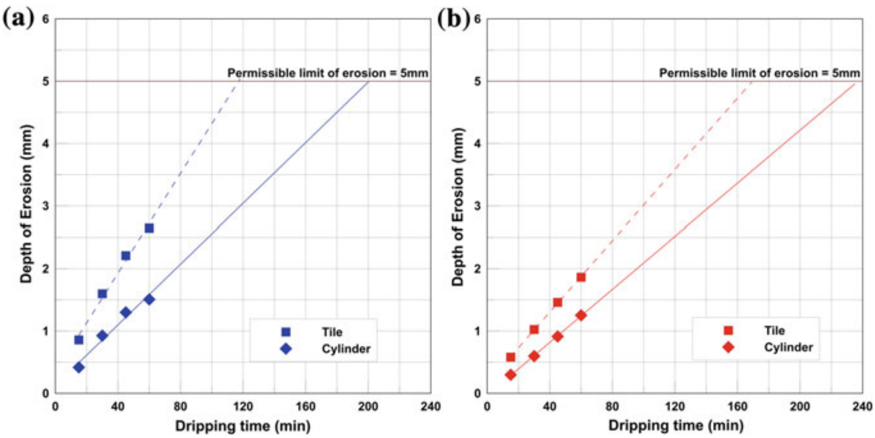

Fig. 17.2 Depth of erosion versus dripping time for both tile and cylindrical samples **a** guar gum, **b** xanthan gum

materials. While the performance of biopolymer-treated earth material cannot match that of cement-treated material, it can still provide an acceptable level of durability as measured by this test. These results support the further investigation of biopolymers for this purpose.

17.5 Hyper-Compaction

It is well known that one of the keys to achieve high strength and stiffness of earthen materials is the compactive effort used in creation of the in situ or unit-based materials. In particular, the application of a pressure significantly higher than that applied during production of conventional earth bricks increases dry density and consequently stiffness and strength, thus resulting in mechanical characteristics similar to those of conventional building materials. An innovative static hyper-compaction method has been developed by the authors using compaction effort corresponding to a 1D stress level of 100 MPa. Table 17.3 summarises previous studies using this

Table 17.3 Comparison in terms of compressive strength

Material	Compressive strength (MPa)
Compressed earth bricks (Bruno et al. 2016)	14.6
Compacted unstabilised and stabilised soils (Guetlala and Guenford 1997)	From 5.2 to 12.9
Standard masonry bricks (ASTM C270 2014)	From 6.9 to 27.6

method (Bruno et al. 2016) indicating that unstabilised hyper-compacted earth bricks are competitive with standard masonry construction according to ASTM C270 (2014) in terms of compressive strength.

In the study presented below, hyper-compaction was applied to soil mixtures containing large proportions of fine materials. Finer soils are able to retain more water than coarser soils thus resulting in stronger hygroscopic behaviour. However, a larger fine fraction may weaken mechanical characteristics and undermine durability. Properties such as stiffness and strength were measured by performing unconfined compression tests on cylindrical raw earth samples compacted at very high pressure (100 MPa) at the optimum water content and after equalisation at the same temperature (25 °C) and relative humidity (62%).

17.6 Materials and Methods: Hyper-Compaction

17.6.1 Soil Type and Index Properties

The earth used in this work has been provided by the Bouisset brickwork factory from the region of Toulouse in France. The grain size distribution is an influential parameter for assessing the suitability of earthen materials for construction and its role affecting the soil behaviour make it central to most existing recommendations (Delgado and Guerrero 2007). The grading curve of the soil used here has been determined by means of wet sieving and sedimentation tests to French standards. The grain size distribution of the Bouisset soil lies close to the upper limit of current recommendations by AFNOR (2001)/CRATerre-EAG (1998) and MOPT (1992) relevant to the manufacture of earth bricks (Fig. 17.3). In order to investigate the role of the grain size distribution, the Bouisset soil was mixed with a sandy soil to obtain three different earth mixes. The percentage of sand added was established looking at the recommended area to obtain three earth mixes with a clay content, respectively, equal to the minimum, the maximum and the average between the maximum and minimum suggested by the guidelines, and the first earth mix is the Bouisset soil itself. Table 17.4 shows the calculated percentages of Bouisset and sand that were mixed together in order to obtain the desired clay content of the resulting earth mix.

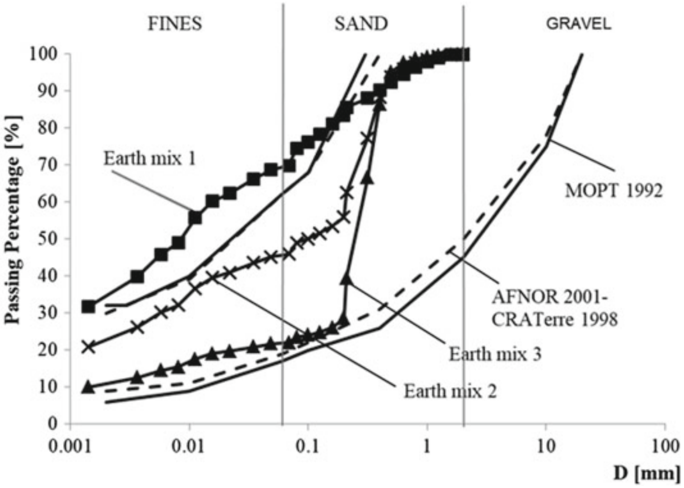

Fig. 17.3 Grain size distribution of earth mixes analysed in relation to recommendations for the manufacture of compressed earth bricks by CRATerre-EAG (1998) and MOPT (1992)

Table 17.4 Physical composition of earth mixes

Sample ID	Bouisset percentage (%)	Sand percentage (%)	Clay content (%)
Earth mix 1	100	0	≈32
Earth mix 2	66	34	≈20
Earth mix 3	32	68	≈10

Figure 17.3 shows the grain size distribution curves of the earth mixes presented above and the discussed guidelines relevant for compressed earth bricks.

The properties of Bouisset soil are summarised in Table 17.5, which indicates that the Bouisset soil can be classified as a well-graded silty clay. The plasticity properties of the fine fraction (i.e. the fraction smaller than 0.400 mm) of the Bouisset soil have been measured in agreement with French standards. The liquid limit, plastic limit and plasticity index, determined as the average of four independent tests, classify the material as a low plasticity clay.

17.6.2 Hyper-Compaction

Prior to compaction, the dry soil was mixed with the desired amount of water and subsequently placed inside three plastic bags to prevent evaporation. After that, the wet soil was left to equalise for at least one day so that moisture could redistribute prior to compaction. The soil was placed inside a stiff cylindrical steel mould with a diameter of 50 mm and vertically compacted by using a load-controlled Zwick

Table 17.5 Bouisset measured index properties

Index property			
Grain size distribution		*Atterberg limits*	
Gravel content (> 2 mm, %)	0	Plastic limit (%)	18.7
Sand content (≤ 2 mm, %)	31	Liquid limit (%)	29.0
Silt content (≤ 63 µm, %)	35	Plasticity index (%)	10.3
Clay content (≤ 2 µm, %)	34	*Mineralogical composition* Goethite, Muscovite, Orthose Kaolinite, Quartz	
Specific gravity	2.65		

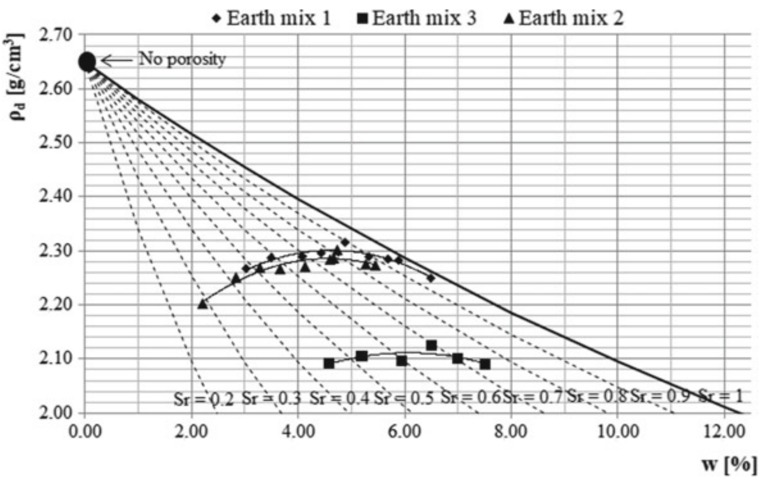

Fig. 17.4 Compaction curves for the static pressure of 100 MPa

press with a capacity of 250 kN. Pressure was applied by two cylindrical aluminium pistons acting at the top and bottom extremities of the specimen. Additional details about the compaction procedure are available in Bruno (2016). Figure 17.4 presents the experimental values of dry density, ρ_d plotted against the corresponding water contents, *w* together with the respective interpolating curves for each earth mix used in the study.

Figure 17.4 also shows the theoretical “no porosity” point corresponding to an extremely high-compaction effort, which produces a dry density equal to the density of the solid particles.

Table 17.6 Results from strength and stiffness testing

Earth mix	Dry density g/cm^3	Young's modulus (MPa)	Compressive strength (MPa)
1	2.31	2851	7.19
2	2.28	1795	3.44
3	2.12	1320	0.45

17.7 Results: Hyper-Compaction

In order to measure the stiffness and strength of the material, unconfined compression tests were performed at the scale of small cylindrical samples of 50 mm of diameter and 100 mm of height. A set of two samples were manufactured for each earth mix considered. A constant displacement rate of 0.001 mm/s, which is the slowest rate that can be applied by the Zwick/Roell Amsler HB250 press, was chosen in order to obtain a regular stress–strain curve without instabilities (Bruno 2016). Young's modulus was measured based on five unconfined loading–unloading cycles performed at a loading rate of 0.005 MPa/s between one-ninth and one-third of the estimated compressive strength of the material. Axial displacements were measured between two points along the height of the cylindrical samples at a distance of 50 mm by means of two transducers placed on diametrically opposite sides. Based on the assumption that material behaviour is elasto-plastic during loading but essentially elastic during unloading, Young's modulus was determined by considering only the unloading branches of the five cycles. In particular, Young's modulus was determined as the average slope of the five unloading branches in the axial stress–strain plane. Table 17.6 shows Young's modulus and compressive strengths of the three soil mixes.

The earth mix characterizsed by the highest value of dry density exhibits the highest Young's modulus, and compressive strength is consistently higher for the more compacted and denser soil. Interestingly, despite the negligible difference in terms of dry density between earth mix 1 and 2, a significant augmentation of the material stiffness and strength is noticeable. An explanation of this result might be the different physical composition of the two earth mixes. Earth mix 2 is, in fact, a combination of a silty clay and a sandy soil characterised by a lower amount of clay. Inspection of Fig. 17.3 indicates a bimodal grain size distribution (gap-graded soil). It is suggested that not just the density but also the inclusion of a coarser soil to a fine-grained soil or addition of fines to sand strongly affects the mechanical behaviour of the material.

17.8 Conclusions

The use of raw earth as sustainable construction material is being explored as one of the most promising possibilities to replace conventional options, but this is only likely to be successful if key issues such as durability and mechanical properties are improved. Biopolymers and hyper-compaction both show promise in this regard, and in this paper, we have focussed on some aspects of their performances. However, further investigations are necessary to understand how to improve not only mechanical properties but also hygroscopic and durability properties developing a sustainable stabilisation method that could not negatively impact one of these performances. In addition, a full LCA for the proposed stabilisers is needed to truly prove the green credentials discussed above.

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