1 Scope

This standard specifies a method for determining the Drilling Rate Index DRI, Bit Wear Index BWI and Cutter Life Index CLI of rock samples.

The Indices are indirect measures for the drillability of rocks, and represent important factors in connection with all kinds of tunnelling and rock excavation.

2 References

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3 Introduction and principle

3.1 Drilling Rate Index *DRI*

The Drilling Rate Index *DRI* is assessed on the basis of two laboratory tests, the Brittleness test and the Sievers'J-value test. The Drilling Rate Index *DRI* may be described as the Brittleness Value corrected for the rock surface hardness.

The Brittleness Test gives a measure of the mechanical properties of a rock sample. The test consists of two parts:

- Determination of flakiness f which is a measure of the shapes of the fragments of the crushed sample.
- Determination of Brittleness Value S_{20} which is a measure for the ability of the rock to resist mechanical impact.

The test method was developed in Sweden by N. von Matern and A. Hjelmér in 1943. Several modified versions of the test have been developed for various purposes. The version of the Brittleness Test described in this standard has been used since the end of the 1950s for determination of rock drillability.

The Siever's Miniature Drill Test gives a measure of the surface hardness (or resistance against indentation) of the rock. The test method was developed by H. Sievers in the 1950s.

3.2 Bit Wear Index *BWI*

The Bit Wear Index *BWI* is assessed on the basis of the Drilling Rate Index *DRI* and the Abrasion Value *AV*. The Bit Wear Index *BWI* is used to estimate the lifetime of drill bits. The BWI expresses lifetime as drilled length or drilled volume.

The Abrasion Value *AV* represents time dependent abrasion on tungsten carbide by crushed rock powder. The test method was developed at the Department of Geology NTH in 1958 –61 (Reidar Lien, Rolf Selmer-Olsen).

3.3 Cutter Life Index CLI

The Cutter Life Index *CLI* is assessed on the basis of Sievers' J-Value *SJ* and the Abrasion Value Steel Cutters *AVS*. The *CLI* expresses lifetime of TBM disc cutter steel.

The same test equipment as for the *AV* measures the *AVS*. As opposed to the *AV* the *AVS* test uses a test piece of steel from a new cutter ring.

4 Symbols and definitions

S_{20} The Brittleness Value is the percentage of a pre-sieved fraction that passes through the smaller mesh after the aggregate has been crushed by 20 impacts in the mortar. The Brittleness Value is the mean value of 3 parallel tests.

f The Flakiness Value is the intermediate ratio for the mean width and thickness of the grains. $w_{50\%} / d_{50\%}$ i.e. $\log f = \log w_{50\%} - \log d_{50\%}$

Comp The compaction index expresses the degree of compaction of the specimen after 20 impacts, according to the classification given in 9.1.3 Brittleness Value test and Compaction index.

ρ_s The rock density (g/cm^3) is the mass of a specific volume of sample material in air at a given temperature divided by the total net volume of the individual particles in the sample determined by immersion in water.

SJ The Sievers' J-Value is the mean value of the measured depth in 1/10 mm of 4 – 8 drill holes after 200 revolutions of the 8.5 mm miniature drill bit by use of a Sievers' J-value apparatus.

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 The Abrasion Value Steel Cutters is the mean value of the measured weight loss in milligrams of 2 – 4 cutter ring steel bits after 1 minute, i.e. 20 revolutions of testing, by using an abrasion apparatus and crushed rock powder.

5 Apparatus

5.1 A laboratory crusher (jaw crusher) with adjustable gap.
5.2 A weighing instrument with a capacity of 20 kg and an accuracy of 1 g.
5.3 A weighing instrument with a capacity of 5 kg and an accuracy of 0.1 g.
5.4 A weighing instrument with a capacity of 1 kg and an accuracy of 0.001g.
5.5 A sieving machine.
5.6 A set of sieves with quadratic mesh (ISO standard):
16.0 - 11.2 – 8.0 – 4.0 – 2.0 – 1.0 – 0.5 mm
5.7 A set of sieves with rectangular mesh (ISO standard):
11.2 – 8.0 mm
5.8 A Brittleness test apparatus;
5.9 A glass-cylinder with a surface grinded upper end, diameter approx. 80 mm, height approx. 150 mm.
5.10 A glass-plate 100 x 100 x 3 mm.
5.11 Distilled water.
5.12 A water bath with constant temperature 20 $\pm$ 0.1 ^{o}C.
5.13 A ventilated oven capable of keeping constant temperature 110 $\pm$ 5 ^{o}C.
5.14 A Sievers miniature drill apparatus.
5.15 A set of tungsten carbide drill bits.
5.16 A grinding machine equipped with a diamond wheel designed for tungsten carbide and a carborundum wheel designed for cutter ring steel.
5.17 An electronic micrometer depth gauge or slide calliper.
5.18 A diamond saw.
5.19 A set of pans.
5.20 A laboratory crusher (small jaw crusher or cone crusher) with adjustable outlet.
5.21 An abrasion testing apparatus.
5.22 A set of tungsten carbide test bits.
5.23 A set of cutter steel test bits.
5.24 A x 10 hand lens.

6 Sampling

The sampling is normally not the responsibility of the test laboratory.

Note:
It is recommended that the following requirements and remarks are communicated to those responsible for the sampling.

Rock sampling for drillability testing should be based on a careful engineering geological mapping.

The necessary number of samples is determined by the variation of the rock properties and the rock types at the site.

Rock samples to be tested in the laboratory should be representative concerning petrography and mechanical properties. It is important to avoid weathered rock samples (unless deep weathering is the prevailing feature of the actual site). Blocks with fissures or cracks from blasting, or blocks that have been subject to high (anisotropic) rock stress should be avoided.

In order to get reliable results from the testing, each sample should have a total weight of 15 - 20 kg. One sample may consist of several blocks (minimum weight per block 0.5 kg). Samples from core drilling must have diameter of 32 mm (1.25") or more, and preferably 10 kg of core material. Less sample weight may be used, but this will result in fewer parallel Brittleness tests.

The Brittleness Value S_{20} is normally calculated as the mean value of 3 Brittleness tests performed on equal extractions from one representative and homogenised sample of crushed and sieved rock material. Accurately performed the Brittleness Value S_{20} shows a standard deviation of three parallel tests on homogenised material (homogenised through the crushing and sieving process), typically less than 2 units (4% for an average S_{20} of 50). If the material is not homogenised, local variations in lithology and texture may cause larger differences.

7 Sample preparations

7.1 Storage

The sample shall be stored indoors at $20^oC \pm 5^oC$ for at least 48h prior to testing.

7.2 Identification

Visually inspect and describe the sample macroscopically with respect to colour, grain size, visible minerals, and any kind of foliation, layering or other kinds of anisotropic structures. Note the sample marking, sample material (i.e. rock core, core diameter, block, small blocks) and remarks regarding weathering etc. It is recommended to include scaled photographs of the sample in the report.

8 Preparations of specimens for determination of Drilling Rate Index *DRI*

8.1 Preparation of specimen for Sievers' Miniature Drill Test

Select a representative piece of the sample and cut a 25-30 mm thick slice by using a diamond saw equipped with a blade. Length and width should be 50-100 mm (not necessary to cut). The sawn surfaces of the specimen shall be parallel, smooth and, in case of foliated rocks, perpendicular to the foliation plane.

Measure the thickness of the slice diagonally at 4 spots by use of an electronic micrometer or slide caliper with an accuracy of 0.05 mm. The readings shall not deviate by more than 0.25 mm

Place the specimen in a ventilated oven and dry at 105 ± 5^oC in 24h. After drying and prior to testing the specimen shall be stored at $20 \pm 5\ ^oC$ until thermal equilibrium is reached. The Sievers'Miniature Drill Test shall be performed within 24 h.

8.2 Preparation of specimens for Brittleness Value S_{20}

8.2.1 Crushing

Weigh the sample material to the nearest 1 g.

Crush larger pieces and blocks with a sledgehammer into hand-pieces that fit into the inlet opening of the jaw crusher.

Adjust the outlet opening of the jaw crusher to approx.13.6 mm in order to produce most aggregates within the fraction 11.2 – 16 mm, see figure 1. The adjustment of the jaw crusher is described in the next section.

Crush the sample in two steps. Ensure that the opening of the crusher is filled with sample material throughout the second step of crushing.

Note any remarks concerning the crushing process.

8.2.2 Sieving (quadratic mesh)

Weigh the crushed sample material to the nearest 0.1 g prior to sieving.

Machine sieve the sample material on sieves with quadratic mesh: 16.0 - 11.2 - 8.0 - 4.0 - 2.0 mm.

Weigh each fraction separately and transfer into suitable pans.

Calculate the grain size distribution in order to verify correct jaw crusher adjustment.

9 Test procedures for determination of Drilling Rate Index *DRI*

Outlines of the principles for the Brittleness Test and the Sievers Miniature Drill Test are given in figure 1 and 2.

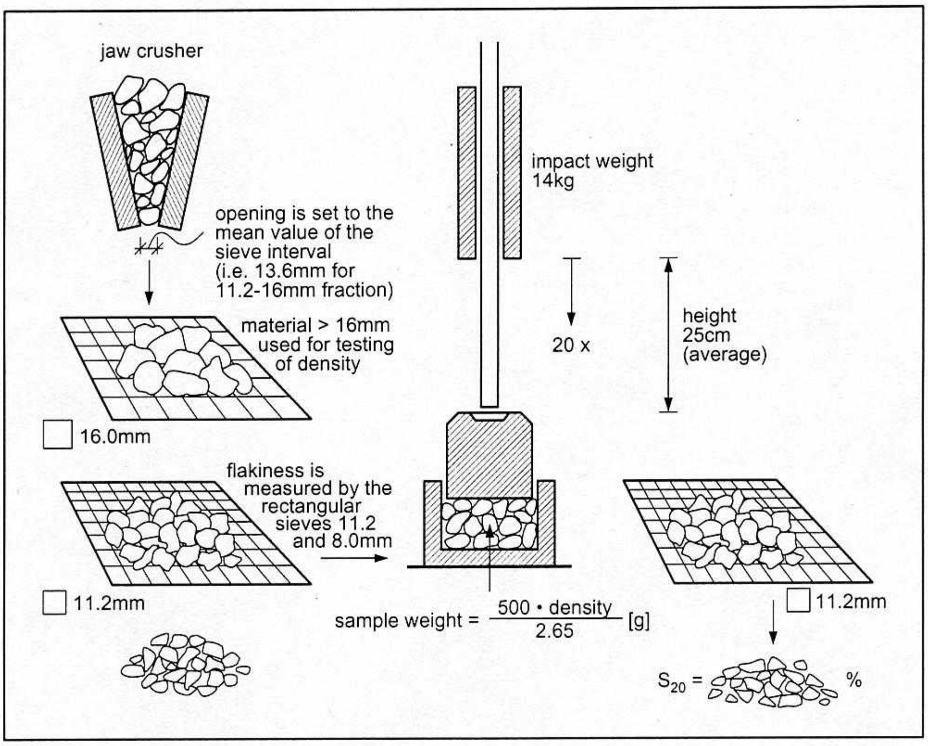

Fig.1. Brittleness Test.

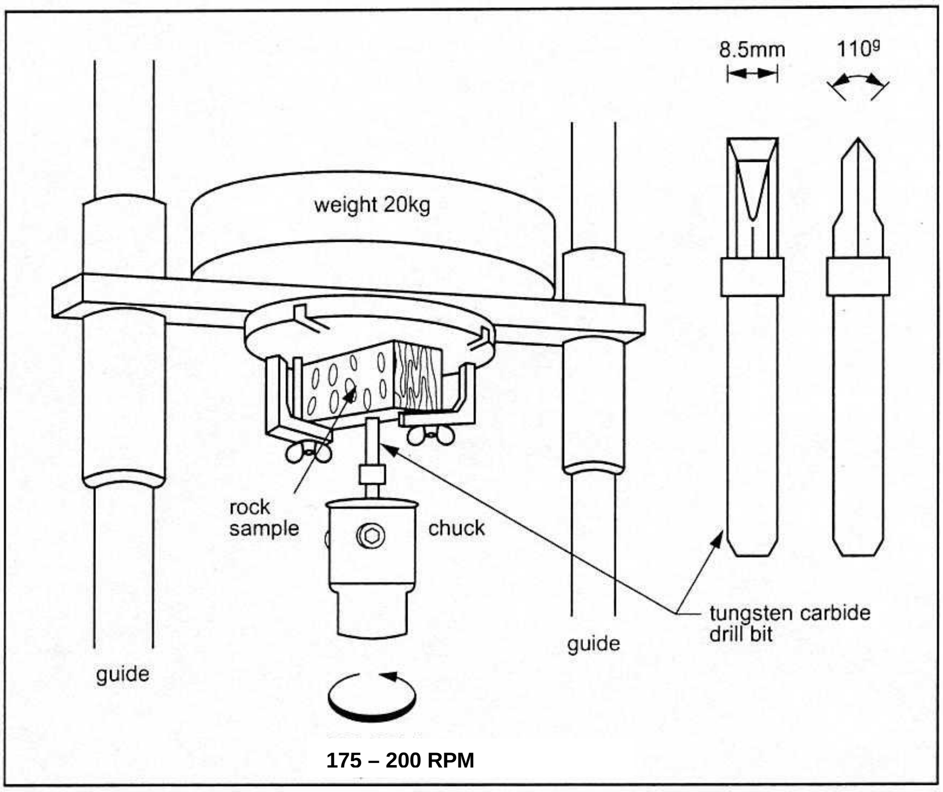

Fig.2. Sievers' Miniature Drill Test

9.1 Brittleness Test

9.1.1 Bulk density ρ_s

Place the glass-cylinder (pycnometer) on a weighing instrument and tare.

Fill the glass-cylinder approximately ¾ full, by fragments from the >16.0 mm fraction.

Note the weight of the specimen (m_1).

Remove the glass-cylinder with the specimen and tare the weighing instrument again.

Add distilled water until it covers the specimen and shake the glass-cylinder gently in order to remove any trapped air bubbles.

Top up with distilled water and place the glass-cylinder in a water bath at 20 ± 0.1 ^{o}C for 1 hour.

Adjust the water level and slide the glass-plate in place on top of the grinded end of the glass-cylinder.

Remove the glass-cylinder with the glass-plate on top from the water bath and dry the surfaces thoroughly before weighing (m_2).

Remove the specimen and the distilled water and wash the glass-cylinder thoroughly.

Fill the glass-cylinder with distilled water and place it in a water bath at 20 ± 0.1 ^{o}C for 1 hour.

Adjust the water level and slide the glass-plate in place on top of the glass-cylinder.

Remove the glass-cylinder with the glass-plate on top and dry the surfaces thoroughly before weighing (m_3).

Calculation of the density is performed as in the following example:

m_1 (mass of specimen) = 623.2 g
m_2 (mass of glass-cylinder, glass-plate, specimen and distilled water) = 1528.4 g
m_3 (mass of glass-cylinder, glass-plate and distilled water) = 1138.9 g

$$\rho_s = \frac{m_1}{m_1 + m_3 - m_2} = \text{g/cm}^3 \qquad \text{i.e.:} \qquad \rho_s = \frac{623.2}{623.2 + 1138.9 - 1528.4} = 2.67\ \text{g/cm}^3$$

9.1.2 Flakiness Value *f*

Hand sieve the fraction 11.2 – 16.0 mm quadratic mesh on sieves with 11.2 – 8.0 mm rectangular mesh.

Control sieve the grains that passes through the 8.0 mm rectangular mesh on a sieve with 11.2 mm quadratic mesh.

Weigh each fraction separately and transfer into suitable pans.

Calculate the percentage of the fractions >11.2 mm, 8.0 – 11.2 mm and <8.0 mm rectangular mesh. The percentages are also used for the calculation and preparation of extractions for the Brittleness test (see 9.1.3).

Sum the percentage of the fractions >11.2 and 8.0 – 11.2 mm rectangular mesh.

The Flakiness Value is determined by using the nomogram in figure 3.

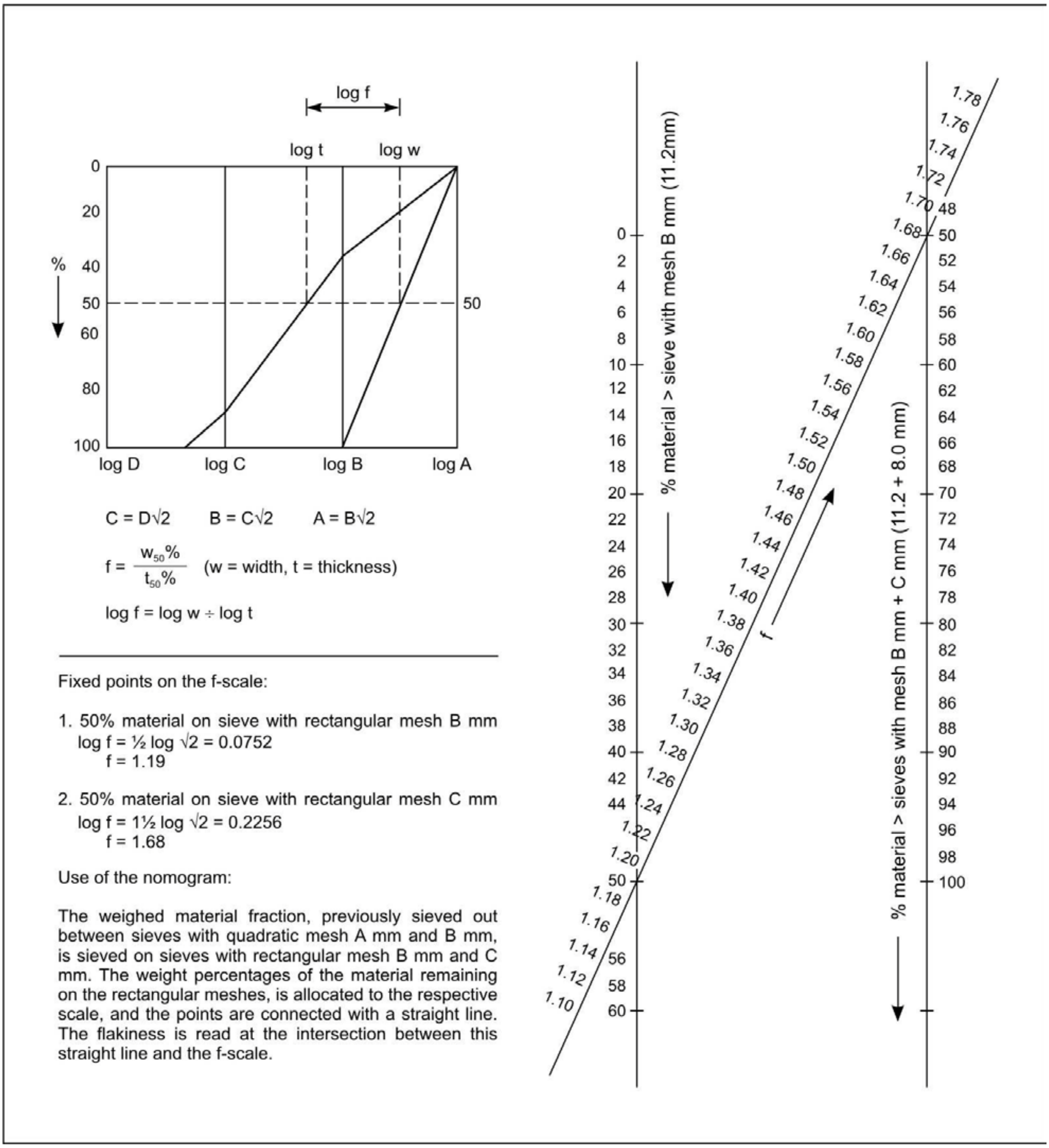

Fig.3. Flakiness

9.1.3 Brittleness Value S_{20} and Compaction Index *comp*

The Brittleness Test is normally performed on 3 equal extractions from the 11.2 – 16.0 mm fraction. For a measured specimen density of 2.65g/cm^3 each extraction shall have a mass of 500 g. The mass is increased or decreased if the density deviates from 2.65 g/cm^3, illustrated by the following example:

Measured $\rho_s = 2.67\ g/cm^3$ $$\frac{2.67}{2.65} \times 500\ g = 503.8\ g$$

Prepare 3 equal extractions using the pre-sieved rectangular mesh fractions and calculated percentages (see 9.1.2).

Calculate the weight of the respective fractions for the extractions as follows:

a = mass of extraction corrected for measured density =503.8 g
b = % of material > 11.2 mm (rectangular mesh) = 35.5%
c = mass of material >11.2 mm (rectangular mesh) for each extraction

$$a \times \frac{b}{100} = c \qquad \text{i.e.:} \qquad 503.8\ g \times \frac{35.5}{100} = 178.8\ g$$

Use the same method in order to calculate the weight of the fractions 8.0 – 11.2 mm and < 8.0 mm.

	%	G
Fraction > 11.2 mm (rectangular mesh)	*35.5*	*178.8*
Fraction 8.0 - 11.2 mm (rectangular mesh)	*49.4*	*248.9*
Fraction < 8.0 mm (rectangular mesh)	*15.1*	*76.1*
Total	*100.0*	*503.8*

Fill the mortar loosely with an extraction. Level the specimen surface by placing the mortar lid gently on top before rotating it half a turn.

Clamp the mortar to the Brittleness Test apparatus.

Adjust the drop height to 25 cm before applying 20 impacts by the impact weight.

Remove the mortar and determine the Compaction index according to the following classification:

Compaction index 0:
No compaction. All sample material falls out of the mortar when turned upside down.

Compaction index 1:
Slightly compacted. Some sample material does not fall out of the mortar when turned upside down. The remaining material is easily removed by finger picking.

Compaction index 2:

Compacted. A small amount of sample material falls out when the mortar is turned upside down. The remaining material is fairly stuck in the mortar and a wooden or metal tool is required to remove it.

Compaction index 3:
Heavily compacted. The sample material is totally compacted and nothing falls out of the mortar when turned upside down. It is only possible to remove material by using a sharp metal object.

Hand-sieve the specimen on a sieve with 11.2 mm quadratic mesh.

Weigh the material that remains on top and the material that passes through the sieve.

Collect all tested material and transfer it into a suitable pan. This material is used for preparation of abrasion powder (see section 11. Preparation of specimens for determination of Bit Wear Index *BWI* and Cutter Life Index *CLI*).

The Brittleness Value is calculated as the mean value of the percentage of material < 11.2 mm after 20 impacts, as illustrated in the following example.

Extraction No.	*1*		*2*		*3*	
	G	*%*	*g*	*%*	*g*	*%*
Weight of sample material 11.2 – 16 mm prior to impacts	*503.8*	*100.0*	*503.8*	*100.0*	*503.8*	*100.0*
Weight of sample material >11.2 mm after 20 impacts	*244.3*	*48.5*	*241.8*	*48.0*	*235.8*	*46.8*
Weight of sample material <11.2 mm after 20 impacts	*259.5*	*51.5*	*262.0*	*52.0*	*268.0*	*53.2*
Brittleness Value S_{20} = 52.2						

9.2 Sievers' J-Value *SJ*

Prepare 4 – 8 tungsten carbide drill bits by grinding them to the geometry specified in figure 4.

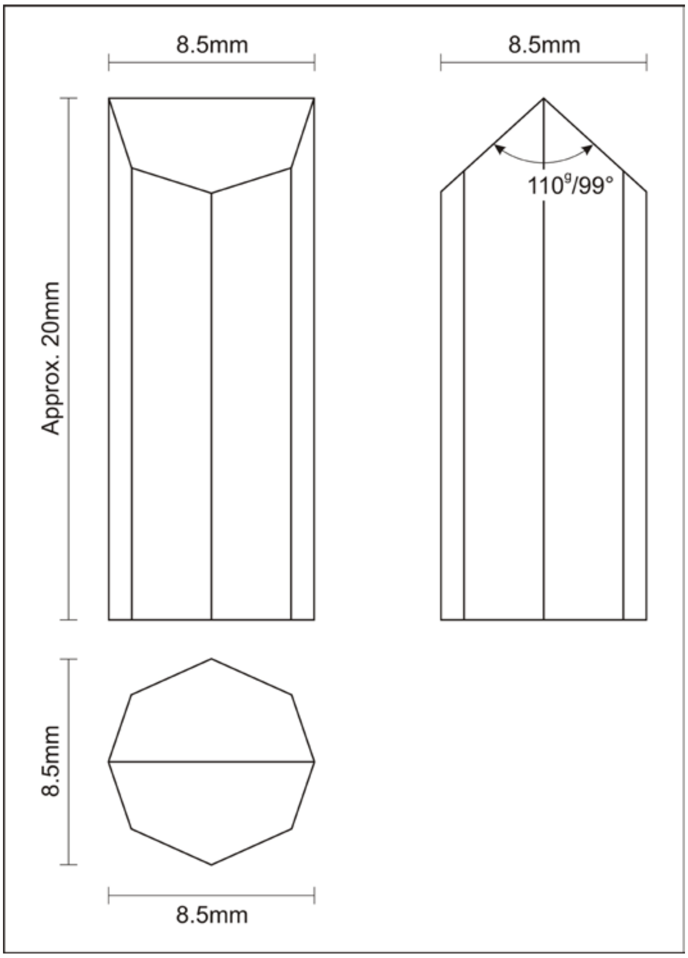

Fig.4. Specification of measurements of tungsten carbide drill bit.

Sharpen the edge of the tungsten carbide drill bit and resharpen it after each drilling.

Visually examine the edge after grinding to check if it is satisfactory (a x 10 hand lens is convenient for this).

Verify that the edge alignment is according to the dimensions given in figure 4.

Insert the drill bit into the chuck and tighten it. Ensure that the drill bit is properly centred in order to avoid any eccentricity.

Examine the test surface of the specimen and mark 4 - 8 suitable drill spots. The number and placement of the drill holes is determined by the heterogenity of the rock.
The drill spots should be placed in soft and hard layers according to a visual inspection of the rock. E.g. 60% hard and 40% soft layers in a sample would result in 3 holes in the hard layer(s) and 2 holes in the soft layer(s). If possible, try to avoid spots with a soft/hard combination, which have a tendency to cause jumping and shaking. This is however in some cases almost impossible to avoid, e.g. thin layers of alternating mineral composition.

Clamp the pre-cut Sievers' specimen to the weight and lower it carefully until it contacts the edge of the drill bit. Verify that the edge is parallel with the test surface and release the lever.

Start the rotation and run the test until the drill bit has performed 200 revolutions.

Note any remarks regarding the drilling as e.g. jumping or shaking.

Apply the lever and elevate the weight and specimen from the edge of the drill bit.

Loosen the specimen and move to the next drill spot.

Perform the required number of drillings and measure the depth of each miniature drill hole by means of an electronic micrometer or slide calliper.

The Sievers' J-Value *SJ* is calculated as the mean value of the depth of the miniature drill holes, measured in 1/10 mm.

10 Assessment of Drilling Rate Index *DRI*

The diagram in figure 5 is used to assess the Drilling Rate Index *DRI* from the Brittleness Value S_{20} and the Sievers'J-Value *SJ*.

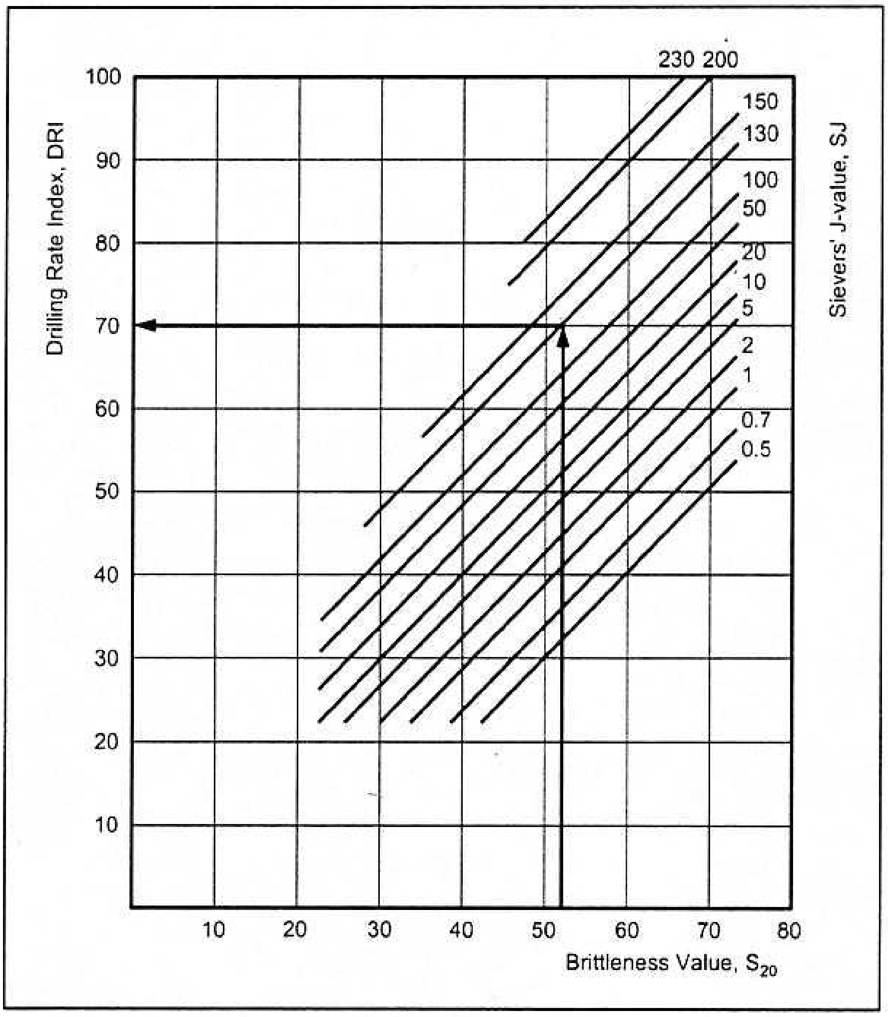

Fig.5. Diagram for assessment of DRI.

11 Preparations of specimens for determination of Bit Wear Index *BWI* and Cutter Life Index *CLI*

11.1 Preparation of abrasion powder for Abrasion Value *AV*

A representative rock sample consisting of approx. 2-kg or the collected material from the Brittleness test (see 9.1.3 Brittleness Value S_{20} and Compaction Index *comp*) is used for preparation of abrasion powder.

It is important to crush the sample gently in several crusher steps in order to avoid excessive production of fines. The following procedure is recommended.

Crush the rock sample in a jaw crusher with the outlet opening adjusted to 10 mm.
This operation can be skipped if the specimen is the collected material from the Brittleness test.

Continue the crushing by use of a smaller laboratory crusher in minimum 2 steps.

Adjust the outlet opening of the crusher prior to the first step to approx. 3 – 4 mm.

Hand-sieve the crushed material on a sieve with 1 mm quadratic mesh. The fraction < 1 mm is transferred to a suitable pan and the fraction > 1 mm is crushed again after adjustment of the outlet opening to approx. 1 mm.

This process is repeated until the grain size distribution is 99% <1 mm and 70 ± 5 % < 0.5 mm.

Mix the crushed powder thoroughly before pouring it into the funnel on the vibrating feeder connected to the abrasion apparatus (see fig. 6).

Start the rotation of the steel disc and the suction assembly. Adjust the vibrating feeder until a thin and uniform layer of abrasion powder covers the surface of the track.

11.2 Preparation of abrasion powder for Abrasion Value Steel Cutters *AVS*

See 11.1 preparation of abrasion powder for Abrasion Value *AV.*

12 Test procedures for determination of Bit Wear Index *BWI* and Cutter Life Index *CLI*

An outline of the principle for the Abrasion tests and specification of measurements for the test bits are given in figure 6.

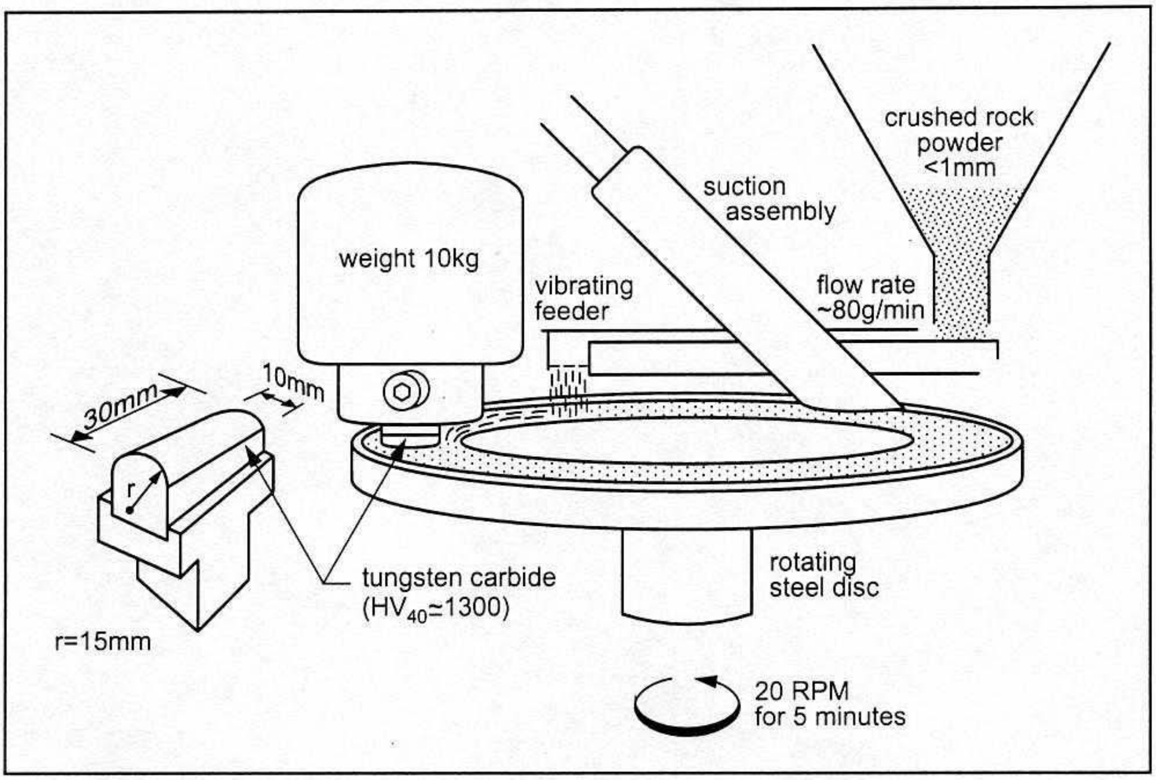

Fig.6. Abrasion Value and Abrasion Value Steel Cutters test.

12.1 Abrasion Value *AV*

Prepare 2 – 4 numbered, tungsten carbide test pieces by grinding them to the specified dimensions.

Note:
Grinding of the test surface is a critical step and extra care is important in order to avoid overheating.

Visually examine the test surface and make sure that it is smooth and straight after grinding.

Polish the edges of the test surface by a hone and ensure that the test bit is absolutely clean and dry before weighing.

Weigh the test piece separately to the nearest 0.001g and note the number and corresponding weight.

Secure a test piece to the weight and place it gently on the steel disc (see fig.6).

Verify that the test surface is horizontally aligned with the steel disc, and if necessary adjust the clamping of the test piece and the suspension of the weight.

Start the test and run it for 5 minutes, i.e. 100 revolutions. Verify whether the amount of abrasion powder fed onto the steel disc is sufficient or excessive. Adjust the vibrating feeder in order to avoid steel against steel abrasion or a pile of powder in front of the test piece. 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.

Loosen the test piece from the weight and rinse and dry thoroughly before weighing.

Note the weight and calculate the weight loss in mg.

Run 2 – 4 parallel tests. The results shall not deviate by more than 5 units.

The Abrasion Value *AV* is calculated as the mean value of the measured weight loss in milligrams after 5 minutes testing time, i.e. 100 revolutions.

12.2 Abrasion Value Steel Cutters *AVS*

Prepare 2 – 4 numbered cutter ring test pieces by grinding them to the specified dimensions.

Follow the steps given in 12.1 Abrasion Value *AV* apart from the testing time.

Note:
The testing time for the Abrasion Value Steel Cutters AVS is 1 min, i.e. 20 revolutions.

The Abrasion Value Steel Cutters *AVS* is calculated as the mean value of the measured weight loss in milligrams after 1 minute testing time, i.e.20 revolutions.

13 Assessment of the Bit Wear Index *BWI*

The diagram in figure 7 is used to assess the Bit Wear Index *BWI* from the Drilling Rate Index *DRI* and the Abrasion Value *AV.* The Bit Wear Index is used to estimate the lifetime of drill bits.

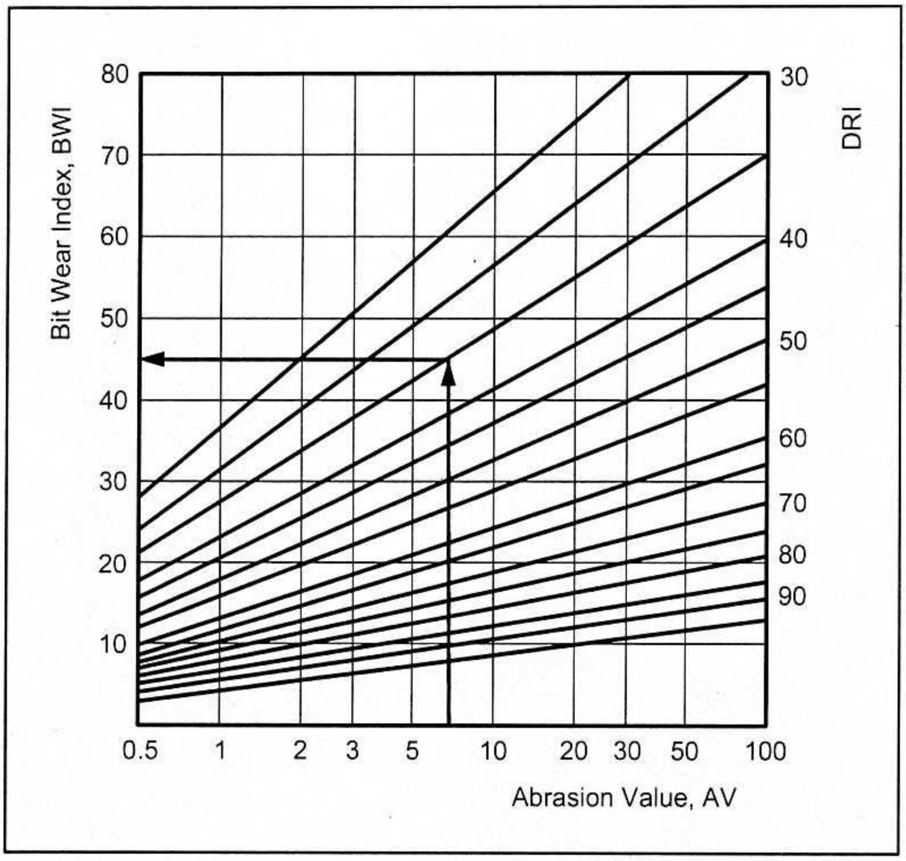

Fig.7. Diagram for assessment of BWI.

14 Assessment of the Cutter Life Index *CLI*

The Cutter life Index *CLI* is assessed on the basis of Sievers' J-value *SJ* and the Abrasion Value Steel Cutters *AVS*. *CLI* expresses life in boring hours for cutter disc rings of steel for tunnel boring machines.

The Sievers' J-value *SJ* and the Abrasion Value Steel Cutters *AVS* expresses the *CLI* by the equation:

$$CLI = 13.84x\left(\frac{SJ}{AVS}\right)^{0.3847}$$

The *CLI* is based on normalising field data of actual cutter ring life versus tested rock parameters

15 Classification of indices

The following intervals are used for the classification categories:

Category	DRI	BWI	CLI
Extremely low	≤25	≤10	<5
Very low	26 – 32	11 – 20	5.0 – 5.9
Low	**33 – 42**	**21 – 30**	**6.0 – 7.9**
Medium	**43 – 57**	**31 – 44**	**8.0 – 14.9**
High	**58 – 69**	**45 – 55**	**15.0 – 34**
Very high	70 – 82	56 – 69	35 – 74
Extremely high	≥83	≥70	≥75

16 Test report

The test report shall contain the following information:

a) unique identification number of the report;

b) the title and date of issue of this standard;

c) the name and address of the test laboratory and the address where the test was carried out if different from the test laboratory;

d) the name and address of the client;

e) it is the responsibility of the client to supply the following information:

- the petrographic name of the rock;
- the country, region and site of sampling;
- the name of the person or organisation which carried out the sampling;

f) the date of delivery of the sample;

g) the date when the specimens were prepared for testing and the date of testing;

h) the number of samples tested;

i) the sample material type and dimension.

j) the colour, minerals (macroscopic description), grain size and structures of the sample.

k) photograph of the received sample material (optional).

l) the individual values from each test, standard deviation and the variation coefficient;

m) the mean Brittleness value (S_{20}) to the nearest 1 %, Flakiness(f), Compaction index (*Comp*), Density (ρ_S) to the nearest 0.01 g/cm^3 , mean Sievers' J-value (*SJ*) to the nearest 0.1 (1/10) mm, mean Abrasion Value (*AV)* to the nearest 1.0 mg and mean Abrasion Value Steel Cutters *(AVS)* to the nearest 1.0 mg.

n) the assessed Drilling Rate Index *DRI*, Bit Wear Index *BWI* and Cutter Life Index *CLI*.

o) the category intervals for the Drilling Rate Index *DRI*, Bit Wear Index *BWI* and Cutter Life Index *CLI*.

p) all deviations from the standard and their justification;

q) remarks

The test report shall contain the signature(s) and role(s) of the responsible(s) for the testing and the date of the report. It shall also state that the report shall not be partially reproduced without the written consent of the testing laboratory.