Tunnelling and Underground Space Technology 31 (2012) 86–96

Contents lists available at SciVerse ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Stickiness and adhesion of conditioned clay pastes

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ARTICLE INFO

Article history:
Received 3 November 2011
Received in revised form 19 March 2012
Accepted 2 April 2012
Available online 30 April 2012

Keywords:
Soil conditioning
Adhesion measurement
Stickiness of clays
Earth pressure balance machine
Clay–chemical interaction
Reduction of sliding resistance
Reduction of stickiness

ABSTRACT

One of the main hazard scenarios for tunnelling with Earth Pressure Balance Machines (EPBMs) in clay soils is the clogging of the shield openings and, in the worst case, plugging of the machine. Application of soil conditioners, particularly foams and dispersing polymers, leads to decreased stickiness and clogging tendency and to improved soil–machine interaction in the excavation process. Due to the lack of standard procedures, an attempt is made to propose new methods for stickiness and adhesion quantification. The first one is a simple procedure which enables the determination of an empirical stickiness ratio by weighing the soil adhering to a mixing tool after the soil preparation process. The second method uses a newly developed device, which allows measuring of the tangential adhesion and sliding resistance between a steel plate and soft soil pastes at different applied pressures, as they occur in the pressure chamber of an EPBM. The stickiness ratio was found to correlate well with the tangential adhesion and sliding resistance following a logarithmic trend for all tested mixtures, exhibiting a higher effect of chemicals on stickiness reduction at soft soil consistencies but a lower effect at stiffer consistencies. The results clearly showed a decreased sliding resistance due to chemical application with a strong dependency on the clay mineral encountered. The mixture water content is of major importance for chemical efficiency, diminishing adhesion reduction at lower water contents.

1. Introduction

Injection of different polymers and foams at the cutter head of an Earth Pressure Balance Machine (EPBM) allows expanding the application of this tunnelling method for various soil conditions. Apart from the basic requirements of mining with low torque and avoiding large settlements, in clayey soils one of the main hazard scenarios is clogging of the shield causing a standstill of the machine. For the operation mode of the machine the supporting soil muck should have ideal pasty consistency with relatively low shear strength, low permeability, certain compressibility and additionally low adhesion strength (Milligan, 2000; EFNARC, 2005).

For determination of the required conditioning and quantification of chemical effects on the muck behaviour, frequently used in practice are index tests from concrete technology such as the slump test (Langmaack, 2000; Vinai et al., 2007) and the mixing test, where the soil behaviour during the moulding process in a mixer is judged intuitively or via power consumption. More sophisticated evaluation of mechanical properties such as compressibility and permeability tests on conditioned sands (Houlsby and Psomas, 2001; Peña, 2007; Borio and Peila, 2010) confirmed important benefits of foam conditioning in sandy soils. Additionally, measurements with model screw conveyors contributed to the understanding of the rather complex excavation process (Merritt and Mair, 2006; Peña, 2007; Peila et al., 2008; Vinai et al., 2007). Besides main influences, the investigations underlined the sensitivity of chemical application and the necessity for detailed consideration of basic conditions, e.g. decreased workability through fastened foam destruction at a higher temperature (40 °C), which can easily be reached during excavation in the cutter head, was observed by Peila et al. (2008). Recently, also the importance of other foam production parameters and its influence on the soil behaviour was studied by Thewes and Budach (2010).

The quantification methods for stickiness and clogging potential of soils are often based on descriptive approaches and experience related to a specific problem. For general excavation operations and for machine tunnelling, clay soils can be classified into zones of zero to high clogging risk, depending on their consistency and plasticity (Schlick, 1989; Thewes, 1999). The consistency of the soil in this context is often described with the help of the consistency index.

$$I_c = \frac{w_l - w}{w_l - w_p} \tag{1}$$

where the parameter w stands for the actual water content, w_l is the liquid limit and w_p the plastic limit of the clay. Consistently, the highest clogging potential for clays is suggested at a consistency index I_c between 0.75 and 1.25 and a plasticity index I_p higher than

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http://dx.doi.org/10.1016/j.tust.2012.04.010

Nomenclature

m_c	mass of dry soil weight
w_{init}	water content simulating the initial water content of the soil
w_{add}	additional water content added with conditioning
w_{tot}	overall water content of the mixture
c_f	weight concentration of foaming chemical related to added water–foam mixture
c_{fs}	weight concentration of foaming chemical related to dry soil
c_p	weight concentration of polymer related to added water–polymer mixture
c_{ps}	weight concentration of polymer related to dry soil
FER	Foam Expansion Ratio: volume of foam related to volume of foaming solution (EFNARC, 2005)
FIR	Foam Injection Ratio: injected foam volume related to volume of in situ soil to be excavated (EFNARC, 2005)
PIR	Polymer Injection Ratio: volume of injected water–polymer solution related to volume of in situ soil to be excavated
$s_{c(max)}$	maximum conditioned shear strength
$s_{c(res)}$	residual conditioned shear strength
$a_{c(max)}$	tangential adhesion strength of conditioned material
$a_{c(res)}$	sliding resistance of conditioned material
α	relation between conditioned adhesion and strength value
G_{MT}	soil sticking to the mixing paddle
G_{TOT}	total weight of soil in the mixer
λ	relation between G_{MT} and G_{TOT}

30%, as established from the experience on tunnelling construction sites (Weh et al., 2010). Nevertheless, to make comparison possible and to evaluate the influence of chemicals on the clogging behaviour at any consistency, a simple and reliable method to measure this property is needed. An attempt in this direction was recently suggested by Feinendegen et al. (2011), quantifying the stickiness of different non-conditioned clays at different consistencies using a cone pull-out test.

Adhesion stresses between soil and steel are regarded as the main cause of clogging problems in tunnelling and are in general dependent on many factors, among others on the direction of loading, the deformation characteristics of the soil, the surface properties of the steel and also on the pore fluid and the chemistry of the clay. Although numerous studies on adhesion strength measurements on clays have been carried out (Fountaine, 1954; Littleton, 1976; Schlick, 1989; Jancsecz, 1991; Thewes, 1999), the results are difficult to compare due to different boundary conditions and objectives of the tests. Furthermore, correlations between both normal and tangential adhesion strength and stickiness or clogging potential are rather rare in the literature. With respect to the machine tunnelling, Burbaum (2009) developed a new testing procedure, based on tension tests between a steel plate and a wetted clay surface. In this procedure, the general clogging potential of soil is related to the normal separation forces between the plate and the soil for the soil consistencies I_c between 0.8 and 1.2. Within this range, however, the soil is not sticking to the steel plate after the test. Nevertheless, high values of the calculated normal adhesion stresses and their high dependency on the consistency within this consistency range are assumed to be linked to serious clogging problems during the excavation process with the TBM. The two main limitations of this procedure are:

– The loading condition in the test is totally different from the loading conditions during excavation. Because most of the material movement with respect to the steel parts in the screw conveyor and the pressure chamber is in tangential direction, the tangential adhesion and sliding resistance between clay and steel are expected to play a more important role than the normal adhesion.
– The interpretation of the test becomes impossible at softer soil consistencies, more realistic for the EPBM conditions. High plasticity clays start to stick in general already at relatively low water contents (Atterberg, 1911) and the optimum soil consistency for EPBM operation (I_c = 0.4–0.75) might be definitely within the range of the soil sticking to the machine. Therefore it is necessary to investigate the adhesional properties also in this consistency range.

No testing device related to tunnelling application has been reported in the literature, which allows measuring tangential adhesion at soft consistencies and the effect of chemicals on it.

The goal of this paper is to improve methodology of mechanical characterization of sticky soft clay mixtures and to quantify the influence of chemicals on both stickiness and adhesion behaviour of the mixtures. Towards this goal first a new procedure is introduced, which allows a quantification and therefore comparison of the stickiness of different soft clay mixtures. Secondly an apparatus is presented, which can measure the sliding resistance between a soft soil paste and a metal steel plate at different applied pressures and shearing velocities as the occur in the pressure chamber of the TBM. Complementary to this shear plate apparatus, a vane shear test apparatus is used to determine the conditioned soil shear strength of the same mixtures. Strength and adhesion measurement results are presented for a commonly used polymer and foam mixed with different types of clays. The results clearly show both the extent and the limits of the chemical effects on the measured parameters. This allows for some insights into the working mechanism of the used chemicals and for evaluation of the influence of the changed adhesion and strength properties on the stickiness of the conditioned mixtures.

2. New measurement devices and methods

2.1. Mixing test and new stickiness ratio

Evaluation of the stickiness of materials in general is often handled on a descriptive basis and depends largely on the problem encountered. With respect to tunnelling problems often the so called "mixing test" is used to observe the soil and therefore also the sticking behaviour of soil pastes during the mixing process in a mortar mixer (Egli, 2009; Ball et al., 2009). The effectiveness of chemicals, however, is judged intuitively, making a proper comparison of different mixtures difficult. Quantification methods of stickiness evaluation resulting in some kind of a parameter are very rare in the literature; Feinendegen et al. (2011) recently suggested using the weight of soil sticking to the surface of a cone after a pull-out test. The following new procedure, based on the existing mixing test, was chosen to solve the issue of stickiness quantification for the presented investigations.

For the mixture preparation in the laboratory, a Hobart mortar mixer with a mixing paddle is used (Fig. 1, the detailed description of mixture composition and ingredients can be found in Section 3.3). All ingredients (soil, water and conditioners) are poured together into the mixing bowl and mixed together for