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ABSTRACT

Because of its economical as well as its sustainable advantages, this deep mixing method, so far confined to the improvement of compressible or high organic content soils has become an attractive alternative to traditional methods for soil reinforcement, retaining walls (temporary or final), foundations and cutoff walls. But these new applications imply new requirements on the method as well as on the material. While numerous researches on the hardened material have been carried out, no widely applicable formula or nomograms are available yet, mainly due to the lack of international standard and practice, and because they often focuses on a particular soil. This paper deals with the mechanical behavior of the Deep Mixing material. It presents an extensive laboratory experimental program carried out to determine the influence of the different constituents of the Deep Mixing material on its mechanical properties evolution, for any given soil. The analysis is conducted to study the influence of soil nature, water and cement contents on Deep Mixing strength, deformability and workability. Relations and nomograms linking those parameters are proposed, making the results presented directly usable for design methods and on site applications.

KEYWORDS

Deep Mixing, mechanical behavior, workability, clay content, cement, plastic, non plastic, soils

INTRODUCTION

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 char-

acteristics 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 results of an exhaustive parametric study focused on the engineering properties of the Deep Mixing material. Three sands and five fine soils were treated 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. Relations between these parameters as well as nomograms and guidelines for design methods are proposed.

PROGRAM, PROCEDURES AND RESULTS REPRESENTATIVENESS

Materials

The soils tested during this study range from pure sands to pure clays (with MBV ranging from 1.25 to 28 and reflecting the activity of the clay) (Table 1), with silts and artificial soils made by mixing sand with clay or Silica Flour to study the impact of the nature and content of fines on the mechanical characteristics of the Soil-Mixing material.

Artificial soils were made of Fontainebleau sand mixed with kaolinite Soka or Silica Flour. In this paper, they are named with the abbreviation cited in brackets in Table 1 followed by the percentage of soil: for example, an artificial soil made of 75% of Fontainebleau sand and 25% of kaolinite Soka will be named SF75-kaoS25. Full details on all these soils can be found in Szymkiewicz et al. (2012) and Szymkiewicz et al. (2013).

Table 1. Grain size distribution and Methylen Blue Value (MBV) of the different soils tested.

Soils	C_{2mm}	$C_{80\mu m}$	$C_{2\mu m}$	MBV
Fontainebleau sand (SF)	100	0,1	0	0.01
Triel sand	89.2	2.33	0	0.1
Fréjus sand	94.2	11.8	0	0.2
Silica Flour (SilicaF)	100	95.2	≈ 5	0.14
Silt TGV	100	98.9	19	2.3
Silt Vémars	96.8	82	30	4
Kaolinite Soka (kaoS)	100	100	82	1.25
Kaolinite de Provins	100	100	92	6.67
Illite du Puy	100	95.1	56	5.4
Illite Arvel	100	100	76	5.9
Montmorillonite Arvel	100	100	53	28

Soils were mixed with various cement contents ranging from 70 to 400 kg/m^3, covering the whole range of dosages of the Deep Mixing applications. 57 different mixes were thus created.

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'). This cement presents a slow strength development, and its initial setting time is 4 hours after hydration.

Mixing, conservation, testing procedures and results representativeness

Soil and cement were first thoroughly dry-mixed manually, in order to obtain a uniform consistency. They were then put in the mixer and water was added. Water content of the mixes (w_i) was chosen in order to achieve a self-compacting material, meaning that it should be fluid enough to flow under its own weight. Thus, w_i must be at least equal to the liquid limit of the mix (Szymkiewicz et al., 2013). This water content is calculated as follow : water originally contained in the soil plus any water added during mixing over the dry mass of the soil plus the added cement.

The material was then mixed for 5 minutes for non-cohesive soils and for 10 minutes for cohesive soils. The mix was then poured into cylindrical moulds of 52 mm diameter, and, to avoid air bubbles in the specimens, were rodded and tapped.

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).

The unconfined compression test and the indirect tension test were chosen, mainly for their reliability and international use. The testing procedures used were directly inspired from the standards NF EN 13286-41 and NF P 94-422. The vertical load was statically applied at a constant displacement rate of 0.3 mm min^{-1}. The external axial displacement was measured using a linear variable differential transformer (LVDT). More details can be found in Szymkiewicz et al. (2012).

Numerous tests on sandy as well as clayey and silty soils were carried out, in order to assess the repetitiveness, reproducibility and repeatability of the results. Results show that the mixing and curing conditions used in this study ensure a good repeatability and reproducibility (Szymkiewicz et al, 2012).

Also, tests were carried out to ensure the repetitiveness of the tests : the coefficient of variation is equal to 7% for the Illite du Puy, and equal to 9.3% for the sandy soils (Szymkiewicz et al., 2013).

RESULTS AND ANALYSIS

Effect of cement and fine contents on strength for non-cohesive soils

Consoli et al. (2010) and Szymkiewicz et al. (2012) proposed a power function, defined by Equation (1), as the most adapted to fit the experimental relation between the unconfined compression strength (q_u) and the cement content (C) (Fig. 1).

$$q_U = a \times C^b \qquad [1]$$

where a is a parameter expressed in kPa and b a dimensionless parameter. Both are experimental parameters.

Szymkiewicz et al. (2012) also observed that the experimental parameter a and b were function (after seven days of curing) of the parameter C_{63}, which represents the particles content smaller than 63µm in percentage. Thus, they proposed a formula predicting 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 (Equation (2)).

As in situ and laboratory results are very comparable in the case of non-cohesive soils, such a formula can be directly used for on-site applications (PWRC, 1999).

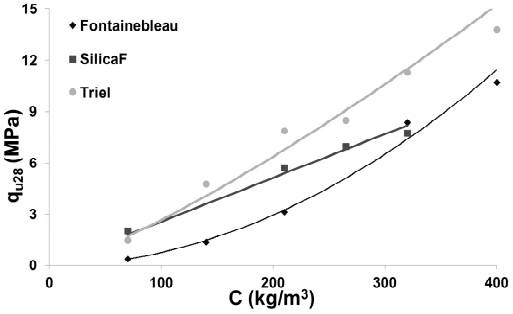


Figure 1. Relationship between q_u and C for three non-cohesive soils.

$$q_{u_{28}} = \frac{w_f}{w_i} \times 64.032 \times C^{1.777-0.171\ln C_{63}} \times C_{63}^{0.544} \quad [2]$$

Effect of water and fines contents on treated clayey or silty soils

For cohesive soils (i.e. clayey or silty soils), however, it is not so simple to analyze the influence of cement and fine contents.

First, whereas the water content needed to achieve a self-compacting material does not vary that much in the case of strictly non plastic soils (as the particles are always inert to water), it greatly varies when particles of clay (which can be of different natures) are present in the soil.

Second, the optimum domain of workability of the Deep Mixing material (defined by Szymkiewicz et al. (2013) as the water content between the liquid and the flocculation limits of the treated soil) is very small in the case of non-plastic material, while on the contrary for plastic treated soil it can be quite large.

Furthermore, the range of workability of the materials evolves according to the amount of cement added and the type of soil encountered. Tests on specimens cured for 28 days also showed the existence of an optimum water content, independent of the cement content but depending on the plasticity index of the original soil.

Therefore, it is almost impossible to decouple cement and water content when studying plastic cement treated soils. This optimum water content is dependent of the plasticity index only (Equation 3).

$$optimum\ w/LL = 0.0464 \times PI + 0.5621 \quad [3]$$

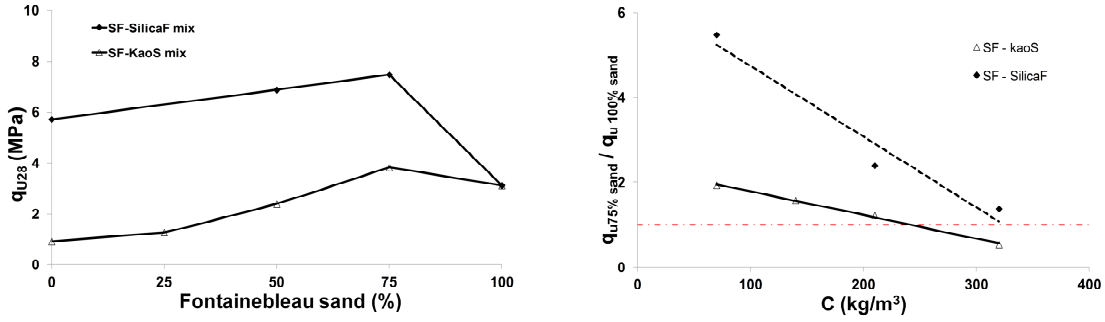
Also, plastic soils present a cohesion that it is very important to take into account, as this cohesion offers an additional strength to the material. To determine the effect of this cohesion, soils made of non-plastic fines and sand on one hand and of plastic fines and sand on the other hand, were treated, with varying cement contents.

Results showed that, for a constant cement content, treated soils made of 75% sand and 25% fine particles were stronger than treated pure sand and also than treated pure fine particles (Fig. 2a). This can be partly explained by an optimization of the grain size distribution, increasing the density of the material.

Plastic particles also add to the strength of the material, via an additional undrained cohesion. Fig. 2b shows that this additional strength due to this cohesion decreases with the increase of cement content. Between 210 and 320 kg/m^3 of cement, clay particles then reduce the overall strength of the material, for treated clayey sands, very much like a polluting agent.

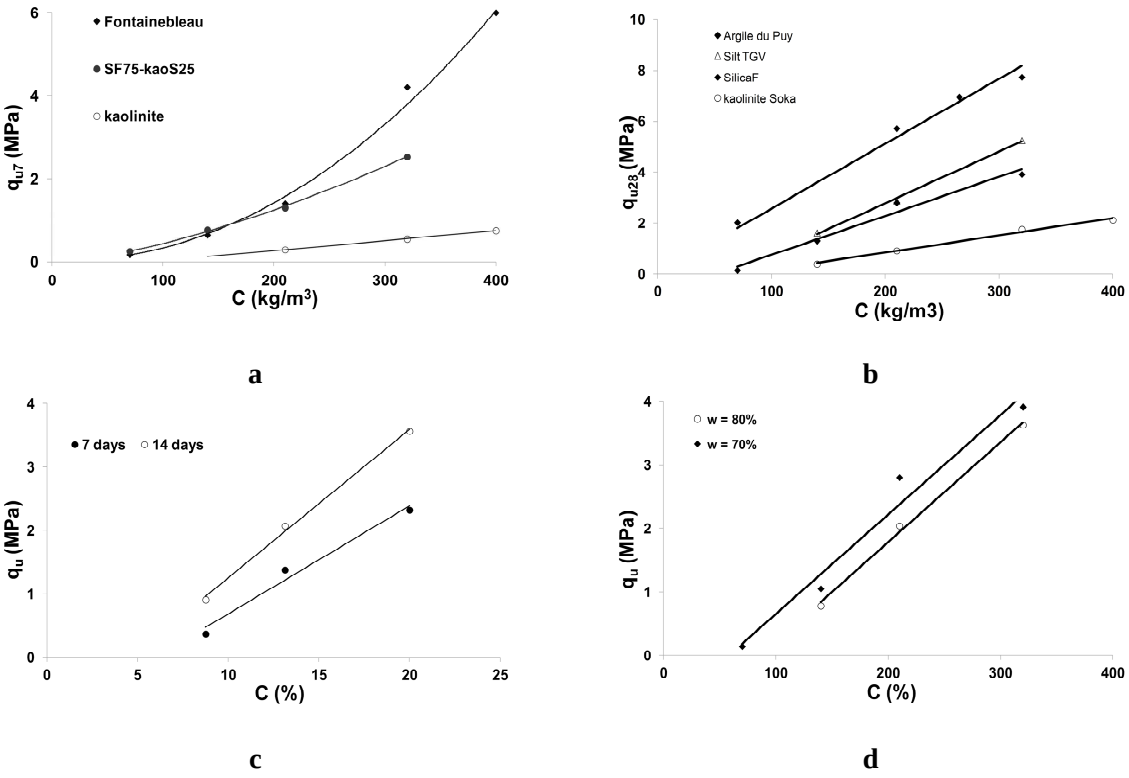
Nevertheless, the function linking the strength to the cement for plastic soils can still be expressed as a power function: the parameter b, previously defined, decreases as the percentage of fines in the soil increase (as for a non-plastic soil) until it reaches 1. The relation is given by Equation 4.

$$q_U = m + a \times C^b \quad [4]$$



a **b**

Figure 2. Influence of the quantity and nature of fines (a) and influence of the cement content and nature of fines (b) on the strength of the treated material.



a **b**

c **d**

Figure 3. Influence of the fine contents on the form of the relation between cement content and strength (a), and influence of the soil nature (b), curing time (c) and water content (d) on the threshold cement content.

This can be seen on Fig. 3a where results of cement treated soils made of different proportions of sand and clay are represented. On Fig. 3b, it can be seen that the parameters m and a vary, depending on the nature of the soil. However no logical relation can be proposed. Age also influences these two parameters (Fig. 3c), while the initial water content of the material seems to influence only m (Fig. 3d).

In the case of Deep Mixing, where the material has to be fluid enough to be self-compacting, m is always null or negative. This parameter could only be positive in the case of compacted Soil-Mixing. Therefore, a threshold cement content exists, under which, for a given curing time and water content, no unconfined compressive strength of the material can be achieved.

Propositions of nomograms and formulas

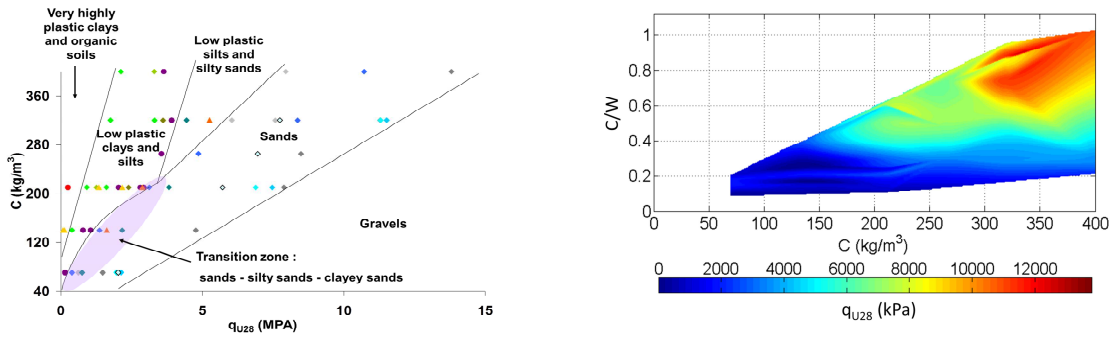
From the results obtained during this study, nomograms can be drawn: the first one, linking the strength of the material to its cement content, is the simplest one to draw (Fig. 4a). It ignores water contents and cement/water ratio: nevertheless, it is the most useful for preliminary feasibility studies, as strength ranges can be determined for each soil.

Six areas can be clearly identified: the first one represents the domain of organic or high plastic soils. The second one represents the mid and low plastic clays and silts, while the third and fourth are dedicated to the sands and gravels. The fifth and sixth zones are transition zones, respectively dedicated to the sands and clayey or silty sands, and to the low plastic silts and silty sands. These zones represent the results previously discussed.

A nomogram such as this one can be used for pre-design studies, as they represents the minimum and maximum strengths achievable, depending on the amount of water added, even if this one is not explicitly expressed in this kind of representation. It should be noted that this nomogram is only valid for Deep Mixing material. For other methods of Soil-Mixing, using compaction, results would be higher for same cement content.

Figure 4b is another nomogram, taking into account the cement/water ratio C/W, with C the mass of cement added per cubic meter of soil and W the total mass of water (including the water in the soil before treatment as well as the water added during the mixing process) . It is interesting to observe that, regardless of the nature of the treated soil, cement/water ratios of 0.4 and 0.6 appear to be clear thresholds in term of strength: with a C/W ratio smaller than 0.4, it is impossible to reach a strength higher than 5 MPa, and with a C/W ratio smaller than 0.6, it is impossible to reach a strength higher than 8 MPa.

5 MPa seems to be the highest strength that can be reached with a plastic soil.



a **b**

Figure 4a and 4b. Nomograms linking cement content / q_{u28} (a) and cement content, cement / water ratio and strength of the material (b)

In the literature, different formulas are proposed to predict concrete strength, depending on cement/water ratio, as seen in the introduction. However, they are not applicable to the Deep Soil Mixing

material. Szymkiewicz et al. (2012) proposed a formula predicting 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 of the Deep Mixing material. However, this formula cannot apply to Deep Mixing materials made of fine and/or cohesive soils. Thus, a new formula needs to be proposed. Looking at the Fig. 5 which represents the strength (after 28 days of curing) of cement treated fine and/or cohesive soils in function of the C/W ratio, a clear linear relation can be observed between these parameters, with a very good correlation ($R^2 = 0.96$) (Equation 5).

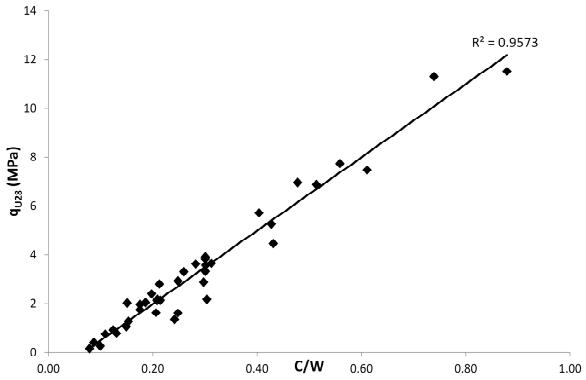


Figure 5. C/W – q_{u28} relation for fine and cohesive soils.

$$q_{U28} = 15.02 * C/W - 1.02 \quad [5]$$

It should be noted that no strength can be reached for a C/W smaller than 0.07. However this limit clearly depends on the nature of the treated soil, for workability reasons due to the method for example.

Indirect tensile strength

Figure 6 presents the relation between the tensile strength q_t and the unconfined compressive strength q_u (after 28 and 90 days of curing). It shows that q_t increases with increasing q_u, indicating that the effect of cementation is equivalent for both tensile and compressive strength. The average q_t/q_u ratio is 0.16, and does not depend on the nature of the soil.

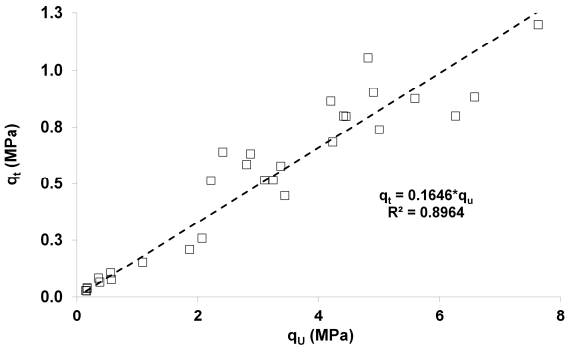
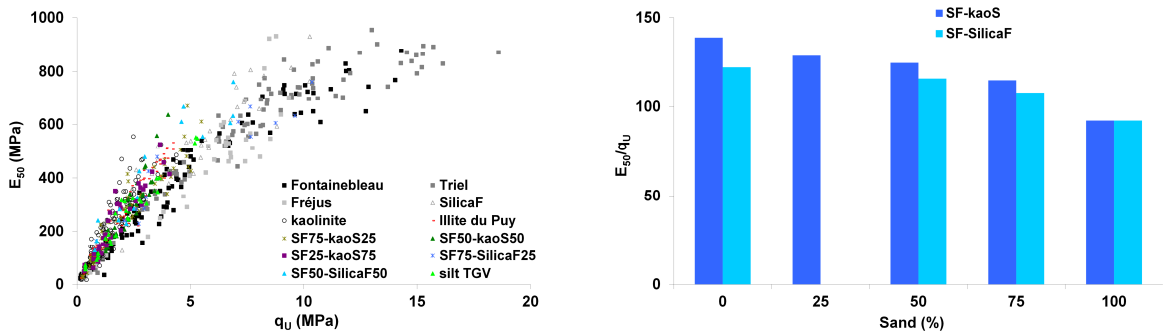


Figure 6. q_t – q_u relation for all soils.

Static deformation modulus and failure strain

It is common in the engineering practice of deep mixing projects to determine the static modulus E_{50} (defined in Swedish Ministry of Transport (2002)) and the failure strain from correlations with unconfined compressive tests. Figure 7a shows the relation between the global deformation modulus and the strength

of material, while Fig. 7b shows the evolution of the E_{50}/q_u ratio with the percentage of fines in the soil for material with a strength inferior to 5 MPa.



a **b**

Figure 7a and 7b. E_{50} - q_u relation (a) and evolution of the E_{50}/q_u ratio with the percentage of fines in the soil for material with a strength inferior to 5 MPa (b) for all soils.

The relation between E_{50} and q_u follow roughly the same trend for all soils. Up to a strength of about 5 MPa, the relation is linear, and dependent of the grain size distribution and nature of the soils. For strengths greater than 5 MPa (meaning for treated sands), the relation is less clear: regardless of the grain size distribution of the soil and of the strength of the material, the modulus varies between 600 and 1000 MPa.

Figure 7b shows that higher concentrations of fines result in a higher E_{50}/q_u ratio, following a linear relation. However, nature of the fines also impacts this ratio: an addition of non-plastic fines seems to lessen the E_{50}/q_u ratio.

Fig. 8 shows the relation between failure strain and strength, for all soils. Independently of the nature of treated soils, the failure strain varies from 0.5 to 2 %, with a tendency to increase with the strength. This is somewhat consistent with the results presented by Jegandan et al. (2010).

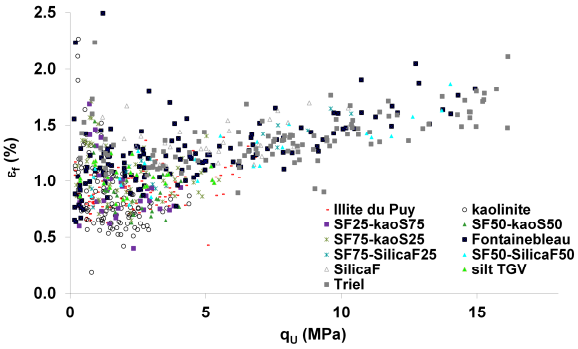


Figure 8. Evolution of the e_f - q_u relation for all soils

GUIDELINES FOR DESIGN

Table 2 is a synthesis of the results presented above, and can be used as a guideline for preliminary studies, design and quality control.

Table 2. Engineering properties of the Deep Mixing material (prepared in laboratory)

Engineering parameters	Granular soils	Fine and/or plastic soils
q_{u28}	$q_{u_{28}} = \frac{w_f}{w_i} \times 64.032 \times C^{1.777-0.171\ln C_{63}} \times C_{63}^{0.544}$	$q_{u\,28} = 15.02 * C/W - 1.02$
q_u (strength gain)	$q_{u14} = 1{,}65 * q_{u7}$ if $q_{u7} < 6$ MPa	$q_{u14} = 1{,}75 * q_{u7}$
	$q_{u28} = 2 * qu_7$ if $q_{u7} < 6$ MPa (light overestimation)	$q_{u28} = 2 * q_{u7}$
	$q_{u90} = 1{,}2 * q_{u28}$ if $q_{u7} < 6$ MPa	$q_{u90} = 1{,}37 * q_{u28}$
q_t	$q_t = 0.16 * q_u$	$q_t = 0.16 * q_u$
E_{50}	$E_{50} = 70 - 200 * q_u$ if $q_u < 1$ MPa $E_{50} = 60 - 160 * q_u$ if $q_u < 5$ MPa $E5_0 = 50 - 120 * q_u$ if $q_u > 5$ MPa with a maximum of 1 GPa	$E_{50} = 70 - 230 * q_u$
	Linear relation between E_{50} and q_u up to 5 - 6 MPa then a plateau is reached	Linear relation between E_{50} and q_u up to 5 - 6 MPa
Failure strain ε_f	0,5 - 2 % (if q_u increases, ε_f increases)	0,5 - 1, 5 %

CONCLUSIONS

In this paper, the effect of cement and fine contents on strength for non-cohesive soils is briefly recalled.

Then, it is shown that the relation between strength and cement content, for a cement treated cohesive soil, is of the same form as the one linking strength and cement content for non-cohesive soils, albeit with some minor differences. Indeed, this relationship is still in the form of a power function, but with the exponent equal to 1 when the treated soil is mainly made of fines particles.

However, unlike for non-cohesive soils, water content plays an important role, as the domain of workability is larger for plastics soils than for granular soils. This water content influences the strength development as well as the workability of the material, and depends on the nature of the treated soil. Nevertheless, the existence of an optimum water content, independent of the cement content but depending on the plasticity index of the soil to be treated, greatly helps to define the quantity of water to add to achieve the optimal quality of the material.

Plastic fines also can have a good influence on the Deep Mixing material, provided their quantity as well as the cement content are low enough to allow them to provide extra strength by mean of an undrained cohesion and density increase, allowing treated silty and clayey sands to be stronger than treated pure sands. This extra strength disappears for a cement content between 200 and 300 kg/m^3 and higher.

Results achieved on 57 mixes allowed the determination of different thresholds and to propose 2 nomograms and 2 formulas to predict the strength of the Deep Mixing material, depending on cement and water contents as well as the nature of the treated soils.

Coupling equations 2 and 5, it is now possible to predict the strength of any given soil treated with cement in laboratory.

Also, tensile strength, deformation modulus and failure strain are presented, for all kind of soils. The relation between tensile and compressive strength is linear and independent of the nature of the soil. The

same can be said of the failure strain. However, results showed that the E_{50}/q_u ratio depends on the grain size distribution and nature of the soil.

From these results, a complete guideline is proposed, that can be used by practitionners.

Researches should now focus on laboratory-on site comparison, taking into account mixing quality (size and number of virgin soil inclusions for example), energy, as well as curing conditions.

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