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THE ADHERENCE OF CLAY TO STEEL SURFACES

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ABSTRACT

Recently the first full face tunnel boring machines were used in the Netherlands. Several problems have been encountered in tunnelling projects in the Dutch soft soils. One was the adherence of stiff clays to the TBM cutting wheel, mixing chamber and the pipelines, which transport the clay from the front.

Adherence of clay can be described in terms of adhesion and adhesive friction. Parameters which influence these two factors are on one hand the mineralogy, texture, the (over)-consolidation ratio and composition of the clay and on the other hand the type of steel and the textural state and condition of the steel surface.

To study the adherence of clay, two types of clays were tested. Tests have been performed on Speswhite, which consists mostly of kaolinite and on Boom clay, which is a mixture of quartz, illite and kaolinite. Samples were prepared from clay powders. The adherence behaviour of clay was investigated by measuring the shear stress required to shear the clay over a steel surface in a direct shearbox. Results show a great influence of the steel roughness, contact time and mineral type. This is in accordance with practical experience and previous literature.

The shearbox test gives a good quantitative impression of the adhesive shear strength, however it is expected that other devices like the simple shearbox and the ring shearbox are better suited to study the parameter variation during the tests.

INTRODUCTION

As traffic activity is growing in the Netherlands, more infrastructure is needed to ensure public transport. Since little space is still available in the Netherlands, the Dutch are forced to increasingly use the underground. Recently, the Tunnel Boring Machine (TBM) has been used in tunnelling projects. This technique has several advantages compared to the cut and fill method. The first project which was performed in the Netherlands with a large diameter tunnel boring machine was finished late 1998. During this project, the second Heinenoord tunnel, problems arose with the adherence of stiff clay to the TBM cutting wheel, its excavation chamber and its transportation system. In the near future, several tunnels will be built through other Dutch clay formations, where similar problems may be expected. Hence, it was decided to investigate the adherence of clay in order to forecast and eventually prevent problems to occur in the future. In this paper the results which provide insight into the factors determining the adherence of clay to steel are presented.

ADHERENCE THEORY

In order to discuss adherence, a certain terminology is proposed. In engineering practice terms such as stickiness and adherence are usually given to clay that adheres to steel. In this paper the term stickiness is reserved for a clay that has the potential to stick. The term adherence is used when the clay is already connected. When a clay is wet, it can have the tendency to stick, to your boots for example, and you can call it sticky. However, when this clay is on your boots and it dries out, it still adheres to your soles but you cannot call it sticky anymore.

Adherence can be quantified by measuring the adhesive strength. Depending on the mode of loading adhesive tensile strength and adhesive shear strength can be obtained. The adhesive shear strength can be described in terms of adhesion and friction while the adhesive tensile strength is only depending on adhesion.

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Myers (1991) defines adhesion in an ideal sense and in a practical sense. The definitions are as follows. Ideal adhesion is “the reversible work required to separate a unit area of interface between two different materials or phases to leave two bare surfaces of unit area.” The work is produced by the interfacial tensions. These are thermodynamic interactions between two surfaces and consist of Van der Waals forces, dipolar forces and electrical forces. Practical adhesion is “the state in which two bodies are hold together by intimate interfacial contact in such a way that mechanical force or work can be applied across the interface without causing the bodies to separate.” This includes, next to the thermodynamic interaction, also chemical bonding and cementation, mechanical interlocking of microscopic asperities and physical interactions such as capillary stresses and differential fluid pressures.

For the adherence of clay to steel surfaces, physical interactions play an important role, as capillary forces and differential fluid pressures can generate considerable high adherence forces. Capillary stresses can be generated at the clay-steel interface between a stiff piece of clay and the steel surface in a partially saturated environment. Besides, capillary stresses can develop in the pores of an unsaturated clay mass. Inside a slurry shield TBM, thus in a water saturated environment, adherence is controlled by the pressure difference between the pore water of clay lumps and the bentonite slurry rather than by capillary forces (Thewes, 1999). This differential fluid pressure is caused by the overpressure of the slurry compared to the internal pore fluid pressure of the clay. It creates a flow of water into the excavated clay lumps, and thus generates a certain suction force.

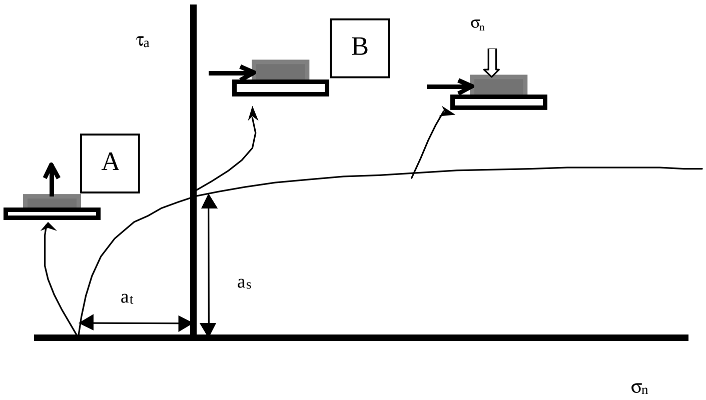


Figure 1 : Empirical graph of the adhesion model. Adhesive shear strength (τ_a) versus applied normal stress (σ_n).

The practical adhesion caused by all the interactions is measured in the laboratory. We distinguish the stress needed to pull off the clay in the direction perpendicular to the contact surface, defined as tensile adhesion and noted a_t (see Figure 1.A) and the stress needed to initiate sliding parallel to the contact surface when no normal stress is present, defined as shear adhesion and noted a_s (see Figure 1.B).

The measured values of the tensile and shear adhesion can be different, because they are measured using different methods of testing. To explain this, the tensile and shear adhesion both are divided into true adhesion and apparent adhesion. True adhesion is the adhesion caused by thermodynamic and chemical interactions, and apparent adhesion is the adhesion caused by mechanical and physical interactions. For both testing methods it is expected that the true adhesion will be equal. The difference between tensile and shear adhesion will be in the apparent adhesion, because interlocking of microscopic asperities, capillary stresses and differential fluid pressures that develop during testing depend on the testing method.

In previous investigations on the adhesive shear strength of a clay-steel contact with varying steel surface roughness (Tsubakihara, 1993), it was concluded that for a given cohesive soil three failure modes can develop. First, for low roughness, sliding occurs along the steel-clay interface. For high roughness, when the adherence of clay to steel is larger than the internal strength of the clay, sliding takes place through the clay sample. In this case the shear strength is of the same magnitude as the internal shear strength of the clay. Mode 3 is the transition between mode 1 and mode 2. Then, the force needed to slide the clay along the steel is also used for internal deformation of the clay sample. This third mode occurs for a certain critical range of steel roughness. An example of a soil-steel surface, after partial sliding at the interface in mode three, is given in Figure 2.

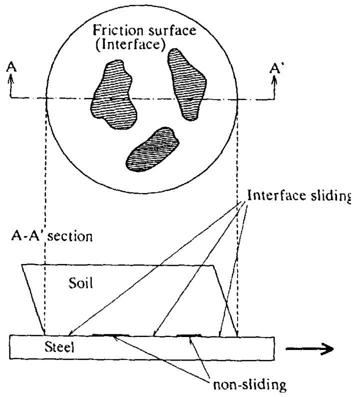


Figure 2 : Mode 3. Partial sliding at soil steel interface (Tsubikahara, 1993)

As expected, the contact surface between two materials is different for each combination of materials. Boisson (1981) published a graph, in which the adhesion of clayey material over surfaces of plexiglass, leather, smooth steel and rough steel is shown. This work illustrates clearly that adherence differs for different surfaces. Kalachov (1975) and Boisson (1981) both mentioned that it is also essential to know the contact time between clay and steel when measuring tensile and shear adhesion in the laboratory. With time, bonding between the clay and the steel surfaces develops and the adhesive shear strength of the interface builds up. Also, with time, consolidation takes place in the clay sample, pore water pressure changes and the soil structure adjusts itself to the stress increment.

There is a relation between the shear adhesion and the soil geotechnical parameters among which the water content and the plastic limits. Thewes (1999) considered several tunnelling projects realised exclusively with a slurry shield TBM and studied the occurrence of adherence problems. Most serious problems were encountered for clays with a plastic index between 20 and 60% and a consistency index between 0.75 and 1.30 (see Figure 3). By definition, the consistency index is the ratio of the liquid limit minus the natural water content to the plastic index. Therefore, for a given clay, with a water content just above the plastic limit, the potential of adherence increases as the water content decreases

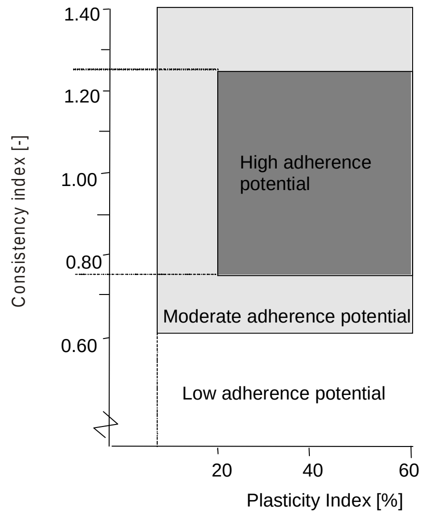


Figure 3 : Empirical relation of adherence potential to consistency index as a function of the plasticity index (After Thewes, 1999)

Kalachov (1975) also found a relation between the tensile adhesion and the water content. Kalachov proved that there is a maximum tensile adhesion for each normal stress at the so-called maximal molecular water content (w_{mmb}), which is the maximal amount of water bonded in the mineral skeleton by molecular forces. It includes the firmly bonded water (adsorbed water), capillary water and part of loosely bonded water (osmosis water). The value of the maximal molecular water content is located between the value of maximal hygroscopic moisture content and the plastic limit and is unique for every clay mineral at given normal stress.

EXPERIMENT

The objective of the experiment was to gain a qualitative insight into the parameters that determine adhesive shear strength. The effects of clay mineral type, roughness of the steel surface, contact time between clay and steel and applied normal stress were investigated. Tests were performed with a direct shear box. In this shear box cylindrical samples with a diameter of 63 mm and a thickness of 10 mm were tested. In the shear box slider steel plates were installed on which the clay samples were sheared. Sliding took place under consolidated and drained conditions at a sliding speed of 0.1 mm/min.

Clay minerals

Two different clays were tested: the Speswhite and the Boom clay. Speswhite is a powder clay produced by English China Clay International Ltd. In this investigation, the SPS grade was used. It contains 79% of particles smaller than 2 μm and according to XRD-diffraction results, its main mineral is kaolinite. Illite (clay variety of muscovite) is also present. Anson (Anson et. al 1998) who performed laboratory tests with the same clay mentioned that a chemical flocculent is added to the powder obtain a stable material. The Boom clay comes from a pit near Boom (Belgium). Clay powder obtained by drying and crushing was used in this investigation. According to sieve analyses 71% of its particles are smaller than 2μm and according to XRD-diffraction, the clay powder consists of quartz, illite, kaolinite and some other components.

Sample preparation

The clay powders were mixed with de-mineralised water. To consolidate the powder clays, a water content higher than the liquid limit was chosen, in order to mix the powder to a good homogenous sample

Table 1 : Atterberg limits and water content at which testing took place

	Plastic limit	Liquid limit	Water content before consolidation
Speswhite	32%	62%	80%
Boom clay	24%	55%	70%

(see Table 1). The samples were then gradually consolidated in an oedometer until the desired normal stress was reached. Testing was performed according to BS 1377 part 5, 1991.

After consolidation, the sample was removed from the oedometer, inserted into the shear box and consolidated again under a slightly higher normal stress. Hence, the clay samples are considered to be normally consolidated clays. Before shearing the clay sample over the steel surface the sample was allowed to adhere to the steel surface for a certain period of time, referred to as the contact time. This contact time includes the consolidation time.

Steel roughness

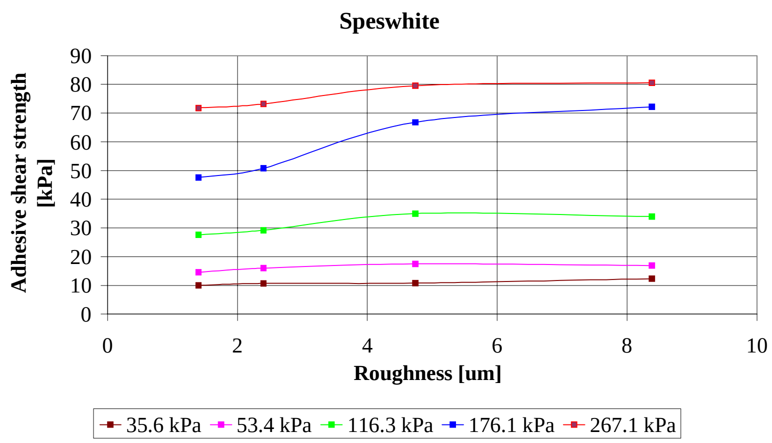
In the shearbox test, clay was sheared over five different stainless steel plates of various roughness. On the first steel plate parallel lines were ground. In doing so, a roughness of 0.2 μm was created. The other four steel plates were sparkled till a roughness of 1.2, 2.4, 4.7 and 8.4 μm. A desired roughness can be obtained by means of varying the intensity of sparkling at the surface. The advantage of the sparkling process is that an isotropic roughness is obtained. The roughness was measured according to the Dutch standard NEN3635 with an amplitude meter (Perthometer M3P), which calculates the average amplitude of the roughness over a desired length, in this case 2 cm. Roughness was measured at six different spots.

Before testing, the steel plate was thoroughly cleaned with Rosal liquid, a soap based cleaning agent with a neutral pH, which is very easy to remove from metal surfaces. The soap was washed away with de-mineralised water. Then, the plate was brushed and dried with acetone before being installed inside the shear box.

TEST RESULTS

For a given roughness and contact time the adhesive shear strength increases linearly when it is plotted as a function of the normal stress, in the range of 0 to 500 kPa. The value of adhesion depends on the mineral type. This is due to the different types of bonding, which can be formed between the different mineral types and the steel surface, as well as within the clay mass.

During the investigation, steel plates of different roughness were tested for both clays (see Figure 4). For both clays the same trend is noticeable. At low roughness adhesive shear strength values are low and increase as the roughness gets higher. This is due to the fact that with increasing roughness more internal deformation takes place,



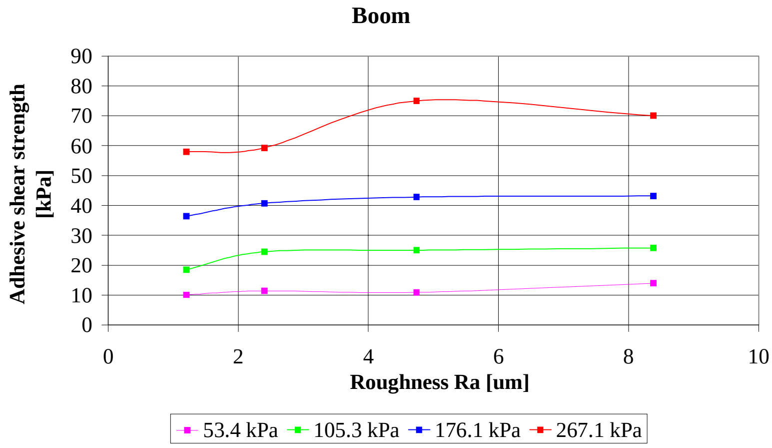


Figure 4 : Results of roughness tests. **above:** for Speswhite **below:** for Boom clay. Contact time for both clays is 1 hour.

causing strain hardening. Then, shearing occurs in mode two rather than in mode one. According to Figure 4 for both clays the critical steel roughness is between 2.4 and 4.7 µm. What also can be seen is that the adherence values of the Speswhite are higher than the values of the Boom clay. This is, apart from the difference in clay mineralogy, probably a result of a higher degree of deformation (strain hardening) of the Speswhite.

A series of tests has been performed to characterise the influence of contact time on adherence of clay to steel, see Figure 5. The steel plate with a roughness of 0.2 µm was selected to ensure that mode 1 was taking place. The effect of contact times equal to the consolidation time and up to ten times greater were monitored. What generally can be stated is that an increase in adhesive shear strength is observed when the contact time is increased. Both the Speswhite and the Boom clays show this behaviour. At higher normal stresses the increase seems even to be higher. This is expected to be the result of decreasing water pressure, increasing bonding between clay and steel and increasing contact surface due to the adjustment of the soil structure to the stress increment. For contact times less than the consolidation time the water pressure probably has the highest influence and it is even expected that the influence of increasing of bonding is negligible or even not present at all (Thewes, 1999).

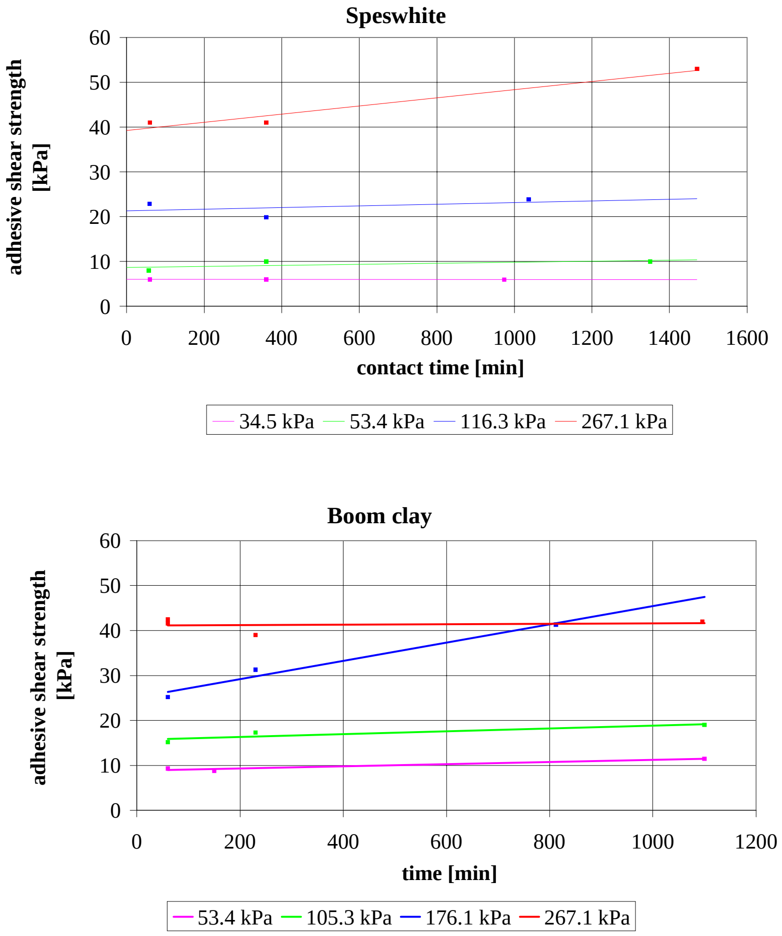


Figure 5 : Influence of contact time on the adhesive shear strength. **above:** Speswhite **below:** Boom clay

Before and after testing the water content of each sample has been measured. In Figure 6 the consistency index is plotted as a function of the normal stress. Before and after shearing the water contents for both clays were above the plastic limit. From Figure 6 it can be seen that after sliding the consistency index increases. Therefore an increase of adherence potential can be expected when sliding a normally consolidated clay sample over a steel surface. For higher normal stresses this feature is more pronounced.

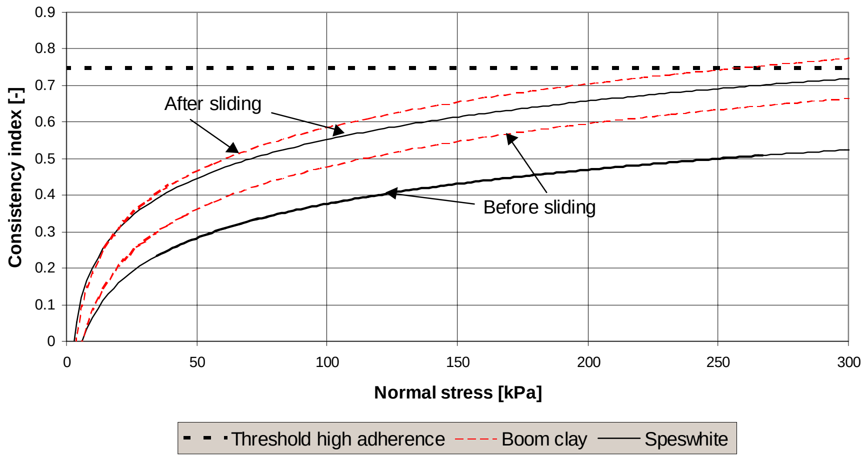


Figure 6 : Consistency index as a function of the normal stress

REMARKS

During our experimental research, attention has been paid to the advantages and limitations of performing tests with the direct shear box test. Littleton (1976) investigated the adherence behaviour of a clay steel contact using the shear box test. He concluded that in the conventional shearbox test the stress distribution at the shear plane is complex. He stated that failure is a combination of shearing and sliding along the asperities of the steel surface. He also concluded, that the particular form of failure depends on the stress normal to the sliding plane. Yoshimi (1981) summed the disadvantages of the shear apparatus for measuring adherence behaviour and investigated whether or not it was better to use a Ring Torsion apparatus. He stated that shear strain and stresses in a shearbox test are not uniformly distributed over the contact surface. Secondly, he concluded that it is not possible with the shearbox test to run tests under constant volume conditions. This results in deformation of the specimen itself. Consequently one is unable to measure the effective normal stress at the interface. Thirdly, the vertical friction along the soil wall interferes with free volume change if the soil specimen is under constant stress conditions. Tsubakihara (1993) made a comparison between the direct shear box and the simple shearbox test. He states the main problem of the direct shear box test is that the physical meaning of the vertical displacement is not clear.

CONCLUSIONS

Adherence was determined by means of measuring the adhesive shear strength in a direct shearbox. Tests have been performed on Speswhite, which consists mainly of kaolinite and on Boom clay, which is a mixture of quartz, illite and kaolinite. On basis of these tests and the literature study, the following can be concluded.

The adhesive shear strength increases with increasing normal stress. The adhesive shear strength increases linearly when it is plotted as a function of the normal stress, in the range of 0 to 500 kPa.

The value of adhesive shear strength depends on the mineral type. This is due to the different types of bonding, which can be formed between the different mineral types and the steel surface, as well as within the clay mass.

The adhesive shear strength increases with increasing roughness of the steel plate over which the clay slides. The range of the critical roughness for which failure is a combination of sliding along the steel surface and through the clay has been identified. For both clays it is between 2.4 and 4.7 μm.

With increasing contact time between clay and steel the adhesive shear strength increases. This is due to the fact that more bondings are formed, excess of pore water pressure dissipates and the soil structure adjusts itself to the stress increment, increasing the contact surface.

During shearing of normally consolidated clay, the water content decreases, which results in a higher adherence potential of the clay.

The direct shearbox gives a good quantitative impression of the adhesive shear strength, however it is expected that other devices like the simple shearbox and the ring shearbox are better suited to study the parameter variation during the tests.

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