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Strength And Aging Of Cement Treated Low Plastic Soils

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ABSTRACT: Deep mixing is a method frequently used for various applications ranging from ground improvement and confinement to foundations. With the increase of the use of deep mixing for foundations, it is imperative to better define the mechanical behaviour and ageing of the material, which depends on the cement content and grain size distribution. This study aims to quantify the impact of these parameters as well as the percentage of fines on the mechanical behaviour of the mixed material. A number of unconfined compression tests were carried out. The results showed that it was possible to predict the strength of the mixed material after seven and 28 days of curing, based on the cement content and the percentage of fines.

Keywords: Deep Soil Mixing, Unconfined Compression Tests; Mechanical Behaviour; Sand, Cement

1. INTRODUCTION

Initially, the main purpose of deep soil mixing was to improve the stability and reduce settlements of structures such as embankments on soft soils of low shear strength or very high moisture contents [1]. These days, improving the strength and deformation properties as well as the permeability of very soft soils by deep soil mixing is a frequently used stabilization method, and the interest in the use of this technique not only for soft soils stabilization but also to construct temporary foundation/structural (load bearing) elements [2] and excavation retaining walls is increasing, as the execution is easier and less costly than traditional methods.

Deep mixing is an all-purpose term for a large number of techniques in which binding agents are mechanically dispersed within the soil in slurry form. The amount of cement used in soil stabilization is usually much lower than the amounts used for the construction of structural elements. Consequently, the cement content varies largely from one application to another, ranging from 50 to 500 kg per cubic meter of soil. However, no binder content methodology has yet been accepted, even if a large number of studies using cement as well as industrial by-products such as wastepaper sludge ash, pulverized fuel ash, etc. have been carried out ([3]; [4]; [5]).

Sandy soils, that simplify the distribution of cement [6], are the most suitable for new applications of deep mixing, as the created material can be compared to a mortar, although with a higher water content. However, grain size distribution influences the unconfined compression strength as it seems that the smallest 25% to 40% of particle size controls the mechanical behaviour of soils ([7]; [8]; [9]).

Furthermore, even if laboratory trials are the usual tests carried out in feasibility studies for soil mixing projects and if a large number of factors (such as the binder and soil type as well as the mixing and curing conditions) are known to influence the strength and deformation properties of the treated soils [10], no international standard exists for the preparation of treated soil specimens in the laboratory [11]. It is therefore difficult to compare results from different sources of the literature.

This study focuses on the mechanical properties of non-plastic sandy soils stabilized with cement to create self-compacting mixes simulating the deep mixing process. The objectives of this research were to evaluate and compare the effects of time, cement content and grain size distribution on strength of sandy soils when mixed in the laboratory with Portland blast furnace cement. Correlations and mathematical relations between different parameters such as strength, cement and fine content are presented, enabling the final design strength to be predicted, depending on the cement content and the grain size distribution.

2. EXPERIMENTAL PROGRAM

2.1 Materials

The soils used in the testing were obtained from different regions of France, depending on the availability of test sites: Fontainebleau sand, which is a French reference sand, comes from the south of Paris. Triel sand comes from the west of Paris and Fréjus sand comes from the south of France, where in situ soil-mixing tests were carried out [2].

Fontainebleau sand is a sub-rounded silicate sand which has a uniform grain size distribution with no fines. Silica flour is an artificial soil created by crushing Fontainebleau sand, and was used in this research to study the influence of high fine content on the strength of the soil mixing material, by using it pure and also mixing it with Fontainebleau sand. Triel and Fréjus sands, which are also silicate sands, show distributions that are more widely spread and contain 3% and 10% of fines respectively. Grain size distributions of all the soils are shown in Fig 1. The soils named SF50 – SilicaF50 and SF75 –

SilicaF25 are composed of mixtures of respectively 50% and 75% of Fontainebleau sand and 50% and 25% of silica flour.

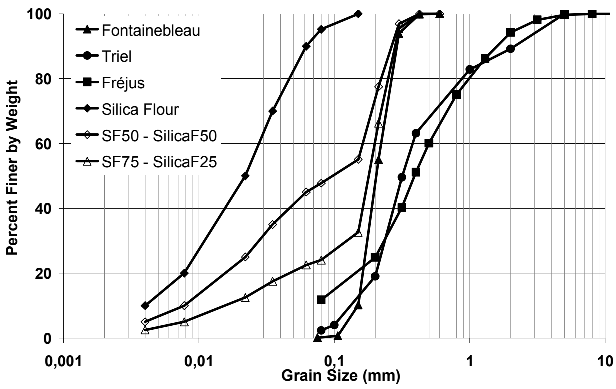

Fig. 1: Grain size distribution of the soils

These soils present Methylen Blue Values ranging from 0 (Fontainebleau sand) to 0.2 (Fréjus), showing the low content of clay particles.
The cement used for this experimental program is a Portland blastfurnace cement containing 85% ground granulated blast furnace slag, with the rest Portland clinker and a little gypsum (European classification: CEM III/C 32,5 N CE PM-ES NF 'HRC') [12].

2.2 Mixing, moulding and storage procedure

The cement contents *C* were chosen to represent the complete range of French soil mixing applications (from ground improvement to structural elements), i.e. from 70 to 400 kg/m^3. Cement contents and equivalences are presented in Table 1.

Table 1: Cement equivalences

C (kg/m^3)	C (%)
70	4.2
140	8.4
210	12.7
265	16
320	19.4
400	24.2

The water content *w* was chosen to attain a sufficient workability, i.e. to ensure that the material was fluid enough to be poured in the moulds and be self-compacting.
The preparation and conservation method of the specimens is described in a few words here. More details can be found in [13]. Soil and cement were first thoroughly dry-mixed manually, in order to obtain a uniform consistency. This premix was then put in the Hobart mixer and water was added. The amount of water was calculated based on the target water content of the mixes, i.e. 19% for the pure sands. After waiting three minutes to ensure complete wetting of the materials, the mixing process could now begin: five minutes in the mixer with constant intervention of the operator. The mix was then poured into cylindrical moulds of 52 mm diameter, and, to avoid air bubbles in the specimens, were rodded and tapped. References [14] and [15] showed this moulding method gives the best homogeneity and continuity (and hence compression strength) to the samples. The moulds were capped, and sealed in a hermetic bag containing a high relative humidity. These were stored at a temperature of 20 ± 3°C until their testing day (7, 14, 21, 28, 56 and 90 days).

2.3 Unconfined compression tests

The samples were taken out of the moulds the day of the test. They were then cut and smoothed to create plan and parallel end surfaces. They were measured and weighed, then tested for their unconfined compressive strength (q_u). Three specimens were tested at each curing time. The mean value of these tests is presented in this paper. In cases of clearly deviating results, an additional specimen was tested.

3 RESULTS AND ANALYSES

As expected, the cement content has a major effect on the strength of these sand–cement mixtures. A small difference in cement content has a significant impact on the performance of the soil–cement mixing.
Reference [16] proposed a power function, defined by Eq. (1), as the most adapted to fit the experimental relation between the unconfined compression strength (q_u) and the cement content (C).

$$q_u = a \times C^b \tag{1}$$

where a is a parameter expressed in kPa and b is a dimensionless exponent parameter. Both a and b are experimental parameters.
Fig. 2a and 2b show the relationships between q_u and C for Fontainebleau sand and the Silica Flour. The q_u versus C data for the Fréjus and Triel sands is given in reference [17]. The best fit curves follow a power function. Similar trends were observed for the Fréjus and Triel sands. However, the curvature is not the same, depending on the type of sand and age.
The power function is the best fit for the range of cement contents tested (up to 25%, which is close to the maximum cement content used for deep mixing applications). However, it is clear that should C increase drastically, a plateau would be reached, then a decrease of strength would appear, meaning that the power function would no longer be the best fit.
Whereas the mixtures made with pure Fontainebleau sand do not show a noticeable change of the values of parameters *a* and *b* (with *a* increasing from 7 to 28 and *b* decreasing from 2.15 to 1.96 between 7 and 90 days of curing), comparatively, the Triel and Fréjus mixtures show a significant variation for those two parameters with time, with *a* increasing from 30 for both sands to 1144 for Triel and to 210 for Fréjus, and with *b* decreasing from 1.8 to 0.9 and from 1.5 to 1.17 for Triel and Fréjus respectively. For the mixtures containing silica flour, *a*

increases significantly with time, whereas *b* is relatively stable.

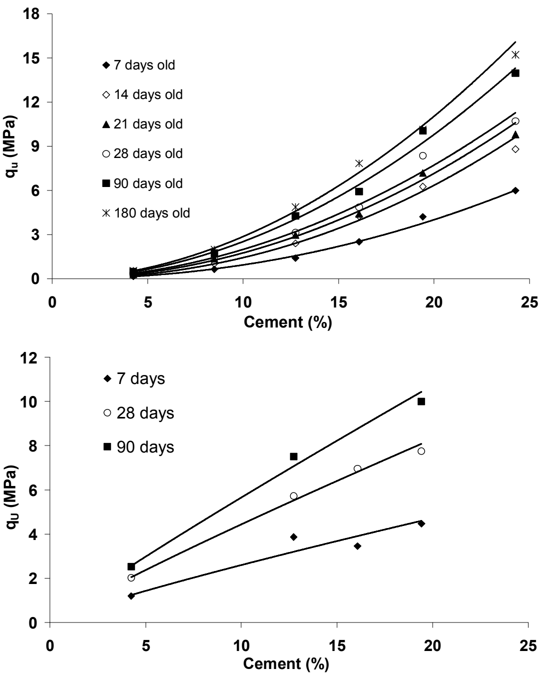

Fig. 2: Evolution of the qu–C relationship with time for (a) Fontainebleau sand and (b) silica flour

The decrease of *b* with time means that the effect of the cement content decreases for older ages.

A clear linear relation in a semi logarithmic plan between the parameters *a* and *b* exists after 7 days of curing (Fig. 3). Eq. (2) describes the relationship between *a* and *b* after seven days of curing.

$$b_7 = -0.3145 \ln a_7 + 2.7097 \tag{2}$$

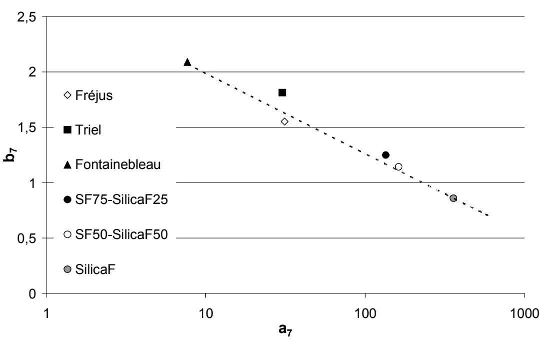

Fig. 3: Parameter b_7 as a function of parameter a_7

Therefore, it is possible to propose a formula (Eq. (3)) linking q_u to C with only b_7 as an experimental parameter:

$$q_u = e^{8.616} \times e^{b_7(\ln C - 3.18)} \tag{3}$$

Introducing the fines content C_{63} (63 µm is a common threshold extensively used in earthworks to separate fine from coarse particles [18], it is possible to find a relation between b_7 and the percentage of fines (Eq. (4)).

$$b_7 = -0.1711 \times \ln C_{63} + 1.7767 \tag{4}$$

Fig. 4 shows the relationship between b_7 and the percentage of fines C_{63}.

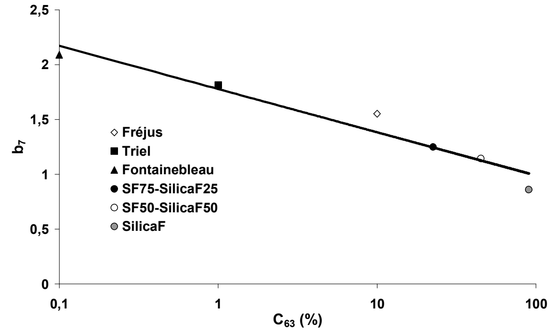

Fig. 4: Relation between C_{63} and b_7

It is therefore possible to propose a formula allowing designers to estimate the strength of stabilised granular soils based on the cement content and the percentage of fines (Eq. (5)).

$$q_{u_7} = 19.428 \times C^{1.777 - 0.171 \ln C_{63}} \times C_{63}^{0.544} \tag{5}$$

This formula gives compression strength after 7 days of curing. Fig. 5 and Eq. (6) show the good correlation between the laboratory results and the values given by Eq. (5).

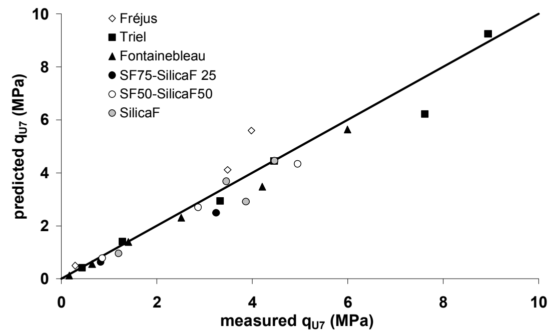

Fig. 5: Predicted q_{u7} versus measured q_{u7}

$$q_{u7_{predicted}} = 0.96 \times q_{u7_{measured}} \tag{6}$$

We have established that it is possible to predict the strength after 7 days of curing for a non-plastic granular soil, depending on the content of cement and fines. This is valuable as contractors have a need to determine the strength of the material as quickly as possible (so as to be able to readjust the cement content for example). However, for design purposes, it is often the unconfined compression strength at 28 days that is taken into account; therefore it is important to be able to predict this strength.

Reference [19] showed that q_{u28} is by no means the highest achievable strength, and that it depends on the grain size distribution of the soil. Therefore, considering q_{u28} is equal to 2 times q_{u7} for design as estimated by [6] can be dangerous. In our case, doing so leads to an overestimation of q_{u28} by almost 10%. On the contrary, it was shown by [19] that the highest achievable strength is at least equal to 2 times q_{u7}, for treated sandy soils.

Looking closer to the shape of the typical curves presenting the strength as a function of time, we observe that the relation linking these parameters follows a logarithmic function (Eq. 7)

$$q_{u_t} = g \times \ln(t) - h \tag{7}$$

Where g and h (in kPa) are experimental parameters. Reference [20] showed that the values of these parameters are in general close to each other, and directly related to q_{u7}. We can then propose the following formula (Eq. 8)

$$q_{u_t} = \beta \times q_{u_7} \times (\ln(t) - 1) \tag{8}$$

With β an experimental coefficient to be determined, and implicitly taking into account the water and cement content.

During the curing process, the only known variable value is the water content, which decreases. Reference [21] proposed a formula enabling us to estimate the final water content of the mix (Eq. 9).

$$w_f = \frac{\rho_{soil} \times \dfrac{w_n}{w_n + 1} - k \times \dfrac{C}{1000}}{\rho_{soil} \times \dfrac{1}{w_n + 1} + (1 + k) \times \dfrac{C}{1000}} \tag{9}$$

Where w_n is the initial water content and k the non evaporable water content, equal to 0.23. Considering that the parameter β is equal to the ratio final water content w_f on initial water content w_i, we have the following formula (Eq. 10).

$$q_{u_t} = \frac{w_f}{w_i} \times q_{u7} \times (\ln(t) - 1) \tag{10}$$

Finally, Fig. 6 shows the comparison between the strength measured after 28 days of curing and the strength at 28 days calculated from the Eq. 11, which combines Eq. 5 and Eq. 10: the precision is very good ($R^2 = 0.88$) with an underestimation of the laboratory results of about 6 %.

$$q_{u_t} = \frac{w_f}{w_i} \times 19.428 \times C^{1.777 - 0.171 \ln C_{63}} \times C_{63}^{0.544} \times (\ln(t) - 1) \tag{11}$$

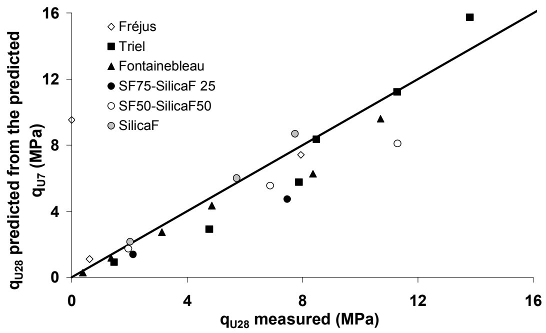

Fig. 6: q_{u28} predicted with Eq. (5) and (10) versus q_{u28} measured in the laboratory

It is then possible to predict the strength of the Deep Mixing material made of a non-plastic sandy soil and cement, knowing only the fine content C_{63} of the soil, the target cement content C (%), and the initial and final water contents w_i and w_f of the Deep Mixing material.

4 CONCLUSIONS

This paper focuses on the influence of fines and cement content on the mechanical strength of the cement mixed granular materials.

This study has shown that the mix strength depends on the cement content, following a power relationship. In addition, the exponent depends directly on the soil fines content: the cleaner the sand, the higher the value. It seems that the upper limit of the value of this parameter is around 2.1 and the lower limit is 0.8.

By studying six granular soils, we have proposed a formula to predict a cement treated granular soil q_{u7} solely from the cement content and the parameter C_{63}.

Finally, a formula to predict 28-day strength is proposed, based on strength after seven days of curing, with very satisfactory accuracy. We are therefore able to predict 28-day strength of a granular soil treated with cement knowing only soil particles size and the cement content used. The results were not compared to other authors' results due to differences in the preparation method. In particular, compaction is a big issue. However, the relationship linking q_u to C is always a power function for the range of applications concerned. Therefore, the formula simply needs to be reviewed for compacted soil mixing applications, taking into account the compaction energy.

This formula needs now to be tested in situ. However, it should not be a big issue to transpose it for on sites mixes, as the sandy soils are the easiest soils to mixes, with a smaller number of inclusions [19] and a ratio in situ / laboratory with a value near one [21]. Hence, this is a real advance for practitioners, when encountering non to low plastic soils. It is now important to study the influence of plastic fines on strength and aging.

5 ACKNOWLEDGMENT

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