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► **To cite this version:**

Alain Le Kouby, Lucile Saussaye, Myriam Duc, Fabien Szymkiewicz, Sébastien Patouillard. Feedback on deep soil mixing technique for Loire levees. Deep Mixing Conference, Deep Foundations Institute, Jun 2021, Hawthorne, United States. hal-04534892

HAL Id: hal-04534892

<https://hal.science/hal-04534892>

Submitted on 8 Apr 2024

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FEEDBACK ON DEEP SOIL MIXING TECHNIQUE FOR LOIRE LEVEES

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ABSTRACT

Deep mixing technique to reinforce Loire levees are currently used. The techniques were implemented with dedicated trench-cutting equipment rotating so that cut-off wall could be continuous in the levee structure and its foundation. It resulted in a mixture between the soil in place, a hydraulic binder and water.

Several formulations are tested for the soils of the levees and their foundation. Indeed, hardening issues appeared locally, on part of Orleans levee, linked to the presence of organic soils. It led to experiment several lime-cement formulations in the laboratory. Subsequently, the best soil-fitted formulation was tested in the lab and applied on site to validate the implementation. This included testing new control timeframes in terms of permeability and mechanical resistance.

The properties of the deep mixing material were assessed by testing clay-cement materials, treated at different cement and water contents. Permeability and strength parameters were confronted to their physico-chemical and microstructural characteristics in order to explain the variations of the mechanical properties and better understand the behaviour of natural soils treated with this technique.

In addition, differences appear between mixture built on site and in the laboratory in terms of hydraulic and mechanical properties but also in terms of soil inclusions.

Keywords: Deep soil mixing, permeability, mechanical properties, research works, Feebbacks

CONTEXT

The Deep soil mixing presents numerous advantages (eco-friendly, easy and quick execution as well as low cost) that have greatly contributed to expand its domain of applications (soil improvement, pollution confinement or realization of structural elements). These new applications require a better understanding of the method and of the material. Quality (particularly homogeneity and continuity) and representativeness of the material are more and more investigated, as the scope of applications for Deep soil mixing widens with an ever increasing demand for better comprehension of the resulting material behavior, as well as development of methods of strength prediction.

Babasaki et al. (1996) cited four factors affecting the mechanical properties increase of the material: the characteristics of the binder, the type and state of the encountered soil, the mixing and the curing conditions. Porbaha (2000) states that it is commonly accepted that the strength of cement-treated soil increases with time, similarly to the behavior of concrete. Many studies have been carried out to propose relations with strength at young age or formulas, regarding the strength prediction of the material. Bruce (2001) and Topolnicki (2004) proposed general strength gain speeds and strength ranges, depending on the characteristics of the soil to be treated. Also, formulas have been proposed to predict the strength and deformability of the material from one or multiple factors enunciated by Babasaki et al. (1996). According to Abrams (1918), for a given set of materials, the strength development depends only on one factor, i.e. the ratio of water to cement content in a given mix. His law has been tested (Horpibulsuk, 2003) but proved inadequate (Hampton and Edil, 1998), but other formulas have been proposed (Ahnberg, 2006; Szymkiewicz et al., 2012), taking into account cement, water and/or fines contents. However, there is still no widely applicable formula for estimating the strength of the material and incorporating all the factors that should be taken into account (CDIT, 2002), as of today, no international standard exists for the preparation of treated soil specimens in the laboratory (Kitazume et al., 2009). Also, some formulas can only be applicable to a particular site, while some others can only be applied on some soils.

Among the various research works around deep soil mixing developed by the research team of this paper (**Erreur ! Source du renvoi introuvable.**), a feedback of the monitoring of reinforced dykes from execution works until about four years of structure in service are presented here. Monitoring of structures allow to get information from temperature and water content within the reinforced dykes. Those dry-wet cycles can be applied to laboratory samples to study long-term properties of mixed materials. A database of an exhaustive parametric study has been carried out and a machine learning method is proposed to be able to use this knowledge. The focus is given on the engineering properties of the Deep soil mixing material and on its durability (Le Kouby 2015 & 2018). Sands and fine soils are considered at different cement and moisture contents in order to assess the influence of the fines, water and cement contents on hydraulic and mechanical properties and their development. Also, artificial soils (made of sand and fine soil) were treated to further study the influence of the fines content and their nature on the properties of the material. The influence of non-mixed materials has also been investigated. In addition, in a second part of the paper, an example of laboratory parametric study is shown. Indeed, the influence of different curing conditions (immersion in water, dry-wet cycles, air curing and endogeneous curing) on the stiffness and strength of cement-stabilized soils and on the hydraulic properties of specimens of soil treated with blast furnace slag cement in the laboratory are studied.

Part 1

GENERAL PROCEDURE TO STUDY THE SHORT- AND LONG-TERMS PROPERTIES OF SOIL-MIXED STRUCTURES

1) Monitoring of a reinforced structure

An example of monitoring within a reinforced dyke to internal erosion is described in this paper but this type of monitoring procedure can be applied to other different structures. It has been carried out to evaluate variations of temperatures and water contents due to environmental solicitations (meteorology, variation of water level during flood...). The observed solicitations will have to be reproduced in the laboratory. On October 2017, a monitoring on structure has been carried out. It consists in putting sensors within the reinforced structure and within the natural material. Five temperature and water contents (TDR) were set up within the mixed materials on a 8m deep treated soil at five different depths. Temperature, water content and suction sensors at 1m depth were installed in natural soil to compare measurements with treated soil response to environmental solicitations. The purposes are to observe the biggest amplitude of variations for temperature and water content as well as their duration in the levee and in the reinforced soil. Correlations between rainfall and water content in the natural soil could be analysed. The maximum depth of monitoring is 5.5 m and Loire River level maximum reached 6.9 m (until now) with an 8m deep cutoff wall. Only capillarity effect can be observed in the soil-cement structure above the Loire river water level. Piezometers near the Loire river and after the dyke are also set up. The suction pressures measured seem to decreases when water content and rainfall increase and reversely. The two-years monitoring shows an increase of the dry period in the service life of the dykes. Within the reinforced structure, small variations of water contents were observed contrary to temperature variations that were more important.

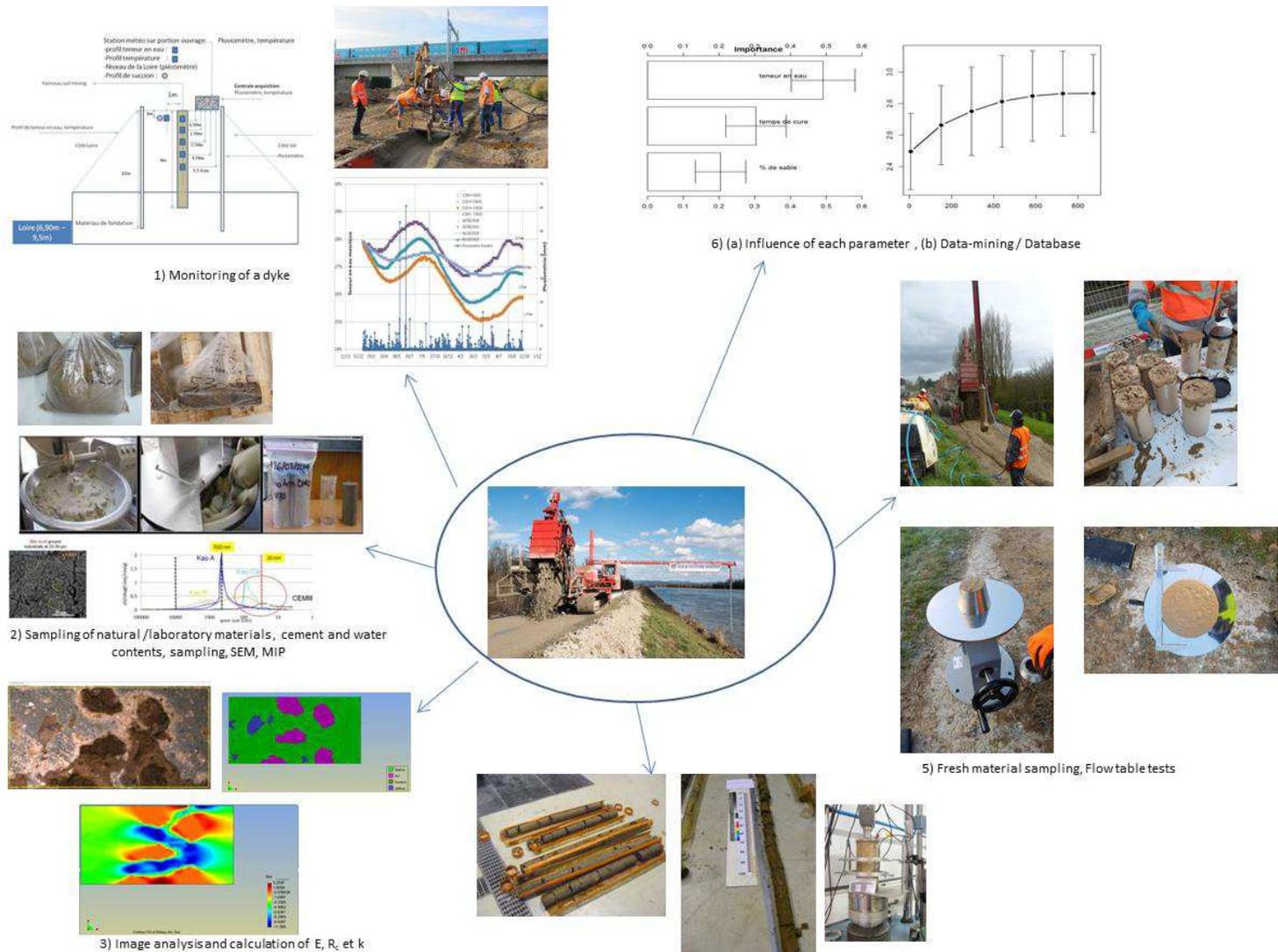


Fig. 1. General overview of the research work around deep soil mixing

2-Laboratory tests

They include the formulation of the mixed material: natural material, cement content and moisture content. Granular soils, fine soils and materials with different percentages of fine soils are taken as artificial natural materials to establish a database. The cement used in this study is a blast furnace slag cement containing 85% in weight of granulated ground blast furnace slag (CEM III/C 32.5 N). Permeability tests and unconfined compression strength tests (UCS) are made in order to characterize the hydraulic and mechanical performance of the soil-cement material for different curing time (7, 28, 90, 180 and 365 days). During these tests, local and global moduli E_{50} are calculated. Non destructive measurements of compression and shear waves speed (V_p and V_s) are also carried out to calculate a dynamic modulus E_0 . These parameters are used to find correlations between parameters measured on artificial soils and field works. The quality of the mixed material on site is a key issue.

On a microstructural point of view, soil mixing materials are lyophilised (put in liquid nitrogen) after UCS test. Mineralogy has been studied with the X-Ray diffraction (XRD) and then compared to initial materials before mixing. Microstructure of the samples has been tested with PMI (porosimetry by mercury intrusion) tests. The samples have also been observed with scanning electron microscope (SEM). The effect of parameters that characterize the mixed materials on the durability of the material is studied. Global porosity, distribution of pores with wave velocities V_p and V_s are some of the indicators that are useful to characterize the durability of the mixed material with porosity- V_p curves.

3-Excavation of site material

To work on long term properties of soil mixed materials, pieces of cutoff wall were excavated to establish heterogeneity of the mixed material. The results of tests on these pieces were completed with sampling of the soil-mixed cutoff walls, which are usually made. From established methods, percentage and surface of inclusions (unmixed materials) were measured or estimated.

Effectively, their distribution as well as their percentage is key parameters to characterize mixed materials. The long term response of the structure has shown that the inclusions might play an important role (Denies et al., 2012). The comparisons in terms of hydraulic and mechanical properties between pieces of cutoff wall and boreholes would be investigated. The procedure to determine the percentage of inclusions can be manual or numerical. The manual method is as follows: with the measurement of the surface occupied by soil particles on a sample through 4 lines at 90° from each other in the case of cylindrical samples. The numerical method is based on the image analysis with a software on a sample face that has been taken into photo. From the photo, matrix (soil mixed material) and inclusions (unmixed materials) surfaces are determined as well as their distribution. From several samples, an average distribution is calculated and the material is homogenized with a fixed characteristic surface. This geometry is introduced in a finite element code to simulate UCS loading, hydraulic conductivity in order to evaluate the behavior of the soil mixed material.

4-Boreholes

For some cutoff walls, boreholes have been made during four to six years to follow hydraulic and mechanical properties of soil mixed materials with laboratory and field tests. The diameter of the borehole is generally 90 mm. The whole borehole is opened, samples of 180 mm high (UCS) and 100 mm high (permeability) are cut. Water contents, pH, V_s , V_p , moduli E_{50} , density are also measured. It has to be checked that inclusions are maximum 1/6 of the sample diameter.

In addition, methods to establish the percentage of inclusions are developed. Besides, natural soil were collected to make laboratory soil mixed samples in order to compare in-situ and laboratory mixed properties and to establish a database.

5-Rheology of the fresh material

Different types of tests are available to establish the properties of the fresh materials. Density, test with the cone penetrometer (for liquid limit measurement for example), flow table tests or other rheological

tests. Flow table tests have been chosen and are used to try to characterize the fresh material during the soil mixing execution works.

The flow table is the most widely accepted apparatus to measure the consistency of mortar. It consists of a circular plate which is lifted and then dropped over a specified height. The basic principle of slump and flow tests is that a sample is poured or scooped in a conical or cylindrical frustum, which is then carefully lifted, so that the material is allowed to deform under its own weight. Be the initial height h_0 and initial base diameter d_0 , and the dimensions after deformation h and d , the (spread) flow is defined as $f = d/d_0$ and the slump as $s = h_0 - h$.

During execution works, sampling of fresh material is made in 11 x 22 cm cylindrical moulds to achieve UCS tests and in 5 x 10 cm cylindrical moulds to achieve permeability tests at different curing time (from 7 to 180 days). Flow table test can be added to follow the homogeneity of the fresh material during execution works.

Besides, the use of geophysical methods to follow properties of the geotechnical structures has been tested. Before a procedure can be proposed, it is still in development (Fargier et al., 2016). The geophysical methods (seismic, GPR, Electric) have been qualified for the assessment of these reinforcement structures. Transversal and longitudinal measurements at different depths have been done but the procedure has to be adapted for this type of structures.

6-Data-driven approach

From the laboratory mixed materials and samples from experimental sites, a data-driven approach is developed proposed for UCS prediction, G modulus, E_{50} modulus of laboratory soil-cement mixtures. Existing model (Tinoco et al., 2016) is able to predict UCS over time under different conditions, e.g. different cement contents or soil types, and can be applied at the pre-design stage. This means that the model can be applied previously to the preparation of any laboratory formulation. The designer only needs to collect information about the main geotechnical soil properties (particle size distribution PSD, Atterberg limits, organic matter content, among other) and select the binder composition to prepare the mixture.

Based on a sensitivity analysis, the key model variables were identified and its effect quantified. Thus, it was caught by the model the most relevant variables in UCS prediction over time and very high prediction capacity.

Aiming to overcome such models dependence of the final mixtures properties, in the paper a model (data-driven approach) is proposed for UCS prediction over time which is independent of final mixtures properties.

The proposed model, based on advanced statistics analysis, allows estimating UCS over time based on about 10 input variables such as the cement content, PSD parameters or type of hydraulic binder. A cross validation approach under fixed numbers of runs was applied for model generalization assessment.

The same approach could be proposed for k prediction.

Part 2

EXPERIMENTAL TESTS

Influence of drying on the stiffness and strength of cement-stabilized soils

Two types of material were mixed to reconstitute artificial soil. The mixes were prepared/made with different amounts of cement. The quantities of cement CEMIII/C 32.5 N and moulding moisture contents used for these mixes are given in Table 1.

Table 1. Composition of soil-cement mixes tested

Mix n°	Soil type	Cement content C (%)	Moulding moisture content W (%)	Water cement ratio W/C	Total number of specimens
1	Sand	11.8	20	2.0	12
2	Silt	13.8	40	3.3	12

The cement content C (%), moulding moisture content W (%) and the water/cement ratio (W/C) were calculated following equations 1, 2 and 3.

$$C = \text{weight of dry cement} / \text{weight of dry soil} \quad [1]$$

$$W = \text{weight of water} / \text{weight of dry soil} + \text{cement} \quad [2]$$

$$W/C = \text{weight of water} / \text{weight of dry cement} \quad [3]$$

The cement and moisture contents tested in this study were used in deep soil mixing projects in France.

Laboratory tests carried out on the soil-cement specimens included the UCS and k tests were performed to evaluate the UCS and static stiffness E_{50} .

In total, 24 soil-cement specimens (12 per mix) were prepared. For each soil-cement mix, the UCS of 3 specimens were determined after 7 days of curing in water. The UCS and E_{50} modulus of 9 remaining specimens per mix were also determined 7 days after moulding. These 9 specimens were divided into 3 groups and placed in different curing conditions:

- Condition 1: specimens remained immersed in water at a temperature of 20°C.
- Condition 2: specimens were subjected to dry-wet cycles by alternating periods of soaking in water and periods of drying in a climatic chamber at a temperature of 20°C and a relative humidity of 65%.
- Condition 3: specimens were placed in a climatic chamber at a temperature of 20°C and a relative humidity of 65%.

It is important to note that the specimens were placed in the different curing conditions at an early age before the cement hydration process was complete. The parameters UCS and E_{50} of the specimens was monitored every 1 to 3 days between 7 and 30 days. During curing, the moisture content of the specimens (w) was followed by measuring the changes in mass (m).

For the specimens subjected to successive periods of wetting and drying (condition 2), after the initial 7-days curing in water, the phases of soaking lasted between 1 and 3 days. The specimens were submitted to drying for 24 hours (except between 20 and 22 days where two successive 24 hours drying periods were applied). The moisture contents determined at the end of each curing period give an indication on the curing conditions at a specific time: an increase in moisture content indicates soaking whereas a decrease indicates drying. After 30 days of curing, UCS tests were performed on the specimens. The experimental program is summarized in Fig. 2. The testing procedures used in this study are detailed below.

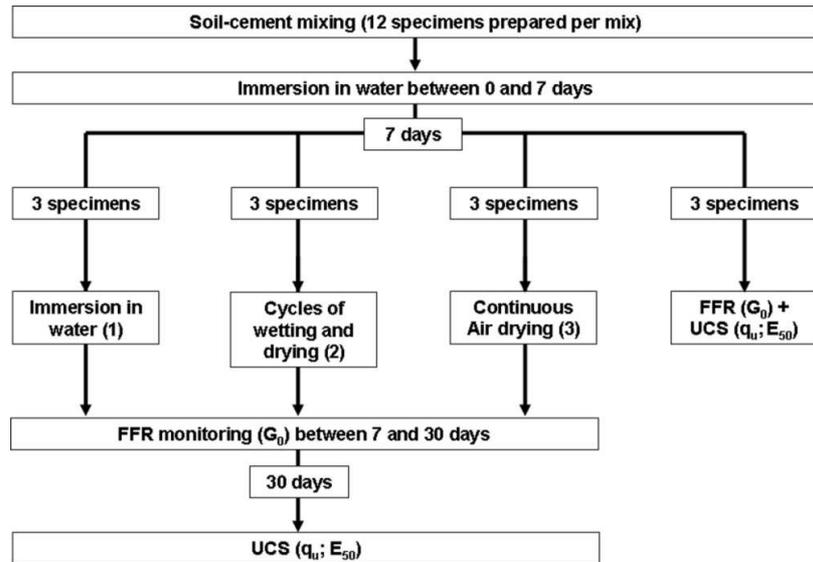


Fig. 2. Details of experimental program for each soil-cement mix

Effects of curing conditions on UCS and stiffness E_{50}

Typical stress-strain curves obtained from UCS tests on specimens of the three soil-cement mixes after different curing conditions and curing times are plotted on Fig. 3.

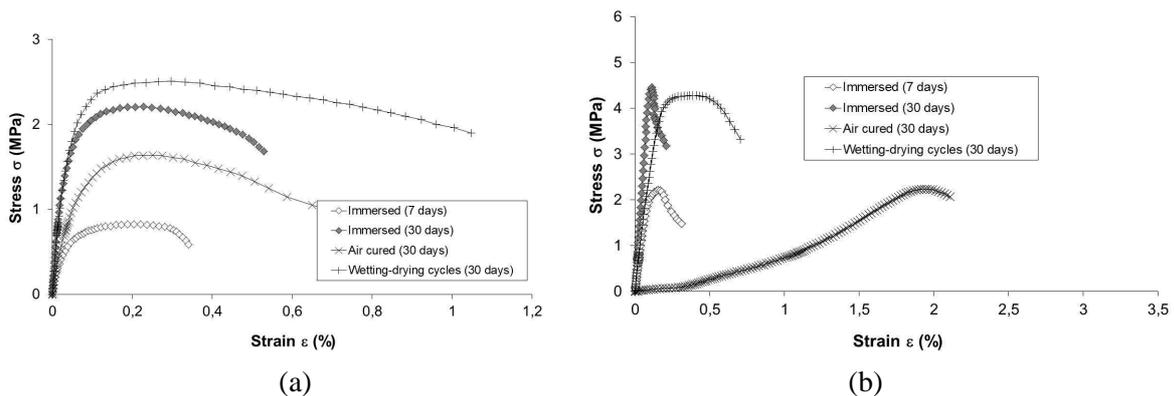


Fig. 3. Typical stress-strain curves (a) mix n°1 Sand $C=11.8\%$; (b) mix n°2 Silt $C=13.8\%$.

The derived values of UCS, static stiffness E_{50} and stiffness to strength ratio E_{50}/UCS , are listed in Table 2 and compared in **Erreur ! Source du renvoi introuvable.**

The stress-strain curves (Fig. 3) show that the sand-cement specimens exhibit ductile behavior whereas the behavior of the silt-cement specimens is more brittle. The UCS and stiffness E_{50} of the specimens immersed in water increased between 7 and 30 days. The E_{50}/UCS ratios are higher for the sand-cement mixes than for the silt-cement mixes (Table 2). For both soils, E_{50}/UCS is slightly lower after 30 days than after 7 days. This indicates that strength increases more rapidly than stiffness between 7 and 30 days in soils mixed with blast furnace slag cement and cured in water.

For both soils, the UCS of the specimens subjected to wet - dry cycles increased when compared to the initial 7-days UCS. The strengths reached are relatively close to those obtained for the specimens in water after 30 days (slightly higher for the sand, slightly lower for the silt, Table 2) pointing to the fact that sufficient water remained present for hydration during these cycles. The E_{50} of the sand-cement and the silt-cement mixes specimens increased between 7 and 30 days despite the cyclic curing condition but remained lower than the stiffness of the specimens cured in water for 30 days. This confirms the negative effect of the imposed wetting-drying cycles on the hydration processes.

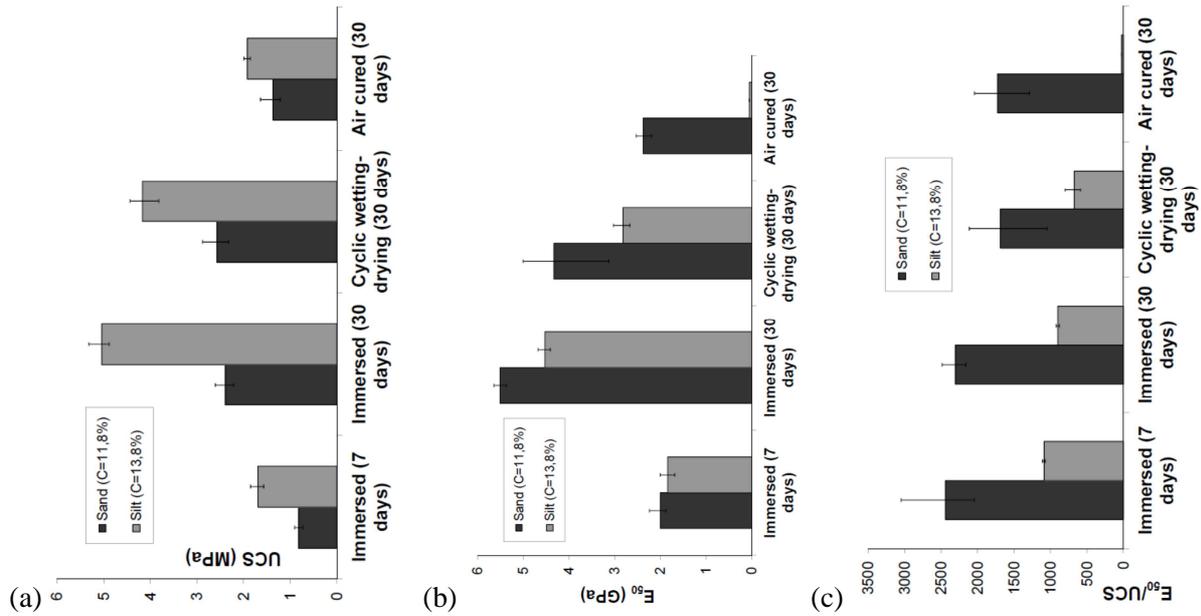


Fig. 4. Effects of curing conditions on (a) UCS; (b) Static stiffness E_{50} ; (c) E_{50}/UCS ratio

After continuous drying between 7 and 30 days, the strengths of the sand-cement and silt-cement mixes specimens were much lower than those of the specimens cured in water. It is reasonable to assume that this is due to insufficient water for hydration. E_{50} of the sand-cement mixes specimens was slightly higher than the initial value of E_{50} measured after 7 days in water. A drastic decrease of E_{50} was measured for the silt-cement mixes specimens (Table 2). This low value of E_{50} is related to the very high strains measured during UCS tests, visible in Fig. 3, and attributed to the microcracks observed on the silt-cement mixes specimens. The initial part of the stress-strain curves, for which strain increases considerably at very low stress corresponds to the closing of the cracks. Once the cracks are closed, the stress begins to increase with strain.

Table 2. Average values derived from testing*: values measured 18 days after moulding

Soil-cement mix	Curing conditions (time of testing)	q_u (MPa)	E_{50} (GPa)	E_{50} / q_u	ϵ_r (%)
N°1	Immersed (7 days)	0.82	2.00	2443.46	0.15
	Immersed (30 days)	2.39	5.51	2305.03	0.24
Sand (C=11,8%)	Cyclic wetting-drying (30 days)	2.57	4.33	1685.43	0.34
	Air cured (30 days)	1.37	2.37	1727.62	0.11
Soil-cement mix	Curing conditions (time of testing)	q_u (MPa)	E_{50} (GPa)	E_{50} / q_u	ϵ_r (%)
N°2	Immersed (30 days)	4.7	5.08	1081	0.11
Silt (C=13,8%)	Cyclic wetting-drying (30 days)	4.17	2.81	674	0.16
	Air cured (30 days)	1.92	0.05	26	2.81

CONCLUSIONS AND PERSPECTIVES

At first, a general overview of the research work that can be carried out from mixed materials built during field works. Six steps have been achieved:

- Monitoring of a reinforced structure to evaluate variations of temperatures and water content of the mixed materials with time to establish wet-drying cycles
- Laboratory mixed materials from artificial soils and fixed cement and water content. Laboratory mechanical and hydraulic tests followed by microstructure tests (MIP, SEM) are carried out
- Determination of percentage and distribution of inclusion from field mixed material from manual and numerical approach methods

- Coring and sampling from existing structures to get long term properties of the mixed materials
- Field tests to get properties of fresh materials, flow table tests were chosen
- Database from artificial and in-situ mixed materials to be able to plan properties of soil mixed material of new field works.

The objectives of this procedure have to be tested on the next field works.

In this paper, an example of a parametric study to study the effect of curing conditions was presented for deep soil mixing materials. Specimens of silt and sand were stabilized in the laboratory with blast furnace slag cement and placed in different curing conditions. For chosen cement content, the procedure has consisted in preparing soil-cement mixes and in curing in water during the first 7 days. UCS tests are then carried out to determine E_{50} and UCS. In second stage, the next steps of curing are done with three different curing conditions until 30 days: immersed in water, submitted to drying and wetting cycles and submitted to air drying. At last, UCS tests show the effects of curing conditions on E_{50} and UCS.

UCS tests were performed to evaluate the UCS and E_{50} . The following conclusions can be drawn:

- (a) Strength increases more rapidly than stiffness between 7 and 30 days of curing.
- (b) The strength of treated soils subjected to cyclic wetting and drying, before the cement hydration process is complete, continues to increase. As long as the periods of drying do not induce microcracks, stiffness also increases with time. However, the measured values are lower than for the specimens cured in water indicating a long term response of the mixed material studied through imposed wet-dry cycles on stiffness.
- (c) Continuous exposure to air drying inhibits strength development due to insufficient water for hydration. Significant stiffness decrease was observed on specimens of silt-cement mixes despite the high cement content was attributed to microcracking.
- (d) The effect of natural soil could also be pointed out. Effectively, the silt (well-graded soil) showed better UCS than the sand (uniform soil) with cement contents of respectively 11.8 and 13.8%. The decrease due to wetting-drying cycles and air drying were in the same order of magnitude for both soils. Nevertheless, the stiffness was greater in the case of sandy-cement mixes specimens. Besides, the decrease of stiffness for the silt-cement mixes was much more important than for the sandy-cement mixes.

The results from this study demonstrate that drying can have a significant influence on the characteristics of soils-cement mixes and suggest that further research is required to understand the processes involved, using advanced laboratory tests and quantitative methods for the description of crack patterns.

ACKNOWLEDGMENTS

The research was funded by DREAL Centre and DGPR .Monitoring was made thanks to the kind support of building companies Vinci Construction Terrassement and Soletanche Bachy. The authors wish to acknowledge the many contributions made by their current and former colleagues at UGE/IFSTTAR. In addition, the authors gratefully acknowledge CEREMA for their technical support on site and for laboratory tests for on site and long term control of reinforced structure.

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