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Feedback on Deep mixing technique for Loire levees

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1) Context

The Deep 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 scrutinized, as the scope of applications for Deep 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 a 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 unadapted (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 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.

This paper presents the some aspects of the feedback of monitoring of reinforced dykes structures from execution works until about four years of structure in service.

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 Mixing material. Sands and fine soils are considered at different cement and moisture contents in order to assess the influence of the fines, water and cement content on the 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 this paper, the effects of different curing conditions (immersion in water, cycles of wetting and drying, air curing) on the mechanical properties of specimens of soil treated with blastfurnace slag cement in the laboratory are also studied.

2) General procedure to study the short and long term properties of soil-mixed structures

From a field test, the research work that can be carried out on a soil-mixed structure can be divided into 6 steps.

Figure 1 presents the different aspects of the research works around deep soil mixing.

Experimental approach

From the execution works, properties of structures are followed in the long terms (Le Kouby 2015 & 2018).

2.1 Monitoring of a reinforced structure has been carried out since 2017 to evaluate variations of temperatures and water contents due to environmental solicitations (meteorology, variation of water level during flood, ...). 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 at five different depths

were set up within the mixed materials. Temperature, water content and suction sensors were installed to compare natural soil and treated soil response to environmental solicitations. The results show that the biggest amplitude of variations for temperature and water content are observed near the surface and it decreases with depth. Correlations between rainfall and water content in the natural soil can be observed. The time necessary for water from rainfall can also be analysed.

As far as water content is concerned within the soil treated panel, variations can be observed with external conditions but their amplitude is very low until a constant value for the 5,5 m depth. Indeed, the end of the panel is about 8m, Loire River level maximum reached 6.9m No capillarity effect are observed in the soil-cement structure above the Loire river water level.

Piezometers near the river Loire and after the dyke show small differences.

The suction pressures measured decreases when water content and rainfall increase. On the contrary, suction pressure increase until values of 250 – 300 kPa during hot and dry periods.

The two-year monitoring shows an increase of the dry period in the service life of the dykes. Within the reinforced structure, water contents of 25-30 % are measured with some variations due to external variations. The amplitude of temperature variations can reach around 20-25 °C. The same peaks (water content and temperature) are reached around the same period at the end of summer.

2.2 Laboratory tests 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 blastfurnace slag cement containing 85 % in weight of granulated ground blast furnace slag (CEM III/C).

Permeability tests and unconfined compression test (R_c) 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 are calculated. Non destructive measurements are also carried out (compression and shear wave speed to calculate a dynamic modulus. 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 and then compared to initial material before mixing. Microstructure of the samples has been tested with MIP (Mercury Porosimetry) tests. The samples have also been observed with Electronic scanning microscope (ESM). 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.

2.3 To work on long term properties of soil mixed materials, pieces of structure were excavated to establish heterogeneity of the mixed material. The results of tests on these pieces of structures were completed with sampling of the soil-mixed panels, which are usually made. From established methods, percentage and surface of inclusions (non mixed 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 between pieces of structures and boreholes are outlined for two field works and need to be confirmed with other structures. 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. The hydraulic and mechanical properties of the different material have to be determined from former studies. 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 R_c loading, hydraulic conductivity in order to evaluate the behavior of the treated material with cement.

2.4 For some structures, boreholes have been made every year during four years 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 90mm. The whole borehole is opened, samples of 180 mm high (R_c) and 100 mm high (k : permeability) are cut. 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.

2.5 Different types of tests are available to establish the properties of the fresh materials. Density, test with the cone of the liquid limit, 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 moulds to achieve R_c and 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.

2.6 From the laboratory mixed materials and samples from experimental sites, a data-driven approach is developed proposed for uniaxial compressive strength (R_c) prediction, G modulus, E_{50} modulus of laboratory soil-cement mixtures. Existing model (Tinoco et al., 2016) is able to predict R_c 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 (grain size, 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 R_c 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 R_c prediction over time which is independent of final mixtures properties.

The proposed model, based on advanced statistics analysis, allows estimating R_c over time based on about 10 input variables such as the cement content, soil grain size distribution or type of cement. A cross validation approach under fixed numbers of runs was applied for model generalization assessment.

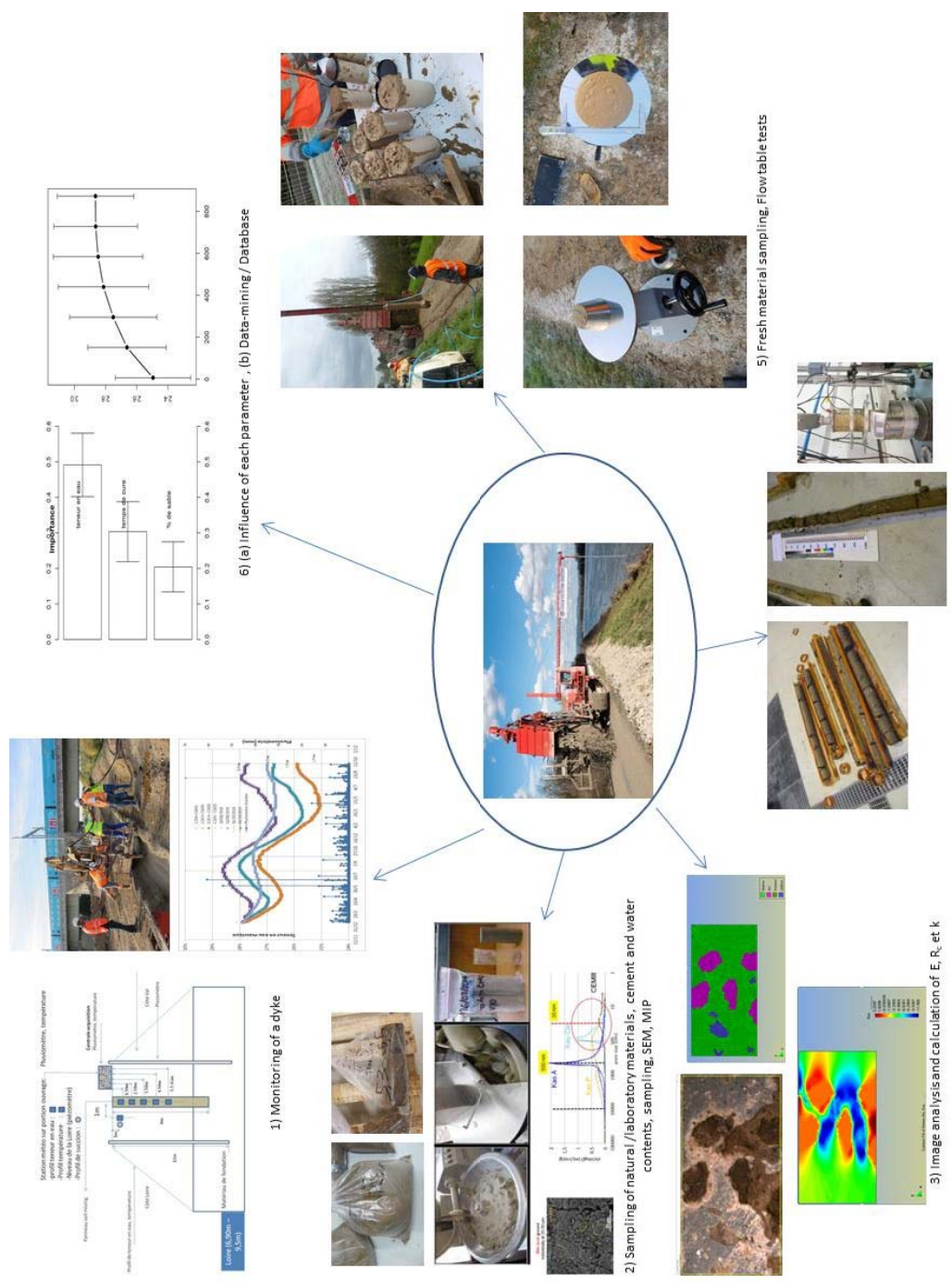


Figure 1 General overview of the research work around deep soil mixing

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

The two soils were mixed with a different amount of cement. The quantities of cement and moulding moisture contents used for these mixes are given in Table 1. The cement contents C (%), moulding moisture contents W (%) and the water / cement ratios (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 compression tests were performed to evaluate the unconfined compressive strength q_u and static stiffness E_{50} .

In total, 24 soil-cement specimens (12 per mix) were prepared. For each soil-cement mix, the unconfined compressive strength q_u of 3 specimens were determined after 7 days of curing in water. The q_u and E_{50} moduli 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 cycles of wetting and drying 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 q_u 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 (curing 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, unconfined compressive strength tests were performed on the specimens. The experimental program is summarized in Figure 2. The testing procedures used in this study are detailed below.

Table 1 Composition of soil-cement mixes tested

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

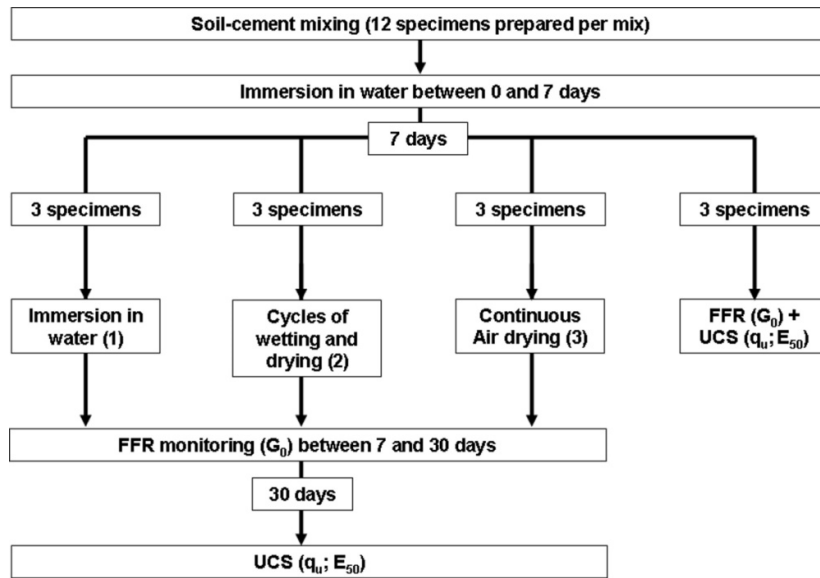


Figure 2 Details of experimental program for each soil-cement mix.

4) Effects of curing conditions on unconfined compressive strength q_u and stiffness E_{50}

Typical stress-strain curves obtained from unconfined compressive strength tests on specimens of the three soil-cement mixes after different curing conditions and curing times are plotted on Figure 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 unconfined compressive strength q_u , strain at failure ϵ_f , static stiffness E_{50} and stiffness to strength ratio E_{50} / q_u , are listed in Table 2 and compared in Figure 4.

The stress-strain curves (Figure 3) show that the sand-cement specimens exhibit ductile behavior whereas the behavior of the silt – cement specimens is more brittle. The unconfined compressive strength q_u and stiffness E_{50} of the specimens immersed in water increased between 7 and 30 days. The E_{50} / q_u ratios are higher for the stabilized sand than for the treated silt (Table 2). For both soils, E_{50} / q_u 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 treated with blastfurnace slag cement and cured in water.

For both soils, the unconfined compression strength of the specimens subjected to cycles of wetting and drying increased when compared to the initial 7-days strength. 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 stiffness E_{50} of the sand and the silt 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.

After continuous drying between 7 and 30 days, the strengths of the treated sand and silt 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. Stiffness E_{50} of the sand 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 specimens (Table 2). This low value of static E_{50} is related to the very high strains measured during unconfined compression tests, visible in Figure 3, and attributed to the microcracks observed on the silt 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 gaps are closed, the stress begins to increase with strain.

In the case of silt, some comparisons can be made with the two cement contents. After 23 days of continuous drying, the strength of the treated sand and silt with 13.8% cement had increased. In addition, a drastic decrease of E_{50} was measured for both silt mixes (leading to high values of E_{50}/q_u). Such low values of E_{50} are related to the very high strains measured during unconfined compression tests, visible in Figure 3 and attributed to the observed microcracking. The initial part of the stress – strain curves, for which strain increases considerably at very low stress corresponds to the closing of the fissures. Once the gaps are closed, the stress begins to increase with strain.

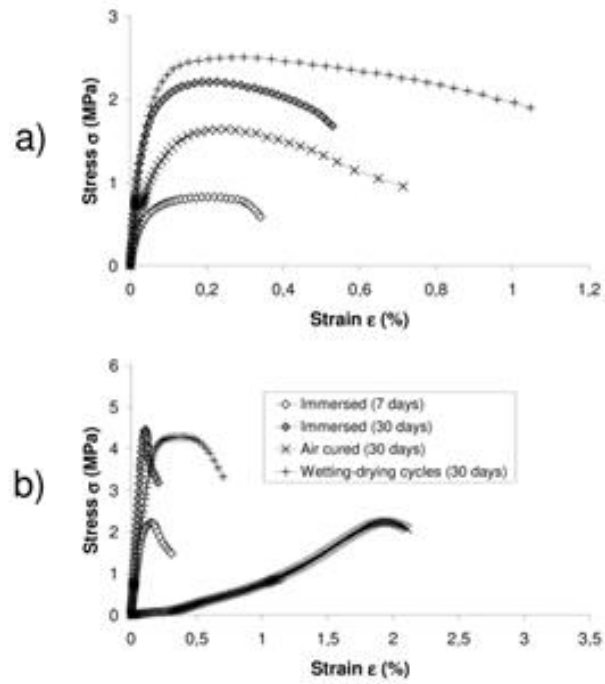
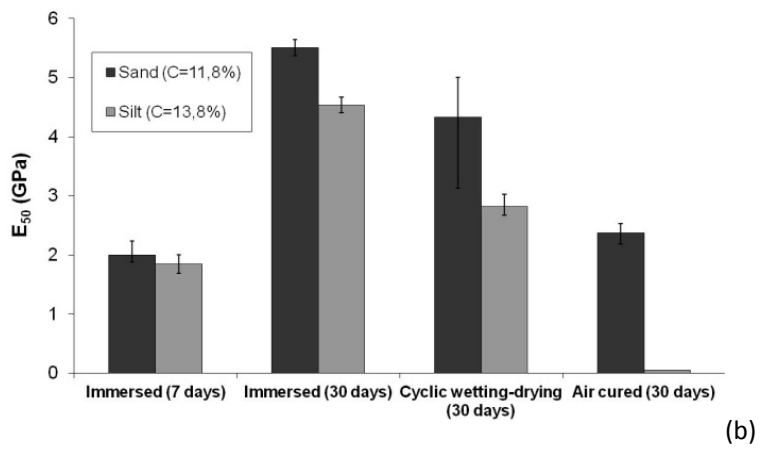
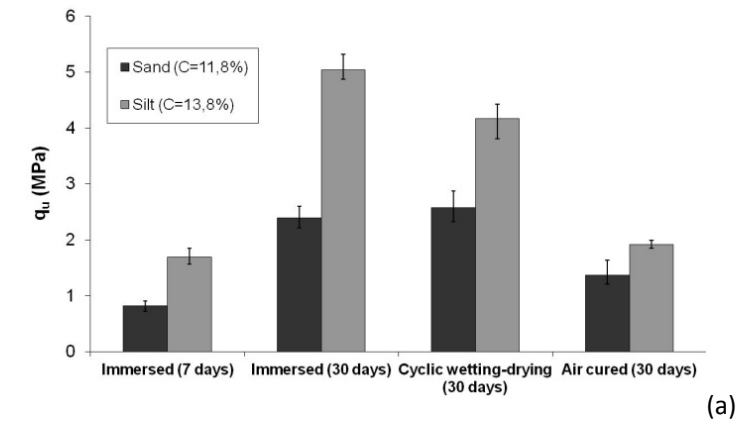


Figure 3 Typical stress-strain curves (a) mix n°1 Sand C=11.8%; (b) mix n°2 Silt C=13.8%.



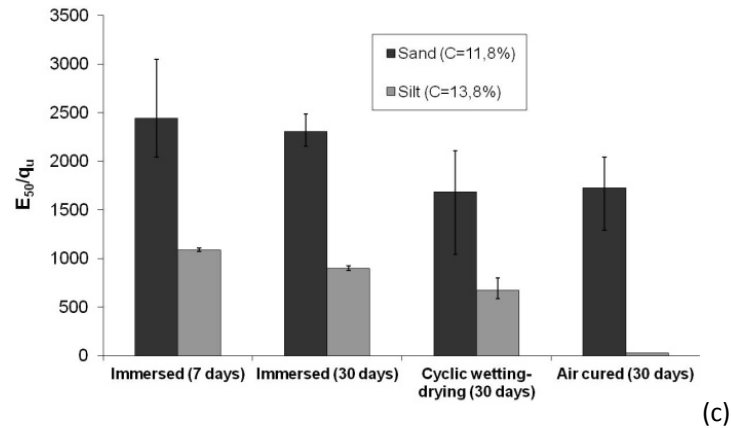


Figure 4 Effects of curing conditions on (a) Unconfined compressive strength q_u ; (b) Static stiffness E_{50} ; (c) E_{50} / q_u ratio.

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 Sand (C=11,8%)	Immersed (7 days)	0.82	2.00	2443.46	0.15
	Immersed (30 days)	2.39	5.51	2305.03	0.24
	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
N°2 Silt (C=13,8%)	Immersed (7 days)	1.69	1.84	1089	0.14
	Immersed (30 days)	4.7	5.08	1081	0.11
	Cyclic wetting-drying (30 days)	4.17	2.81	674	0.16
	Air cured (30 days)	1.92	0.05	26	2.81

5) 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, the effect of curing conditions was investigated for deep mixing materials. Specimens of silt and sand were stabilized in the laboratory with blastfurnace 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. R_c tests are then carried out to determine E_{50} and q_u . 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, R_c tests show the effects of curing conditions on E_{50} and q_u .

Unconfined compression tests were performed to evaluate the strength q_u and static stiffness 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 disruptive effect of the imposed wetting-drying 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 stabilized silt 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 resistance q_u 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 (E_{50}) was greater in the case of sandy specimens. Besides, the decrease of stiffness for the silt mixes was much more important than for the sandy specimens.

From stress-deformation curves, the significant effect of curing conditions on stiffness for the silt mixes can be observed. It might be due to the different effect of air-drying and wetting-drying cycles on natural soils with similar cement contents (11.8 % and 13.8 % respectively for sand and silt).

The results from this study demonstrate that drying can have a significant influence on the characteristics of soils treated with cement 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.

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