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Deep mixing research results in under water conditions

Discussion sur les essais et recherche de malaxage en profondeur sous-marin

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ABSTRACT
The present paper deals with the improvement of mechanical properties of dredged material treated on site with addition of cementing agents, by means of wet mixing. Moreover, the influence of temperature on the improvement has been studied on specimens mixed with blast furnace cement. The results of the laboratory testing do suggest the choice of blast furnace cement for the under water deep mixing application in the field, installing columns of about 1.9m in diameter and about 8m long. The column quality control also revealed that the improvement level in the field was higher than on samples prepared in the laboratory; a Scanning Electron Microscopic analysis on specimen from the laboratory and the field has demonstrated the premise that the type of mixing procedure in the field (called SSI) is a key parameter and maybe the main cause of such beneficial difference.

RÉSUMÉ
Cette contribution a pour but de discuter les charactéristiques mécaniques d'une alluvion des matériaux de dragage, améliorée par malaxage en profondeur avec des agents comme le ciment de haut fourneau, dans des conditions sous-marin. L'influence de la température a été étudiée ainsi que la façon de l'exécution du malaxage. Les résults des essais de laboratoire nous menaient au choix du ciment de haut fourneau pour reáliser l'amélioration des couches molles sous-marin de matériaux de dragage avec des colonnes de sol-ciment. L'analyse type microscope électronique (SEM) sur des échantillons prélevés des colonnes sur terrain et des échantillons de malaxage mécanique en laboratoire nous ont éclairci l'influence importante de la méthode d'exécution du malaxage même.

1 INTRODUCTION

Land reclamation activities in the harbour of Antwerp in Belgium have encouraged the design and construction of a 27 m-high sand embankment founded on a man made deposit of soft dredged material in 20 m of water depth. The presence of such soft foundation layer has caused some concern for the overall stability of the embankment. Finally, a partial deep mixing as improvement of the foundation soil was proposed together with a controlled staged construction (Van Impe et al, 2004.b).

The present paper focuses on the laboratory investigation carried out to evaluate the improvement of mechanical properties of the dredged material with binders. In addition to that, a field inspection has been carried out to evaluate the actual improvement of stabilized soil by means of the SSI deep mixing technique in situ (Soft Soil Improvement, SSI, is a technique patented by HSS).

2 UNTREATED SOIL PROPERTIES

The soft soil studied here is a man made deposit of fine grained material, result of a prolonged sedimentation and self-weight consolidation process of dredged material.

The consistency of the sludge remains very soft even after attempts of inducing consolidation by means of vacuum with horizontally installed drains. The natural water content of the soil is of the order of 115%, the plasticity index of the order of 77 and the organic content of about 6%.

The in-situ undrained shear strength (c_u) of the soil has been determined by means of field vane tests and laboratory testing on "undisturbed" specimens collected from the site. The results (Fig. 1) do show that the undrained strength of the soil, in its natural state, remains quite low (c_u of about 3 kPa). The data together with results from oedometer tests on samples at different depths have shown that the soil is in a NC state with a slightly OC crust.

3 BINDERS

In the present project a number of 7 different binders were chosen for studying their stabilization effect on the dredged material. An overview of the results of this extensive program was reported by Van Impe et al. (2004.a). In the present article, only the results found using Portland cement and Blast furnace cement are discussed in more detail.

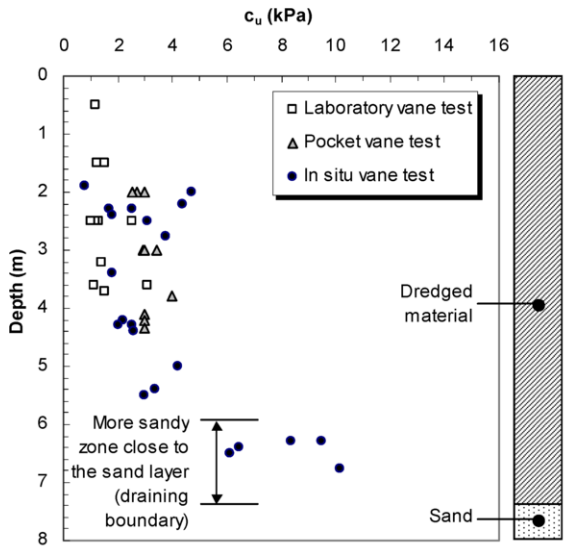


Figure 1. Initial undrained shear strength of the dredged material.

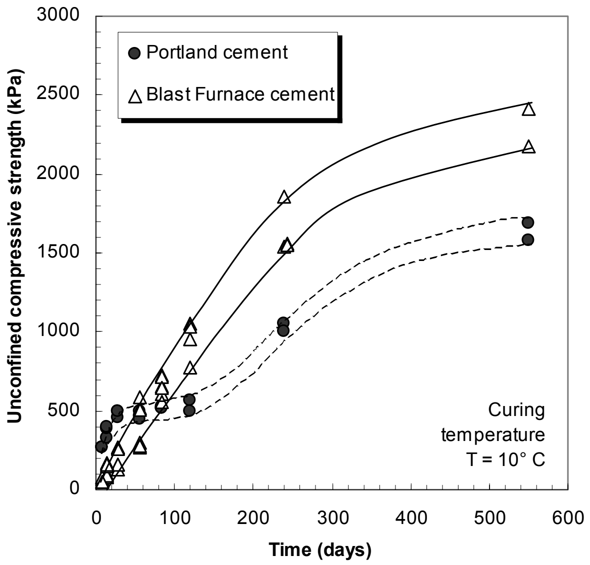


Figure 2. UCS of stabilized specimens cured under water at 10°C

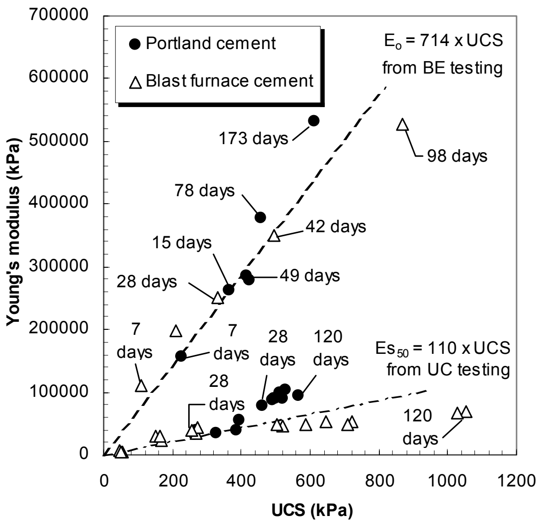


Figure 3. Young's modulus at small strain levels (E_0) and secant Young's modulus at 50% of deviatoric stress (E_{s50}) vs. UCS (10°C)..

4 CEMENT-STABILIZED SOIL PROPERTIES IN THE LABORATORY

The soil samples collected from the site were thoroughly homogenized and remolded prior to mixing with the binders. A dough mixer was employed here to mix the soil and a slurry of cement (w/c=0.8) at a dosage of 275 kg/m^3. A mixing time of 10 minutes was implemented here. Cylindrical specimens with a diameter of 57 mm and a height of 115 mm were prepared by pouring the mix into split molds. The moulds were sealed later on with paraffin and stored under water in a conditioned room at 10°C with no surcharge loading whatsoever acting on the specimens.

A number of such specimens were tested in the laboratory to evaluate the unconfined compressive strength (UCS) at different time intervals up to 550 days. The results of the testing program are summarized in figure 2. It can be clearly seen that blast furnace cements perform well, showing a continuous improvement UCS-related, even up to 550 days of age. The Portland cement instead leads to a more rapid hardening, only during the first days, then it ceases and, according to later on measurements, it picks up again only starting after 3 months. This phenomenon has not been clarified in the soil-cement chemical interaction process.

Figure 3 illustrates the secant Young's modulus E_{s50} evaluated from the unconfined compression tests. Although the trend shows some scatter, all data could be quite reasonably correlated. It was found that $E_{s50} \cong 110$ UCS. The same modulus for Portland cement tends to be higher. Similarly, the small strain modulus E_0 was evaluated by means of bender element testing (Dyvik & Madshus, 1985). A more or less linear relationship between the small strain stiffness E_0 and UCS was found at $E_0 \cong 714$ UCS. The small strain modulus for the Portland cement is again slightly higher. In general, E_0 was found to overtop about 7 times the E_{s50} value.

5 EFFECT OF CURING TEMPERATURE ON LABORATORY SPECIMENS

In an attempt to more reliably recreate the conditions in the field, a large cylindrical specimen (H= 0.8 m, ϕ= 0.6 m) was prepared in the laboratory using blast furnace cement with the aim of evaluating and monitoring the temperature changes due to exothermic reactions within the stabilized mass.

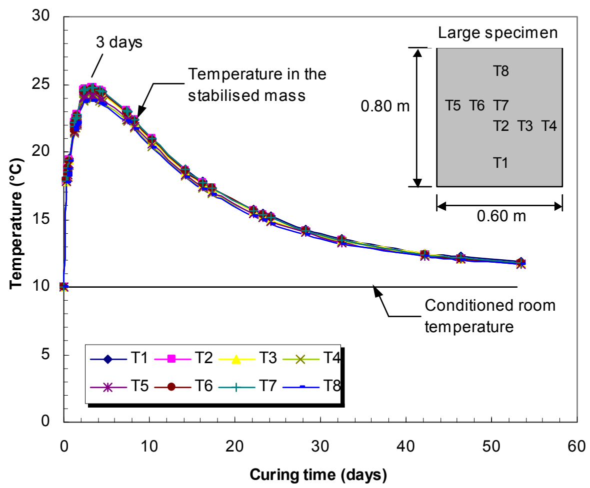


Figure 4. Hydration temperature monitoring of a large specimen of dredged material with blast furnace cement (275 kg/m^3) stored in a conditioned room at 10°C.

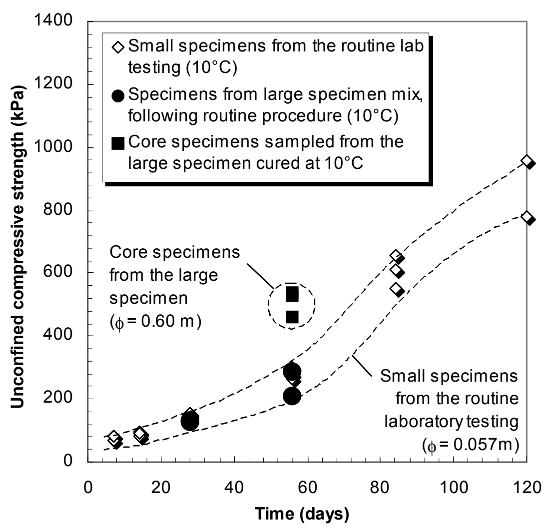


Figure 5. UCS of core specimens from the large stabilized specimen.

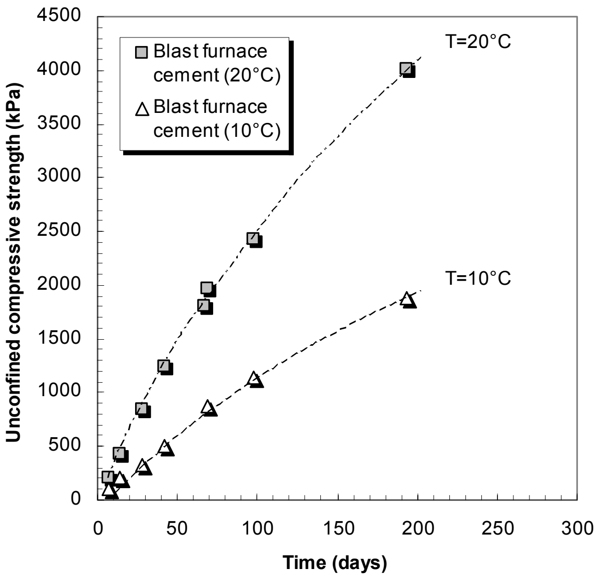


Figure 6. Effect of the curing temperature on UCS.

The virgin soil had been kept at a temperature of 10°C prior to mixing. After mixing of the soil and the cement slurry in a concrete mixer, the stabilized mass was poured into a large plastic mould (also stored at 10°C and with dimensions H=0.8 m, ϕ=0.6 m) where eight temperature transducers (labeled T1, T2…T8) were installed at different locations within the sample. A few small cylindrical specimen were also prepared following the ordinary procedure described in the previous section and cured at 10°C.

The temperature measurements within the stabilized mass over a period of 56 days are illustrated in figure 4. The readings of all temperature transducers do show a common trend. Immediately after stabilization a sudden temperature increase was observed. After 3 days a maximum temperature of about 25°C was reached. The temperature in the large specimen seems to gradually decrease; after 56 days, the temperature in the large stabilized mass (about 11.7°C) leveled out at values only slightly over the conditioned room's temperature (10°C).

By the end of the temperature monitoring some core samples have been taken from the large specimen. Figure 5 shows the UCS of such core samples. The figure also indicates the UCS of small specimens from the routine laboratory testing as described in the previous section. Clearly, the UCS of the large specimen cores doubles the UCS values of the small specimens. It is suggested that the transient temperature increase due to the exothermic reactions within the large specimen leads to such notable difference. Indeed, the larger the sample, the slower the heat dissipation and so the higher the UCS to be expected.

In order to study the effects of the curing temperature on the UC strength of the stabilized dredged material an extra series of tests has been carried out; this time on small specimens mixed with blast furnace cement, cured under water at 20°C. The results (Fig. 6) demonstrated that the strength of the samples stabilized with blast furnace cement is indeed temperature dependent. The hydration of the blast furnace cement clearly benefits from high temperatures; in fact, the UCS of samples cured under water (up to 200 days) at 20°C could be about 1.7 to 2 times larger than the UCS of specimens cured at 10°C.

6 CEMENT-STABILIZED SOIL PROPERTIES IN THE FIELD

The results of the laboratory testing program has inclined us to choose for the blast furnace cement (CEM III/B 42.5) in case of the deep mixing application in the field. Cement-stabilized columns of about 1.9m in diameter and about 8m long were installed under water with a dosage of about 275 kg/m^3 using the SSI-technique. Soft Soil Improvement (SSI) is a deep mixing method (patented by HSS) that makes use of a pressurized-mixing tool provided with nozzles homogeneously distributed along the later on diameter of the column. A cement slurry (water/cement=0.8) was injected through the nozzles of the rotating mixing tool at pressures ranging from 50 to exceptionally 300 bar.

Several columns have been selected for inspection. Core specimens (ϕ=100 mm), over the full length of each column, have been sampled 56 days after the installation. Each specimen has been tested in the laboratory to evaluate the actual unconfined compressive strength. Figure 7 illustrates the UCS of the field specimens at different depths. A trend of UCS increase with depth has been noticed. This could be explained by the more sandy nature of the deeper dredged material layer and by some extra overburden effect. The UC strength in the profile ranges from 2 to > 4 MPa in the zone where pure dredged material was treated; and from 5 to 8 MPa in a zone of more sandy dredged soil.

The figure also shows the UCS from laboratory testing, limited to a maximum of 0.9 MPa. This clearly indicates that the common practice of mechanical mixing (with a dough mixer) of specimens in the laboratory has underestimated very severely the strength of very-high-pressure stabilized soil in the field; with a factor of about 3 (as a mean value).

This discrepancy on the results of mechanical testing of specimens from laboratory on the one hand and field stabilization on the other hand have been evaluated by Van Impe et al. (2004.b) at a micro scale level by means of scanning electron microscopy (SEM). At the moment of the SEM analysis both types of specimens were about 300 days old. The laboratory specimen all had been stored under water at 10°C and the specimen from the field had been cored 3 months after installation and finally stored under laboratory conditions.

A number of pictures have been taken with an amplification factor ranging from 35 to 1700. Specimen from the laboratory do show more and larger pores; this has been attributed to the mixing action of the dough mixer that incorporates certainly air during the process.

The specimen from the field suggests a more regular distribution of cement hydration products such as the calcium-silicate-hydrate (C-S-H) and the calcium hydroxide (CH). Also the morphology of the C-H-S phase present in the field specimen suggests a more advanced degree of hydration. A more

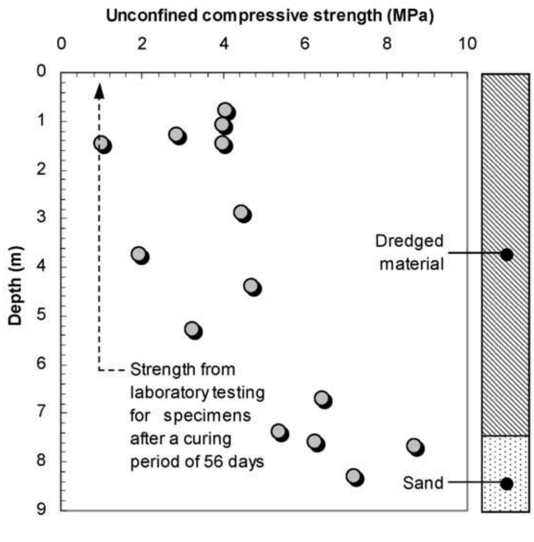
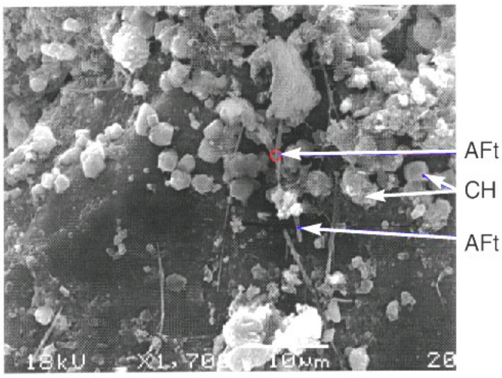
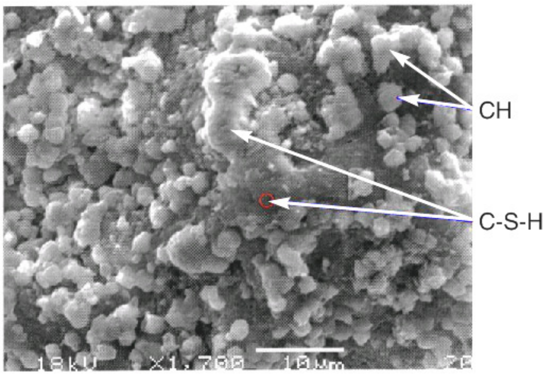


Figure 7. UCS of core specimens from SSI-stabilized columns.



a) Laboratory specimen



b) Field specimen

Figure 8. Scanning electron microscopy analysis of cement-stabilized specimens (amplification factor x1700).

complete description of the SEM picture analysis has been summarized in another paper to this conference (W. Van Impe, I. Tomac, D. Verástegui)

Figure 8 illustrates SEM pictures with an amplification factor of 1700. In the pictures one can clearly identify the hydration products of the cement. The field specimen shows a highly matured C-S-H phase together with uniformly distributed CH crystals covering completely the soil matrix. On the other hand, the laboratory specimen clearly shows less CH, and much smaller C-S-H related phase and some "ettringite" (AFt phase) that is formed during early hydration. AFt should actually not appear at all in matured and well hydrated cement pastes.

It could be suggested here that the pressurized SSI mixing method as applied in the field has played an important role, improving the distribution of cement particles around the soil particles; as a consequence, a faster hydration and hardening has taken place.

7 SUMMARY AND CONCLUSIONS

The purpose of the present paper was to illustrate the laboratory and in-situ behavior of a cement-stabilized dredged material. In the laboratory, the ordinary practice of mechanical mixing by means of a dough mixer was used, while in the field, a newly developed deep mixing method was implemented, namely, the SSI technique that makes use of high pressures for injecting a cement slurry through nozzles at the mixing tool.

The extensive laboratory testing program strongly suggested that blast furnace cements have a great potential to improve such dredged material. After more than 500 days the UCS reached, is of the order of 2.2 MPa, still even slightly increasing. The Young's modulus at small strain, E_0, and the secant modulus, E_{u50}, were roughly linearly correlated to UCS at E_0 about 7 times E_{u50}.

Moreover, it was found that the effect of the curing temperature may be of relevance when blast furnace cements are employed. The ratio of $UCS_{T=20°C}$ / $UCS_{T=10°C}$, measured in the laboratory was of the order of 2 within the first 200 days.

The inspection of trial columns installed on site, in under water conditions, implementing the SSI technique with blast furnace cement was successful. In fact, the strength of samples from the field was found to be much higher than the strength of laboratory prepared samples; with a mean factor of UCS_{field} / UCS_{lab} = 3.

In addition, SEM analysis was carried out to investigate the microstructure of specimen from the laboratory and the field. Such analysis has demonstrated a more compact and homogeneous texture of the field specimen. Also the specimen from the field shows a higher degree of hydration and a more regular distribution of the cement hydration products. Clearly, the SSI high pressure mixing improved the distribution of cement particles around the soil particles, the specific soil particle area was used in a more outspoken way; as a consequence, a faster hydration and hardening has resulted.

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