Pressurized vane shear test for soil conditioning

Cisaillement sous pression avec un scissomètre pour conditionnement des sols

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ABSTRACT

Soil conditioning is increasingly used to improve the performance of tunneling in many types of soil. Addition of suitable agents leads to enhanced properties of the soil at various points of the tunneling process. In this paper a new vane shear device is introduced, which allows to measure shear strength of clay mixtures under pressure and with different vane velocities. The new testing apparatus and the corresponding procedure are evaluated on kaolinite clay conditioned with foam and polymer additives. A strong pressure and rate dependency of the shear strength and a large effect of polymer type could be observed.

RÉSUMÉ

Le conditionnement des sols est employé de plus en plus souvent pour améliorer le performances en construction de tunnel. L`ajout d`additifs appropriés améliore les propriétés du sol à différents points du procès de construction de tunnel. Un nouveau scissomètre est présenté qui permet de mesurer la résistance au cisaillement des sols conditionnés sous pression et à différents vitesses du scissomètre. L'appareil est testé sur de la kaolinite avec des additifs à base de mousse et de polymère. On a clairement pu observer la vairiation de la résistance au cisaillement en fonction de la pression et de la vitesse de chargement ainsi que l`effet important du au polymère.

Keywords : vane shear apparatus, conditioned soil, earth pressure balance machine

1 INTRODUCTION

1.1 *Background*

Tunneling machines with closed shields use air, liquids or solids inside the shield chamber in order to apply the pressures needed to stabilize the tunnel face. The chosen shield chamber medium depends mostly on the ground properties. For tunneling close to the surface, in highly permeable and unstable soils or in urban areas, where spoil recycling or deposition is restricted, solid shield chamber medium is the preferred possibility. The closed shield machine, which uses solid shield media, is called earth pressure balance machine (EPBM).

The solid shield medium is formed out of the spoil and should preferably be of low permeability with low internal friction and pasty consistency. This is necessary to minimize the forces and the abrasion in the machine and to optimize the pressure distribution over the tunnel face and the spoil extrusion process. If the natural properties of the spoil do not provide the conditions required for the tunneling using an EPBM, the spoil is usually being conditioned with chemical additives such as foams and polymers. At present this conditioning process is performed mostly empirically, because the mechanical and chemical mechanisms are not yet well understood (Milligan, 2000; Langmaack, 2000). This does not allow for the rational optimization of the conditioning and tunneling technologies.

1.2 *State of the art*

The state of the art in characterization and selection of the appropriate conditioning agent and the choice of its necessary concentration and injection rate is largely based on trial and error, on experience and on index tests like the slump or the mixing test (EFNARC, 2001). The slump test is a standardized method for the classification of concrete and is used for conditioned soil in order to investigate the fluidizing effects of additives on coarse soils (Quebaud et al., 1998, Maidl, 1995, Langmaack, 2000). The mixing test measures the power consumption during mixing of conditioned soil with a standard kitchen mixer (Quebaud et al., 1998). This test can also be performed under confining pressure (Bezuijen et al., 1999). Both tests give some information about the plasticity and soil strength of the mixture but it is not possible to derive a full set of objective mechanical parameters from these tests. A major number of case studies on different tunneling projects have been carried out, linking together material properties of the in situ soil and index tests of conditioned soil with practical experiences and datas from construction site. A summary can be found in Borghi (2006). The necessity to develop and introduce testing techniques that deliver parameters which can describe the material behavior has been clearly stated in the professional literature (e.g., Milligan, 2000; EFNARC, 2001). Within this context, Psomas (2001) and Houlsby & Psomas (2001) performed standard oedometer and a shear box tests in order to investigate the compressibility and shear strength of coarse and fine grained sands conditioned with a mixture of foam and polymer. Importance of the confining stress for the shear strength determination has been clearly stated.

Merritt et al. (2003) and Merritt (2003) investigated the undrained shear strength of London clay conditioned with foams, polymers and foam-polymer mixtures at different injection ratios using a large scale fall cone test. This research was a major step towards systematic investigation of the mechanical behavior of conditioned soil. However, no information about other parameters, like viscosity or thixotropy, effect of pressure in the working chamber and the chemical interaction of the agents with the clay particles could be gained. Also the effect of conditioning agents on different clay types has not been investigated, limiting these results to the applications of EPBM in London clay only.

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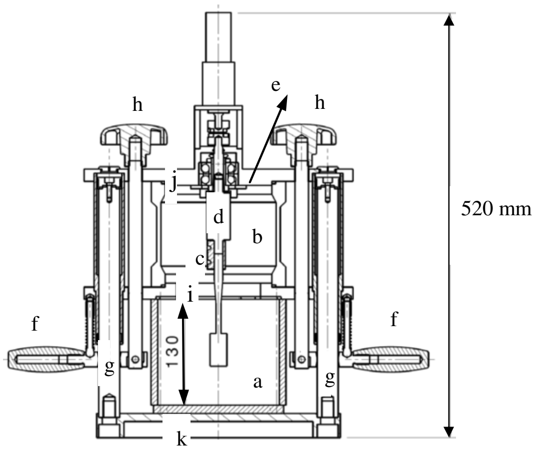
1.3 *Objectives of this research*

For a better understanding, application and optimization of soil conditioning, it is necessary to be able to define the mechanical parameters which can describe the material behavior of soil-foam-polymer mixtures. Of particular interest is the dependency of the shear strength on the strain rate (viscosity) and pressure (friction). The vane shear test, a simple and reliable test for derivation of the undrained shear strength and its rate dependency, has not yet been systematically used in the literature for mechanical characterization of conditioned soils. This in spite of the fact, that in terms of the boundary conditions, this test simulates pretty closely what happens with the mixture in the screw conveyer and working chamber. This paper uses a modified vane shear apparatus, in order to achieve a proper mechanical characterization of conditioned soils. Details about the mechanical setup of the apparatus and the sample preparation procedure can be found in Messerklinger et al. (2009). First results on conditioned kaolinite mixtures are presented.

2 TESTING METHOD

2.1 *Modified vane shear apparatus*

A new testing device based on the standard vane shear apparatus is presented in Messerklinger et al., 2009. The requirements for the design of the device were high resolution with a low internal friction in the bearings and the possibility to bring an air buffer on top of the specimen, with the pressure that can be regulated. No membrane separating the air pressure from the sample has been used in order to simulate conditions in the EPBM working chamber more closely.



a sample container
b cylindrical pressure container
c clamp for the vane
d torque sensor
e ball bearings
f handholds for adjustment of height
g pillars
h vertical fixation screws
i connection plate
j top plate
k bottom plate

Figure 1: Modified vane shear apparatus (from Messerklinger et al., 2009).

The schematic layout of the apparatus is shown in figure 1. Figure 2 shows a section and the picture of the open device.

After preparation of the conditioned soil and filling up of the sample container, the container is placed on the bottom plate of the device. The upper part of the device, with the cylindrical pressure container, the torque sensor, the connection plate and the vane is moved down by hand to close the apparatus. In the process, the vane penetrates the soil and is placed in the middle of the sample. With the vertical fixation screws, the connection plate is pressed down to the sample container, sealing it airtight. The main advantage of this test setup is that the shear vane, the torque sensor and the step motor are in the pressure cell. This does not cause any friction in the bearings.

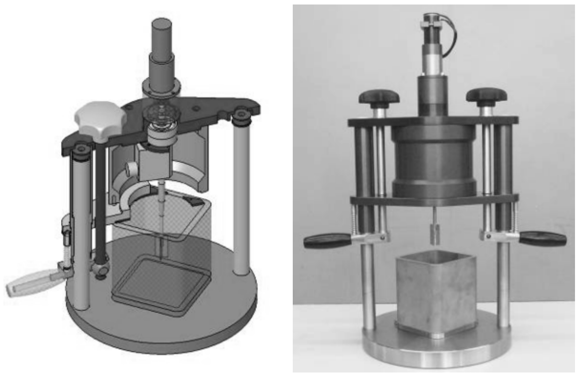


Figure 2: 3D section and photo of the new pressurized vane shear apparatus (from Messerklinger et al., 2009).

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A rather larger vane of 20 mm in diameter and 40 mm height was chosen (Geonor AS, Oslo) from a standard range in order to increase the resolution of shear strength in rather soft specimens and reduce the effects of the soil inhomogeneity. The inner sample container size of 100 mm and the height of 130 mm is a function of the vane diameter and height, according to the standards of laboratory vane shear test (ASTM D 4648). Corresponding to the specifications there should be a distance of at least two blade diameters between all points on the circumference of the shearing surface and the outer edge of the sample in horizontal direction. In vertical direction it has to be ensured, that the top of the blade is at least one blade height below the sample surface.

The vane rotates at constant velocity and carves a cylinder in the specimen. The applied torque M, which is a function of the vane diameter D, the vane height H=2D and the undrained shear strength s_u of the material, is recorded in time. According to ASTM standards, s_u can be estimated as

$$s_u = \frac{6M}{7D^3\pi} \quad (1)$$

2.2 *Tested materials*

For the limited testing program carried out to validate the device performance, different mixtures of kaolinite conditioned by foam and polymers to the optimum workable paste were used. The pure kaolinite powder (H1, Dorfner) had an initial water content of 1%. To exclude any chemical reactions of dissolved minerals in water, demineralised water was utilized. The conditioning agents (the foam MEYCO Fix SLF 30, the polymers Rheosoil 211 and Rheosoil 214) and their optimum concentration was chosen with the help of BASF based to their experience and traditional test methods (Egli 2008).

2.3 *Sample preparation procedure*

The sample preparation procedure for a conditioned kaolinite foam-soil-polymer-mixture is described below:

(1) The ingredients
The following ingredients were used for the mixture:

- 1750 g dry kaolinite powder;
- 438 g demineralised water
- 315 g of the foam-polymer-mixture with water: with foam concentration of c_f=3% and polymer concentration of c_p=2%.

The amount of the demineralised water to be added corresponded to the optimum water content of the material (Kaolin and water without additives) to achieve a maximum density in Proctor tests. The amount of the foam-polymer-water mixture corresponded to the optimum characteristics of the conditioned soil determined by BASF using traditional methods. If the concentrations of foam and polymer in this mixture are related to the weight of the dry soil this leads to concentrations of c_{fs}=0.54% and c_{ps}=0.36%.

(2) Foam Production
The foam-mixture was expanded during 1 min, with a laboratory stirrer at a speed of 2000 U/min. The expansion volume was chosen to be 3.15 liter resulting in a foam expansion ratio (FER) of 10.

(3) Soil Mixing
The three ingredients (Kaolin, water and conditioner prepared as foam) were poured together into the mixing container of a Hobart kitchen mixer and mixed for three minutes, until it could be ensured that the soil mass was homogeneous.

(4) Fill-up of the sample container and compacting
During validation of the testing procedure, a significant effect of the way of compaction of the soil mass in the sample container was observed. Two different methods were investigated: dynamic compaction with falling weight and vibration compaction on a vibrating table.

For the dynamic compaction a falling weight procedure similar to the Proctor test was proposed. This manual tool consisted of a plunger and a steel weight, which was made of a hollow steel cylinder with an inner diameter of 18 mm and allowed a frictionless movement along a guiding rod (ø 15 mm). The plunger itself consisted of a bottom plate 60 x 60 mm and a rod (ø 15 mm, length: 500 mm). The shape and size of the bottom plate was chosen to fit in the sample container at each corner, allowing for a 20 mm overlap when another corner is compacted. The number of the compacted layers and the optimum number of the compaction rounds needed to achieve the sample status at which further compaction does not influence the shear strength behaviour anymore.

For the vibration compaction a vibrating unit was used, which allowed to shake the sample at a frequency of 50 Hz and amplitude of about 1.5 mm. The vibration period lasted 1 minute. Also in this case some important parameters, like vibration time, vibration amplitude and the influence of waiting time after vibration had to be calibrated.

(5) Flattening of the sample surface
After the sample container was placed on the bottom plate of the testing device, the upper part of the device with the vane, the pressure chamber and the sensor were lowered so that the vane was placed in the soil. Before closing the apparatus completely, there had to be ensured that the surface of the sample was flat. It appeared that some polymers caused surface tension in the material, which led to formation of conical surface depression where the vane penetrated the soil. This could lead to the pressurized air penetrating along the blade and affecting the test results. The depression could be easily flattened by slightly tapping on the sample surface around the vane rod using a spoon-like tool.

2.4 *Testing procedure*

After the surface was flattened, the apparatus could be closed completely and sealed, desired air pressure was applied and the test was carried out automatically at a chosen vane velocity.

3 RESULTS

3.1 *Comparison between dynamic and vibration compaction*

Two materials described below were compacted one time using dynamic (falling weight), another time vibration compaction:

- **material A**: dry kaolinite (100g)+ demineralised water (42.46g)+ Rheosoil 211 (0.54g)
- **material B**: dry kaolinite (100g) + demineralised water (46g)

When compacted using dynamic compaction, the two materials showed almost the same peak and residual strength (figure 3). Polymer in material A reduced the amount of water needed to get to the same shear strength.

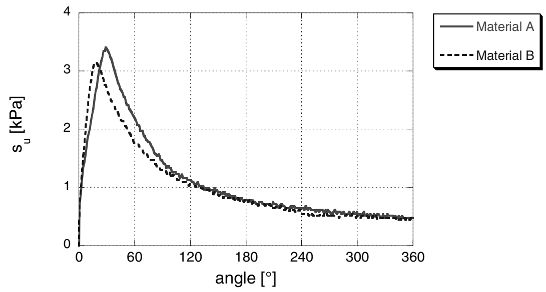

Figure 3: undrained shear strength against rotation angle of the vane for material A and B after dynamic compaction (vane velocity 360°/min, applied pressure p= 0 kPa)

Visual observation, however, indicated a drastic difference in the material behavior (Figure 4). When, after the dynamic compaction (figure 4.1), both materials were subjected to 10 s vibration, it had little effect on material B, while material A liquefied completely (figure 4.2). After vibration was stopped, the material A stayed liquid, but only if the applied strain was small, after certain strain level the material became solid again (it flowed until it reached the state in figure 4.3 and then it “froze”). Further small vibration liquefied the material A again and allowed it to flow further, having no effect on B.

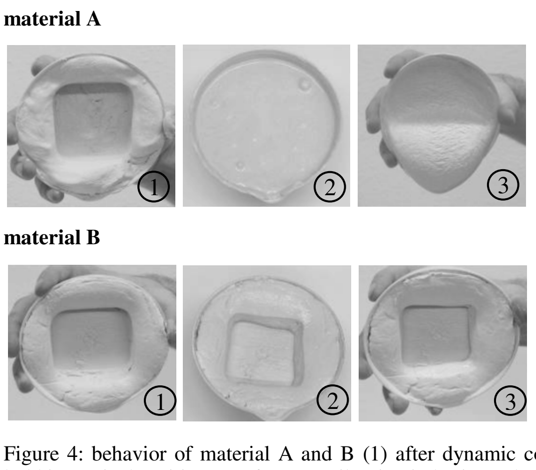

Figure 4: behavior of material A and B (1) after dynamic compaction hold in vertical position (2) after 10 s vibrating in horizontal position (3) materials in situation 2 turned to vertical position.

Obviously, when the material was compacted dynamically this important difference in the material behavior was not reflected in its stress-strain curve (figure 3). However, when the sample was compacted using vibration, the difference in the curves was drastic (figure 5): material A had almost zero stiffness at small to medium strains (i.e., liquid behavior), followed by the stiffness and strength increase and subsequent degradation.

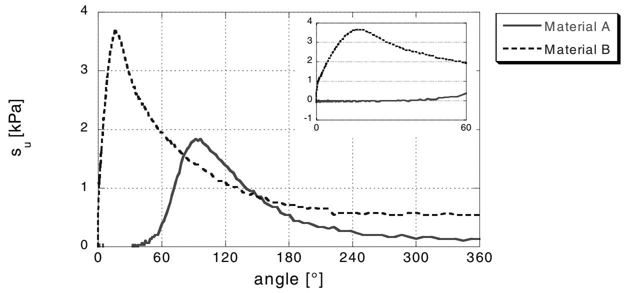

Figure 5: undrained shear strength against rotation angle of the vane for material A and B after vibration compaction (vane velocity 360°/min, applied pressure p= 0 kPa).

3.2 *Typical results for vibration compaction*

For the optimized mixture of kaolinite with foam and Rheosoil 211 compacted using vibration the liquefaction effect described above was also clearly visible, though becoming less pronounced under higher pressures.

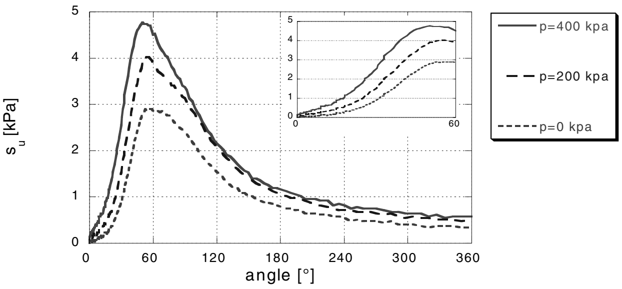

Figure 6: undrained shear strength against roation angle of the vane for different pressures (v=360°/min).

3.3 *Effects of pressure and velocity*

When maximum and residual shear strengths of the optimized conditioned soil were plotted for different strain rates and pressures, a clear dependency on pressure and velocity could be observed. For the peak strength the dependency on pressure was non-linear, following the non-linear compression of the foam.

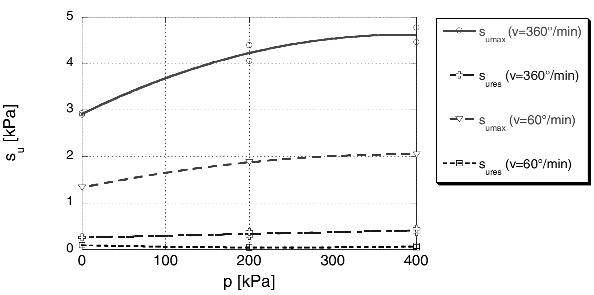

Figure 7: maximum and residual strength against applied test pressure for different vane velocities

The residual strength was almost pressure independent, because the foam bubbles on the sliding surface were probably destroyed after so much sliding, and the material was almost saturated. A significant influence of the vane velocity was observed: a six times higher velocity doubled the strength. Another interesting feature of the conditioned kaolinite: the ratio between maximum and residual shear strength could be as high as 10.

4 DISCUSSION AND CONCLUSIONS

With the new vane shear apparatus it is possible to measure with a high accuracy (±0.1 kPa) soil strength of conditioned clay soils for different velocities and pressures, allowing for the friction and viscosity in the conditioned soils to be quantified.

Introduction of vibration compaction in sample preparation process allowed for capturing the effect of liquefaction in the clay polymer mixtures. For one specific polymer (Rheosoil 211) a large influence of vibration was observed, which changed the material behavior dramatically during and after vibration of the kaolinite sample.

The proposed testing procedure and device can build a new basis for finding optimum mixtures in different clayey soils for tunneling applications and to collect more information about clay-polymer interactions and their effect on the mechanical behavior of the conditioned soils.

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