RECOMMENDED LABORATORY ROCK TESTING FOR TBM PROJECTS

Levent Ozdemir, Professor of Mining
Colorado School of Mines, USA
and
Björn Nilsen, Professor of Geological Engineering
Norwegian University of Science and Technology (NTNU), Norway

INTRODUCTION

A degree of uncertainty is always present when evaluating the ground conditions of a planned TBM project. To optimize the tunnel design and minimize the impact of unexpected ground conditions, thoroughly planned and detailed site investigations are crucial. Typically, the investigations are carried out in a stepwise manner with the main objective to develop a basis for:

- Overall planning, including siting and design optimization.
- Analyzing stability and rock support requirements.
- Evaluating alternative excavation methods, selecting equipment and predicting performance.
- Assessing environmental impact and the disposal/use of excavated material.
- Estimating costs, schedule and preparing tender documents.

The main aspects of a site investigations program are discussed in a recent paper prepared for the 1999 RETC Conference (Nilsen & Ozdemir, 1999). In this paper, the physical and mechanical rock properties, which may greatly influence the feasibility and costs of a TBM project, are discussed in more detail. Without a properly designed and executed laboratory test program, the required information on important rock properties will be incomplete, which may result in gross errors in planning, design and construction of TBM tunnels. In some cases, the lack of adequate or sufficient pre-construction testing has led to major claims.

The paper is intended to present a brief overview of the recommended testing methods, and to provide a set of guidelines concerning the methodology and extent of testing, as well as the interpretation of test results.

SAMPLING

In all TBM project planning and performance prediction efforts, careful sampling of subsurface conditions is a key factor. If the test samples are not representative of the actual field conditions, predictions, of course, will not be reliable. The decisions concerning the location and number of samples should always be based on thorough geological mapping. The sample selection criteria should focus on the mechanical character of the rock, rather than sophisticated mineralogical and petrographical features (as can be seen in some project reports).

The number of samples required will depend on several factors, such as the complexity of the geology, length of the tunnel, intended test methods, type of project, type of contract, etc. As a general rule, the number of sampling locations from each rock type should, however, not be less than two, and if very different results of those two are obtained, additional locations should be sampled. A logical first step is to obtain small hand specimens to get a general overview of the distribution of the different rock types present and the variations within each rock type. The fewer the number of samples that are analyzed, the more important the representativity of the samples becomes. To avoid the effect of surface weathering, blasting may sometimes be required to obtain fresh rock samples more closely representing in-situ conditions. Great care should be exercised in such cases to select samples relatively free of any blast-induced fractures.

In addition to being a key aspect of the overall site investigation program, core drilling offers a very useful and accurate sampling for a variety of testing purposes. The extent of drilling will vary from project to project, depending on the complexity of the project and the geology of the actual region, and to some extent, the traditions. In the United States, common rules of thumb concerning borehole spacing are 15 - 60 m and 150 - 300 m for hard rock tunneling in adverse and favorable conditions, respectively. For soft ground tunneling, the recommended spacings vary 15 - 30 m to 90 - 150 m.

The required size or volume of samples to be collected for TBM projects varies within wide limits, depending upon the type of testing intended, as shown in Table 1.

Table 1. Sample requirements for different categories of rock testing for TBM projects.

LABORATORY TEST/ INVESTIGATION	SAMPLE TYPE	SIZE/VOLUME
Petrography, mechanical properties	Most commonly: drill cores (alternatively hand specimens and larger blocks for coring in laboratory)	Most commonly: NX' (54 mm)
Boreability index testing (DRI, CLI)	Block(s)	Minimum 12 - 15 kg
Linear cutting tests	Block	Up to 100 x 50 x 50 cm
Rotary cutting tests	Large block	Up to ~ 2.5 m diameter

FACTORS INFLUENCING TBM PERFORMANCE

The principal aspects of rock fragmentation in hard rock tunnel boring are illustrated in Figure 1. In principle, the TBM boring combines the elements of rotation and percussive drilling. The high thrust allows the cutters penetrate a small distance into the rock face (1 to 10 - 15 mm, depending upon the strength of the rock). Very high contact stresses are developed beneath the cutter tip which results in the creation of a highly crushed zone of rock material, usually referred to as the "pressure bulb". This zone generally is in a hydrostatic state of stress, producing tensile stresses along its boundary. When the stress level is sufficient to exceed the rock tensile strength, cracks are developed, extending into the rock mass. When these cracks extend far enough to the adjacent grove(s) or meet with cracks already developed from adjacent cuts, chips are formed.

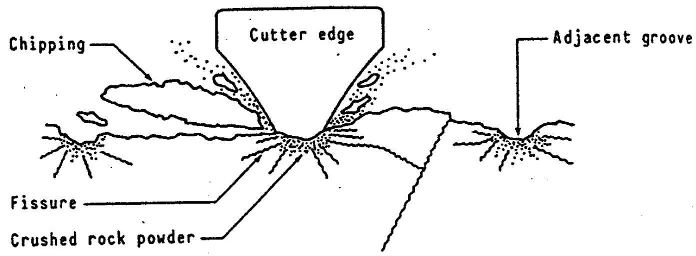

Figure 1. Rock breaking mechanism of TBM excavation.

Naturally, any rock directional properties caused by existing foliation, bedding or other features, can significantly affect the initiation and growth of the cracks and the resultant chip formation. Hence, in foliated and closely bedded rock formations or where rock exhibits a preferential grain alignment and/or orientation, specific attention needs to be given to the potential impact of these features on TBM performance.

In general, the TBM penetration and cutter wear is governed by rock strength and hardness, toughness/brittleness, anisotropy and abrasivity. Each of these rock parameters can be evaluated in the laboratory using a variety of testing methods. Following is a discussion of the recommended test methods and procedures for measuring these rock properties and for developing a reliable assessment of their influence on TBM performance.

RECOMMENDED TESTING AND INVESTIGATION METHODS

Some of the methods described here are used for TBM projects on a fairly general basis. The majority, on which the main emphasis is placed, are specialized and used in the most widely accepted TBM performance prediction models, those developed at the Colorado School of Mines (CSM) and the Norwegian University of Science and Technology (NTNU, formerly NTH). Details of the respective models are described in previous publications from CSM and NTNU/NTH. Despite using different approaches, studies to date have shown a very close correlation between the two methods for TBM performance prediction.

In the CSM model, the following laboratory tests are performed to develop data for input into the model:

- Uniaxial compressive strength (including deformability).
- Brazilian tensile strength.
- Density measurement.
- Punch penetration.
- Cerchar abrasivity.
- Petrographic analysis.

In the NTNU performance prediction model, the main tests and investigations include the following:

- Petrography.
- Siever's J-value.
- Brittleness.
- Abrasivity (AVS).

The description of the above tests together with a discussion of how the results are used forms the main focus of this paper, as follows:

Petrographic analysis

Methods like X-ray diffraction (XRD) or differential thermic analysis (DTA) may be used for semi-quantitative determination of the mineral composition. However, a reliable determination of mineral content, and a detailed study of rock texture (small scale structures), can be obtained only by thin section analysis (i.e. study of a transparent section of the rock under microscope). For TBM projects, main emphasis should be placed on factors of key importance for evaluation of TBM performance and cutter wear, including:

- Type and content of hard minerals (such as quartz, garnet and epidote).
- Grain orientation, directional properties.
- Grain size/shape/elongation.
- Grain suturing/interlocking.
- Microfractures and pores.
- Any other unusual microscopic features.

Some examples of rock textures as seen under microscope are shown in Figure 2. Here, the granoblastic texture of the quartzite to the left generally gives a higher degree of interlocking, and thus a higher strength than the rounded structure of the sandstone to the right. Also, the irregular quartz grains of the quartzite most likely cause a much higher cutter wear than the rounded grains of the sandstone. The parallel orientation of the mica grains of the mica schist in the middle most definitely makes this rock to exhibit strong directional properties.

In particular, any grain suturing/interlocking found to be present in thin-section analysis should be given detailed attention for boreability evaluations. Grain suturing/interlocking can significantly increase the difficulty of boring.

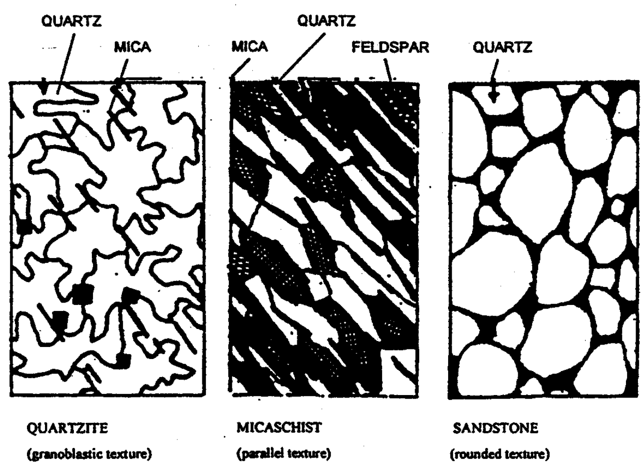

Figure 2. Some characteristic rock textures.

Hardness

Moh's hardness

All minerals have a 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 rock forming 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). This is determined by thin section analysis described earlier, or alternatively, by hand-lens examination of fresh rock surfaces. The higher the percentage of harder minerals, the more abrasive the rock and the shorter the cutter life.

The use of Moh's hardness is restricted mainly to developing preliminary estimates of cutter life. This parameter is not used directly as input in the CSM or the NTNU performance prediction models.

Vickers hardness

Measurement of 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 (square millimeters). 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 relationship has been found between Moh's hardness and VHN (in log-scale), as shown in Figure 3.

As with Moh's hardness, the use of VHN is primarily for the purpose of preliminary estimates of rock abrasivity and the expected cutter wear. VHN is not used directly as input in the CSM or NTNU performance prediction models.

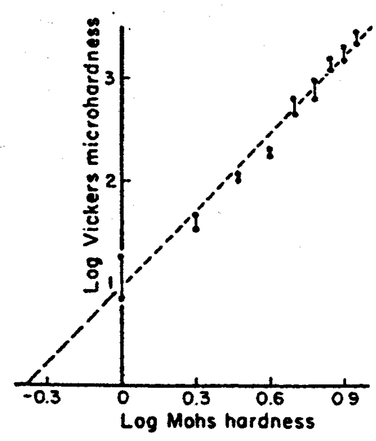

Figure 3. Correlation of Vickers micro-hardness with Moh's scale of hardness (after Young and Millmann, 1964).

Siever's J-value

The Siever's J-value test gives a measure of the surface hardness of the rock, and is used as one of the main input parameters in the NTNU performance prediction model. In this test, a precut rock sample is used, as shown in Figure 4. The drill is ground carefully for each test to ensure a constant geometry. The Siever's J-value (SJ) is the drill hole depth in 1/10 mm after 200 revolutions, taken as the mean value of 4-8 drill holes. The precut surface must be parallel or perpendicular to the foliation of the rock. The SJ-value measured parallel to the foliation is used to calculate the Drilling Rate Index (DRI). The SJ-value may vary between 0.5 and less for hard rocks like quartzite to more than 200 for soft rocks such as shales, schists and certain sandstones.

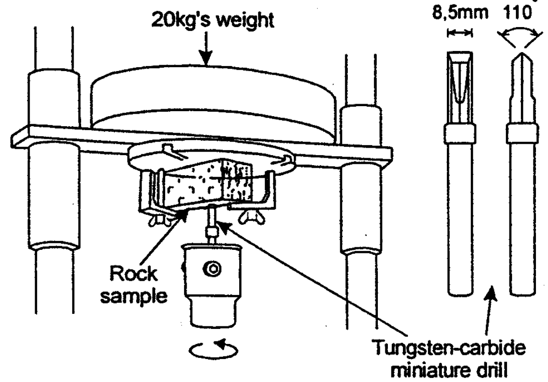

Figure 4. The Siever's miniature drill test.

<u>Toughness/brittleness</u>

Indentation (punch-penetration) test

The Punch test is a reliable means of evaluating rock toughness/brittleness. In this test, a standard indentor is pressed into a rock sample cast in a steel ring to provide confinement during testing (Figure 5). The load and displacement of the indentor are recorded with a computer system. The particular shape and slope of the load-penetration curve provides a reliable basis for estimating the excavatability of the rock, i.e. the energy needed for efficient chipping. In addition to rock strength, the load-penetration behavior is affected by the stiffness, brittleness and porosity of the sample. Also during testing, visual observations are made of how the rock fails under the indentor. The evaluation of the load-penetration curve together with these visual observations are then used in the CSM predictor model.

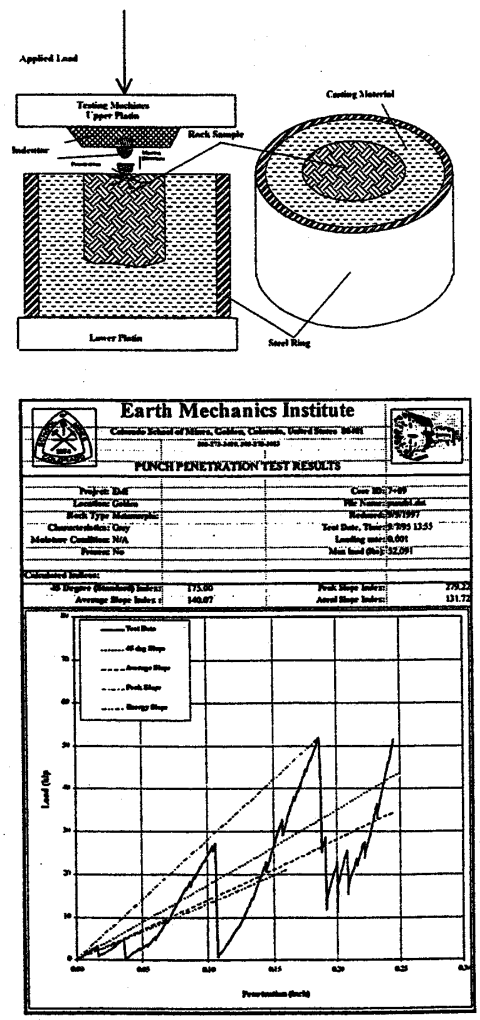

Figure 5. Punch penetration test set-up and typical results.

Fracture toughness test

The fracture toughness test defines the fracturing strength of the rock sample. It uses a specimen with a notch cut perpendicular to the core axis (Figure 6). The specimen rests on two support rollers, and a compressive load is applied to press apart the two notched sides, causing transverse splitting by crack growth in the un-notched part. This test can be useful for classifying intact rock with respect to its resistance to crack propagation, but further research and analysis is required for this to become a routine and reliable test for TBM performance evaluation.

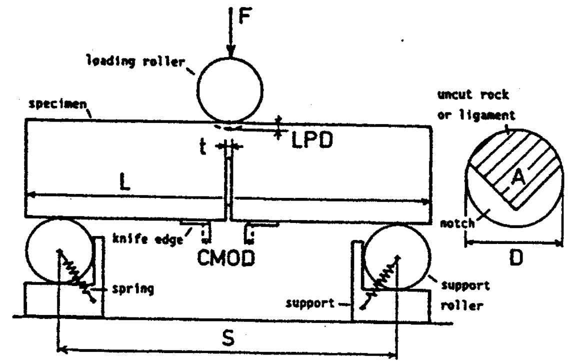

Figure 6. The principle of fracture toughness testing (ISRM, 1995).

Brittleness test

The brittleness test is the second test used to define the DRI in the NTNU performance prediction model. It is an aggregate impact test, and gives a measure of the ability of the rock to resist crushing from repeated impacts, as shown in Figure 7. The volume of test material corresponds to 500 grams of density 2.65 g/cm^3 of the fraction 11.2-16 mm. The brittleness value (S_{20}) equals to the percentage of material passing the 11.2 mm mesh after the aggregate is crushed in the mortar, taken as the mean value of 3-4 tests.

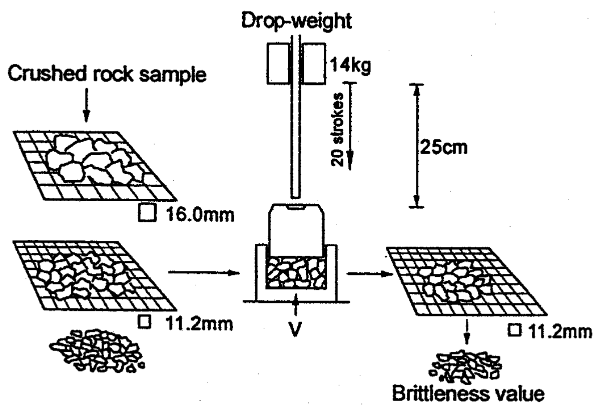

Figure 7. The brittleness test.

The S_{20} value may vary between from 20 for fine grained, very strong and massive rocks like basalt and amphibolite, to 80-90 for weak and brittle rocks, such as marble.

Recently, attempts have been made to modify the brittleness test (and also the SJ-test) to use smaller size samples, as those obtained from drill cores and drill chips (Bruland et al., 1997). The reason for this is that sometimes, when the bedrock is highly weathered or has a thick soil cover, sampling of material sufficient for the standard test (about 15 kg) may not be feasible. Promising correlations between the modified and the standard boreability test results have already been established. Further development is, however, required before the reliability of the miniature drill testing can be confirmed and the method used on a routine basis.

Mechanical strength

Uniaxial compressive strength (UCS) test

This is the rock strength most commonly measured and used in TBM performance prediction. It involves the use of a cylindrical specimen of rock loaded axially between the platens of a compression testing machine (Figure 8). The stress value at failure is defined as the uniaxial compressive strength (σ_c) of the specimen, and is given by the relationship:

$$\sigma_C = F/A$$

where: F = applied force at failure
A = initial cross sectional area

It is very important to carefully observe the type of failure during UCS testing. If the sample failure occurs along an existing fracture/bedding or foliation, this should be noted as a structural failure. Only the intact (i.e. non-structural) test results should be considered for performing boreability predictions. Otherwise, the actual UCS of the rock would be underestimated, resulting in more optimistic TBM performance estimates.

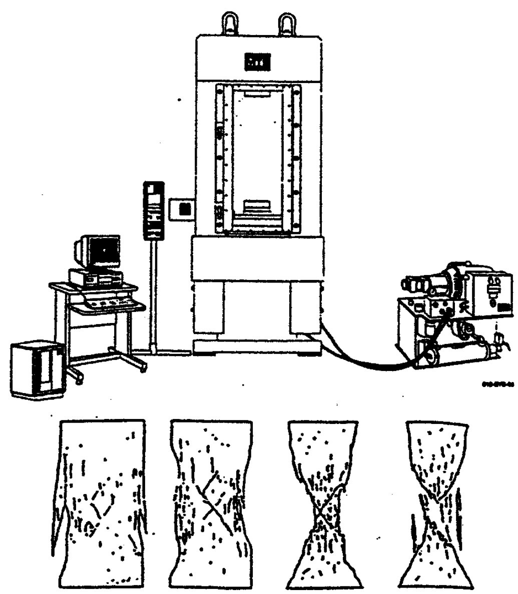

Fig. 8. The uniaxial compressive strength test.

The uniaxial compressive strength of rocks can vary within wide limits. For very strong rocks, it may be higher than 300 MPa (ISRM testing conditions), and for weak rocks, only a few MPa.

Triaxial test

In the triaxial test, the axially loaded test specimen is subjected to additional diametrically directed confining pressure, which greatly increases the failure load, as illustrated in Figure 9. The confining pressure is obtained by the use of hydraulic oil pressure on a rubber sleeve inside a triaxial cell.

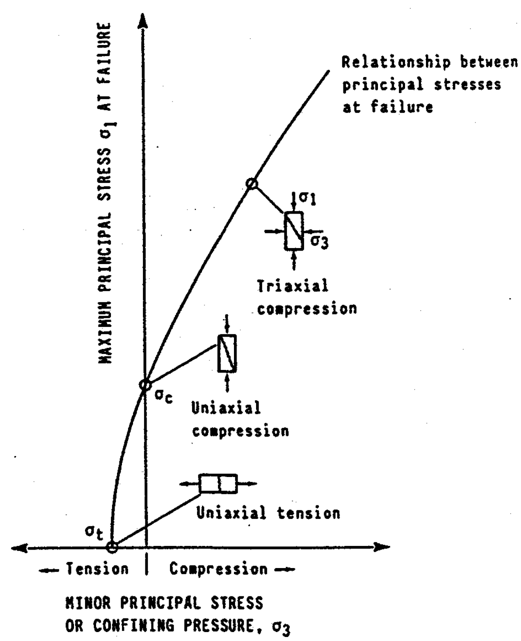

Figure 9. Alternative stress conditions for failure of intact rock (after Hoek and Brown, 1980).

Although widely used in many sectors of rock mechanics/rock engineering, the triaxial test is not commonly used for TBM performance prediction.

Brazilian tensile strength test

The direct tensile strength testing as illustrated in Figure 9 is difficult to perform and generally expensive for routine applications. Further, it often is prone to giving low results due to the effects of existing microfractures and other rock defects. Therefore, an indirect method, the Brazilian disk test, is most commonly used to determine the tensile strength of rocks.

In the Brazilian test, the specimen used is a circular disk with a thickness to diameter ratio (L/D) of between 0.5 and 0.75. The load is applied across the sample diameter, as shown in Figure 10.

The splitting tensile strength (σ_t) is defined as:

$\sigma_t = 2P/\pi LD$

where: F = failure load
L = sample length
D = sample diameter

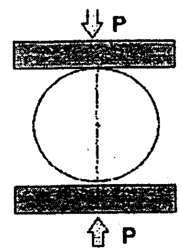

Figure 10. The Brazilian disk test.

In foliated/bedded rocks, it is crucial to orient the sample so that the failure occurs in the same direction as the rock failure between the adjacent cutters of the TBM. Hence, the disk should be loaded either parallel, perpendicular or at some oblique angle to foliation/bedding depending on the direction of boring.

Point load test

In the point load test, the tensile strength is measured indirectly by loading the rock specimen between two conical, or point shaped, platens. Test specimens may be cores or irregular lumps of rock. Core samples can be tested both diametrically and axially, as illustrated in Figure 11. As with Brazilian testing, attention should also be paid to correct orientation of the sample when foliation/bedding planes are present.

The point load strength index (I_s) is calculated as:

$I_s = P/D_e^2$

where: P = failure load
D_e = distance between platen tips
$D_e^2 = D^2$ for diametrical test
$= 4A/\pi$ for axial, block and lump test
A = W·D = minimum cross sectional area of a plane through the platen contact points

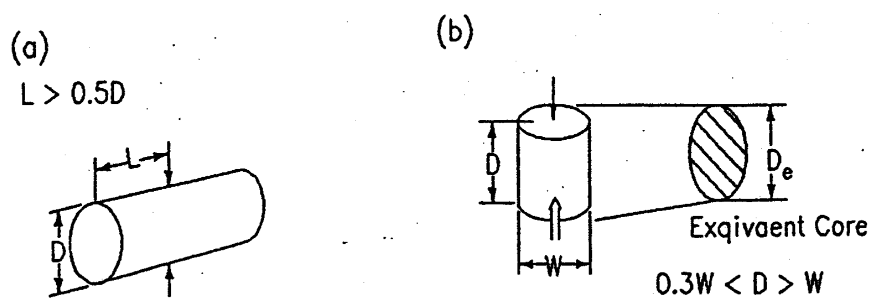

Figure 11. Point load testing; a) diametrical test, b)axial test (after ISRM, 1985).

For crystalline rocks, the point load strength indices normally vary between 5 and 20 MPa (50 mm cores). Weak rocks may have indices lower than 1 MPa. The point load anisotropy index (the ratio between maximum and minimum point load strength index) may reach values of 5 or higher in highly anisotropic rocks, such as shales and schists.

Although the point load index is not a direct input parameter in the CSM or the NTNU performance prediction models, it can be used qualitatively to provide a separate estimate of rock strength and the degree of anisotropy.

Abrasiveness

Cerchar test

The Cerchar test provides a reliable measure of rock abrasivity for cutter wear estimation. The test is performed by scratching a freshly broken rock surface with a sharp pin of heat-treated alloy steel (Figure 12). 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 test can be performed on irregular rock pieces.

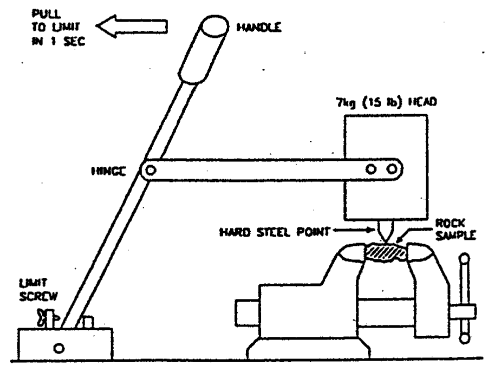

Figure 12. The Cerchar test.

The CAI value is related directly to cutter life in the field. The CAI values for various rock types bored with TBMs are listed in Table 2.

NTNU abrasion test

This is the third principal laboratory test used for the NTNU performance prediction model. Crushed rock material with grain size smaller than 1 mm is fed on to a rotating steel plate as shown in Figure 13, and the abrasion value (AVS) is defined as the weight loss in mg of a cutter steel test piece after 20 rotations of the plate (corresponding to a test time of 1 minute). Careful grinding of the test piece is carried out for every test according to specified procedures.

The AVS value may vary from close to zero for soft materials, such as limestone and shale, to 60-70 for very abrasive rocks, such as quartzite.

The abrasion value AVS should not be confused with AV, which is also measured as shown in Figure 13, but with a test piece made of hard metal (tungsten carbide) instead of cutter steel, using 100 rotations/5 minutes. The AV-value is used in performance prediction for conventional drilling.

Elasticity

Young's Modulus (also referred to as the modulus of Elasticity or the E-Modulus) is determined during UCS testing by recording the axial deformation history of the sample in addition to its load history, and the Poisson's ratio by recording also the diametrical strain. As shown in Figure 14, elasticity may be defined by the tangent to the stress/strain curve, or by the secant. When presenting results, it is therefore important to define the Young's Modulus as either the tangent or the secant modulus.

The Poisson's ratio (ν) is defined as the ratio between the axial strain and the diametrical strain.

For very stiff rocks the E-modulus may be 100 GPa or more, and for very soft rocks less than 10 GPa. The ν-value normally varies between 0.10 and 0.25.

At present, neither the Young's Modulus or the Poisson's ratio are used in the CSM or the NTNU models. However, research work is currently underway at CSM to utilize the Modulus value as part of a rock brittleness index for improving the accuracy of boreability predictions.

Table 2. Measured CAI values of some rock types.

ROCK NAME	CAI	COMMENT
Sandstone	0.3	Fontenelle
Shale	0.9	Rochester, New York
Shale	1.1	Cleveland, Ohio
Dolomitic limestone	1.1 to 1.5	Chicago, Illinois
Sandstone	1.3	Navajo
Phyllite	1.3	Norway
Micaschist	2.2	Washington D.C.
Andesite	2.3	Buckskin tunnel
Quartz diorite	3.2	Norway
Red sandstone	3.6	Kentucky
Amphibolite	3.6	Norway, 14% quartz
Gabbro	3.7	0% quartz
Amphibolite	4.0	8% quartz
Öjeby granite	4.0	Sweden, 30% quartz
Gneiss	4.1	Atlanta, Georgia
Quartzitic gneiss	4.3	40% quartz
Quartzite	4.3	East Africa
Gneiss	4.4	Norway, 18% quartz
Gneiss	4.4	Norway, 27% quartz
Sandstone	4.7	Kentucky
Quartzitic gneiss	4.8	Norway
Granitic gneiss	4.8	Norway, 38% quartz
Granite	4.8	Atlanta, Georgia
Micaschist	5.3	New York
Granitic gneiss	5.3	13% quartz
Quartzite	5.9	Norway

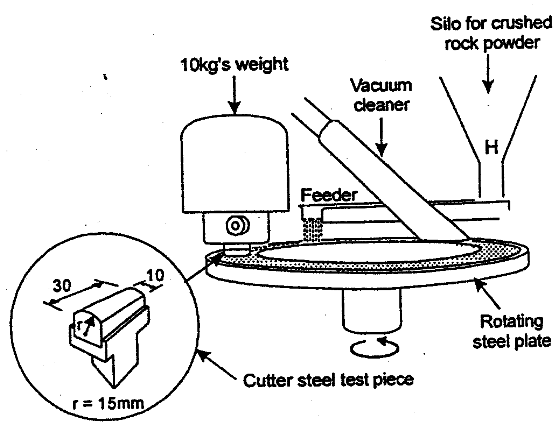

Figure 13. The NTNU abrasion test.

Physical properties

Sonic velocities

Sonic velocities measured with transducers mounted on drill core specimens provide quick and reliable information on the physical character of the rock. Particularly, this test is useful for detecting pores and microfractures, and for investigating the anisotropy of rocks. The test is non-destructive and can therefore be performed on specimens which can later be strength-tested.

Rocks may almost double their P-wave velocity from dry to fully water saturated conditions. Crystalline rocks, for instance, commonly have P-wave velocities between 5,000 and 6,000 m/sec in water saturated condition, and between 3,000 and 4,000 m/sec in dry condition. High porosity rocks, such as some sandstones, generally have P-wave velocity less than 2,000 m/sec.

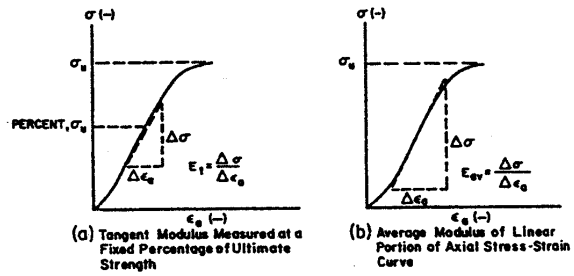

Figure 14. Young's Modulus calculated as tangent modulus (to the left) and as secant modulus (to the right). (After ISRM, 1979).

The sonic velocities are not used as input parameters in the CSM and NTNU prediction models. They are used primarily to provide a preliminary indication of rock anisotropy.

Density

Density is measured by weighing and measuring drill cores, or alternatively by a simple pychnometer test. Depending primarily on mineralogy and porosity, rocks generally have a density in the range of 2.5-3.2 g/cm^3.

Porosity

The porosity, defined as the volume of pores in per cent of total rock volume, is most simply measured by weighing a drill core specimen in dry and water saturated conditions. Crystalline rocks normally have porosity less than 1 %, while young sedimentary rocks and certain volcanics may have porosities up to 30 % or more.

<u>Laboratory cutting tests</u>

As noted earlier, the above described tests are performed for developing data as input into CSM and NTNU TBM performance models. In general, both of the models are capable of providing a very accurate estimate of boreability based on the tests described. In some cases, however, the models fail to closely predict actual TBM field performance due to one or more rock behavioral properties not fully reflected in the physical and mechanical property measurements described. For example, rock may exhibit some unusual toughness or resistance to boreability which the property tests fail to detect.

In most instances, the existence of such unusual behavior can be disclosed qualitatively by the punch-penetration test or the thin-section petrographic analysis. When such conditions are determined to exist, a series of laboratory cutting tests can provide more accurate data on the cuttability of the particular rock formation. In this respect, the most commonly used test is the linear cutting test which is routinely performed by CSM and other institutions around the world.

Linear cutting test

In this test, the rock sample (size up to 100 x 50 x50 cm) is cast in concrete within a heavy steel box to provide the necessary confinement. A servo controlled hydraulic actuator forces the sample under the cutter at preset depth of penetration and width of spacing (Figure 15). Thus, various promising combinations of cutter spacing and penetration can be tested directly with this equipment. The best combinations are those which produce the largest volume of rock chips using the least amount of cutting energy (i.e. lowest specific energy).

The LCM-test uses full size cutters and is capable of generating the full range of cutter loads and penetrations experienced in field boring. As a result, the test results can be directly applied to field performance prediction since no scaling of results is needed.

This test has been used extensively over the last 20 years and has proven highly reliable for accurately predicting field TBM performance. The test can also be used to conduct performance optimization studies in terms of determining the most efficient cut spacing and cutter geometry for obtaining the highest rates of penetration for a proposed tunnelling project. The cuttings generated from linear cutting tests are also collected and sieve analysis performed to determine chip size distributions. This information proves very useful in cases where TBM cuttings are to be evaluated for use as tunnel invert backfill or as road base material.

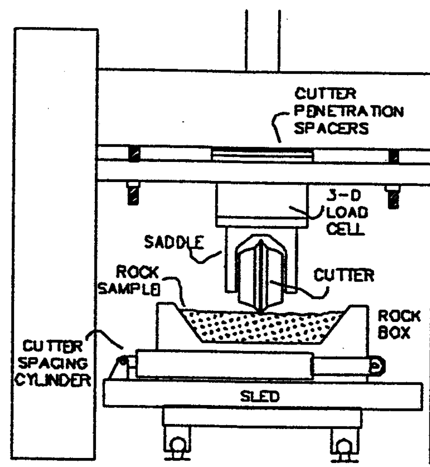

Figure 15. The CSM Linear Cutting Machine (LCM).

Rotary cutting test

For large tunnel projects or for testing of new cutterhead designs, full-scale boring tests can be performed on a 2-m diameter, computer-controlled rotary cutting machine available at CSM (Figure 16). This test fixture allows testing and evaluation of different cutter types, spacings, rpms, thrusts and input powers under field simulated conditions.

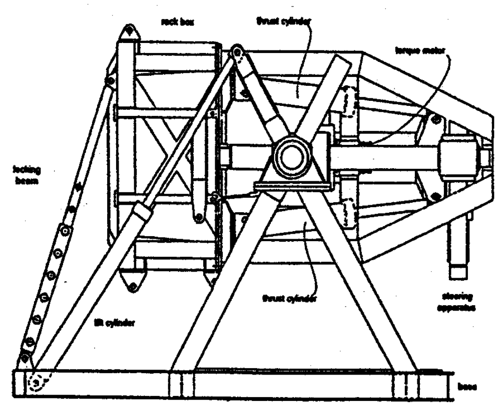

Figure 16. CSM Rotary Cutting Machine.

Relevant standards

When presenting the results of rock testing, it is very important to describe all relevant testing conditions, such as sample size, type of failure, degree of saturation, orientation relative to structural features, etc. Without such information, the test results may lead to inaccurate interpretation of data for developing boreability estimates.

The laboratory testing should always be based on established or generally recognized standards and recommendations. For some of the principal tests, the existing standards of the International Society for Rock Mechanics (ISRM) and the American Society for Testing and Materials (ASTM) should be followed. The more specialized tests should be conducted according to established guidelines of the originator of the particular test, as shown in Table 3.

Table 3. Available standards, suggested methods and descriptions for rock testing for TBM projects.

TEST/INVESTIGATION	ISRM SUGGESTED METHODS	ASTM STANDARDS	OTHER DESCRIPTIONS
Petrographic description	ISRM (1978)		
Hardness			
Moh's hardness	ISRM (1978)	-	
Vickers hardness	ISRM (1978)	-	
Siever's J-value	-	-	NTH (1990)
Toughness/brittleness			
punch penetration	-	-	CSM (1987)
fracture toughness	ISRM (1988, 1995)	-	
S_{20} (NTNU)	-	-	NTH (1990)
Mechanical strength			
UCS	ISRM (1979)	ASTM D 2938-95	
Triax.	ISRM (1983)	ASTM D 4406-93	
Brazilian	ISRM (1978)	ASTM D 3967-95	
Point load	ISRM (1985)	ASTM D 5731-95	
Abrasiveness			
Cerchar	-	-	CSM (1987)
AVS (NTNU)	-	-	NTH (1990)
Various physical and mechanical properties			
Elasticity	ISRM (1979a)	ASTM D 3148-96	
Sound velocity	ISRM (1978d)	ASTM D 2845-95	
Density	ISRM (1979b)	-	
Porosity	ISRM (1979b)	-	
Cutting tests			
Linear	-	-	CSM (1985)
Rotary	-	-	CSM (1986)

CONCLUDING REMARKS

This paper was intended to provide an overview of the type and extent of laboratory testing suggested for TBM projects. The goal is to perform sufficient testing to accurately characterize the rock properties influencing TBM performance in order to develop reliable performance estimates.

Extensive work is still underway worldwide to expand our understanding of rock boreability and to improve the accuracy of the existing TBM performance prediction models. Both CSM and NTNU are continuing their efforts to further improve their models by including more rock properties, new testing methods and also by analyzing more field data from past and current TBM projects. It is without any doubt that all these efforts will contribute to the development of more accurate performance prediction tools and models in the future.

REFERENCES

ASTM 1998. Annual Book of ASTM Standards. Soil and Rock, Vol. 04.08 and 04.09.

Bruland, A., T.S. Dahlö & B. Nilsen 1997. Development of new miniature drillability tests for performance prediction. Proc. 4th Symposium on Mine Mechanization and Automation, Brisbane, 2:A5.59-66

CSM 1996. Test and model descriptions for performance and cost prediction of mechanical excavators for mining, underground construction and microtunneling. Excavation Engineering and Earth Mechanics Institute, Department of Mining Engineering, Colorado School of Mines, July 1996, 22p.

Hoek, E. & E.T. Brown 1980. Underground excavations in rock. Inst. of Mining and Metall., London, 527 p.

ISRM 1978-95. Suggested methods. ISRM Commission on Standardization of Laboratory and Field Tests.

Nilsen, B. & L. Ozdemir 1999. Recent developments in site investigation and testing for hard rock TBM projects. Proc. Rapid Excavation and Tunneling Conf., Orlando 1999, SME (in print).

NTH 1990. Drillability - Drilling Rate Index Catalogue. Project report No. 13-90. The Norwegian Institute of Technology, Div. of Constr. Eng./Dept. of Geology, 177 p.

Rostami, J., L. Ozdemir & B. Nilsen 1996. Comparisons between CSM and NTH hard rock TBM performance prediction models. Proc. 16th Annual Techn. Meeting of the Inst. of Shaft Drilling Technology, Las Vegas 1996, 11 p.

Young, B.B. & A.P. Millman 1964. Microhardness and deformation characteristics of ore minerals. Trans. inst. Min. Metall., 73:437-466.