In the second of a series of three articles, B Nilsen of Norwegian University of Science and Technology (NTNU), F Dahl of SINTEF Rock and Soil Mechanics, J Holzhäuser, of Babendererde Ingenieure, and P Raleigh, of Babendererde Engineers, discuss existing test methods to describe the abrasiveness of rock and soils

Abrasivity testing for rock and soils

All rocks and soils consist of minerals that have a distinctive scratch hardness. To define this hardness, the Moh's hardness scale is the standard reference used. The scale is divided into 10 increments, ranging from talc (with a hardness of 1) as the softest, up to diamond (hardness 10) as the hardest. The scale is naturally linear from a 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 characterised 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 TBM cutter wear.

Cutter life can be estimated from the relative percentage of minerals of different Moh's hardness classes (>7, 6-7, 4-5 and <4). For coarse-grained rock and soil this is most commonly determined by petrographic analysis using a microscope. For fine grained rock and soil it is most commonly determined by X-ray diffraction (XRD), sometimes 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, TBM performance is also influenced by many other textural features, such as:

- grain size, shape and elongation
- grain orientation, directional properties
- grain interlocking
- microfractures 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 has not to date been used directly as an input in any TBM performance prediction model.

Test methods for rock

There are several methods for estimating the abrasiveness of rocks. 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

Fig 1 - Correlation between Vickers micro-hardness (VHN) and Moh's hardness (after Young and Millmann, 1964).

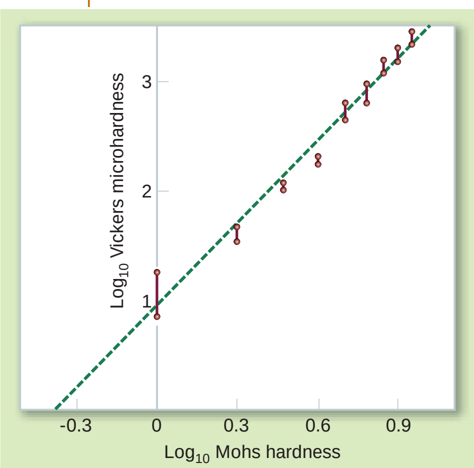


Fig 2 - The Cerchar test

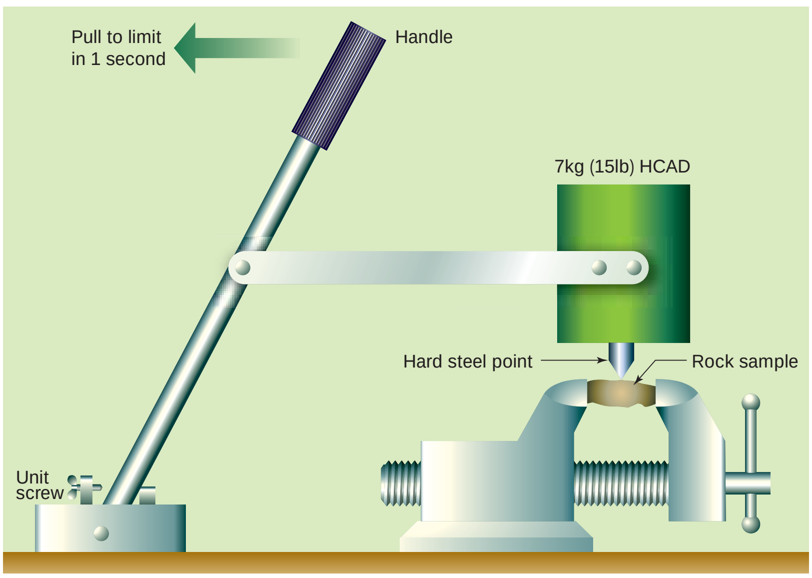
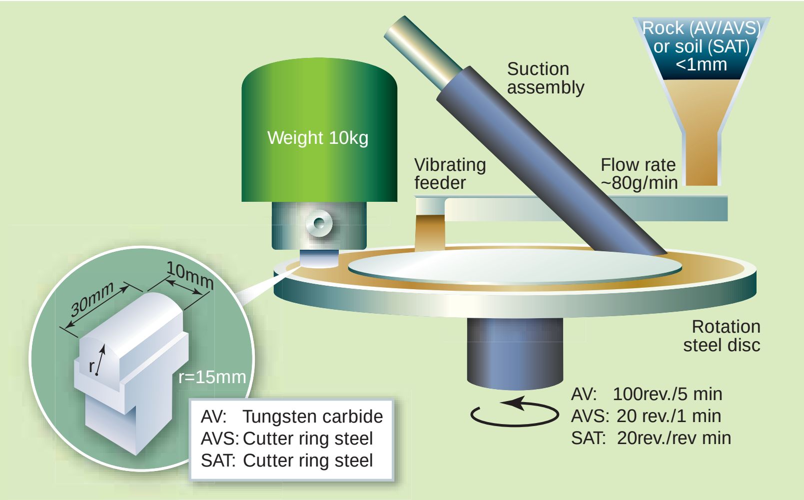


Fig 3 - Principle sketch of the NTNU abrasion test



These methods normally give a fairly reliable estimation of the abrasiveness. The greatest challenge in most cases is to collect representative samples.

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 indentor (gram or kilogram force) divided by the contact area of the impression (mm^2). The Vickers indentor 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 relation has been found between Moh's hardness and VHN (in log-scale), as shown in Figure 1.

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 (figure 2). 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 10mm 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. 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 involves the taking of samples of rock, soil or synthetically created material and testing using the 4mm-6.3mm fraction. Coarse grained material has to be crushed and sieved and fine grained material (<4mm) is not included in the test. An air dried sample is placed into a cylindrical drum and a rectangle steel propeller is rotated at 4500rpm speed. The propeller is made of relatively soft steel, which can be easily scratched with a knife. The abrasion coefficient ABR corresponds to the weight loss of the propeller per tonne of sample. The LCPC test is mainly used for rock samples, and a fairly good correlation exists between the LCPC test, Cerchar test and the UCS of the rock tested.

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) in the early 1960's (Lien, 1961). Abrasion testing of crushed rock particles <1mm, as illustrated in Figure 3, 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 1980's, the tests have been used mainly for predicting hard rock TBM wear performance according to the method developed by the NTH/NTNU Department of Building and Construction Engineering (in 1996, as result of a merger, NTH changed name to NTNU - the Norwegian University of Science and Technology - and the Norwegian method now is referred to as the NTNU method), Bruland, Dahlø & Nilsen (1995). For TBM cutter wear prediction, a test piece of cutter steel 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 tunnelling data has become available, and is now based on data from about 250km of bored tunnels in Norway and many other countries around the world (NTNU-Anleggsdrift, 1998).

Since the introduction of the NTNU drillability/boreability testing, a comprehensive database representing about 3,000 different rock samples has been established. Today, SINTEF Rock and Soil Mechanics is operating the drillability laboratory in co-operation with NTNU.

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, but instead of the tungsten carbide test pieces used for AV, the AVS test uses test pieces of steel taken from a cutter ring.

The two tests are defined as follows:

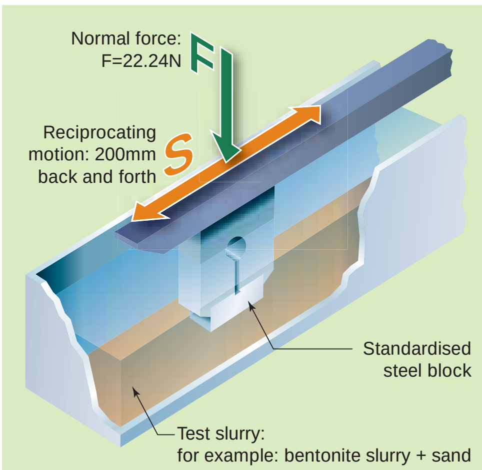
AV: The Abrasion Value is the mean value of the measured weight loss in milligrams of 2 - 4 tungsten carbide test bits after 5 minutes, i.e. 100 revolutions of testing, by using an abrasion apparatus and crushed rock powder.

AVS: As described for AV, but with 1 minute, i.e. 20 revolutions of testing.

For the AVS-test, the standard NTNU/SINTEF test procedure (shown in figure 3), is as follows:

- A representative rock sample consisting

Fig 4 - Miller test to determine the Slurry Abrasivity (Miller Number) and the Slurry Abrasion Response (SAR Number)



of approx. 2kg is used for preparation of abrasion powder.

- Crushing is done gently in several crusher steps to avoid excessive production of fines. The initial crushing is performed in a jaw crusher with the outlet opening adjusted to 10mm. Further crushing is performed using a smaller laboratory crusher in minimum 2 steps. The outlet opening is adjusted to approx 3mm-4mm prior to the first crusher step.
- The crushed material is sieved on a 1mm quadratic mesh. The fraction < 1mm is transferred to a suitable pan and the fraction > 1mm is crushed again after adjustment of the outlet opening to approx. 1mm. This process is repeated until the grain size distribution is 99% <1mm and 70 ± 5 % < 0.5mm.
- The crushed powder is mixed thoroughly before pouring it into the funnel on the vibrating feeder connected to the abrasion apparatus. The test apparatus is set-up by starting the rotation of the steel disc together with the suction assembly and gradually adjusting the vibrating feeder until a thin and uniform layer of abrasion powder covers the track.
- 2 – 4 cutter steel test pieces are prepared by grinding them to the specified dimensions. The grinding of the test surface is a critical step and extra care is needed to avoid overheating. The edges of the test surfaces are ground, honed and visually examined to make sure that they are smooth and straight. The test bits must also be absolutely clean and dry before weighing to the nearest 0.001g.
- One of the controlled test pieces is clamped under the load and placed gently on the steel disc. The test surface should be horizontally aligned with the steel disc, as it should otherwise be adjusted by the clamping of the test piece and the suspension of the load.
- Testing time is 1 minute, i.e. 20 revolutions. The amount of abrasion powder fed onto the steel disc should be sufficient, but not excessive. It is therefore important to adjust the vibrating feeder during the test in order to avoid steel against steel abrasion or a pile of powder in front of the test piece. The operator should also make sure that the test piece runs in the middle of the track and that a single point of it does not bear directly against the steel disc.
- Test pieces from 2 – 4 parallel tests are rinsed and dried thoroughly before weighing. The weight loss is calculated, and the results should normally not deviate by more than 5 units (mg).

Test methods for soil

For soils the situation is quite different. There are 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 (0.7m diameter ; L = 0.52m) which is filled with 48mm diameter cast iron spherical balls along with the aggregates (5-10kg). The cylinder is rotated at a speed of 30 to 33rpm for 500 to 100 revolutions. Then the material is sieved through 1.7mm 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, which is common in Scandinavia and Iceland, is similar to the 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.

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, called the 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 (figure 4). 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 be investigated.

The test consists of a tray covered with a layer of Neoprene on the bottom and filled with the test slurry (e.g. bentonite slurry + soil). A standardised steel block is dipped into the test slurry and is loaded with a fixed weight (22,24N is applied as a normal force). The steel block is driven in a reciprocating motion through the test slurry for 6 hours. The mass loss of the steel block is measured and gives the Miller Number which is an index of the relative abrasivity of slurries in terms of wear of a standard reference material. The wear damage on the standard wear block is worse as the Miller Number gets higher.

If materials other than the standard steel block are used the measured mass loss indicates the Slurry Abrasion Response (SAR Number).

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 Part 3 next month, a new attempt has been made for an abrasion test for soils, the NTNU Soil Abrasion Test (SAT), which 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. T&T

REFERENCES

1. L Ozdemir & B Nilsen, 1999. "Recommended laboratory rock testing for TBM projects". AUA News 14:2, 21-35.
2. E Büchi, JF Mathier & Ch Wyss, 1995. "Rock abrasivity – a significant cost factor for mechanical tunnelling in loose and hard rock". Tunnel 5/95, 38-44.
3. R Lien, 1961. "An indirect test method for estimating the drillability of rocks". Dr. thesis, NTH Dept. of Geology, 90p.
4. A Bruland, TS Dahlø & B Nilsen, 1995. "Tunnelling performance Estimation Based on Drillability Testing". ISRM Congress, Tokyo, 1995, 123-126.
5. JT Gudbjartsson & K Iversen, 2003. "High-Quality wear-resistant paving blocks in Iceland". International Conference in Concrete Block Paving, Sun City, Oct 2003.
6. ASTM G75-01 Standard Test Method for determination of slurry abrasivity (Miller number) and slurry abrasion response of materials (SAR number). Sep 2001.
7. NTNU-Anleggsdrift, 1998. "Hard Rock Tunnel Boring". Norwegian University of Science and Technology, Dept. of Building and Construction Engineering, Report 1B-98, 164p.
8. BB Young & AP Millmann, 1964. "Microhardness and deformation characteristics of ore minerals". Trans. Inst. Min. Metal, 73:437-466.