Quality control of Cutter Soil Mixing (CSM) technology – a case study

Contrôle de la qualité des la technologie Cutter Soil Mixing (CSM) – une étude de cas

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ABSTRACT: The Cutter Soil Mixing (CSM) is a relatively new Deep Mixing (DM) method that offers versatile construction solutions suitable for various types of ground improvement. Besides the many advantages compared to the most common DM methods, CSM has a high level of process control. Quality control and quality assurance (QC/QA) procedures are essential aspects of each DM project, and a successful treatment is related closely to the professional ability to control and verify the DM construction. This paper presents the results of laboratory tests carried out on wet grab samples collected from a CSM construction site characterized by the presence of sandy soil. Similar soil-binder mixture were then produced and tested in the laboratory accordingly, using the same binder adopted for the in situ panel construction and the sandy soil taken directly from the jobsite. A comparison between the results obtained by UC tests carried out on the wet grab and the laboratory mixed samples is also presented. The results obtained using an innovative experimental apparatus underline the influence of the physical and chemical characteristics of the natural soil on the strength gain of the stabilized material.

RÉSUMÉ : Le Cutter Soil Mixing (CSM), appartenant à des méthodes Deep Mixing, est une technique récente qui offre des solutions constructives adaptés à différents types d'amélioration du sol. En plus des nombreux avantages sur les méthodes les plus courantes, le CSM a un niveau élevé de contrôle de processus. Les procédures de contrôle et d'assurance de la qualité (QC/QA) sont des aspects essentiels du projet, et le succès du traitement est étroitement liée à la capacité de contrôler la phase d'exécution. Cet article présente les résultats de tests de laboratoire effectués sur des échantillons prélevés “wet grab” d'un site à CSM caractérisé par la présence d'un sol sableux. Semblables sol-liant mélanges ont ensuite été fabriqués et testés dans le laboratoire avec le même liant adopté pour la construction des panneaux in situ et le sol sablonneux prises directement à partir du site. En particulier, il est présenté une comparaison entre les résultats obtenus avec des essais de compression simple, effectuée sur des échantillons prélevés “wet grab” sur le site et éprouvettes réalisés en laboratoire. Les résultats obtenus par l'utilisation d'un appareil expérimental innovateur ont souligné l'influence des caractéristiques physiques et chimiques du sol naturel sur l'augmentation de la résistance du matériau stabilisé.

KEYWORDS: deep mixing, cutter soil mixing, sandy soil, unconfined compressive strength.

1 INTRODUCTION

The Cutter Soil Mixing (CSM) offers numerous advantages over the more traditional methods of mixing soils using standard rotary tools (Fiorotto et al. 2005), being equipped with two sets of cutting wheels rotating around horizontal axes producing treated soil panels of rectangular shape.

Several successful applications in different geotechnical contexts for various engineering purposes have been recently documented by Gerressen and Vohs (2012).

The Quality Control/Quality Assurance (QC/QA) programs have the objective to ensure the compliance between the actual field performance and the design requirements, therefore special attention is required.

Due to the significant uncertainties related to the site activity, most of the mix design and mixing procedure calibration is performed in the laboratory.

In order to develop a tool for an effective comparison between laboratory and field values, a specific CSM jobsite located in the city of Zandvoort (NED) has been selected. The subsoil condition is characterized by the presence of sandy soil.

Despite the fact that higher performance are usually obtained in the laboratory (Porbaha et al. 2000), the comparison between strength tests on wet-grab samples and laboratory specimens have shown sometimes opposite outcomes (Bellato et al. 2012).

The mechanical properties of in-situ improved soil may be found larger than that of laboratory specimen when using cement slurry (wet method) to stabilize loose sandy ground due to water drainage (Yoshimura et al., 2009).

Three types of water drainage may occur during soil mixing operations: potential expulsion of part of pore-water contained in the original soil by the injection of the cement slurry; bleeding of the soil-binder mixture, i.e. drainage of water due to sedimentation processes; possible drainage towards the surrounding soil layer of part of the water in the mixture due to consolidation under the effective overburden pressure.

In this paper the effect of water drainage was investigated trough an original laboratory experimental apparatus.

To assess the influence of the granular soil type on test results, the analysis were replicated on a different marine sand.

Moreover, important considerations regarding the significant influence of the physical and chemical characteristics of the natural soil on the strength gain of the stabilized sands are presented and discussed.

2 SITE DESCRIPTION

A requalification activity was planned in Zandvoort, a small village next to the North Sea coast at about 30 km west of Amsterdam. Preliminary geotechnical ground investigations were performed in the jobsite area. The results show a relatively uniform sand profile characterized by the prevalence of a medium to fine sand, generally of medium density, whose grain size distribution is reported in Figure 1. The groundwater level ranges around 2.5 m below the ground surface.

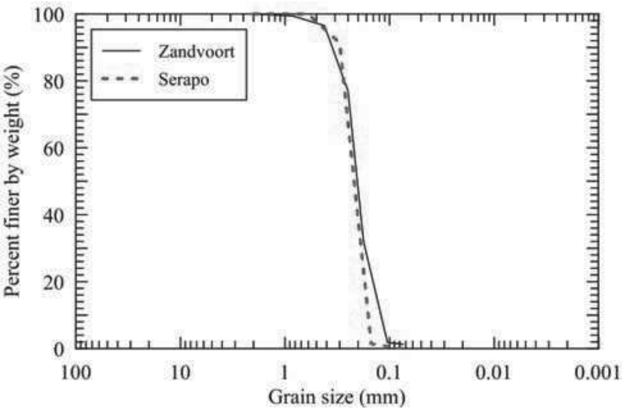

Figure 1. Grain size distribution of the Zandvoort and Serapo sands .

To construct the 11.5 m deep CSM panels (2.4 x 0.55 = 1.32 m^2 sectional area) the 1-Phase system was chosen, therefore the grout was injected on both downward and upward stroke. The grout composition adopted for the panel production was characterized by a water-to-cement ratio w/c = 1.12 and a binder factor α = 509 kg/m^3 of natural soil. The cement used was a special composite cement especially produced for ground improvement applications.

After mixing, several wet-grab samples were collected from the fresh panels at about 2,0 m from the ground level and immediately sealed into watertight tins (inner diameter of 98 mm and height of 113 mm).

3 MATERIALS AND TESTING PROGRAMME

The *wet-grab* samples collected from the site (in the following referred as “SWGS”) were cured under controlled condition (room temperature of about 20°C and at a relative humidity > 95%.) for 40 and 125 days in order to measure also the time influence on the unconfined compressive strength (UCS) of the treated soil. Before testing, the wet-grab samples were cored to provide specimens of 37 and 54 mm in diameter with an aspect ratio of 2. Finally, the specimens were trimmed to regularize the bases and wrapped with plastic film to prevent moisture loss.

Laboratory soil-binder mixtures were prepared at the same grout/sand ratio used on site, according to the treatment parameters evaluated from the elaborated machine production data. The grout and the soil were first prepared separately and then mixed together for 10 minutes using a high power mixer to produce the stabilized soil, according to the recommendations for laboratory mixed specimens provided by the Japanese Geotechnical Society (JGS0821-2000).

The stabilized soil was then poured into plastic moulds 50 mm in diameter and 100 mm in height using the No Compaction technique (simply consisted in filling the mold) to realize the *laboratory mixed specimens* (referred as “LS”).

Past experiences of sandy soil stabilization (Yoshimura et al, 2009, Grisolia et al, 2010, Bellato et al., 2012) showed the following occurrences related to water drainage conditions:

- ✓ The physical properties (water content and wet density) of sandy soil collected from the site, especially when taken below the groundwater table, typically are different from the initial in-situ conditions, due to the loss of fine particles and water during sampling and transportation to the laboratory;
- ✓ Bleeding, i.e. separation of water from the soil-binder mixture, generally occurs immediately after the mixing process in the bowl and causes the sedimentation of some amount of cement at the surface;
- ✓ Every molded sample usually shows the occurrence of bleeding phenomena, that inevitably leads to a reduction in the specimen’s height;
- ✓ In addition, when the mixture is taken from the bowl for molding operations, separation among constituent materials may be observed. This further increases the variability in terms of amounts of binder, water and sand of the samples.
- ✓ Moreover, during in-situ soil treatments, some water drainage may also arise depending on the type of mixing procedure adopted and the specific subsoil conditions. In particular, sedimentation mechanisms in the liquid soil-binder slurry mixture may develop just after the passage of the mixing tools and some amount of water can be radially drained away into the surrounding permeable sandy layers (Yoshimura et al, 2009).

To simulate the effects of water drainage on the mechanical properties of stabilized soils in the laboratory an original experimental set up was designed and used (Figure 2).

The apparatus was essentially composed of a watertight container in which a cylindrical sand core, reproducing the site conditions, is placed and surrounded by a gravel filter, with installed an open pipe for water level control (Figure 2a).

A cylindrical cavity was then prepared and filled with the stabilized soil just after the mixing operations (Figure 2b). After a time span equal to that adopted on site before sampling, a laboratory wet-grab specimen was retrieved (Figure 2c and 2d).

The two types of specimens, i.e. laboratory (“LS”) and *laboratory wet-grab* (“LWGS”), were cured at 20°C and at 95% relative humidity in curing tanks and removed from the moulds just before the test.

In order to investigate the influence of the sand type and mineralogy on the performance of the stabilized material, a marine soil namely Serapo Sand (Figure 1) was also used to prepare laboratory and laboratory wet-grab specimens.

The experimental investigation mainly consisted of unconfined compression tests. The specimens were tested at different curing times, ranging from 7 to 125 days.

To evaluate the influence of the physical and chemical characteristics of the natural soils (Zandvoort and Serapo sands) SEM (Scanning Electron Microscope) and EDS (Energy Dispersive Spectroscopy) analysis were carried out.

A CamScan MX2500 electron microscope, equipped with a EDAX EDS (energy dispersive X-ray spectrometer) system was used to determine both the morphology and chemical composition of the grains. Two small samples for both sands were first oven dried at 40°C for 24 h and then coated with a layer of carbon using an high-vacuum evaporative coater to prevent the accumulation of electrostatic charges at the surface during irradiation.

4 RESULTS AND DISCUSSION

The results of the unconfined compression tests performed on the three series of samples (SWGS, LS, LWGS) are presented in

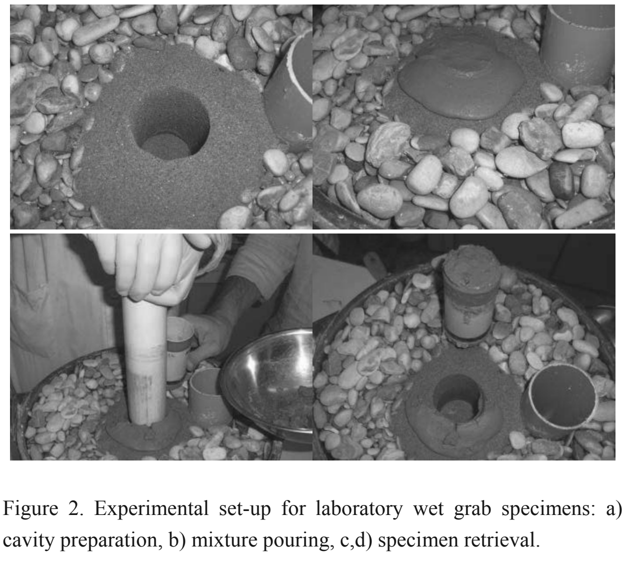

Figure 2. Experimental set-up for laboratory wet grab specimens: a) cavity preparation, b) mixture pouring, c,d) specimen retrieval.

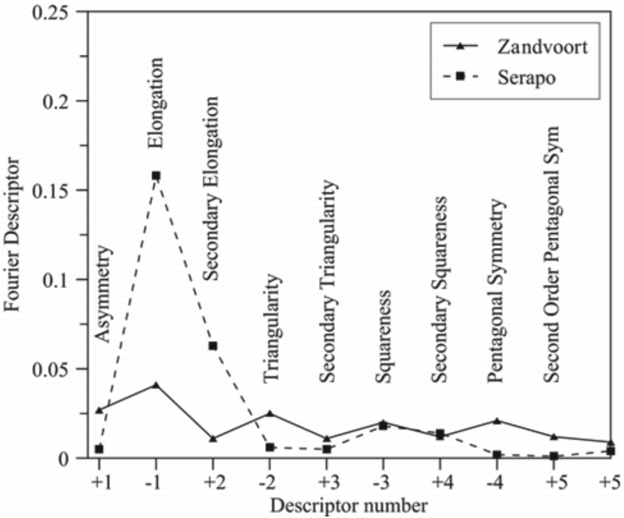

Figure 3. UC test results on Zandvoort sand specimens

Figure 7: Lower order Fourier Descriptors obtained from the two types of sands.

Figure 3.

From this figure it clearly appears that higher strength was provided by the tests carried out on the SWGS, for which UCS has been found to range between 12 and 16 MPa at 40 curing days.

UCS obtained from the LS is lower at any curing time investigated. In particular the UCS was found to be about 7.0 MPa at 40 curing days.

From the same figure, it also appears that UCS of LWGS approaches the field values.

These results underlines the effectiveness of the experimental set up in simulating the real field conditions, and emphasizes the significant effect of drainage conditions, which increase the UCS of about 1,9 times at 40 curing day.

To evaluate the influence of the type of sand, and, therefore, of the related drainage effect on strength properties, the same experimental procedure for sample preparation was replicated on Serapo sand.

The results of Figure 4 confirm also for this kind of sand an increment, even though less significant, of the UCS due to the drainage effect. The increment was about 40% at 40 curing days for the LWGS specimens with respect to the classical LS.

It is important to note (Figure 4) that similar UCS at 40 curing days was obtained from the LS of both Zandvoort and Serapo sands (prepared according to JGS0821-2000). This was expected since the two sands presents similar grain size distributions.

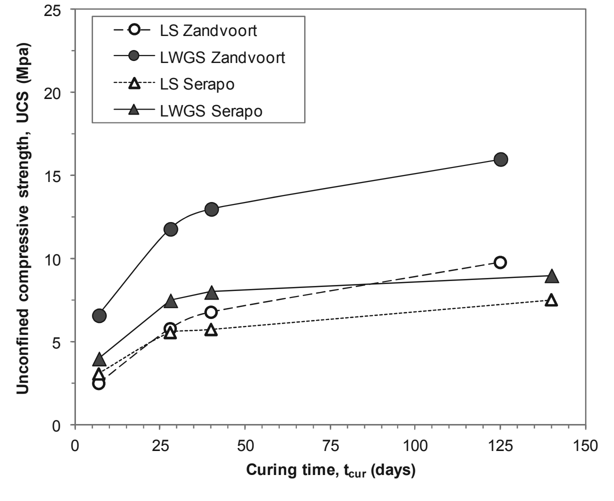

Figure 4. UC test results on Zandvoort and Serapo specimens

The results obtained from the newly developed experimental apparatus show that the type of sand and the corresponding water drainage effect may greatly influence the mechanical properties of the stabilized sandy soils.

To investigate in more details the reason of this particular outcome, mineralogical and microstructural tests were performed on the two types of sand.

The SEM and EDS analyses results are shown in Figure 5 and 6.

Figure 5 presents two backscattered electron (BE) images of two different sand grains: the grain on the left referring to Zandvoort sand, whereas that on the right to Serapo sand.

Generally, both sands are predominantly composed of quartz minerals, but in the Serapo sand a significant portion of carbonate particles is present (Figure 6).

In addition, it is easily detectable the more irregular and angular morphology of quartz grains of Zandvoort sand with respect to the more rounded, sub-angular carbonate grain of Serapo sand.

To quantify the degree of angularity different methods have been proposed in the literature (de Santiago et al., 2008). Among them, the procedure based on the Fourier descriptors (Bowman et al, 2001) is one of the most diffuse recent approaches.

The boundary of the particle is circumnavigated in the complex plane at a constant speed. The step size is selected so that the circumnavigation takes 2π and the number of steps is 2^k. The complex function presented in Eq. (1) allows to determine the aforementioned Fourier descriptors

$$x_m + i\,y_m = \sum_{n=-N/2+1}^{N/2} Z_n \exp\left(\frac{+i2\pi\, n\, m}{M}\right) \qquad (1)$$

where *x*, *y* are the coordinates of the particle boundary, *N* is the

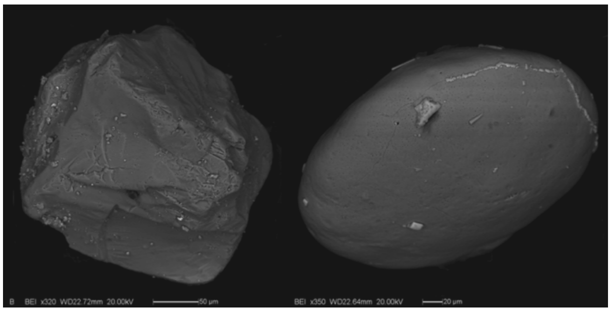

Figure 5. Comparison between SE images of a Zandvoort (on the left) and Serapo sand grain (on the right)

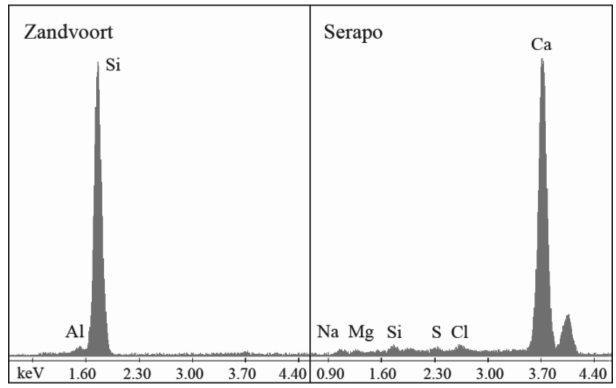

Figure 6. Chemical compositions from EDS analysis performed on a Zandvoort (on the left) and a Serapo sand grains (on the right).

total number of descriptors, n is the descriptor number, M is the total number of points describing the boundary, m is the index number of a point on the boundary, Z_n is the Fourier descriptor and i is the imaginary number.

Each Fourier descriptor, especially those of the lower order, are associated to specific and morphological features of the particle shape.

The average shape descriptors obtained for a reasonable number of grains taken from each sand sample are shown in Figure 7.

A clear more unevenness in the boundary of the Zandvoort grains can be recognized due to the higher contribution of higher order Fourier descriptors to the shape morphology.

5 CONCLUSIONS

The calibration of relationships between real and laboratory scale treatment may support soil mixing QC/QA procedures.

In sandy soil, laboratory specimens tests results may be lower than that obtained by wet grab samples due to water loss during in situ mixing operations.

The results show that quite a good match may be achieved by simulating in laboratory the in situ water drainage.

The results obtained from the newly developed experimental apparatus show that the kind of sand may greatly influence the water drainage effect on the mechanical properties of the stabilized soil.

The different degree of angularity of the grains and the different nature of the minerals composing the two sands considered in this study should be considered as relevant factors affecting the performance of the stabilized soil, as well as the grain size distribution.

Further study are needed to validate and extend the results and findings described in this case history.

To simulate in situ condition it is also necessary to carefully take into account other possible factors such as: mixing energy, use of compressed air, molding technique and curing conditions.

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