NEW TEST METHODOLOGY FOR ESTIMATING THE ABRASIVENESS OF SOILS FOR TBM TUNNELING

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INTRODUCTION

Tunnel excavation using tunnel boring machines (TBMs), has become increasingly common in recent years, despite the fact that precise evaluation of certain risks have not kept pace with the use of these machines. One of the risks easily overlooked by Engineer and Contractor alike are the effects of abrasive ground on the costs and schedule of a given project. The impacts of worn and damaged TBM cutter heads have been observed on hundreds of tunnel projects around the world. It would appear that a reliable prognosis of the abrasiveness of soils on a project would be of great importance for designers, clients and contractors alike. Several well acknowledged test and prognosis methods already exist for rock, however there is only very limited knowledge available to describe the abrasiveness of soil and its impact on soft ground TBMs. This paper will examine approaches to this problem and suggest a new approach based on a current project undergoing design.

DEFINING WEAR

For the purposes of the following discussion it will be necessary to introduce the terms to be used, *primary wear* and *secondary wear*. By *primary wear* we refer to the expected wear on the excavation tools and surfaces such as drag bits, disc cutters, scrapers and buckets etc. which are designed for excavation and require “normal” replacement at appropriate intervals. *Secondary wear*, on the other hand, is an unplanned wear and occurs when the primary wear on the cutting tools described above is excessive leading to wear of the structures designed to hold or support the tools in place such as cutting head spokes or cutter mounting saddles and wear on other surfaces not anticipated by the designers and TBM manufacturers (Herrenknecht and Frenzel, 2005).

IMPACT OF ABRASIVE GROUND ON TBM TUNNELING

In abrasive ground, wear can occur on several parts of the TBM, including wear on the excavation tools, front, rear and periphery of the cutterhead structure, bulkhead and plunging wall structures, on outlet devices such as screw conveyors on EPB-TBMs or slurry pipes, valves and pumps on Slurry-TBMs. It is clear that during

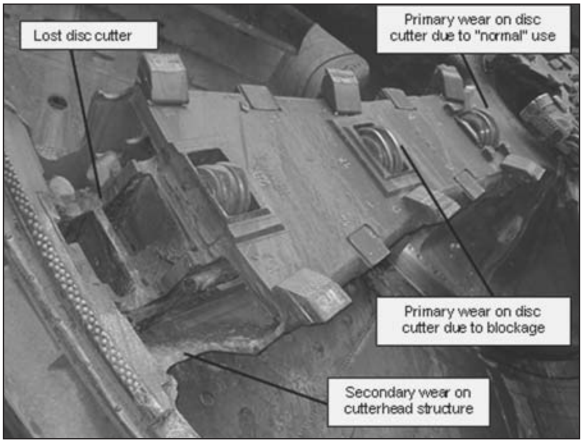

Figure 1. Excessive wear on the cutterhead of a slurry—TBM Ø 11.7 m

the design phase, TBM manufacturers should have access to objective wear characteristics of the ground to be encountered in order that a rational approach to TBM component selection and wear protection may be adopted. Moreover, during the operational phase when the TBM components are exposed to the abrasive ground, an agreed plan for scheduled inspections and maintenance should be prepared by the Contractor. Daily cutter head inspections are common in hard rock TBM drives where cutter head access is relatively easy, however cutterhead inspections on soft ground TBM projects are typically executed where convenient or as indicated due to reduced TBM performance. Typically the presence of groundwater in soft ground tunnels makes cutter head interventions more complicated and time consuming compared to hard rock tunnels.

The examples in Figures 1 and 2 illustrate the extent of wear which can be observed on soft ground TBM tunnel projects. If primary wear remains undetected and the carbide inserts on drag bits or the disc cutter ring steel and hub body of these tools fitted to the face of the cutterhead become excessively worn, subsequent secondary wear on the cutterhead structure itself can develop rapidly as observed on the periphery of the cutterhead after breakthrough of the first tube on the Wesertunnel in Germany, shown in Figure 1. Sticky clay can block disc cutters from rotating, so that they remain in one position and are ground down on one side (flat-spotted).

Wear on the outside of the cutter head rim caused by inappropriate gauge cutter material that resulted in failure and loss of originally fitted chromium carbide wear plate on the cutterhead rim is shown in Figure 2, as observed on the ECIS project in Los Angeles. Here the cutterhead radius shows the loss of 2 cm of carbide plate in addition to 2 cm of structural wear. This loss increased the required thrust force applied and slowed the TBM progress rate. Extensive underground repair works were required, delaying the works for several months.

On Slurry-TBMs *secondary wear* can occur if the rear part of the cutterhead turns within the shield (Nilsen et al. 2006a)). The excavated material drops down into the bottom of the excavation chamber where the cutterhead must then plough through a volume of accumulated spoil (Babendererde et al., 2000). For example on the 4th Elbe tunnel project in Germany (bore diameter 14.2 m) severe wear occurred in this area of the TBM and had ground down the steel structure of the cutter head from 80 mm thickness to just 15 mm.

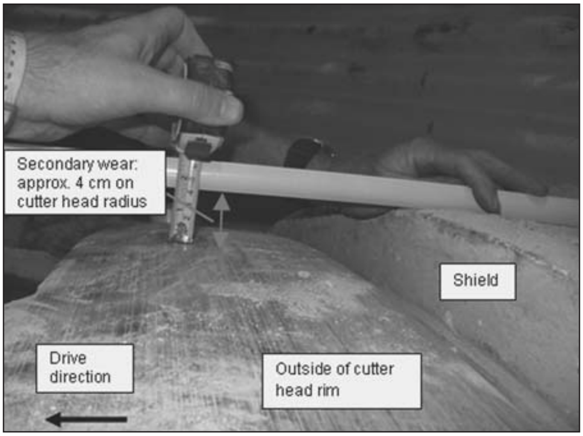

Figure 2. Excessive secondary wear on the outside cutterhead rim of an EPB-TBM Ø 4.7 m

Figure 3. A bucket tool before repair showing wear through fixing bolts (left) and after repair (right)

On EPB-TBM tunnel drives significant *secondary wear* can occur while the excavation chamber is filled with excavated material and pressurized. As the pressure within the excavation chamber increases, the *secondary wear* increases as a function of pressure, as has been observed on major projects in such places as the Porto Metro in Portugal and the MTA in Singapore.

Figure 3 illustrates the peripheral area of the cutterhead before and after repairs had been affected underground adjacent to the 24 do Agosto station on the Porto Metro. The wear was largely due to the abrasive Porto granite in its various states of weathering. The use of closed mode (EPB) operation where the TBM excavated mixed soil conditions also contributed to the observed wear requiring six weeks of around-the-clock working in order to complete the cutter head refurbishment.

Figure 4 summarizes the cutter consumption, ground conditioning used and the ground type actually encountered along the Porto Metro line S. The ground conditions

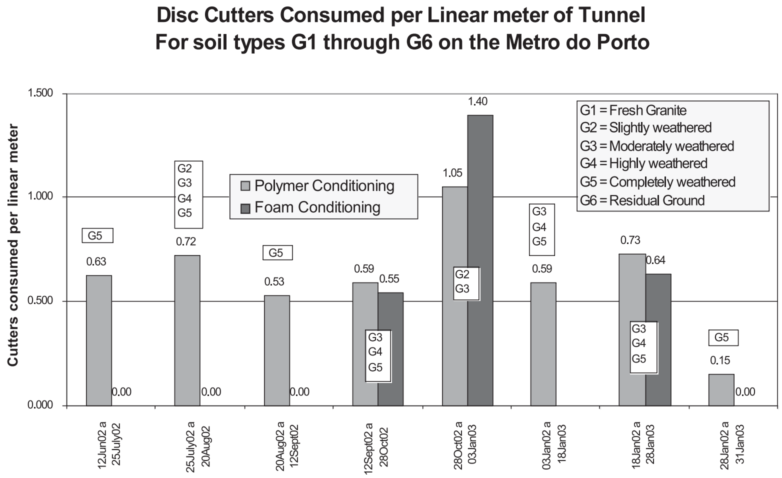

Figure 4. Disc cutter consumption for polymer and foam ground conditioning in the various weathered granites found along the Porto Metro line S.

range from G1–fresh granite to G6–residual ground. As can be noted there does not appear to be a great difference between the types of ground conditioning employed, however the degree of weathering seems to play a crucial role in determining wear. It was quite typical to change 4 to 5 cutters per day which required almost an entire shift to accomplish, thus permitting only 7.5 to 9m per day of advance.

The examples as previously described give a first indication of the variety of wear problems in soft ground TBM tunneling. Up to now there has been no generally acceptable method for estimating the amount of wear to be expected in relation to objectively tested soil properties other than recourse to the anecdotal references of adjacent projects. It is clear that the ground abrasiveness characteristic is only one of the factors which affect both the primary and secondary wear observed. TBM operational modes, the type of TBM be it EPB or Slurry, and the additives used for ground conditioning and timely maintenance are among other important factors. However the characterization of the abrasive properties of the ground plays the most important role in the development of effective strategies for dealing with the problem of wear.

EXISTING TEST METHODS TO DESCRIBE THE ABRASIVENESS OF ROCK AND SOIL

All rocks and soils consist of minerals, which all have their distinctive scratch hardness. To define the hardness, the Moh's hardness scale is most commonly used. The scale is divided into ten increments, ranging from talc, with a hardness of 1, as the softest to diamond (hardness 10) as the hardest. The scale is linear from hardness of 1 to 9, with each mineral being able to scratch the one below it in the scale.

Among the most common minerals, mica and calcite are very soft (hardness 2.5 and 3, respectively), while feldspar, pyroxene and amphibole may be characterized as medium hard (hardness 6). Quartz and garnet are very hard (hardness 7 and 7–7.5, respectively), and to a great extent, determine the degree of cutter wear.

Cutter life can be estimated from the relative percentage of minerals of different Moh's hardness classes (>7, 6, 4–5 and <4). For coarse grained rock and soil this is most commonly determined by petrographic analysis in microscope. For fine grained rock and soil it is most commonly determined by X-ray diffraction (XRD), some times supplemented by differential thermal analysis (DTA). The higher the percentage of hard minerals found at the face, the more abrasive the soil or rock, and the shorter the cutter life.

In addition to mineral composition, many other textural features however also influence on TBM performance, such as: grain size, shape and elongation, grain orientation, degree of anisotrpy, grain suturing, interlocking, micro fractures and pores.

The use of Moh's hardness therefore is restricted mainly to preliminary estimates of cutter wear. As far as is known, Moh's hardness is not used directly as input in any TBM performance prediction model.

Test Methods for Rock

For rocks several methods for estimating abrasiveness exist already. The most commonly used are (Ozdemir & Nilsen, 1999 and Büchi et al. 1995):

1. The Vickers test, giving the Vickers Hardness Number (VHN)
2. The Cerchar test, giving the Cerchar Abrasivity Index (CAI)
3. The LCPC abrasimeter test, giving the LCPC abrasivity index (ABR)
4. The NTNU abrasion test, giving the Abrasion Value (AV/AVS)

These methods normally give a fairly reliable estimation of the abrasiveness. The greatest challenge in most cases is to collect representative samples. The first three methods are briefly discussed in the following part of this section, while the NTNU-test is discussed in more detail below.

Vickers hardness defines the micro-indentation hardness of a mineral, and provides a Vickers hardness number (VHN). The hardness number is defined as the ratio of the load applied to the indenter (gram or kilogram force) divided by the contact area of the impression (square millimeters). The Vickers indenter is a square based diamond pyramid with a 130° included angle between opposite faces, so that a perfect indentation is seen as a square with equal diagonals. A virtually linear relationship has been found between Moh's hardness and VHN (in log-scale). As with Moh's hardness, the use of VHN is primarily for the purpose of preliminary estimates of abrasivity and the expected cutter wear.

The Cerchar test is performed by scratching a freshly broken rock surface with a sharp pin of heat-treated alloy steel The Cerchar Abrasivity Index (CAI) is then calculated as the average diameter of the abraded tip of the steel pin in tenths of mm after 1 cm of travel across the rock surface. The advantage of this test is that it can be performed on irregular rock samples. The CAI value is related directly to cutter life in the field. The CAI values vary between less than 0.5 for soft rocks such as shale and limestone to more than 5.0 for hard rocks such as quartzite.

The LCPC abrasimeter test was developed in France to test the "abrasivity" and "breakablity" of granular material such as crushed rock or synthetically created materials (Büchi et al. 1995). Layout of the test apparatus and the procedure of the LCPC test are described in the French Code P18-579. As only the 4 mm to 6.3 mm fraction is used, coarse grained material, such as rock samples, have to be crushed and sieved after drying at typically 105 °C (limestone at <50 °C). Fine grained (<4 mm) and very coarse grained material (>6.3 mm) are not included in the original LCPC test.

A total amount of 500 g of the 4 mm to 6.3 mm fraction is filled into a steel cylinder at an internal diameter of 93 mm (approx. 4 inches). Within the cylinder a rectangle steel propeller is rotated at 4,500 rpm for 5 min (Figure 5). The propeller is made of relatively soft steel (Rockwell B 60-75), which can be easily scratched with a

Figure 5. The LCPC abrasimeter test apparatus

knife. The abrasion coefficient ABR corresponds to the weight loss of the propeller per tonne of sample.

The NTNU Abrasion Test (AV/AVS)

A methodology for estimating the drillability of rocks by percussive drilling was developed at the Engineering Geology Laboratory of the Norwegian Institute of Technology (NTH) already in the early 1960s (Lien, 1961). Abrasion testing of crushed rock particles <1.0 mm, as illustrated in Figure 6, was then introduced together with the Brittleness test and the Sievers-J miniature drill test for estimating the drillability parameters DRI (Drilling Rate Index) and BWI (Bit Wear Index).

Since the early 1980s, the tests have been used mainly for predicting hard rock TBM wear performance according to the method developed by the NTH (since 1996 named NTNU) Department of Building and Construction Engineering, Bruland, Dahlø & Nilsen (1995). For TBM cutter wear prediction, a test piece of steel taken from a cutter ring is used instead of the tungsten carbide test piece used for percussive drilling estimation, and the parameter CLI (Cutter Life Index) is calculated instead of BWI. The NTNU prognosis model has been continuously revised and improved as new tunneling data has become available, and is now based on data from about 250 km of bored tunnels in Norway and many other countries around the world (NTNU, 1998).

The Abrasion Values AV/AVS represent time dependent abrasion of tungsten carbide/cutter steel caused by crushed rock powder. The same test equipment as for the AV is used to measure the AVS.

The two tests are defined as follows:

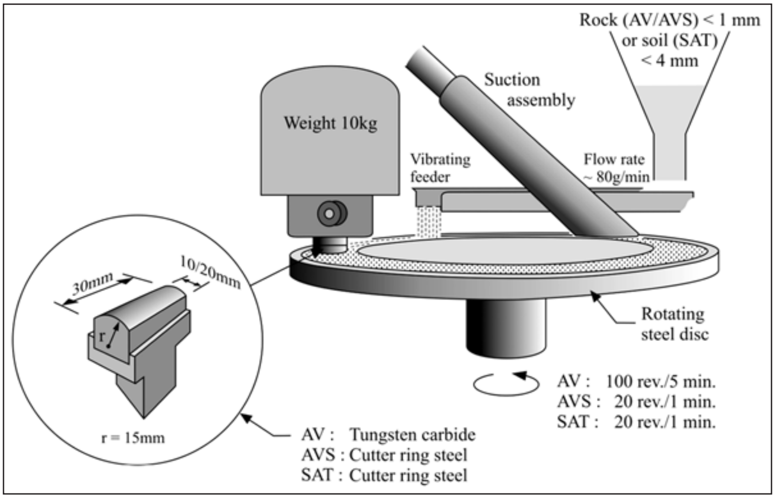

Figure 6. Principle sketch of the NTNU abrasion tests

AV	The Abrasion Value is the mean value of the measured weight loss in milligrams of 2–4 tungsten carbide test bits after 5 minutes, i.e., 100 revolutions of testing, by using an abrasion apparatus and crushed rock powder.
AVS	As described for AV, but with 1 minute, i.e., 20 revolutions of testing.

Test Methods for Soil

For soils the situation is quite different. There are only very few test methods to describe the abrasive characteristic of soils. Typically tests are limited to describe the hardness of minerals, such as the Vickers Hardness Number (VHN), Mohs hardness, quartz content and abrasive mineral content (AMC), but grain size of the soil is not taken into account.

Additionally there exist some abrasivity model tests for soils, such as the Los Angeles Abrasion Test, the Nordic Ball Mill Test (NBMT) and Dorry's Abrasion Test, which were developed to study the abrasion of aggregates to be used in road pavement works (Gudbjartsson and Iversen, 2003).

- The Los Angeles Abrasion Test rig consists of a rotating circular drum (∅ 0.7 m; L = 0.52 m) which is filled with cast iron spherical balls ∅ 48 mm along with the aggregates (5–10 kg). The cylinder is rotated at a speed of 30 to 33 rpm for 500 to 1,000 revolutions. Then the material is sieved through 1.7 mm sieve and the passed fraction is expressed as a percentage of the total weight of the sample. This value is called "Los Angeles abrasion value."
- The Nordic Ball Mill Test is common in Scandinavia and Iceland (similar to L.A. abrasion test).
- Dorry's abrasion test uses the resistance of aggregates to surface wear by abrasion induced by a rotating steel plate and is determined by measuring the volume loss of the aggregate specimen.

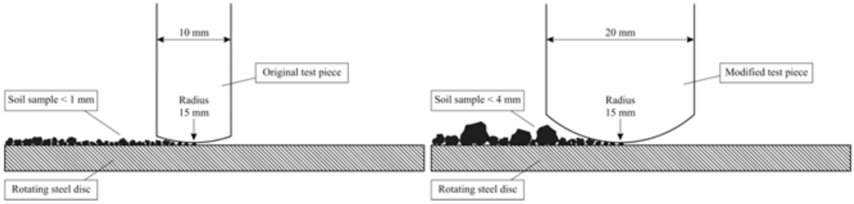

Figure 7. The original (left) and modified SAT test pieces (right)

The former three tests are suitable to measure the abrasion of soil grains due to abrasion induced by steel or by contact to other soil grains but they are not valid to determine the abrasion of steel induced by soil, which is the case in TBM tunneling.

On a Slurry-TBM abrasion can have an adverse impact on the slurry discharge components, pipes and pumps. Particularly on long tunnel drives severe abrasion can occur due to the long period of exposure of the discharge components to flowing slurry mixed with excavated soil.

In the USA there is a standardized test, the so called Miller test (ASTM G75-01), which was originally developed in the oil industry for deep vertical borings, but deals with a similar abrasion problem as on Slurry-TBM drives. This test can be used to collect data from which the relative abrasivity of a slurry related to a standardized steel surface can be known, additionally the response of different materials to an abrasive slurry can also be investigated.

As described above, only few abrasion test methods are available for soils. They provide information on the abrasion characteristic of minerals within the soil and of slurry-soil mixtures, which is important information, but limited to specific aspects of the abrasion problem.

As will be described in the following, a new attempt has been made for an abrasion test for soils, the NTNU Soil Abrasion Test (SAT), describes the abrasiveness of soils in a more objective way. The initial testing has given quite promising results, and the test is believed to have a great potential for soft ground.

THE NEW NTNU SOIL ABRASION TEST (SAT)

Test Procedure

The new NTNU Soil Abrasion Test (SAT) is a further development of the existing abrasion tests for rock. Compared with the AVS test only one detail has been changed: instead of crushed rock powder <1 mm a sieved soil sample <4 mm is used in the SAT test. The initial SAT tests were performed with an upper grain size limit of 1 mm (Nilsen et al. 2006a to c), but has now by a modification of the original test pieces, as shown in Figure 7, been increased to 4 mm.

To enable comparison with previous test results and to take advantage of the extensive NTNU database it is considered important to follow the standardized NTNU abrasion test procedures as closely as possible. The following preparation of soil samples therefore is recommended, and has been followed for the soil testing described here.

In order to reduce or avoid changes of the original properties, soil samples should be dried gently in a ventilated oven at 30°C for 2–3 days. The following techniques should be used after drying in order to disintegrate and separate the particles for the abrasion powder:

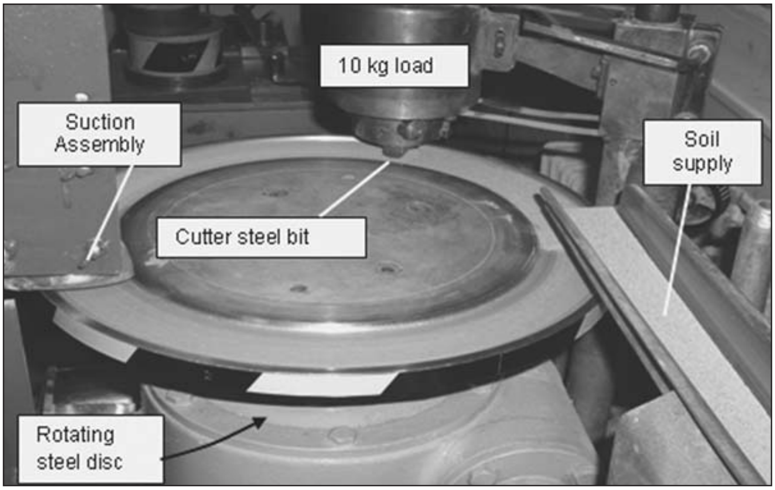

Figure 8. SAT testing in the NTNU abrasion test rig. The test piece is clamped under the 10 kg load and is running on sand supplied on the rotating disc by the vibrating feeder.

1. Disintegration by use of a soft hammer.
2. Sieving with steel balls as gentle milling/disintegration aid.
3. Initial disintegration in a jaw crusher if the samples contain very hard lumps of cohesive material after drying. Crushing of intact grains should be avoided.

Action (1) had to be carried out for most of the samples described below, action (2) for all of the samples and action (3) for some of the samples.

SAT-testing of the sieved fraction was then carried out according to the same procedures as for AVS-testing, see Figure 6, and the SAT-value is calculated as the mean value of the measured weight loss in mg (to be accepted, the results of 2–4 parallel tests should not deviate by more than 5 units). SAT-testing in progress is illustrated in Figure 8 and examples of the appearance of test pieces after completed tests are shown in Figure 9.

Descriptions of Samples

The soil samples all originated from planned or completed TBM soft-ground tunnel projects in the Seattle area, USA, comprising the Brightwater Conveyance System, Henderson and Alki projects. They represent 4 typical soil types which may be described as follows:

- Clay: Low and high plasticity clays, low and high plasticity silts and scattered organic zones. Liquid limit average 46; plastic limit average 24. Average moisture content 24%. About 80% passes the No. 200 sieve.
- Silt: Non-plastic silt. Average moisture content 23%. About 75% passes the No. 200 sieve.
- Sand: Silty sand, poorly-graded/silty sand and poorly-graded sand. About 18% passes the No. 200 sieve.
- Gravel: Poorly-graded gravel, silty gravel, well-graded sand and well-graded gravel. About 10% passes the No. 200 sieve.

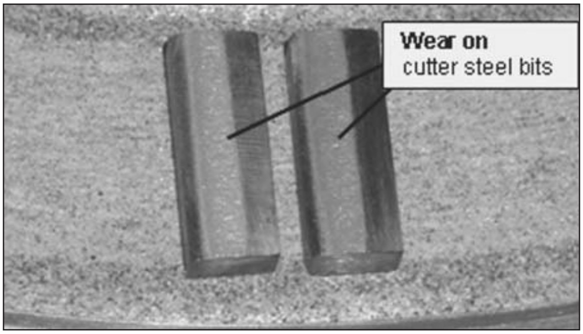

Figure 9. Abrasion of test pieces (L = 30 mm) after Soil Abrasion Test (SAT) (minimum 2 test runs per soil sample)

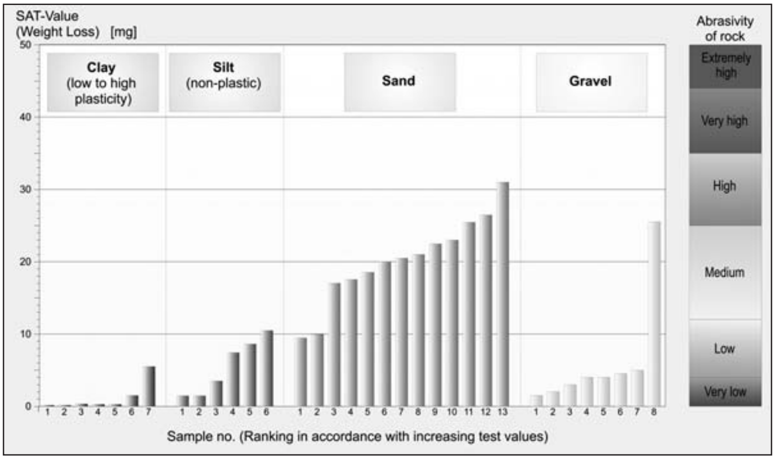

Figure 10. SAT test results for the Seattle area soil samples

Test Results

As can be seen in Figure 10, there is a considerable variation in abrasiveness, also within each soil type. This reflects the different mineralogical compositions of the samples and other features such as grain shape. Apart from a few exceptions the tested Sand has the highest SAT-values, and Clay the lowest.

EVALUATION OF SAT TEST RESULTS AND POTENTIAL OF METHODOLOGY

Compared to the standard AVS-classification based on testing of rock samples as shown in Table 1, the SAT-results based on sieved material <1.0 mm classify as "High" for 4 of the samples, and "Medium" for 8. The remaining 17 samples classify as "Low" to "Extremely low" concerning AVS.

Table 1. AVS classification for rocks based on the NTNU/SINTEF database of 1590 rock samples

Category	% of Total	AVS
Extremely low	5	<1
Very low	10	2–3
Low	20	4–2
Medium	30	13–25
High	20	26–35
Very high	10	36–44
Extremely high	5	>44

Table 2. AVS values for some sedimentary rocks and quartzite tested at NTNU/SINTEF

Rock Type	Number of Samples	AVS
Limestone	17	0.2–1.4
Shale	17	0.4–10
Siltstone	4	0.4–44
Sandstone	36	0.4–52
Quartzite	20	17–63

As already mentioned, the NTNU-abrasion test was developed originally for rock testing, and no previous experience exists for use of this test related to tunnel projects in soil. Tunneling in soil is quite different from TBM rock excavation, but there are also many similarities concerning cutter-tool abrasion.

These similarities can be evaluated and compared to the results in the extensive NTNU/SINTEF rock test database.

In order to get the maximum benefit from the SAT-testing, the test conditions and procedure have been kept as similar as possible to the conditions and procedure for rock testing. Although no database for SAT-testing exists, this testing is believed to give a fair indication of the abrasiveness of the various soils.

Based on rock testing, the content of quartz and other hard minerals like garnet and epidote have a major impact on the abrasion on the test pieces, but grain shape and grain binding may also contribute substantially. In Table 2, AVS-results for some sedimentary rocks tested at NTNU/SINTEF are shown, illustrating that there is a considerable difference in AVS-values between the softest (i.e., limestone) and hardest (i.e., quartzite) rocks. As also shown, the AVS-value may also differ significantly within one type of rock.

As illustrated by Table 2, the Seattle area soil samples have SAT-values similar to the AVS-values of rocks. Since a SAT-database for soil and a performance prediction model for soil tunneling based on SAT-values does not yet exist, the soil test results can not be used directly for estimation of wear of cutter tools. The test results do, however, provide a good basis for comparing the abrasiveness of the respective soils, and by comparing the results with those for rock, useful indications of relative abrasiveness may be obtained.

Table 3. Comparison between SAT test and LCPC test

	SAT Test	**LCPC Test**
Type of material to be tested	Soil	Crushed rock
Grain size range	<4 mm Clay, Silt, Sand, Gravel (partly)	4 mm to 6.3 mm Gravel only (partly)
Material of test piece which is subject of abrasion	Cutter ring steel	Very soft steel
Rotation speed within contact surface which is subject of abrasion	20 rpm	4,500 rpm
Type of contact causing abrasion on test piece	Friction at **low** velocity within contact surface	Friction due to hitting impulse and due to **high** velocity within contact surface

COMPARISON BETWEEN SAT TEST AND LCPS TEST

As the SAT test and the LCPC test follow different approaches it seems useful to give a short comparison of both test methods concerning the key aspects. (Table 3)

Compared to the LCPC test it appears that the conditions of the SAT test are closer to the in-situ conditions during a TBM tunnel drive, where the cutter head rotates at a relatively low velocity of typically 1.5 to 2 rpm in soft ground. Due to the high rotation speed of 4,500 rpm, the abrasion produced within the LCPC test is caused predominantly by a hitting impulse and at high velocity within the contact surface of steel propeller and test material. The kinetic energy increases in square order at increasing velocity and increases linear with increasing mass and grain size respectively. This is probably the main reason for the LCPC test results published by Thuro et al. (2006), which indicate that "the LCPC abrasion values (ABR) increase more than linear with increasing grain size and that sand, silt and clay do not play a significant role on abrasion even at high quartz content." These results published by Thuro et al. (2006) do not correspond to the SAT test results, which indicate the highest SAT abrasion values for sand and lower values for gravel and silt/clay respectively.

Currently there is no database available which shows the actually encountered wear on TBM drives, abrasion values of lab test results (such as SAT or LCPC values) and type of soil or grain size distribution. We are currently on the way to develop such a database which will remain a key task over the next few years. Nevertheless, on several completed projects it appears that sand can be very or extremely abrasive, sometimes even more abrasive than gravel or sand/gravel mixtures.

CONCLUSION

The abrasiveness of soils:

- Results in schedule delays to many tunneling contracts
    - due to a failure to fully evaluate abrasion at the design stage
    - due to a failure of the contractors to properly inspect and maintain the TBM
- Is a soil property, which needs to be determined during design phase (site exploration)
- Should be taken into account by designers/owners in relation to

    - number and duration of inspections and cutter changes (and additional measures if required)
    - time
    - cost
    - development of contract documents
- Should be taken into account by contractors in relation to
    - pricing during bidding process
    - scheduling to accommodate reasonable TBM maintenance

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