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The impact of mineralogy and chemical conditioning on the mechanical and adhesive properties of clays

L'impact de la minéralogie et du conditionnement chimique sur les propriétés mécaniques et adhésives des argiles

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ABSTRACT: When using tunnel boring machines in cohesive soil, the excavation and conveying equipment is often subjected to clogging, which leads to significant additional expense and delays in the construction process. Work interruption by clogging causes frequently disputes between clients and contractors about the financial responsibility. Up to date no generally recognized evaluation method has been established to predict and quantify the clogging potential in sufficient detail. In this article the clogging behaviour of four sticky clays with different mineralogies, i.e. London Clay, Vienna Clay, Frankfurt Clay and Wimpfsfeld II Clay, is discussed on the basis of cone pullout tests. By using different anti-clay admixtures the variation in clogging is quantified. Results show that Atterberg limits of the clays change reducing the adhesion on the steel cone. It can be stated that adhesion is directly related to the basic mechanical and mineralogical characteristics of the fine-grained soils.

RÉSUMÉ: L'interruption de travail par encombrement provoque fréquemment des conflits entre clients et entrepreneurs. Dans cet article, le comportement encrassement de quatre argiles collantes avec différentes minéralogies, à savoir London Clay, Vienna Clay, Frankfurt Clay et Wimpfsfeld II Clay, est discuté sur la base d'essais de retrait au cône. En utilisant différents mélanges anti-argile, la variation du colmatage est quantifiée. Les résultats montrent que les limites d'Atterberg des argiles changent en réduisant l'adhérence sur le cône d'acier.

Keywords: Clays; Clogging; EPB-TBM; Atterberg limits; Chemical conditioning

1 INTRODUCTION

The selection of the Tunnel Boring Machine (TBM) type depends on the lithological properties of the soils to be excavated as well as on technical, logistical and economical considerations of the area where the excavation is performed. Earth Pressure Balance (EPB) Shields were developed for use in weak fine grained ('cohesive') soils. However, due to the rare occurrence of pure 'cohesive' and 'cohesionless' soils in practice, there has been an effort to widen the application of the machine. The cutterhead can contain either picks or discs, or a combination of both (Chapman et al. 2017). EPBs use the earth pressure in the excavation chamber to stabilize the tunnel face by controlling the advance rate and the rate of extraction of spoil through a screw conveyor. By this the excavated material is removed in a controlled manner so that the pressure is maintained in the chamber. At the same time, the pressure at the other end of the screw conveyor is atmospheric, i.e. there is a pressure loss from one end to the other. This means that the plasticized spoil in the screw conveyor needs to form a plug to help maintain this pressure differential.

The ideal material for EPBs is a fine grained ('cohesive') soil with stiff to soft consistency (I_C = 0.5-0.75), which extrudes through the openings of the cutterhead towards the screw conveyor. If the excavated material does not have these properties, it must be 'conditioned', i.e. artificially modified (Chapman et al. 2017). Consistency is defined by the Atterberg Limits and the natural water content:

$$I_C = \frac{LL-w}{LL-PL} \tag{1}$$

where LL is the liquid limit (in %), PL is the plastic limit (in %) and w is the natural water content (in %) of the excavated soil. Note that $LL - PL$ gives the plasticity index PI.

During mechanical headings with EPB in clay-rich soils, the excavated material often sticks to the cutting tools, cutterhead or conveying system. This may cause great difficulties in the excavation, transport and reuse of the material. According to Thewes and Burger (2005), the profitability of a tunnelling project can depend very much on the clogging potential of the soil encountered. Tunnelling progress in clay can be as low as 1/10 of that in granular soils.

Generally, clogging is the result of adhesion processes that occur at the interfaces between the surfaces of the clay minerals and the tools (e.g. Spagnoli et al., 2011; Feinendegen et al., 2011a). For instance, according to Jancsecz (1991), Weh et al. (2009), Spagnoli et al. (2011) clays which lead to clogging problems are highly cohesive clays with high liquid limits and a high plasticity index. These types of soil tend to become very sticky in contact with water, due to the swelling effect of the clay particles. Several approaches to prevent this problem are available on the market, but their performance is not always satisfactory. The clogging problem, therefore, remains a significant concern in tunnel construction. The risk is especially high when water comes into contact with soils prone to clogging. If they are mixed in the excavation chamber, a critical consistency can be reached and may result in clogging. According to Weh et al. (2009) soils prone to clogging have a high density and a high consistency. The most important parameters which influence clogging are:

- mineralogy;
- water content;
- grain size distribution;
- chemistry and pH level of water.

It is clear that mineralogy has a strong influence on the Atterberg limits (e.g. Sridharan et al., 1986; 1988; Mitchell and Soga, 2005; Spagnoli and Sridharan, 2011; Spagnoli et al., 2018). According to Girmscheid (1997a; 1997b) the critical liquid limit leading to clogging is LL > 35% and the plasticity index PI > 15-25%. Also the critical clay content from the grain size curve was estimated > 15-20% (Guillaume and Mauroy, 1997). Adherences may occur on all surfaces that are in contact with the excavated material during excavation, transport or disposal. The material first sticks to the tool surfaces due to adhesion forces. Clogging problems will follow when the amount of adhering soil leads to a narrowing in the transportation channels. The material is compacted and pressed onto the tool surfaces or already adhering soil. At high and low consistency, the clogging is usually not as pronounced as in the critical area between high and low (Fig. 1). Usually, clogging is observed much less on moving parts, where not only gravitational forces are present (as with stationary parts), but also rotational or shear forces are acting on the parts. However, the mechanical wear of the material in connection with the machinery working on the EPB leads to a massive rise of the temperature, which again results in very tough and permanent adherences. This can be very unfavorable, for example when these hard adherences act as a kind of support for softer material (Weh et al. 2009).

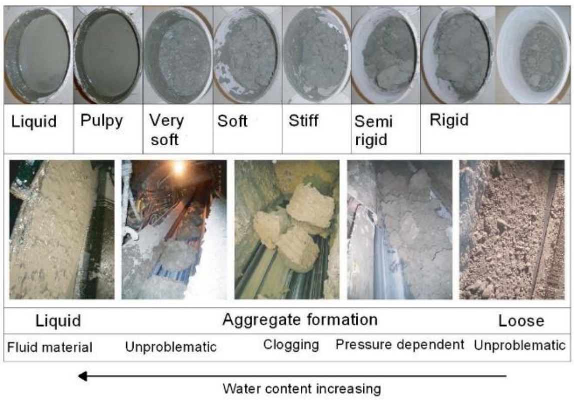

Figure 1. Critical consistency (soft/stiff) during tunnel excavation modified from Weh et al. (2009) (Spagnoli 2011)

When the excavated material does not meet the required consistency and/or clogs to the metallic part, it must be conditioned. This can be done using:

- water;
- bentonite, clay or polymer suspension;
- foam (surfactants mixed with water and compressed air);
- foam with polymer (the polymer helps to stabilize the foam).

Foams and anti-clay additives help increasing the tunnel excavation, decreasing torque and adhesion to the metallic surfaces. This research presents some laboratory tests on four sticky clays to assess the basic soil mechanical behaviour and the adhesive properties by means of the cone-pull out test (Feinendegen et al., 2010). Four different additives were used to observe the impact on the adhesive properties as well as on the Atterberg limits.

2 MATERIALS AND METHODS

For London Clay, Vienna Clay, Frankfurt Clay and Wimpfsfeld II Clay the basic classification parameters were determined (see Tabs. 1 and 2) and cone pullout tests were performed to examine the clogging behavior.

Table 1. Atterberg limits of the clays tested in this research

Clay	*LL* (%)	*PL* (%)	Nat. water content (%)	Natural consistency (%)
London	76.1	24.1	25.1	0.98
Wimp II	47.4	19.2	16.7	1.09
Frankfurt	71.1	28.7	32.9	0.90
Vienna	46.8	17.6	22.9	0.82

Table 2. Other parameters of the clays

Clay	Loss on ignition (%)	Calcium content (%)	Grain density (g/cm^3)
London	6.3	1.3	2.663
Wimp II	6.9	2.2	2.637
Frankfurt	6.5	24.8	2.547
Vienna	3.9	5.8	2.659

Clay mineralogy of the four clays tested in laboratory is shown in Tab. 3 and it was obtained by means of X-ray diffraction analyses carried with a Bruker AXS D8-Advance diffractometer using CuKα radiation. XRD data were collected between 2 and 92° 2θ and measurements were made using a step scanning technique with a fixed time of 3 s per 0.02θ.

The experimental setup of the cone pullout test is shown in Fig. 2. The sample material, a cohesive soil or -if preparation is possible- a variable solid rock, is first crushed and homogenized according to standards as for the determination of plasticity. The desired water content (i.e. the desired consistency) is adjusted, the material is stored for 48 hours for swelling and then installed and compacted in accordance with a Proctor test DIN 18127 - P 150 X. A conical depression is then made (phase (1)), into which the actual test cone is introduced (phase (2)). In the following loading phase (phase (3)), the cone is slowly pressed into the specimen at a speed of 0.23 mm/min for 10 minutes and finally pulled out again at 5.83 mm/min in the tensile phase (phase (4)). During the test, the compression and tensile forces are recorded electronically. The tests are carried out as standard at five (possibly six) different consistencies with increasing water content: $I_C \approx$ 0.85 / 0.70 / 0.55 / 0.40 / 0.25 / (0.10). Since the scatter of results is sometimes quite large, at least four, sometimes six or eight individual tests are required for each consistency.

Table 3. Clay mineralogy

Clay	Smectite (%)	Kaolinite (%)	Illite (%)
London	34.4	7.8	24.3
Wimp II	9.7	30.9	28.9
Frankfurt	21.2	7.5	21.0
Vienna	23.7	4.1	21.2

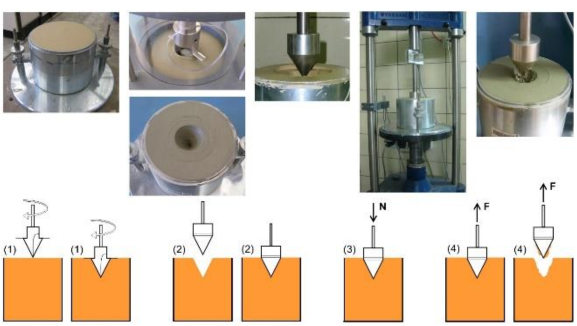

Figure 2. Cone pull-out test

After each test, the mass of soil adhering to the test cone is determined by weighing and related to the cone surface area. The value is plotted against different consistencies and quantifying statements can be made about the clogging tendency at different water contents.

Four BASF products with a target concentration of 1.5% active ingredient in the feed water were tested as conditioning agents:

- Pluriol® E400 = Polyethylene glycol that conforms to the general formula HO(CH2CH2O)nH, CAS 25322-68-3; grade: 100 %;
- Sokalan® PA 20 = aqueous solution of sodium salt of polyacrylic acid, density 1.32 g/cm^3;
- MasterRoc ACP 147 = aqueous solution (20-25%) of D-Glucopyranose, ligomers, decyl octyl glycosides, CAS 68515-73-1;
- MasterRoc ACP 214 = aqueous solution of sulfonated polymer;

3 RESULTS AND DISCUSSION

Results from Atterberg limits determination are shown in Fig. 3. One immediately recognizes the high plasticity of some of the clays investigated.

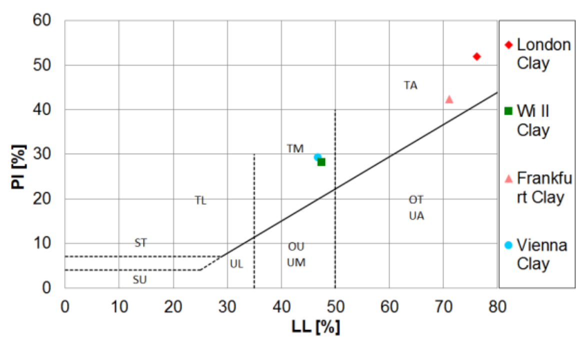

Figure 3. Casagrande chart showing the investigated soils

Fig. 4 shows the results of the cone pullout tests. It is possible to observe:

- London Clay with an extremely high adherence value reaching almost 6.000g/m^2 at I_C = 0.55;
- maximum adherences for all tested clays in an I_C range between 0.3 and 0.55;
- Vienna Clay, Frankfurt Clay and Wimpfsfeld II Clay with high adherences between 1.500 and 2.000 g/m^2;

Results agree with previous tests performed by Feinendegen et al. (2011a; 2011b). It is interesting to note that the maximum adherences for the four tested clays occur in the consistency range suggested by Chapman et al. (2017), defining the ideal material for EPBs.

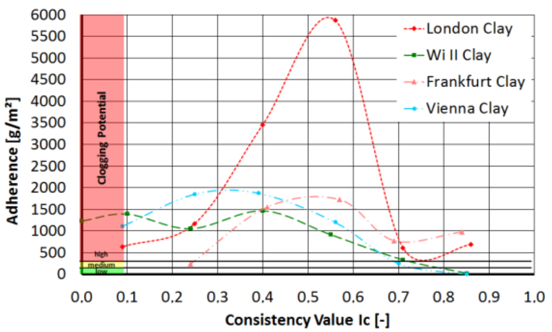

Figure 4. Adherences measured in laboratory for the investigated clays with the cone pull-out test

Adhesion, Atterberg limits and mineralogy seem to be related (e.g. Jancsecz, 1991, Weh et al., 2009). Fig. 5 shows the results of the maximum adherence from Fig. 4 plotted with the mineralogical composition of the tested clays. It is worth to notice that London Clay, which shows the highest adherence has also the highest amount of smectite (34.4%) and a low amount of kaolinite (7.8%). Considering only the smectitic amount, adhesion seems to be proportional to this, as Wimpfsfeld II Clay, which has only 9.7% of smectite is also the clay showing the lowest adherence. However, smectite only cannot justify the adhesion potential as this depends also on the grain size distribution, the in situ stress state and soil texture.

Casagrande chart values were obtained for the clays mixed with the fluid. Interestingly results vary with different magnitude depending on the tested soil. For instance Fig. 6A shows the results obtained for the London Clay whereas Fig. 6B shows the results obtained for the Vienna Clay. For the London Clay the additives cause in general no change or a decrease of the plasticity except for fluid 1139. As clays are colloids, their physical and chemical properties change if the pore fluid is different from water and this, in turn, reflects on the mechanical behavior of the fine-grained geo-materials (Spagnoli et al. 2017). It seems that for the London Clay MasterRoc ACP 147 disperses the clay, leading to an increase in plasticity.

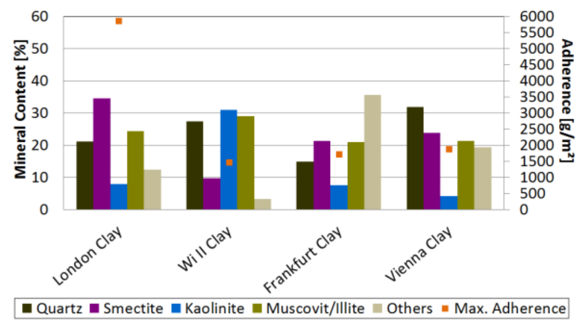

Figure 5. Mineralogy and maximum adherence measured with the cone pull-out test

Fig. 6B shows the results for the Vienna Clay. Vienna Clay has a smaller smectite content (23.7%) which is similar to its illite content (21.2%). Data in the Casagrande chart do not change with different additives. Sridharan et al. (1986, 1988) observed that a change in pore fluid properties (e.g. a decrease in the dielectric constant) results in an increase of *LL* for kaolinitic soils (and conversely a decrease in the liquid limit of smectitic soils). Sridharan (2014) states that for kaolinite, the net effect of increase in dielectric constant is to decrease the attractive force and hence, shear strength decreases resulting in the reduction of *LL* values. Low dielectric constant values in kaolinite causes a flocculation hence an increase in LL. For smectite, the increase in diffuse double layer (DDL) overshadows the effect of the decrease in the shear strength as the dielectric constant increases, resulting in an increase of LL.

The other two clays (not shown) have a similar behavior as the London Clay, however for the Wimpfsfeld II Clay with the highest kaolinitic content among the tested clays, the increase in plasticity is given by the Pluriol® E 400. Considering the outcome of Fig. 6, cone pull-out tests were performed on the 'conditioned' clays. Starting with the natural water content, the respective solution was added to the sample until the desired consistency was obtained.

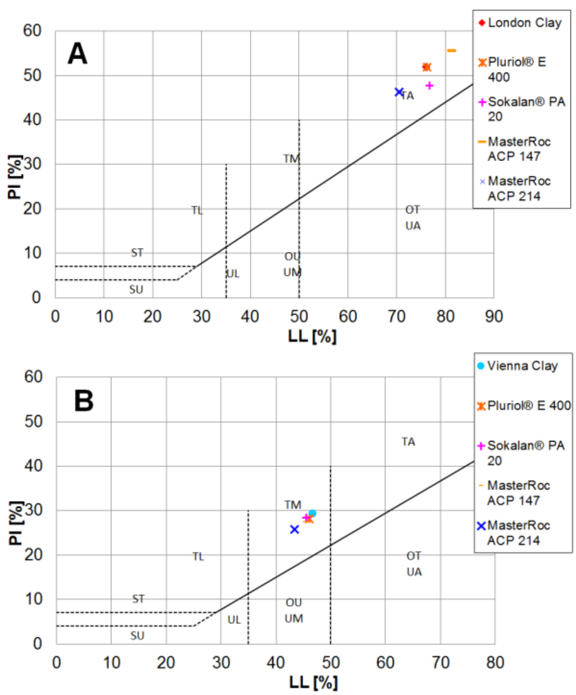

Figure 6. Casagrande chart showing London Clay (A) and Vienna Clay (B) modified for the different soil conditioning fluids.

Fig. 7A shows the results for the London Clay. The red line refers to the adherences obtained with water (see Fig. 4), the points refer to those obtained with the different additives. The arrows refer to the shift from the target consistency to the actual consistency measured after perfoming the tests. As can be seen in Fig. 7, the consistency changes quite considerably in some cases and sometimes also in different directions with different fluids. It is interesting to note that fluid 1139 causes an increase in I_C, i.e. the material becomes stiffer. Atterberg limit results show however an increase in plasticity, i.e. the material becomes more disperse.

In general, a significant decline in adherences can be observed (up to factor 6). The influence of pore fluids on the adhesion reduction was already investigated by Spagnoli et al. (2011). The theory to describe the phenomenon is the DDL which tends to decrease for increasing ionic strength or decreasing permittivity of the fluids. Fig. 7B shows the results obtained for the Vienna Clay, which also has a high smectite content (23.7%). It can be seen that adherence is reduced by factor 1.3 to 4 depending on the different additives. The arrows still refer to the target vs. actual consistency.

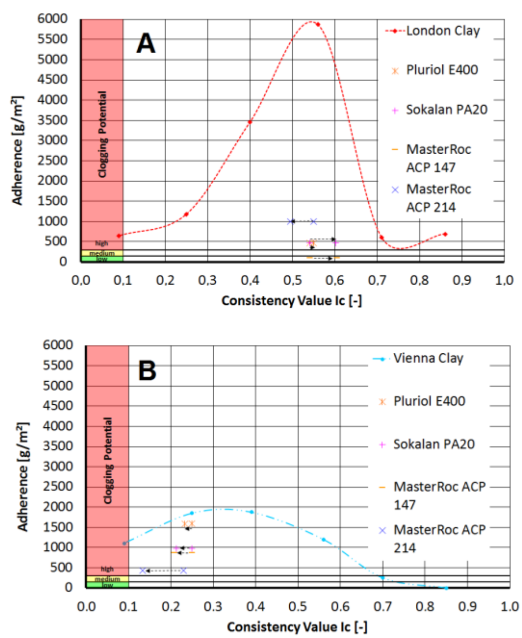

Figure 7. Cone pullout tests on London Clay (A) and Vienna Clay (B) mixed with the different additives

Fig. 8 shows the results for the London Clay at I_C 0.55 mixed with water (A) and MasterRoc ACP 147 (B). It is quite evident the strong reduction in adherence on the metal part.

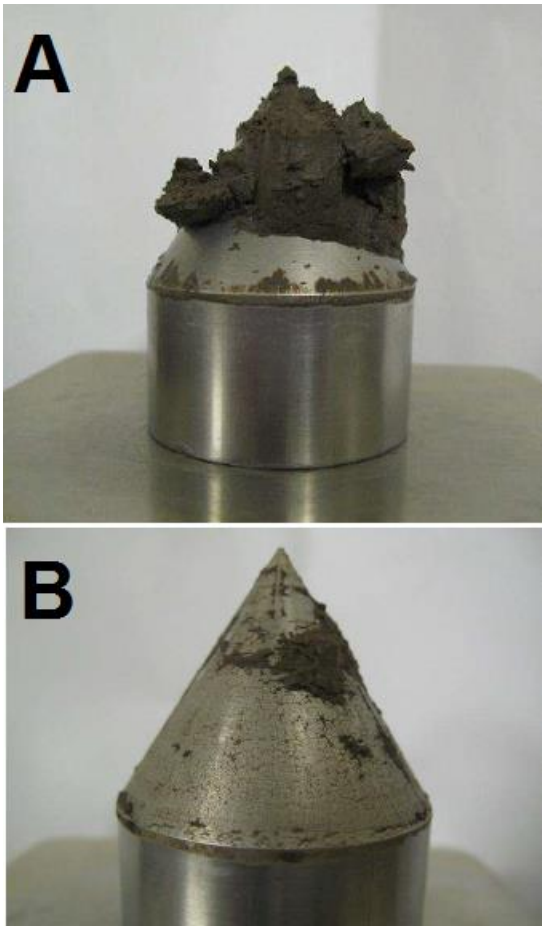

Figure 8. Picture of the cone after a test on London Clay for I_C 0.55 mixed with water (A) and MasterRoc ACP 147 (B)

4 CONCLUSIONS

Four different clay soils were tested in laboratory to assess their geotechnical and adhesive behavior. Result show that mineralogy plays an important role. London Clay showed the highest adhesive behavior which seems to be connected to the high plasticity. Additives with different chemistry were used to assess the impact on the change of geotechnical and adhesive properties. Results show that adhesion and geotechnical properties change depending on the fluid utilized. Kaolinitic clays seem to be less reactive to variation and respond mainly to the mechanical interaction between the clay particles overcoming the chemical interaction in this clay type whereas smectitic clays respond stronger to a change of pore fluid. This clearly indicates that the clay composition as well as the used admixture and thus its chemistry impact the soil conditioning. The challenge is to understand the connection between clay composition and its characteristics and the right admixture more closely to predict in future suitable chemistries for efficient soil conditioning.

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