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Effect of stabilisation on mechanical properties, moisture buffering and water durability of hypercompacted earth

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HIGHLIGHTS

- Stabilisation affects hygroscopic and mechanical behaviour of hypercompacted earth.
- Alkaline activation and silicone-based admixture are adopted to stabilise earth.
- Strength, stiffness, moisture buffering and water durability are investigated.
- Stabilisation improves durability but reduce strength, stiffness and moisture buffering.

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ABSTRACT

This paper investigates the effect of stabilisation by alkaline activation and silicon based admixture on the mechanical properties, moisture buffering capacity and durability of an earthen material for building construction. The stiffness and strength of both unstabilised and stabilised cylindrical samples were measured, under different humidity conditions, by means of unconfined compression tests. The effect of stabilisation on moisture buffering capacity was instead explored by subjecting samples to cyclic variations of relative humidity at constant temperature, according to the experimental procedures prescribed by the norm ISO 24353 [21]. Finally, durability against water erosion was assessed by performing immersion, suction and liquid contact tests on both unstabilised and stabilised samples according to the norm DIN 18945 [16]. Results from this extensive experimental campaign highlighted that the chosen stabilisation methods improved the durability of the material while maintaining a relatively good mechanical performance and a good to excellent moisture buffering capacity.

1. Introduction

The expression "raw earth" (translated from the French "terre crue") describes a construction material consisting of a mix of soil and water subjected to the least possible transformation before being put in place. Depending on the adopted building design, the use of raw earth can reduce energy consumption during construction but also during operation of buildings by cutting down air conditioning. Because of its hydrophilic nature, raw earth exhibits a strong tendency to absorb or release moisture, and therefore to emit or store latent heat, depending on the current levels of ambient humidity. This characteristic helps to smooth out the variation of relative humidity and temperature inside dwellings, thus contributing to the health and comfort of occupants [2,31,37,19,38].

Unfortunately, the hydrophilic nature of raw earth is also the cause of its poor resistance against water infiltration. For this reason, raw earth is often chemically stabilised by addition of hydraulic binders such as cement or lime [40,9,32], which improve water durability but also introduce undesirable collateral effects on stiffness, strength and moisture buffering capacity. A number of studies have analysed the effect of stabilisation by hydraulic binders on stiffness and strength [40,23,30,8,12,6,11,24,4] but also on moisture buffering capacity [26,27,3]. These investigations have shown that stabilisation by hydraulic binders generally improves the mechanical properties of raw earth but considerably reduces the ability of the material to store and release moisture.

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

The present paper explores the use of some of these alternative stabilisation methods on hypercompacted earth bricks [6]. These stabilisation methods consisted in a combination of alkaline activation and silicone-based admixture.

Alkaline activation employs a solution of $Ca(OH)_2$, NaOH or KOH to dissolve the clay minerals naturally present in raw earth so that they can reticulate again in the form of non-swelling binding materials. Among the different alkaline activators, sodium hydroxide (NaOH) is selected in this work because it provides the largest improvement of mechanical and durability characteristics [17,10,36]. Instead, silicone-based admixture consists in mixing the earth material with a water emulsion of silane and siloxane. This emulsion reacts with the soil substrate by creating a hydrophobic nanomolecular polysiloxane film inside earth capillaries, which impedes the infiltration of liquid water while largely retaining the permeability to vapour [25].

The effects of these alternative stabilisation methods on mechanical properties have been the object of very few studies mainly limited to earth plasters [39]. In this work, these studies are extended to the investigation of the stiffness and strength of stabilised hypercompacted earth by performing unconfined compression tests on cylindrical samples equalised at different ambient conditions. Moreover, the effect on moisture capacity is equally assessed by subjecting cylindrical samples to cycles of relative humidity at constant temperature to determine the Moisture Buffering Value (MBV) according to the norm ISO 24353 [21]. Finally, the work investigates the water durability of the material, i.e. the resistance of the material to water erosion, by performing immersion tests on cylindrical samples as well as suction and contact tests on brick samples according to the norm DIN 18945 [16].

The purpose of this study is to identify a stabilisation method that can balance the different material requirements in terms of water durability, moisture buffering capacity, stiffness and strength. The effect of stabilisation method on the embodied energy of the material is not assessed in the present work. Therefore, the environmental impact of the relatively small amounts of stabilising additives used in this study will be the object of future research.

2. Material and methods

The soil used in the present work has been provided by a brickwork factory from the region of Toulouse (France). Table 1 summarises the main properties of the tested soil. In particular, grain size distribution and plasticity properties satisfy existing recommendations (e.g. [29,13,1]) for raw earth construction as discussed by Bruno [6].

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

Clay activity, defined as the ratio between the plasticity index and the clay fraction, is equal to 0.79. This classifies the clay fraction as normally active [35], which is consistent with mineralogy data from the soil provider that indicate a predominantly illitic material with a small quantity of montmorillonite. Illite is a three-layer clay with good bonding properties and a limited swelling potential upon wetting, which makes it particularly suited to raw earth construction [15].

Stabilised and unstabilised samples were prepared at the scale of both small cylinders (50 mm diameter and 100 mm high) and bricks ($200 \times 100 \times 50$ mm^3) by compaction inside stiff moulds of corresponding dimensions at a relatively large pressure of 100 MPa and an optimum water content of 5.2%. The optimum water content had been previously determined by compacting specimens with variable moisture at the same pressure of 100 MPa as discussed by Bruno et al. [7].

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

An initial evaluation of the durability of both unstabilised and stabilised cylindrical samples was performed by means of water immersion tests in compliance with the German norm DIN 18945 [16]. Prior to immersion, all stabilised and unstabilised samples were equalised to the atmosphere of the laboratory, where humidity and temperature were about 40% and 25 °C, for a minimum time of two weeks until a constant mass was attained. For stabilised samples, this time also allowed curing of cementing additives.

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

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

NaOH is highly soluble in water and produces virtually no increase in viscosity of the solution compared to pure water, which means a negligible change of the dry density of the compacted earth. On the contrary, the silane-siloxane emulsion is not soluble in water and marginally increases liquid viscosity, which results in a slight reduction of the dry density of the compacted earth. In fact, silane-siloxane stabilised samples exhibited an average dry density of 2250 kg/m^3 that is about 1% lower than that of unstabilised and NaOH stabilised samples.

After compaction, all samples were equalised to the atmosphere of the laboratory for two weeks and subsequently subjected to immersion tests for evaluating the effect of the different stabilisation methods on the measured mass loss. As shown in Fig. 1, the erosion resistance of samples stabilised with the silane-siloxane improves significantly as the concentration of the emulsion increases. The addition of the NaOH solution also enhances the water resistance of the material with a considerable improvement as solution molarity grows from 1 mol/l to 2 mol/l followed by a deterioration as molarity increases further. The achievement of the best stabilisation properties at an intermediate molarity level of 2 mol/l may be explained by the chemical interaction between the saline solution and the clay minerals inside the earth material as indicated, for example, by Das and Thyagaraj [14] and Beckett et al. [5]. It is therefore possible that the optimum molarity depends on the mineralogical composition of the earth and on the amount of liquid content.

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 [16].