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APPRAISAL OF STICKINESS OF NATURAL CLAYS FROM LABORATORY TESTS

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ABSTRACT

Excavation of clayey soils by mechanical tools is often hindered by the stickiness of the clay on metal parts. Hindrance may occur at the cutting tool itself, or during the subsequent transport of the soil through the excavation system. The effects of stickiness were also experienced in a recent tunnel boring project carried out in The Netherlands.

In this study the soil parameters that influence stickiness of clayey soils are investigated. Stickiness can be described in terms of adhesion and adhesive friction. These parameters can be determined in the laboratory by undertaking shear box tests during which the clay is sheared over a standard metal surface.

The relation of the basic clay classification parameters (Atterberg limits, percentage of clay, clay mineralogy) with adhesion and adhesion friction has been examined. For one clay type, a potters clay, the variation of the adhesion parameters with the moisture content of the clay has been investigated. For a given metal surface, adhesion and adhesive friction are shown to depend on the clay mineral but also on clay fraction, plasticity, moisture content, degree of consolidation and normal stress.

Although for an improved understanding of the phenomenon much more testing on different types of clay is required, the first results indicate that prediction of the occurrence of stickiness is possible if the operational parameters of the tunnel boring machine and the adhesion and adhesive friction parameters of the soil material are known. Using the operational parameters, the driving forces in the system can be estimated while knowing the adhesion properties of the clay-metal contact allows the calculation of the resistive forces in the system. The standard soil investigation should therefore include shear box tests to determine these adhesive parameters.

During tunnel boring stickiness can occur in three zones: at the cutting wheel, in the mixing chamber and in the slurry line during pipeline transport. Simple force balance models that examine the movement of the clay along the cutting teeth, along the arms of the cutting wheel or along the walls of chamber or pipeline have been made. If the driving forces are smaller than the resistance along the metal-clay surface, no movement will occur along this surface and sticking is assumed to take place. Several factors are important in the analysis:

- the cohesion and internal friction of the clay,
- the adhesion and adhesive friction between clay and metal,
- the shear resistance between clay lumps,
- the roughness of the contact surface.

INTRODUCTION

The recent tunneling projects in The Netherlands involve the use of tunnel boring machines. In many cases tunnels are excavated into clay or clayey formations. One of the problems that might be encountered is sticking of clay to metal surfaces within the machine, causing clogging. For example, during tunneling through the Boom Clay in Antwerp, the machine had to be stopped regularly and to be cleaned by hand with the help of water jets. While boring through Kedichem Clay layers during the construction of the second Heinenoord tunnel, similar measures were needed. Many future tunneling projects are planned through clay layers (Westerschelde tunnel: Boom Clay, Botlek tunnel: Kedichem Clay, Noord-Zuid lijn Amsterdam: Eem Clay) and problems with stickiness of clay may be expected there as well.

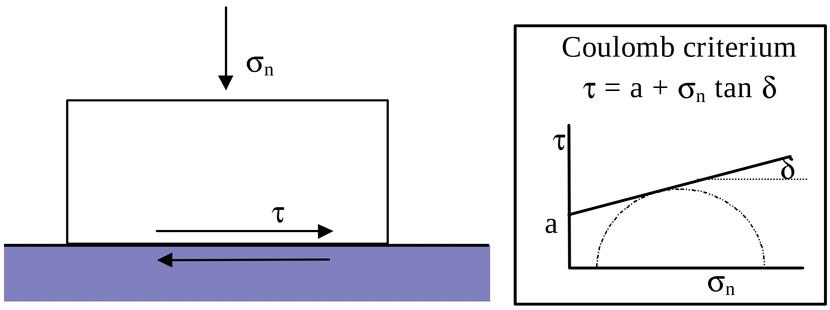
As not much is known about the causes of clay sticking and the conditions under which it occurs, experimental research has been undertaken at TU-Delft to investigate which clay properties are involved in the adhesion and adhesive friction of clay in contact with a metal surface. Focus has been put on two parameters known to influence greatly clay behaviour: the water content and the degree of consolidation.

In this symposium, which is concerned with the “added value of the engineering geologist”, the pertinence of typical geological and mineralogical information that is commonly available on clay-bearing deposits, to assess stickiness is examined. Is such information adequate to predict problems of stickiness during mechanical excavation?

ADHESION AND ADHESIVE FRICTION

When clay is sheared over a metal surface, several possibilities can be envisaged:
Case 1. *Shear occurs at the contact surface of metal and clay*. The shear resistance of the interface between clay and metal may be described by the Coulomb criterion. It has two components: the adhesion (resistance at zero normal stress; a) and a frictional component (adhesive friction; described by the angle δ). In Figure 1 the linear Coulomb relation between the shear stress (τ) and the normal stress (σ_n) is illustrated. In this case, the adhesive shear strength of clay onto metal is less than the applied shear stress and also less than the internal shear strength of the clay.

Case 2. *Shear occurs within the clay.* In this second case sticking of clay onto metal occurs (Koolen 1983): as shear is localized within the clay and no displacement along the metal takes place, a small slice of clay sticks to the metal. This situation occurs if the internal shear strength of the clay is less than τ_e, the applied shear stress and if τ_e is also less than $a + \sigma_n \tan\delta$, the adhesive shear strength of clay on metal. The internal shear resistance of the clay is classically described by the Coulomb criterion as shown in Figure 2 and is equal to $c + \sigma_n \tan\varphi$, with c, the cohesion of the clay and φ, its internal friction angle.



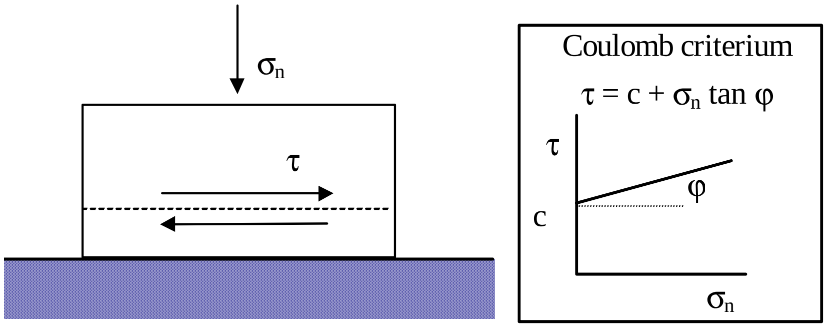


Figure 1. Shear surface at the contact of metal and clay

Figure 2. Internal shear surface in the clay

Therefore sticking occurs if:

$$\tau_e > c + \sigma_n \tan\varphi \qquad (1)$$

and

$$\tau_e < a + \sigma_n \tan \delta \qquad (2)$$

i.e., if

$$\sigma_n < \frac{a - c}{\tan\varphi - \tan\delta}\,. \qquad (3)$$

It is possible to predict whether sticking will occur if the adhesion (a), the cohesion (c), the adhesive friction angle (δ), the internal friction angle (φ) and the normal stress (σ_n) are known.

Case 3. *No shear surface.* In the preceding cases it is assumed that shearing of the clay always occurs. This is reasonable when the cutting of clay is concerned; in that case the previous analysis can be applied to the cutting of the clay by the cutting wheel of the tunnel boring machine. But in the mixing chamber of the tunnel boring machine and in the slurry line during the hydraulic transport of clay, situations of sticking without internal failure of clay are encountered. In these cases, the applied shear stress is lower than the internal and adhesive shear strengths of the clay. Sticking occurs if the following inequations are fulfilled:

$$\tau_e < c + \sigma_n \tan\varphi \qquad (4)$$

and

$$\tau_e < a + \sigma_n \tan\delta \qquad (5)$$

Hypothetical adhesion model

An intuitive model of adherence may be developed, based on the classical adhesion theory developed by Bowden and Tabor (1950, 1964). Adhesion and adhesive friction are known to depend on the real contact surface of the clay and the metal. True adhesion is defined in taking into account the real contact area instead of the apparent contact surface. The real contact surface will increase with normal pressure, due to the plastic deformation of the clay. The shear force needed to shear through the real contact areas along the metal-clay surface will have to increase as well. If we assume that normal and shear force increase proportionally with real contact area, the friction coefficient is constant and the linear behaviour of the Coulomb criterion applies (Figure 1).

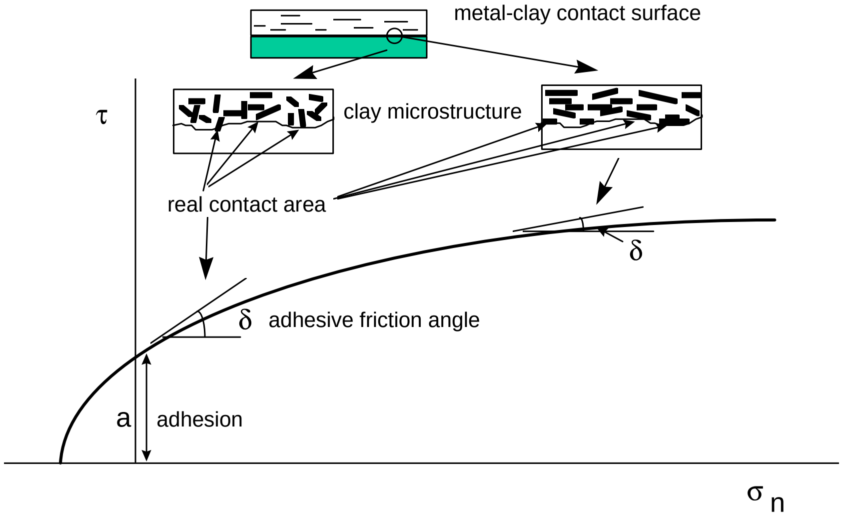


Figure 3. Expected shape of the adhesive shear strength envelope, based on clay microstructure and real contact area.

The real contact surface will depend on factors such as the micro-roughness of the metal surface and on clay properties such as shape and size and micro-structural configuration of the clay minerals. Depending on clay type and degree of consolidation the microscopic structure of the clay can be an open card-house structure (clay minerals in edge-to-face contact), with much pore space, or layered, anisotropic, and more dense (face-to-face contact of the clay platelets). The real contact surface of the metal with a clay with an edge-to-face microstructure is expected to be smaller than that of a similar clay with a face-to-face structure. The adhesion of the clay with a configuration of parallel platelets arranged parallel to the metal surface will be higher due to the higher real contact area, whereas the adhesive friction is expected to be lower than that of a similar clay with a rougher surface due to a face-to-edge structure. Therefore, with increasing degree of consolidation it is expected that the adhesion will increase and that the adhesive friction coefficient will decrease. Such a mechanism leads to a non-linear parabolic shear stress-normal stress adhesive friction envelope, as depicted in Figure 3.

Both cohesive and adhesive forces in clay systems originate from the electrostatic properties of the clay minerals. The electrostatic properties are directly influenced by the chemical composition of the clay mineral and the crystal structure.

Clay minerals have typically a sheet-like, plate-like, crystal structure. The sheet structure is formed by the stacking of octahedral Mg-Al hydroxide sheets and tetrahedral Si-oxide sheets. These unit layers are stacked in one-to-one fashion (one tetrahedral on one octahedral sheet: t-o) in clay minerals of the Kaolin type. And in a two-to-one fashion (t-o-t) in clay minerals of the Illite and Montmorillonite type. Within the stacking units, the ions are held together by covalent bonds, which makes the units layer stable. The layers in the crystal lattice are held together mainly by Van der Waals-bonds which are weak electrical attractive forces due to the polar nature of particles made up of dissimilar atoms. Therefore clay minerals easily cleave along the basal sheet plane.

In the ideal combination of tetrahedral and octahedral sheets, a crystal structure in which the metal ions in the octahedral layer are of one kind and those in the tetrahedral layer of another is formed, so that the mineral structure is balanced and electrically neutral. Real clay minerals, however, are electrically unbalanced. This is due to the presence of metal ions in the structure that are different from the predominant type, carrying a different ionic charge. For example, isomorphous substitution of Mg^{2+} by Al^{3+} leads to a charge deficiency. This leads to a negative potential at the basal sheet plane of the clay mineral. This negative potential may be neutralized by the adsorption of a cation, such as Na^{+}, from the surroundings. If the clay particle is placed into water, a diffuse electric double layer of positively charged ions and water molecules appears around the negatively charged clay platelets (Van Olphen 1963). Clay minerals actively exchange cations and water molecules, both internally in the sheet-like crystal structure and externally in the double-layer zone. The resulting electrostatic properties of a clay mineral vary with cation- and water content.

A good measure of the potential chemical activity of a clay is the cation exchange capacity (CEC). One convenient way of determining the CEC is by measurement of the amount of adsorption of a cationic dye, methylene blue (Verhoef 1992). The CEC is expressed as the milli-equivalent of dye adsorbed by 100g of dry clay. Obviously geotechnical properties, such as cohesion, are directly related to the chemical activity of clay and therefore to CEC. Standard classification tests, such as the Atterberg limits are also a function of the clay type (Grim, 1962).

Since true adhesion depends on the attractive forces between the clay mineral and the metal surface, the electrostatic properties of the clay are expected to influence adhesion as well. For example, with increasing water content, internal and external bonded crystal water and external free water molecules are present in the system and the adhesion is expected to decrease. Dissolved ions in the system may influence the size of the electric double layer around the clay crystals. High valence ions tend to neutralize the mineral and the electric double layer thickness decreases. This probably results in higher adhesive friction coefficients.

Experimental program

In the pilot study of Kooistra (1998) several clay samples were examined. A commercial potters clay (K122); a kaoline (China clay); a drilling mud named bentonite, but actually consisting of the clay mineral sepiolite (instead of montmorillonite) (Table 1); Boom clay, a clay type in which tunneling and underground construction has occurred in Belgium and which will be excavated in the Westerschelde tunneling project; Kedichem clay, which has recently been excavated during tunneling near Heinenoord (Rotterdam); Eem clay, a clay which will be excavated in the Noord-Zuid tunnel project in Amsterdam. On the samples dry volumetric weight, water content, grain size distribution by wet sieving, Atterberg limits (liquid and plastic limit) were determined. Test results and data assembled in the pilot study are given in Table 1. Classification properties such as liquid limit (LL) and plastic limit (PL) and plasticity index (PI=LL-PL) are related to the chemical activity of the clay as was discussed above. The cation exchange capacity (CEC) of the bulk samples was also determined.

Identification of clay mineral types requires mineralogical examination by applying several different analysis techniques. For this pilot study X-ray diffraction was only carried out on bulk specimens of three samples. In the sepiolite drilling mud sample not all mineral phases present could be identified. The activity has been calculated by:

$$A = \frac{PI}{c\%} \qquad (7)$$

with c%, the clay content expressed as a percentage.

Some of the clays are active, such as the Eem clay, despite a low clay content. The cation exchange capacity (CEC) was determined by the methylene blue spot method (Verhoef 1992). An estimate of the
CEC for the clay mineral of the sample can be made by assuming that only the clay fraction is responsible for the cation exchange:

$$CEC_{\min} \approx CEC \times \frac{100}{c\%} \qquad (8)$$

The estimated CEC_{min} indicates that swelling clays are present in the Eem samples, which explains their high activity. Table 2 gives the ranges of properties of the three main clay types Kaolinite (non-swelling

	Sample	mineralogy (XRD)	clay fraction (%)	cohesion (kN/m^2)	consistency	activity		CEC (meq/100g)	CEC min. (meq/100g)	LL (%)	PL (%)	watercontent (m/m%)
1	K122	Q, k, ill	53	28	medium stiff	0.62	inactive	15	28	62	29	38
2	China clay		24			1.04	active			55	34	0
3	Sepiolite	sep, k?, Q?	62			3.9	active	58	94	287	44	0
4	Eem # 35		3	100	very stiff	4	active	4	133	37	25	33
5	Eem # 50		8	149	very stiff	3.7	active	9	113	58	29	42
6	Eem # 59		11	238	hard	3.5	active	10	91	74	34	52
7	Eem # 66		9	129	very stiff	5.8	active	8	89	106	53	83
8	Eem # 79		3	75	stiff	4.3	active	3	100	33	20	20
9	Boom clay	Q, k, ill	54	103	very stiff	0.93	normal	16	30	81	31	29
10	Kedichem clay			94	stiff / very stiff			16		39	13	30
11	Kedichem 234	Q, F	68	79	stiff	0.5	inactive	12	17	56	22	21
12	Kedichem 249	Q, F	62	100	very stiff	0.4	inactive	13	22	38	14	22
13	Kedichem 252	Q, F, ill	63	78	stiff	0.6	inactive	23	37	62	24	33
14	Kedichem 264	Q, F, ill	51	165	very stiff	0.6	inactive	17	33	48	20	22
14	Kedichem 278	Q, F	59	127	very stiff	0.3	inactive	10	17	35	17	26
16	Kedichem 292	Q, F, ill	45	131	very stiff	0.8	normal	15	33	55	20	23

Kedichem 234 - 292: data from Heinenoord tunnel samples provided by S. Sonneveldt (TUD)

Q = quartz, F = feldspar, k = kaolinite, ill = illite, sep = sepiolite.

Activity: <0.75 inactive, 0.75-1.25 normal, >1.25 active.

Table 1. Classification test results on clay samples. Samples 1-10 were used for adhesion shear tests.

clay), Illite (normal clay) and Montmorillonite (highly swelling clay). The CEC of some other clay minerals is given as well, to illustrate that by determining Atterberg limits or CEC alone, no determination of clay minerals can be done. However, these tests do give information on the activity of the clay. The higher the CEC, the more plastic the clay will behave and also higher cohesive and adhesive shear strengths may be expected.

Clay type	LL (%)	PL (%)	A (activity)	Spec. surface (m^2/g)	CEC (meq/100g)
Kaolinite	30-110	25-40	0.01-0.5	10-20	3-15
Illite	60-120	35-60	0.5-1	80-100	10-40
Montmorillonite	100-900	50-100	1-7	800	80-150
Halloysite	35-65	30-60	0.02-0.16	40	5-40
Chlorite				5-50	10-40
Vermiculite				5-400	100-150
Attapulgite-Sepiolite	160-230	95-125	0.6-1.2		15-30 (90)

Table 2. Typical properties of clay minerals (data from Grim 1962, Kerr et al. 1951,Lambe & Whitman 1969, Mitchell 1976).

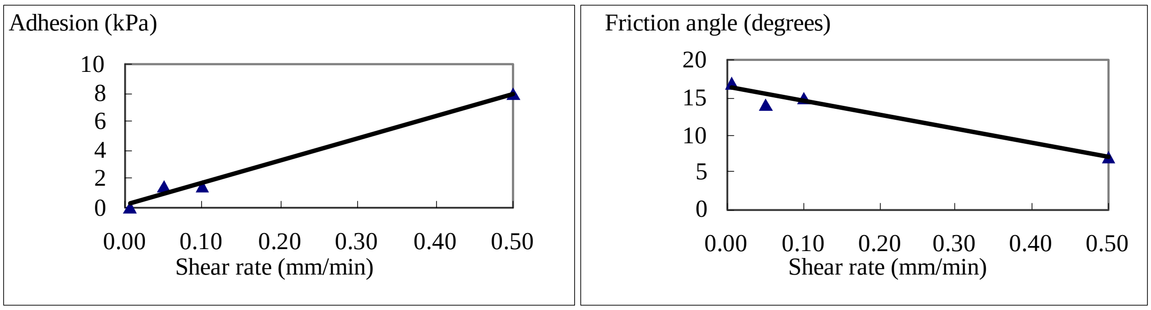


Figure 4. Dependence of adhesion and adhesive friction on shear rate in the shear box.

Shear box tests: determination of adhesive shear strength envelope

To determine the adhesive shear strength of clay, shear box tests have been carried out on the K122 clay and on Boom clay and Kedichem clay. In the shear box the clay was sheared over a metal surface. The chosen metal plate had a rusted and therefore rough finish. The shear rate selected for the tests was relatively low, 0.5 mm/min. It is known that shearing resistance depends on shear rate. In the relatively low range of shear rates possible with the laboratory apparatus, an increase in adhesion and a decrease in adhesive friction was found (tests on K122 clay, Figure 4).[1] The chosen velocity of 0.5 mm/min allowed controlled failure and a measurable adhesion in the subsequent tests examining the effect of variation of the clay parameters. The tests have been carried out under consolidated undrained conditions, following the procedures outlined in ASTM D-3080-90. The normally consolidated K122 clay was tested at a water content of 38%. The shear tests on the Boom clay were carried out at a water content of 28%, roughly about the natural water content. The normal loads used varied up to 500 kPa, a range relevant to the pressures existing in the mixing chamber of the tunnel boring machine of the second Heinenoord tunnel (Van Vliet 1996b). Sample size was 100x100x12 mm and the box used was a commercially available direct shear box apparatus (ELE).

The results of the tests on the normally consolidated clay are given in Figure 5. At low normal stress (<25kPa) the shear stress at peak failure is constant, about 9 kPa and the adhesion is equal to 9 kPa. Above 25 kPa normal stress the shear resistance increases linearly. The results on the tests on the overconsolidated Kedichem and Boom clays are given in Figure 6. As shown in Figure 6, the adhesive shear strength envelopes of both clays present two branches. At low normal stress and at natural water content, the adhesion is very low and only adhesive friction contributes to the adhesive resistance of these clays. At higher normal stress, the apparent adhesion is higher and reaches 30 kPa for the Kedichem and 80 kPa for the Boom clay. Interpretation of the bi-modal nature of the adhesive shear strength envelope for these overconsolidated clays requires further testing.

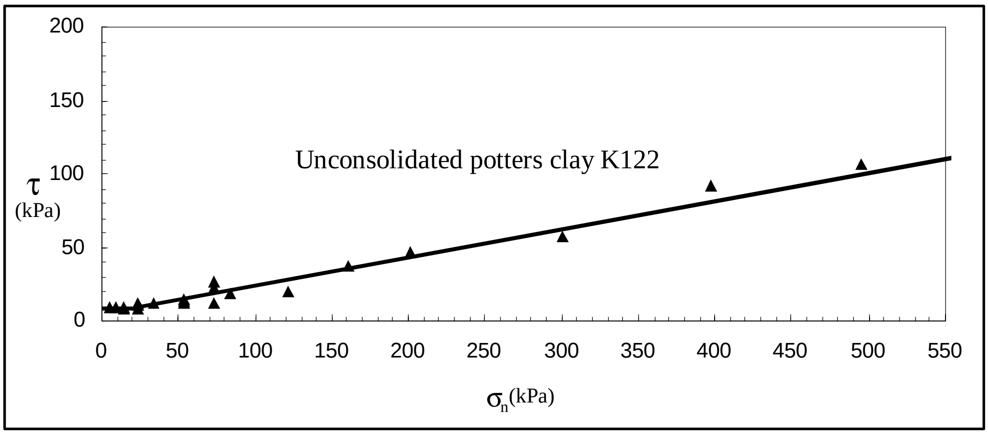


Figure 5. Shear resistance of normally consolidated potters clay in metal-clay shear test.

[1] In the ranges of velocities relevant to excavation machines (1-5 m/s), Stafford and Tanner (1983) found a logarithmic dependence of friction angle and shear rate and no relation with adhesion.

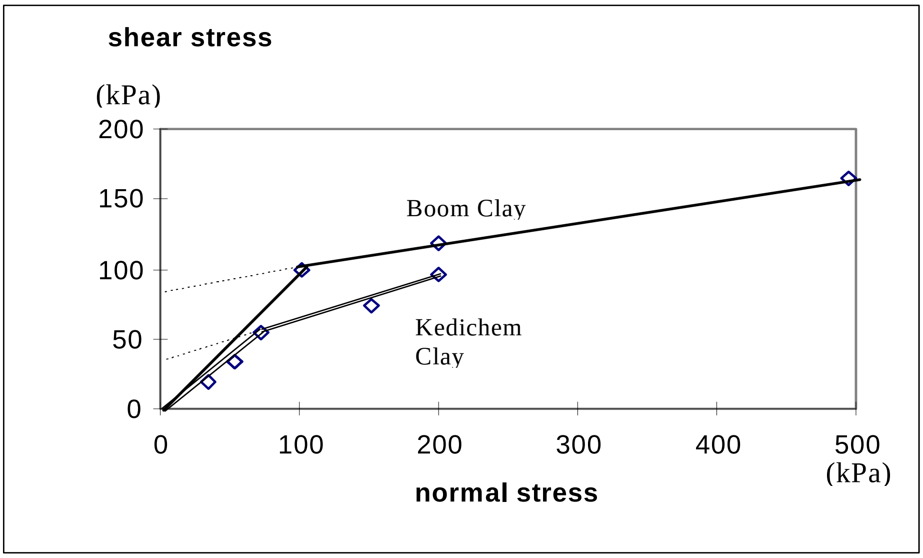


Figure 6. Adhesive shear strength envelope for overconsolidated clays.

Shear box tests: influence of water content

According to Jancsecz (1991) adhesion varies with water content, and the peak adhesion would lie in between the liquid limit and the plastic limit of the clay (Figure 7). No information on the nature of the clay, nor the data were provided by the author. According to Yusu et al. (1990), the maximum value of adhesion should lie near the plastic limit.

The potters clay K122 was chosen to examine the effect of water content. Shear box tests were carried out at three normal stresses (25, 35 and 55 kPa). Shear rate was 0.5 mm/min. Both adhesion (metal-clay) and shear strength tests (internal strength of the clay) were performed. The adhesion was determined by linear regression. Figure 9 shows the variation of both adhesion and cohesion with water content of the clay. In this case the peak adhesion is found near the plastic limit, similar to the results of Yusu et al. (1990). It can be seen that for this clay cohesion is higher than adhesion and that cohesion exponentially decreases with water content (Kooistra 1998). The contrast with Figure 8 is obvious. The working hypothesis we are using at present is that the behavior of Figure 8 is illustrative for a montmorillonite-type clay and that the results of Figure 9 illustrate an illite-type clay (see discussion below).

adhesion

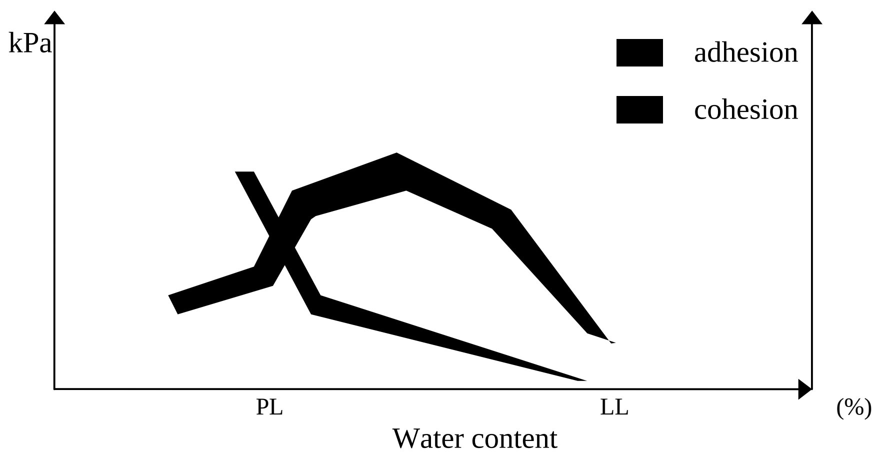


Figure 7. Relationship of water content and adhesion and cohesion: ranges of test results as given by Jancsecz (1991).

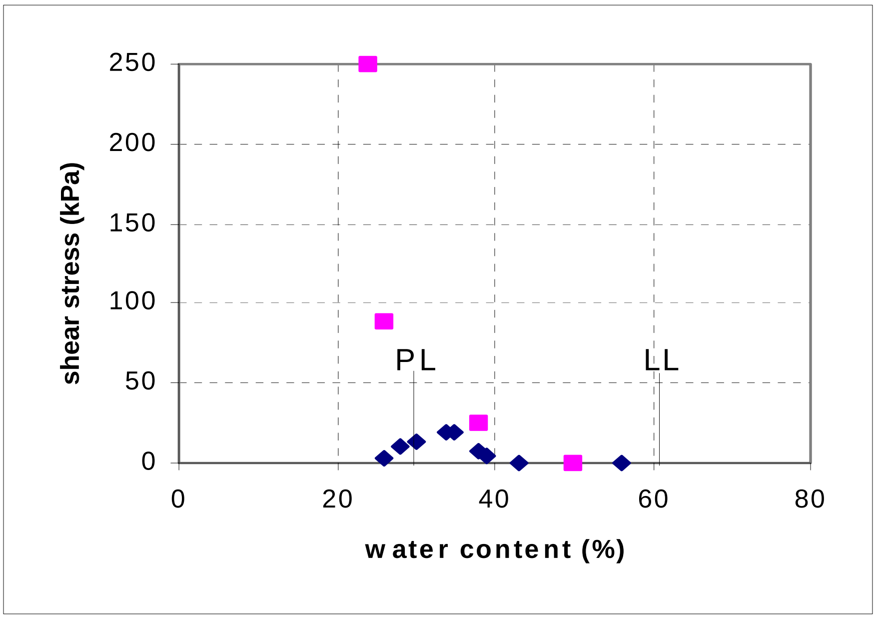


Figure 8. Relationship of water content and adhesion (◆) and cohesion (■) of sample K122.

Shear box tests on different clay types

Further shear box tests were carried out on the clay samples, at a water content near the plastic limit. Values of adhesion (or apparent adhesion in case of the two consolidated clays: Boom clay and Kedichem clay; see Figure 6) were determined by linear regression. Also the friction angle determined this way is given. As discussed below, it is now thought that peak adhesion will occur at relatively higher water contents for montmorillonite type clays. Samples which were not tested at the estimated peak adhesion water content are indicated in Table 3.

Sample	water content (%)	adhesion (kPa)	adhesive friction angle (°)	remark
K122	34	18.5	8	
China clay	43	1.7	17	too high water content
Sepiolite	65	17.3	13	too low water content
Eem # 35	27	0	31	too low water content
Eem # 50	36	0	20	
Eem # 59	50	0	37	
Eem # 66	75	0	14	
Eem # 79	20	5.1	21	too low water content
Boom clay	27	80	10	overconsolidated; too low water content
Kedichem clay	32	35	15	overconsolidated

Table 3. Adhesion properties determined by shear test under standard conditions (shear rate 0.5 mm/min, sample size 100x100x12 mm, consolidated, undrained).

Discussion

Grim (1962) mentions a *sticky limit* that was defined by Rieke in 1923, to establish the workability of clays for ceramic industry. This sticky limit is the water content at which the clay loses its stickiness. The sticky limit is intermediate between the plastic and the liquid limit. The *Rieke index* is the difference between the plastic limit and the sticky limit. A Rieke index less than 10 is desirable of clays for ceramic use. From Table 4 we see that the Na-montmorillonite has a very long moisture range through

Clay	PL (%)	Sticky Limit (%)	LL (%)	Rieke Index
Amberg kaolinite	37	41	52	4
Spergauer kaolinite	42	50	71	8
Ca-montmorillonite	89	101	157	12
Na-montmorillonite	76	102	520	26

Table 4. Atterberg limits and the sticky limit of Rieke (Grim 1962, data from Fendius & Endell 1935).

which the clay exhibits stickiness. Comparing the schematic graph of Jancsecz (Figure 7) and the results of the shear tests on the potters clay (Figure 8), it seems likely that Jancsecz tested a montmorillonite type clay. The shear box tests performed so far suggest that the clay mineral type plays an important role in the adhesion properties: low CEC clays have a sticky limit near the plastic limit, high CEC
clays have a limit further into the plasticity field. This understanding is important for further investigations to be carried out. Manipulation of the clay properties by adding water or salt or by mixing with additives like polymers are known to affect the rheological properties of the clays. Natural soils, like the Eem clay are mixtures of clay with silt and sand fractions. This also will affect adhesive properties.

APPLICATION TO TUNNEL BORING

Once the strength envelopes are defined for both the soil-metal contact (Figures 5 and 6) and the soil itself, they may be used in calculations to establish whether problems with sticking or clogging may occur. Of course, the water contents at which the shear properties are determined should be well defined. Kooistra (1998) has used simple force equilibrium models to make estimates for the Heinenoord tunnel situation in the Kedichem clay. The Kedichem clay is a lightly overconsolidated stiff clay occurring at a depth of about 30 m. The properties of this clay as given in Table 1 do not point to problems with stickiness, but the degree of consolidation and the adhesive friction envelope (Figure 6) do.

At the *cutting wheel* adhesive sticking will occur when no displacement occurs on the contact surface between the clay and the cutting blades or knives. In the extreme case the cutting wheel will get stuck, if both adhesive and internal clay strengths are higher than the cutting forces. Sometimes shearing takes place internally in the clay, when the adhesive shear strength is higher than the internal shear strength. In this case shear surfaces will develop in the clay, causing pushing away of the soil instead of cutting, which is unfavorable. The "normal" potters clay has an internal shear strength which is always higher than its adhesive shear strength (Figure 8) and will therefore only stick to the wheel if adhesive friction is higher than the cutting forces, which is highly unlikely when the operational parameters of the tunnel boring machine are well chosen. The Kedichem clay is also an illite-type clay, so no problems with cutting are expected.

In the *mixing chamber* and the *slurry pipes* sticking or clogging will occur if the resisting forces due to adhesion of clay on the walls are higher than the driving forces. The opening of the discharge pipe in the excavation chamber is critical for the calculation of the driving forces. Calculations were done for one block of clay partially blocking the entrance and for clay balls completely blocking the entrance of the pipe. The operational parameters for the Heinenoord tunnel case used for the calculations were taken from Smits (1997) and are given in Table 5. The driving stresses estimated from these data can be compared with the adhesive friction of the Kedichem clay (Figure 6). Kooistra (1998) comes to the following estimates: sticking or clogging will occur:

in the slurry line, if

- $(a + \sigma_n \tan\delta) > 0.05$ kPa in case the pipeline is completely filled,
- $(a + \sigma_n \tan\delta) > 1\text{-}13$ kPa in case the pipeline is half filled,

  in the mixing chamber, if
- $(a + \sigma_n \tan\delta) > 5\text{-}61$ kPa in case one lump of clay partially blocks the slurry line opening,
- $(a + \sigma_n \tan\delta) > 0.2$ kPa in case the slurry line opening is completely blocked.

The effective volumetric weight of the Kedichem clay used for the calculation was 19.5-10 = 9.5 kN/m^3. The height of the clay blocks in the pipe or mixing chamber varies from 0.1 to 0.4 m, so the maximal effective normal stress is 3.8 kPa. Therefore for the calculation of the adhesive friction, since $\sigma_n < 70$ kPa (Figure 6), $a = 5$ kPa and $\delta = 30^o$ were used. For the resistance between metal and clay this resulted in:

- 6 kPa in case of a completely filled pipeline; then sticking can occur on the pipeline walls,
- 5.5 kPa in case of a half filled pipeline; then sticking can occur on the pipeline walls,
- 5.5 kPa in case of a partial blocking of the opening of the slurry line; then sticking on the walls of the excavation chamber probably does not occur
- 6.5 kPa in case of a total blocking of the opening of the slurry line; then sticking can occur on the walls of the excavation chamber.

According to the simple force balance models used by Kooistra (1998), the Kedichem clay at the Heinenoord might be expected to give problems with sticking, as the estimated driving forces are not high. As soon as the adhesion is higher than 1 kPa, problems can occur. If clogging takes place, the situation is worsened by the clogging of the bentonite slurry stream. The bentonite slurry greatly assists the driving force.

	Pipeline		Mixing chamber	
pressure loss (kPa/m)	0.6		0.6	
Reynolds number slurry	>> 600		>> 600	
density bentonite (kg/m3)	1150		1150	
relative velocity bentonite slurry-clay (m/s)	1.2-4.2		1.2-4.2	
shear stress slurry-clay (kPa)	1.6-20.3		1.6-20.3	
	degree of filling		cubic block of clay	
	100%	50%	1 block	entrance blocked
surface area cross section (m2)	0.096	0.048	0.01	0.16
surface area clay-slurry contact (m2)	0	0.35	0.03	0
surface area clay-metal wall (m2)	1.099	0.55	0.01	0.04

Table 5. Operational parameters for the Heinenoord tunnel (Smits 1997).

CONCLUSION

Sticking of clay in tunnel boring machines is a complex phenomenon which results from the interaction of clay lumps with steel contact surfaces. While a steel surface can easily be quantified by its roughness and its corrosion state, a clay is a multi-phase material and its behaviour depends on numerous parameters such as: clay mineralogy, clay fraction, silt fraction, sand fraction, water content, water saturation, Atterberg limits, sticky limit, activity, cation exchange capacity, degree of consolidation and stress state. It is therefore likely that adhesion of clay on steel is also affected by these clay parameters.

Shear box tests consisting in shearing normally consolidated and overconsolidated clays over a steel surface under undrained conditions were undertaken by Kooistra (1998). These tests have shown that linear Mohr Coulomb criteria of failure were adequate to model the adhesive shear strength of clay for various ranges of normal stress. During Kooistra's pilot study, the influence of some of the clay parameters listed above on clay adhesion was also quantified. For a potters clay rich in kaolinite and illite, adhesion was shown to vary with the water content and to present a peak at a water content near the plastic limit. This results is in accordance with those published by Grim in 1962 on the workability of clays for ceramic industry: low cation exchange capacity clays such as the potters clay tested by Kooistra have their sticky limit close to their plastic limits while high cation exchange capacity clays such as montmorillonites have a sticky limit further into the plasticity field and a large water content window through which they exhibit strong stickiness. Determination of clay mineralogy, cation exchange capacity and sticky limit in addition to the usual characterization tests on clay appears to be crucial when assessing risks of sticking and clogging in a tunnel boring machine or when designing remedies to problems of clay adhesion.

In the near future, further laboratory tests are going to be carried out at TU-Delft to investigate the following points:

- relation between undrained cohesion, adhesion and water content for a bentonite,
- influence of silt and sand fractions on adhesion parameters,
- impact of shearing rates up to 2mm/mn,
- impact of steel surface roughness and corrosion,
- determination of residual adhesion parameters.

Attention will also be paid on the following aspects with respect to adhesion properties:

- suction forces due to pore pressure differences generated in clay lumps during cutting,
- wrapping and penetration of clay lumps by the bentonite slurry,
- conditions under which adhesion is greater than undrained cohesion.

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