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Hydro-mechanical behaviour of soilcretes through a parametric laboratory study

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HIGHLIGHTS

- Soil-cement mixtures are much more sensitive to drying-shrinkage than ordinary concretes.
- Permeability can be determined from the porosity and the characteristic pore diameter.
- Mechanical damage under loading mainly depends on cement content.
- Poisson's ratio (0.23–0.37) increases with the soil clay content, mostly for low cement dosages.
- Results underline the importance of density for estimating the Young's modulus from UCS.

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ABSTRACT

The study focuses on hydro-mechanical properties of soil-cement mixtures. This material produced by Deep Soil Mixing is used as foundations or cutoff walls and therefore must have appropriate mechanical properties and hydraulic conductivity. Laboratory soilcretes were manufactured with various amounts of cement and types of soil. Compared with ordinary concrete, drying shrinkage is particularly high. The results highlight the link between the hydraulic conductivity and the mix design parameters through the pore size distribution. Tests investigating Poisson's ratio provide information on this understudied parameter. Several empirical relationships are proposed for estimating static modulus, strength and permeability from physical parameters.

1. Introduction

The soil-mixing and the jet-grouting are soil improvement methods using a hydraulic binder. Many sophisticated mixing processes have emerged since their introduction in the 1950s. In Japan, these methods are mainly used for the embankment stability and reduction of settlement. In France, the method was first tested in 1986 [1], for railway line reinforcement. When the structures do not require high mechanical performance, the Deep Soil Mixing is now often used in Europe as an alternative to traditional methods of underpinning, cutoff wall, and foundations. It is thus essential to have a good knowledge of hydraulic conductivity, compressive strength, and Young's modulus which are the main properties necessary for the soilcrete structure design [2].

In the field of special foundations, the Water/Cement ratio (W/C) depends on the soil clay content. This ratio is generally quite high, because the mixing process requires a self-compacting mixture. Overall, the high water content and the small particle size of the soils [3] considerably limit the mechanical properties of soilcretes. The high porosity of these materials makes them more vulnerable to different chemical aggressions. Thus, it is important to analyse the porous network characteristics that affect the transfer properties, the porosity and the hydraulic conductivity as the two most important durability indicators.

Clayey soils are problematic soils due to their high deformability even after the soil treatment. The soilcretes are particularly sensitive to drying-shrinkage, so that protection is essential for structures exposed to air [4]. Soil-cement Young's modulus may also significantly affect the distribution of load between soilcrete and surrounding ground [5]. Soilcrete is a much "softer" material than concrete and its Young's modulus is 5 to 8 times lower than that of an ordinary concrete [6]. Actually, the Eurocode 2 (EN

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1992) proposes relationships that are currently used to estimate Young's modulus but the predictive models proposed must be adapted to soilcrete's specific behaviour.

Whatever the method used, the design of mechanical properties is complicated [7,8]. According to Bellato (2013), the hydro-mechanical properties of soilcretes are mainly influenced by the quantity of cement injected and its hydration conditions [9]. This paper focuses on shrinkage, hydraulic conductivity and elastic properties, which are important characteristics but understudied according to the mix-design parameters. Although many previous studies examined the hydraulic conductivity and proposed large quantities of data [10,11], the transfer properties are rarely related to the soil type or to the cement dosage, let alone to the microstructure as we are going to suggest. Given the composition of soilcrete, the Poisson's ratio is more likely to vary considerably. This parameter was therefore determined to provide a basis of modelling activities and determine as precisely as possible the dynamic modulus. A part of this work focuses also on mechanical damage assessment under mechanical loading and therefore allows a better understanding of the material's behaviour in the operation phase.

In this study, the large numbers of experimental results are linked to proposed correlations between the various physical and/or mechanical properties for different compositions of soilcretes. The aim is to propose mathematical relationships to determine the properties requiring expensive or time-consuming procedures from properties that can be obtained more quickly and simply.

2. Experimental methods

2.1. Preparation of test specimens

The soilcrete mixtures were designed as those presented by Helson et al. (2016). The different proportions and some properties of the different mixtures are given in Table 1. Six artificial soils are prepared by substituting sand with different volume proportions of clay. The soils produced in the laboratory are composed of Fontainebleau sand NE 0/1 (XP P 18-545 standard) and kaolinite Speswhite™, which are widely used in the physical modeling of soils [12].

Two cement dosages were tested independently on the soil type. The cement used was a CEM III/C 32.5 N CE PM-ES NF "HRC" containing more than 81% of blast furnace slag [13], responsible for the slow development of strength, but whose latent character is favorable in terms of workability [14].

The amount of water is fixed according to the deep mixing methods requiring a self-compacting consistency. The mixing water amount is adjusted to keep a constant workability between all the mixtures (32 cm diameter mini-slump flow). Without clay in the soil, the desired workability cannot be obtained due to the segregation of Fontainebleau sand (uniform particle size). Thus, K0 soilcretes were designed with the same effective cement to water ratio (C/W) as the other mixtures. The C/W effective weight ratio corresponding to the amount of cement divided by the amount of water mixing reduced by the amount of water retained by clay (96% of its weight in water).

Sand, clay and cement have previously been mixed in a dry state for 5 min and then with water for 10 min in a mortar CONTROLAB mixer. Cylindrical molds are filled in three layers by tapping method. For each layer, the mold was tapped against bench 15 times, except for K0 mixtures because the lower flowability requires higher energy to remove the entrapped air. Each layer was therefore vibrated for 20 s on a vibrating table. The samples are removed from the molds after 7 days, wrapped in wet textile and placed in sealed plastic bags. This storage method preserves moisture and prevents soilcretes from early drying. Thereafter, the designed mixtures will be identified using abbreviations related to their soil's clay content and cement dosage. For example a soil containing 75% of Speswhite™ kaolinite and 25% Fontainebleau sand, and treated with 200 kg/m^3 of cement will be named K25C200.

2.2. Hydric behaviour

2.2.1. Water porosity and mercury intrusion porosimetry

The water porosity under vacuum (η), the dry (ρ_d) and wet bulk (ρ_h) density are determined on cylindrical specimens (40 mm diameter × 100 mm height) according to NF P18-459 standard [15]. The mercury intrusion porosimetry was used to analyze the microstructure of soilcretes. The tests were carried on a Micrometric AutoPore IV porosimeter. Cubic samples of 18 mm side were sawn and dried at 60 °C before the test. This testing includes two successive intrusion/extrusion phases. The maximum pressure applied was 200 MPa. Therefore the pores diameter accessible by mercury vary between 0.006 μm and 404 μm.

2.2.2. Shrinkage

Shrinkage tests were carried out according to NF P 15-433 for hydraulic mortars [16]. For each mixture, shrinkage was measured on three soilcretes prisms 40 × 40×160 mm^3, removed from the molds after 3 days of moist curing and then placed in a climatic chamber at 20 °C and 50% relative humidity. Reference stainless steel studs are casted into the mid-points of the top and bottom faces of the prisms. The measurement is carried out using a metal frame equipped with a comparator. Calibration of the length is achieved by an Invar bar of 160 mm long.

Table 1
Parameters of the analyzed mixtures per cubic meter of soilcrete and workability.

Kaolinite [%vol]	Water [%mass]	Cement [kg/m3]	Clay (kaolinite) [kg/m3]	Sand [kg/m3]	Water [kg/m3]	C/W mixing	C/W effective	Workability	[cm]
0	20	200	0	1534	352	0,57	0,57	Slump	0,9 ± 0,6
		300	0	1441	353	0,85	0,85		3,3 ± 0,4
5	27	200	67	1295	417	0,48	0,57	Diameter mini-slump flow	32,0 ± 1,4
		300	63	1215	414	0,73	0,85		33,0 ± 1,2
10	31	200	125	1144	451	0,44	0,60		31,4 ± 0,8
		300	115	1059	452	0,66	0,87		33,4 ± 0,7
15	36	200	173	998	488	0,41	0,61		32,8 ± 1,0
		300	158	912	492	0,61	0,87		33,0 ± 1,2
25	47	200	243	743	557	0,36	0,61		32,0 ± 2,0
		300	220	672	559	0,54	0,85		31,6 ± 1,8
50	74	200	347	353	664	0,30	0,59		32,8 ± 1,5
		300	299	305	667	0,45	0,78		33,6 ± 1,7