PREDICTION AND CLASSIFICATION OF TOOL WEAR IN DRILL AND BLAST TUNNELLING

Ralf J. Plinninger[1], Georg Spaun[1] and Kurosch Thuro[2]

ABSTRACT: After introducing basic ideas on tools, rock fragmentation and wear mechanisms this paper presents and discusses options to classify bit wear types and to predict the rate of button bit wear. Results show that model tests, such as the CERCHAR scratch test may only give an idea of the rocks abrasivity but show no distinct correlation between encountered tool wear rates. Based on conventional rock parameters and taking into account the whole range of scale from grain mineral to rock mass, the presented schemes may help to predict tool wear rates and hint at possible problems in excavation and specific requirements for the tools used

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INTRODUCTION: TOOLS AND WEAR BASICS

Tool wear in drill and blast tunnelling

Drill & Blast is a commonly used excavation method for the construction of underground openings (e.g. tunnels, caverns) in hardrock conditions worldwide. The working cycle itself consists of the main steps: 1) drilling of blastholes 2) charging 3) blasting 4) ventilation and muck-out 5) rock supporting and surveying (Figure 1). Wear of the employed tools takes place during different working steps, affecting a wide range of machinery and materials. Although wear of rock cutting tools (i.e. drilling bits, excavator chisels, picks) is the most expensive wear phenomenon, excavators, dump trucks or conveyor belts are also permanently exposed to the excavated rock mass and therefore undergoing geologically influenced wear. Nevertheless, this paper will only deal with the wear of drilling bits because of the predominant importance of geological factors on this process.

Drilling equipment and fragmentation process

Common blasthole diameters range from 38 to 48 mm. Holes are typically drilled by use of hydraulic rotary percussive drilling hammers with an impact power of about 15 to 20 kW. The hammer's rotation and impact energy is transferred to the drilling bit via a steel rod. In most geological conditions, predominantly button bits are used. These tools consist of a number of cemented carbide buttons (mostly tungsten carbide in a cobalt binder), inserted and/or solded into holes of a steel body (Figure 2). The properties of the button bit can be adjusted effectively to the local circumstances by variation of the amount of inserted buttons, button composition, button geometry, solding and steel quality or the bit's flushing system.

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[1] Dipl.-Geol. Ralf J. Plinninger, Prof. Dr. Georg Spaun, Lehrstuhl für Allgemeine, Angewandte und Ingenieur-Geologie, Technische Universität München, Arcisstrasse 21, D-80290 München, Germany

[2] Dr. Kurosch Thuro, Ingenieurgeologie, Eidgenössische Technische Hochschule Zürich, Schweiz

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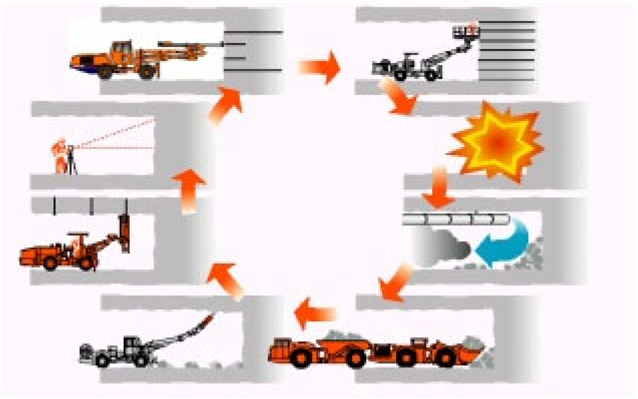


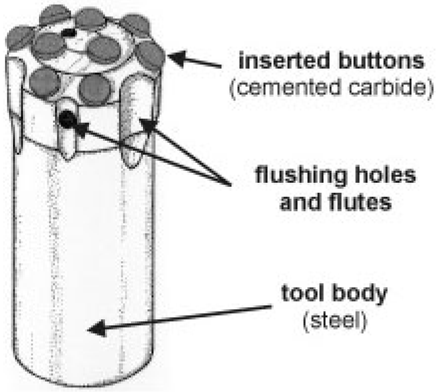
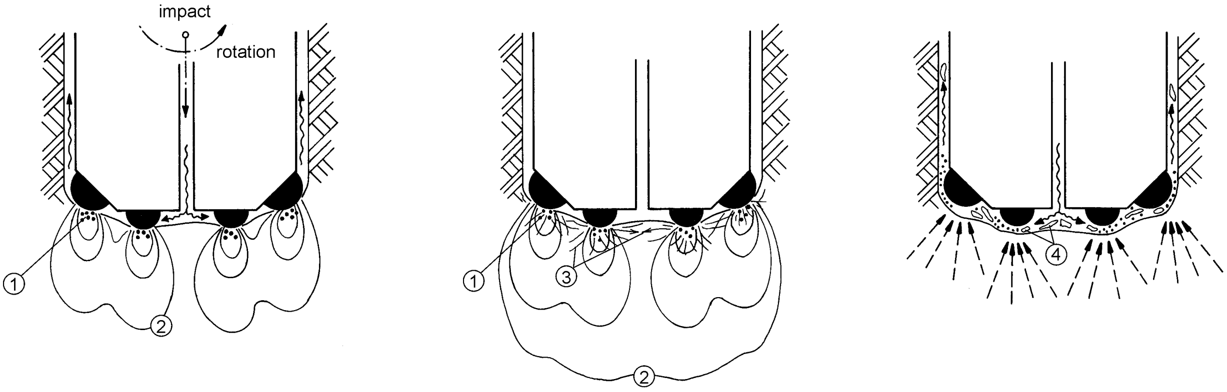


Figure 1. The drill and blast cycle (Tamrock Corp.).

Figure 2. Main characteristics of a button bit.

For the investigation of tool wear processes the understanding of rock fragmentation by button bits is of crucial importance. The schemes presented in Figure 3 give an impression of how bit and rock mass are supposed to interact during drilling. It appears noticeable, that though the rotary percussive method is much more effective in hardrock than rotary drilling itself, most rock particles seem to be produced by impact and not by shearing (Maidl, 1997).



1. Begin of impact:
Rotating hard metal buttons are forced into the rock mass. Extremely high local stresses cause the prompt formation of crushed zones ① below the tips. From there, low level stress fields ② are built up in the drilling direction.

2. Cracking:
The rising stresses exceed the rock strength, initial cracks ③ form at the edge of the crushed zones and propagate into the rock. Cracks from neighbouring zones begin to interact and form chips. Shearing takes place due to bit

3. End of stroke:
The bit is pulled back, the stresses are released. Elastic rebound of the rock mass and the flushing system separate chips and crushed material ④ from the front. They are flushed out of the hole consequently.

Figure 3. Scheme of the rock fragmentation process during rotary percussive drilling.

Tribosystems and parameters describing wear

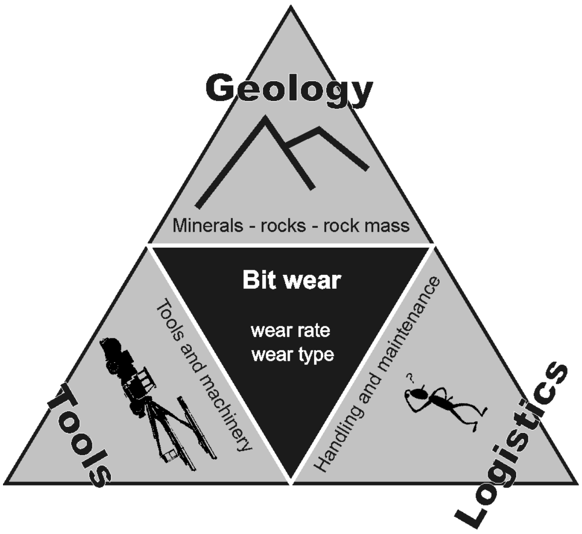
Wear phenomena are results of complex tribosystems. According to german standard DIN 50320 a tribosystem consists of a solid body (object which is affected by wear) which interacts with the counterbody (object causing the wear) under a certain environment. All materials and processes involved in the system interact with and influence each other and have a certain effect on the wear of the solid body. In rock drilling processes tool and rock interact under certain loads, rotation, temperature and in abundance of a flushing fluid, typically water. *Wear type* and the *wear rate* can be used as parameters describing the effect of the wear process.

The *wear type* describes the specific form of wear observed on the tool. It can be described qualitatively by use of a wear classification system as presented later (Figure 10).

The *wear rate* describes the velocity of material removal from the tool. This term is normally expressed in drilled meters per bit [m/bit], also entitled the "drill bit lifetime". The wear rate is a basic factor for the calculation of tool consumption and wear costs. It is obtained on site from measurements on single tools or calculations based on stock lists and delivery notes.

Factors influencing bit wear

The complex structure of tool wear tribosystems leads to a vast amount of factors, that can dramatically influence tool wear. Figure 4 gives an impression of the three fields Geology-Tools-Logistics and some of the main factors influencing rate and type of tool wear.



Geology	Tools	Logistics
rock properties *(mineral composition, rock strength, grain size, grain shape)*	tool characteristics *(carbide composition, button shape, button number, steel composition)*	maintenance tool handling
joint features *(spacing, orientation, aperture, roughness)*	flushing *(fluid, number & geometry of flushing holes and flutes, flushing pressure)*	supporting methods
weathering / alteration of rock	feed and rotating velocity	
water situation	temperatures	
composition of rock mass *(homogenous / inhomogenous)*		
stress situation *(stress direction, stress level)*		

Figure 4. Some of the main factors influencing button bit wear

ASSIFICATION OF BIT WEAR

Relevant wear processes in blasthole drilling

An exact observation of wear processes and conditions in the tribosystem during operation is a somewhat impossible task. Nevertheless valuable information can be gained from measurements and observations on the used tools and excavated rock mass. The very detailed descriptions of wear processes used in the field of tribology are therefore not practical - and also not necessary - for the engineering geologist on site. Simplified, 4 wear processes can be identified macroscopically:

Abrasive wear is the predominant wear process in most rock types. This wear type includes wear due to abrasion (material cut, plought or microcracked out of the surface) and adhesion (material loss due to cold welding between tool and rock that are separated again). This phenomena cause more or less steady displacement of material from the tool surface during movement of the rock cutting tool. It is caused by direct contact of tool and hard particles in the rock mass or contacts between tools and particles in between rock and tool. The abrasive wear rate can be described as a function of the hardness contrast between the two interacting bodies. At low ratios (rock minerals softer than tool material) wear occurs, but only with low wear rates ("low level abrasive wear"). Deketh (1995) and Verhoef (1997) state, that the wear rate increases dramatically at ratios of about 0,7 to 1,1, which is only slightly below the values observed by Mulhearn and Samuels (1962) and Osburn (1969), who demand a hardness contrast of more than 20 % for a mineral to cause "high level abrasive wear" on the tool. It seems remarkable, that below and above this transition hardness differences seem to have a only little influence on the abrasive wear rate (Figure 5). Following these considerations, minerals of a Mohs hardness of more than $5^1/_2$ can be classified as "abrasive" (causing high level abrasive wear) against the steel tool body, minerals with a Mohs hardness of more than 9 are "abrasive" against both, tool body and hard metal buttons. Although "abrasive" minerals with respect to cemented carbides exist (corundum, diamond), they appear most seldomely in rock. The fact, that cemented carbides are also undergoing (low level) abrasive wear can be explained by microcracking processes and "erosion" of the softer cobalt binder and consequently removal of whole carbide grains out of the button surface.

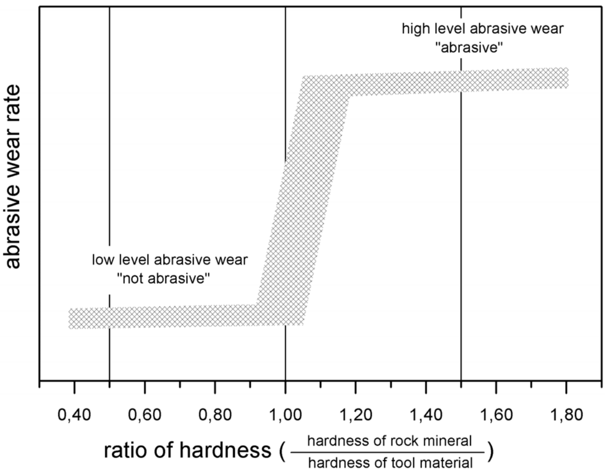


Figure 5. Relation of abrasive wear rate and the ratio of hardness between the interacting materials.

Although often not respected as "wear" in the strict sense of the word ***wear due to macroscopic material failure*** is another very common and cost intensive phenomenon in hardrock drilling. In contrast to abrasive wear, macroscopic material failures - for example buttons cracking or breaking out - cause no steady displacement of material but catastrophically removal of considerable tool parts due to brittle failure. The scale of such failures has to be considered, since in very brittle materials - like cemented carbides - even abrasion takes place due to microscopic failure ("microcracking") of the tool surface. Material failures can effect both, buttons and steel body of bits. The main cause for such failure are high dynamic impact forces.

Thermic wear is not a process by its own, but a phenomenon where other wear processes, like abrasion and material failure are increased considerably by high tool temperatures. These high temperatures lead to lower material strength ("softer" steel and carbides) and may even cause specific changes in tool materials, like differentiation of cobalt binder out of the cemented carbide, which gives the buttons a more brittle behaviour. As a very relevant example, the temperature-dependent hardness contrast between quartz and tungsten carbide should be kept in mind: Quartz is one of the most important rock forming minerals in

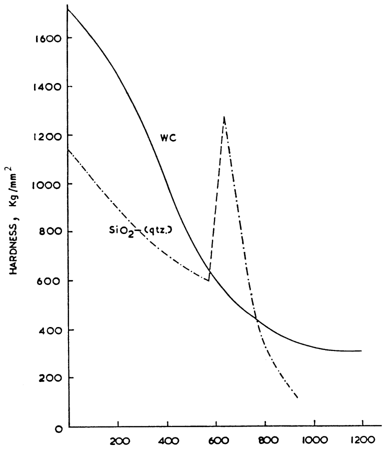


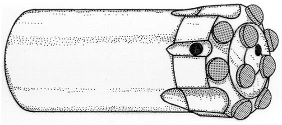
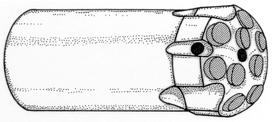
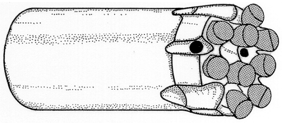
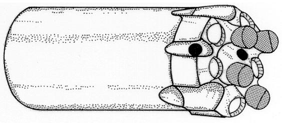
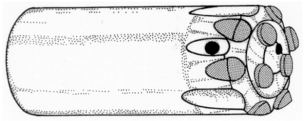
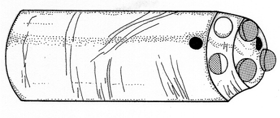
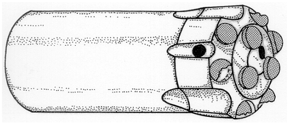
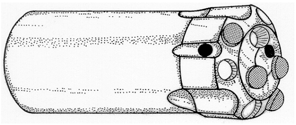
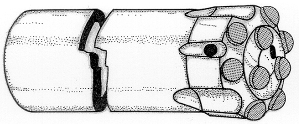
Figure 6. Hardness-temperature curves for tungsten carbide and quartz. (Osburn, 1969: Fig. 4, p. 478)

sediments, metamorphic and also igneous rocks. Figure 6, taken from Osburn, 1969 gives the hardness curves for both, quartz and tungsten carbide. While the hardness of tungsten carbide continuosly decreases with increasing temperature, quartz changes its modification from low-quartz to high-quartz at 573°C at normal pressure. Connected with this, its hardness suddenly increases, determined by a transition in Knoop hardness from 6000 MPa to about 13.000 MPa. With rising hardness contrast, the quartz mineral hardness exceeds that of the tool materials and abrasive wear increases dramatically.

The term "***special wear processes***" includes besides others cavitation and erosion processes, which may be caused by the flushing fluid or suspended particles in the fluid. These wear mechanisms are supposed to contribute only minor amounts of wear to the tool.

Classification of bit wear type

The bit wear type can be used as a "fingerprint" of the wear process. From classification of the wear type it is possible to obtain valuable information about the typical processes taking place and geological and machinery causes for the encountered wear forms. Based on schemes presented by Thuro (1996) and Thuro & Plinninger (1998) a easy-to-use classification system for button bits is shown in Figure 7. A similar scheme for point attack picks on roadheaders is also available (Plinninger, 2001). It is evident, that transitions and mixed types between the presented types are possible.

Wear type	Wear scheme	Abbr.	Description
New tool		**BB-0**	New, unused button bit
Abrasive wear		**BB-A1**	„Normal" wear: more or less evenly abrasive wear of tool body and inserts. The tool has been changed in time.
		**BB-A2**	Predominant abrasive wear of the tool body. The buttons may fall out due to missing embedding (-> BB-A3).
		**BB-A3**	Falling out / breaking out of whole buttons due to insufficient embedding and binding at the bottom of the buttons.
		**BB-A4**	Wear of diameter: buttons and tool body are predominantly worn down at the sidewalls.
		**BB-A5**	Continued wear of diameter: Immense reduction of the bits diameter. Peripheral buttons are broken out.
Wear due to failure of tool materials		**BB-F1**	Internal failures of buttons, buttons are particularly broken.
		**BB-F2**	Total button removal out of the bits body due to failure of bit-button-connection
		**BB-F3**	Failure of bit shaft

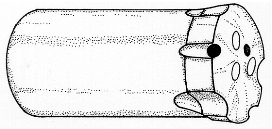
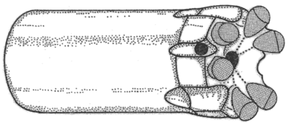
Wear type	Wear scheme	Abbr.	Description
Thermic wear		**BB-T**	Thermic wear types equal A- and F-types. Specific temper colours may be visible and hint to encountered tool temperatures.
Special types and mixed types		**BB-Sp1**	Total wear down. Bit was changed late. Clear classification of tool wear process mostly impossible.
		**BB-Sp2**	Widening of flushing holes, which may even affect embedding of central buttons and removal of central buttons. Wear type mostly in combination with other types.

Figure 7. Bit wear type classification.

Normal wear (BB-A1) is observed when tool body and hard metal inserts are more or less evenly undergoing abrasive wear. This wear type is typical for abrasive rocks with high compressive strength, as there is fresh quartzite, gneiss, granite or quartzitic sandstones. The evenly wear distribution can be explained by the low penetration of the bit in such rock types, so that mainly the hard metal inserts get in contact with the rock and are therefore worn with low wear rates - even by minerals that can be classified as "non abrasive" to cemented carbides. The steel body is worn at high level wear rate, when directly exposed to the rock due to wearing of the buttons.

Predominant *wear of the tool body* (BB-A2) with possible *breaking out of buttons* (BB-A3) is a typical phenomenon for drilling weak rock types. It can often be observed in poorly cemented or weathered sandstone, sandy marlstone or weathered and hydrothermally altered granite or gneiss. In this rock the bit penetrates deep into the rock mass and produces a lot of debris material, so that both steel body and buttons are more or less evenly exposed to rock and rock debris. Since at the same mineral hardness steel and cemented carbide are undergoing different wear rates, the tool body wears faster than the inserted buttons. Buttons are preparated out of their steel bedding and begin to fall out or are broken out of the bit when embedding is insufficient (BB-A3). If one button is being broken out, this may also affect other buttons, because the broken out hard metal button is hardly removed from the hole and may cause high dynamic impact forces on other buttons.

Wear of diameter (BB-A4, BB-A5) is typical for unstable or highly stressed abrasive rock mass when the drilled hole is deformed during drilling. Abrasive rock material is forced to the bit from the walls. First, the peripheral buttons begin to show wear on the outer side (BB-A4), later the tool body itself is affected, the hole diameter of the bit is reduced and peripherical buttons break out (BB-A5).

Macroscopic *failure of buttons* (BB-F1, BB-F2) is mostly independent from the rock's abrasivity and mineral content. It is mostly influenced by the rock strength and fabric, properties of the rock mass, machinery and tools and support method. Dynamic impact is the main cause for this material failure. Type BB-F2 (total button removal) can easily be caused by no or bad soldering of the buttons into the steel body. These main geological factors have been recognised to cause button failure:

- inhomogeneous rock masses with rock of high rock strength in combination with open joints or joints filled with soft rock.
- inhomogeneous rock types with very hard components (> approx. 80 MPa) exceeding diameters of about 2 cm, like conglomerates, fanglomerates or breccias.
- breaking of peripheral buttons is also increased, when holes have to be drilled through already installed steel support measures - for example during forepoling through lattice arches or during anchoring through reinforced shotcrete.

Failure of the bit shaft (BB-F3) is mainly a result of manufacturing problems or bad handling. In these cases, no conclusions may be drawn on geological circumstances.

The occurrence of *thermic wear* (BB-T) of button bits depends on the effectiveness of the flushing system. Under normal circumstances button bits are cooled very effectively by their water flushing system so that tool temperatures normally don't exceed 40°C. If no or insufficient flushing is available (i.e. insufficient air flushing, water-mist-drilling) thermal wear may occur. Wear types equal those of abrasive wear and wear due to material failures since high tool temperatures only increase those wear mechanisms. When heated above 200°C specific temper colours (Table 1) may show on the steel body and can be used diagnostically to estimate the maximum tool temperature.

Table 1. Temper colours for tool steel (Steinmüller, 1991: Taf. 2.).

Colour	**detailed colour description**	**temperature**
yellow	light yellow - yellow - gold	200-230 °C
brown/red	yellow brown - reddish brown - red - purple red	240-270 °C
violet/blue	violet - dark blue - blue - light blue	280-320 °C
grey	blue grey - grey	340-360 °C

At present there are two *special wear types* listed in the classification: Total wear down and widening of flushing holes. These types occur mostly independent from the geological circumstances:

- Total wear down (BB-Sp1) is stated, when the bit is worn down to or below the buttons. In such cases one may not be able to definitely recognise the predominant wear process.
- Widening of flushing holes (BB-Sp2) and flutes is a phenomenon, which in most cases is caused by aggressive flushing fluids or suspended abrasive particles in the flushing. It may even be caused by cavitation alone which means material loss out of the tool surface due to forming and implosion of microscopic vapour bubbles under high velocities of flow.
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Classification of bit wear rate

According to Thuro´s classification for button bits ∅ 43 - 48 mm (Thuro, 1996). Table 2 gives a system for the description of the button bit wear rate and drill bit lifetime. These terms have proven to be suited in numerous projects since their introduction in 1996.

Table 2. Bit wear rate classification for button bits ∅ 43 - 48 mm (Thuro, 1996).

wear rate term	**bit wear rate / crown life value [m/bit]**	**drill bit lifetime term**
very low	> 2000	very high
low	1500-2000	high
moderate	1000-1500	moderate
high	500-1000	low
very high	200-500	very low
extremely high	< 200	extremely low

PREDICTING BIT WEAR RATES

Testing and prediction methods - an overview

Prediction of tool wear rates can be based on a numerous variety of testing procedures and standards. Procedures cover a wide span of scale, ranging from on-site real-scale drilling test to model tests with simplified tools and furtheron to microscopic and chemical analysis of rocks and minerals. Depending on their scale they are able to take different factors into account whilst disregarding others. Some of the most important procedures - listed in order of their scale, from large-scale-methods to small scale methods - are:

- on site drilling tests (large scale) or block drilling tests (small scale) with original tools and machines
- model tests with simplified tools, f.e. the Siever´s Miniature Drill Test and Abrasion-Value-Test used for calculating the "Button Wear Index", BWI (Bruland et al., 1995; Bruland, 1998), the Cerchar scratch test for determining the "Cerchar Abrasiveness Index", CAI (CERCHAR, 1986) or the LCPC "Abroy" abrasimeter for determining the abrasivity index "ABR" (LCPC, 1995)

- geochemical or geotechnical methods used for estimation of indices like the SiO_2- and Al_2O_3-content, the "abrasive mineral content", AMC also known as "mean hardness" (Atkinson, 1993), the "equivalent quartz content", EQC (Thuro, 1996), the "Vickers hardness number of the rock", VHNR (Bruland, 1998), the "Schimatzek wear index" (Schimatzek & Knatz, 1970) including a modification by Ewendt (1980), the "Cutting Wear Index" (McFeat-Smith & Fowell, 1977), Deketh´s Specific wear equation, SPW (Deketh, 1995) or a new factor, the "Rock Abrasivity Index", RAI, introduced by Plinninger (2001).

The following chapters present results of some of the most common prediction methods, used in 12 drill-and-blast projects investigated in Germany and Austria from 1989 to 2001.

On-site and block drilling tests

Real-scale drilling tests, using the original drilling tools and machinery and being performed on representative outcrops or samples of the rock are a reliable testing method to obtain data for tool wear and drilling performance. Depending on the condition and size of the testing area or sample nearly all influencing factors are taken into account. Unfortunately, the procedures are rather expensive with respect to personnel and material costs and therefore carried out most seldomely.

Bit Wear Index (BWI; model test)

The Bit Wear Index, BWI is - besides the Drilling Rate Index, DRI and Cutter Life Index, CLI - part of a testing procedure used for predicting the performance of different excavation methods in hardrock conditions. The factors developed at the NTNU Trondheim are based on three model tests, a impact crushing test ("Brittleness test"), a model boring test ("Siever´s Miniature Drill Test") and a model abrasion test ("Abrasion Value"). There are currently no diagrams available to estimate bit lifetime from a given BWI. Bruland (1998) reports that "... the BWI has been found to have some weakness... We are currently working to replace the BWI with VHNR..." (p. 5).

Cerchar Abrasiveness Index (CAI; model test)

In western europe the Cerchar scratch test is one of most commonly used testing methods when it comes to the laboratory investigation of a rock samples abrasivity. The test is performed on a rock sample of hand specimen size and features a steel needle of defined geometry being scratched over the rock surface under static load. The CAI is then calculated from the diameter of the needle wear flat. From this setup it is evident that the testing procedure neglects most of maschinery, logistic and geological factors influencing wear. Extensive studies on geological factors influencing the CAI have recently been carried out at TU Munich by Käsling (2000). In contrast to West (1989), who stated a linear correlation, Käsling found no correlation at all between CAI and equivalent quartz content, but a moderate correlation between CAI and a product of the rock´s deformability (Young´s modulus) and its equivalent quartz content.

The 15 data sets plotted in Figure 8 show only bad correlation between CAI and encountered drill bit lifetimes. This gives rise to the opposition, that the CAI may be used for a rough estimation of a rock´s abrasivity, but is not suitable for a more precise calculation of drill bit lifetime and drill costs.

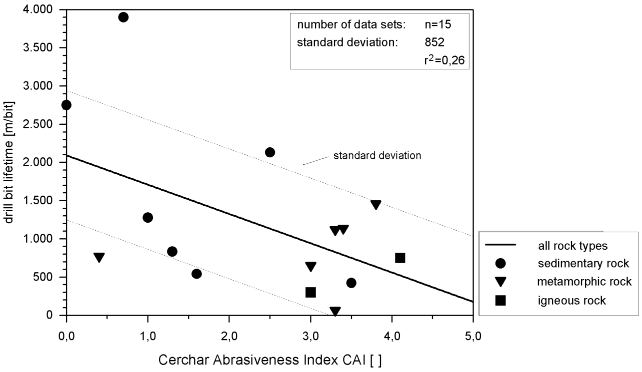

Figure 8. Drill bit lifetime, plotted against CAI.

Abrasive Mineral Content (AMC), Vickers hardness number of the rock (VHNR) and Equivalent quartz content (EQC; geotechnical indices)

AMC, VHNR and EQC are very similar geotechnical parameters using petrographical thin section analysis. They are calculated by multiplying the content of a mineral with a specific hardness value and then adding the values up. The indices vary in the use of different hardness values: AMC uses Mohs scratch hardness, VHNR uses Vickers indentation hardness and EQC uses the Rosiwal grindig hardness. VHNR and

EQC have proven to be suitable for drill lifetime calculation. Prediction diagrams are given in Johannessen et al (1995, Figure 9), Thuro (1996) or Plinninger (2001).

Schimatzek Wear Index (geotechnical index; Schimatzek & Knatz, 1970))

The wear index was developed in the 1970s in order to estimate roadheader pick consumption in german coal mining operations. Besides the content of abrasive minerals (calculated similar as the EQC) the factor uses the brazilian tensile strength (BTS) and the grain size. As it was primarily defined for clastic quartz-rich sediments only, Ewendts investigations (1980) lead to a modified Schimatzek wear index, adapted to all kinds of rocks and using the Point-Load-Strength I_{50} instead of the BTS. This modified index has proven to be a more reliable factor for bit lifetime prediction than the EQC, but is less reliable than the RAI (see below). A prediction diagram is available from Plinninger (2001).

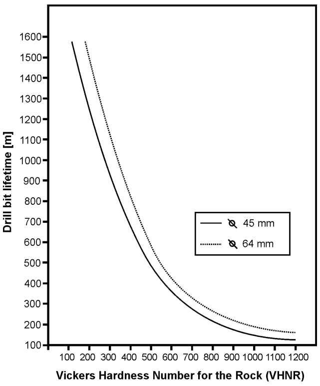

Figure 9. Drill bit lifetime plotted against VHNR (Johannessen et al., 1995)

SiO2- and Al2O3-content (geochemical parameters)

In Figure 10 encountered bit wear rates for 12 rock types are plotted against their SiO_2- und Al_2O_3-content derived from X-Ray Fluorescence Analysis. Judging from this data one can propose a bad correlation between SiO_2-content and bit wear rate and no correlation at all for the Al_2O_3-content. Since these element oxides are only calculated from the analysed Si- and Al- contents of the rock sample, non-abrasive clay minerals and mica are included as well as quartz and corundum. Wear relevant rock characteristics like grain size or grain shape are also totally neglected. This means, that for example quartz grains with silt size, which are only of minor importance for tool wear are included in the same kind as quartz grains in the size of sand or gravel.

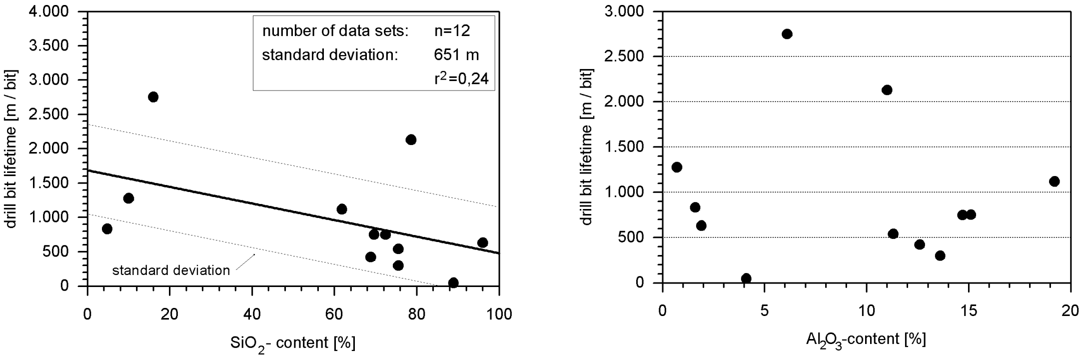

Figure 10. Drill bit lifetime, plotted against SiO_2- und Al_2O_3- contents.

The Rock Abrasivity Index and RAI prediction procedure (geotechnical index)

The Rock Abrasivity Index, RAI is a new geotechnical wear index, part of a prediction procedure for drill bit wear rate. This procedure suggests a investigation program taking into account the hole range of scale from rock mass to mineral scale (Table 3). It is based on easy-to-obtain, conventional rock and rock mass parameters, which in most cases are already available from standard stability assessment of the underground opening. Based on the

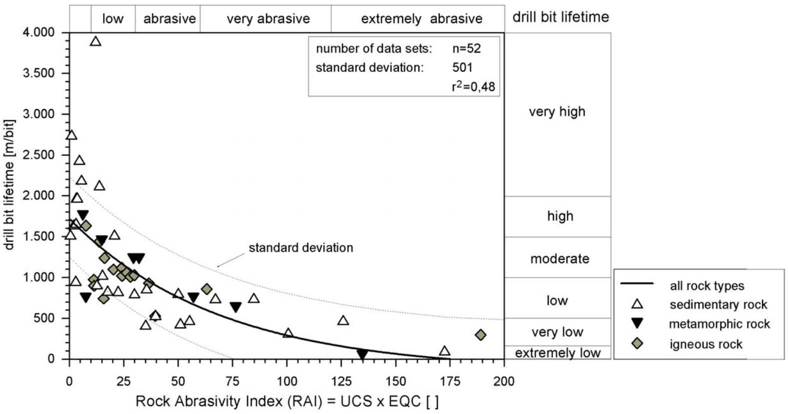

Figure 11. Drill bit lifetime, plotted against RA

"mineral scale"- and "rock scale"-investigations, the RAI is calculated for relevant rock types by multipliing the rock´s Unconfined Compressive Strength and Equivalent Quarz content. Rock mass scale informations are then taken into account by use of "positive" and "negative" factors, that can either increase or decrease the drill bit lifetimes derived from the RAI prediction diagram (Figure 11).

Table 3. Important geological informations about rock mass, rock and minerals for wear prediction.

1. rock mass scale (dm-km)
Which areas with homogenous rock composition and identical rock characteristics can be distinguished ?
How are these areas located (orientation, thickness, occurence) ?
What are discontinuities (joints, faults, bedding planes) like in these areas (number of sets, spacing, roughness, aperture, orientation) ?
Are there areas, where the rock characteristics have changed due to weathering or hydrothermal alteration ?
What is the water situation like (amount, location and chemical composition of water inflow) ?
What is the primary stress field like (orientation and intensity) ?
2. rock scale (cm-dm)
To what amount are identified minerals (see "mineral scale") included ?
What is the fabric of the rock (grain size & shape, orientation of minerals, degree of density) ?
What are the rock´s mechanical properties (compressive strength, tensile strength) like ?
3. mineral scale (mm-cm)
What minerals are included in the rock ?
In what condition are included minerals (alteration) ?

CONCLUSIONS

The complex rock drilling tribosystem leads to a vast variety of factors influencing the bit wear in hardrock drilling operation. The bit wear type and bit wear rate can be used as parameters describing the effect of the wear process. Easy-to-use classifications for both are given. From the presented data the conclusions may be drawn, that model tests (such as the BWI or CERCHAR scratch test) may only give an idea of the rocks abrasivity but show bad or no distinct correlation between encountered tool wear rates. The Rock Abrasivity Index (RAI) is part of a prediction procedure based on conventional rock parameters. Taking into account the whole range of scale from grain mineral to rock mass, the presented scheme may help to predict tool wear rates and hint at possible problems in excavation and specific requirements for the tools used

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