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Hard rock tunnel boring, cutting, drilling and blasting: rock parameters for excavatability

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ABSTRACT: Determining tunnel stability is a key issue during preliminary site investigation. In contrast, problems of excavatability have been largely ignored. While the choice of an economic tunnelling method is admittedly a clear priority in the planning stage, special investigations focussing on rock fragmentation (e.g. drilling or cutting performance, rock mass blastability or tool wear) are rarely carried out. This paper explores possibilities to quantify key parameters for rock mass excavatability in drilling, blasting and cutting by TBMs and roadheaders.

RÉSUMÉE: La détermination de la stabilité du tunnel est une question clé lors des études préliminaires. En revanche, les problèmes d'excavabilité sont souvent en grande partie ignorés. Tandis que le choix d'une méthode de percement économique est évidemment une priorité claire dans l'étape de planification, des investigations spéciales se concentrant sur la fragmentation de la roche (par exemple le comportement de la roche au forage, à l'excavation ou au dynamitage et l'usure des outil) sont rarement effectuées. Cet article explore les possibilités pour quantifier les paramètres clé de la roche lors d'excavation par forage, dynamitage, au tunnelier (TBMs) ou à l'excavatrice.

ZUSAMMENFASSUNG: Beim Tunnelbau wir meist die Vorhersage der Stabilität des ausgebrochenen Hohlraums als Schlüsselfragestellung betrachtet. Im Gegensatz dazu werden Probleme der Gebirgslösung weitgehend ignoriert. Während der Wahl einer wirtschaftlichen Vortriebsmethode während der Planungsphase meist noch eine gewisse Priorität beigemessen wird, werden spezielle Untersuchungen zur Gebirgslösung (Bohr- oder Schneidbarkeit, Sprengbarkeit oder Werkzeugverbrauch) nur sehr selten durchgeführt. Diese Publikation zeigt Möglichkeiten der Quantifizierung von Schlüsselparametern für die Gebirgslösbarkeit auf, also der Bohr- und Sprengbarkeit, der Fräsbarkeit mit Teilschnittmaschinen und der Schneidbarkeit mit TBMs.

Introduction

Cutting and drilling performance as well as the wear of tools and equipment are decisive for the progress of excavation works. The estimation of these parameters in predicted rock conditions might bear an extensive risk of costs. Therefore an improved prediction of cutting performance and bit consumption would be desireable. For some years now basic rock drilling processes and bit wear have been studied in hard rock tunnelling [1, 2]. Extensive field studies and laboratory work has been carried out to record the connection between some geological features and geotechnical parameters on the one side and technical parameters such as cutting or drilling performance and disc or bit consumption on the other. For that reason 24 tunnel projects in Europe and overseas in different geological settings have been followed more or less extensively.

Excavatability is a term used in underground construction to describe the influence of a number of parameters on the drilling, blasting or cutting rate (excavation performance) and the tool wear of a drilling rig, roadheader or TBM (wear or usage criterion). The interaction of the main factors involved is illustrated in Figure 1: . These terms are used in underground as well as in surface construction. In this thesis, only the aspects relating to tunnelling are discussed.

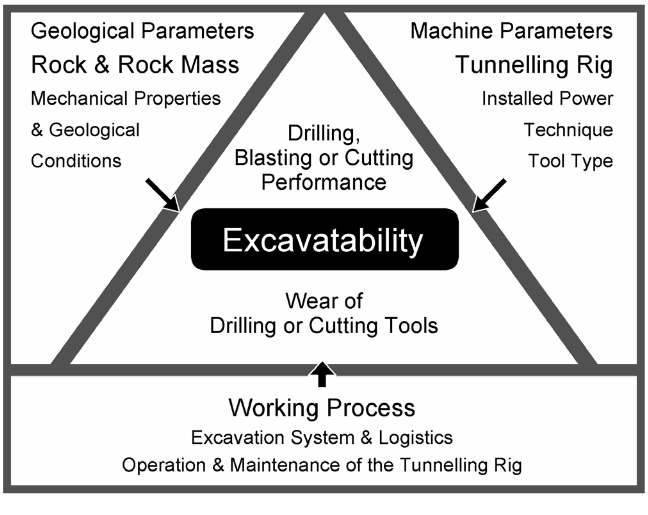

Figure 1: Conceptual overview of the three main parameters influencing excavatability.

In the first interaction, the excavation performance is influenced by the machine parameters of the chosen tunnelling rig: the installed power, the type of drilling rig or cutter head and the rock cutting tools mounted. Apart from technical parameters, the geological parameters may especially influence the cutting performance and tool wear. The specific characteristics of intact rock and rock mass material may be at least partly put into figures with the help of mechanical rock properties. But rock mass conditions also highly depend on the geological history, weathering conditions, hydrothermal decomposition and the structure of discontinuities.

The last important factor influencing rock excavation performance is the working process itself. Firstly, smooth operation and permanent maintenance of the tunnelling rig contributes to a successful cutting performance. Secondly, a high penetration rate at the tunnel face does not automatically lead to a high performance of the tunnel heading[3]. Therefore, it is a matter of understanding the entire excavation system before applying expertise to the investigation of excavation performance.

Excavation Techniques

For further discussion some elementary terms of underground excavation techniques must be explaned. The term ‘drillability’ is used in the context of drill and blast tunnelling when drifting blastholes for explosives and rock bolting for support with diameters ranging from 32 to 100 mm. To study drillability, two key parameters have proved to be most valuable: the (net) drilling rate in meters per minute (i.e. the drilling performance, derived from the time of drilling one single borehole); and the bit life span in meters per drilling bit that can be drilled in a homogeneous tunnel section. Since wear occurs in six basic forms, generally in accord with rock mass conditions, some qualitative aspects of tool wear can be distinguished by analysis of worn-out drilling bits [2].

The term ‘blastability’ is only used in the context of drill and blast tunnelling and the consumption of explosives. Quality aspects of blasting and/or control of material fragmentation were not included. As a property relating to blastability, the specific consumption of explosives was recorded in the crown heading along homogeneous rock mass sections. The specific explosives consumed can be derived from the total consumption of explosives in one blow divided through the volume blasted. As a statistical value, the specific consumption of explosives only shows the amount of explosives needed to blast a certain rock mass volume. Since the blasting engineer has to estimate this amount according to rock mass conditions (quality of rock, discontinuity spacing etc.), experience shows that there is quite a variation in the used quantity and therefore in the values of specific explosives consumed.

The term ‘cuttability’ is used both when excavating with roadheaders or with TBMs. In principle, the term is also valid for similar techniques using trench and dredge cutting [4, 5] and road pavement shaping. Analogous to drillability, two key parameters are invoked to describe roadheader cuttability [6, 7, 8]. In roadheader excavation the cutting performance is measured as the excavated rock volume in cubic meters per working hour, and the bit wear is determined by the number of worn-out bits that have to be changed after cutting a cubic meter of rock (specific bit consumption). Since roadheader bit wear occurs in seven basic forms, relating to rock mass conditions, some qualitative aspects of tool wear can be distinguished by analysis of used bits [2].

During TBM boring, the cutting performance is measured in this study as the specific penetration (penetration divided by thrust) in a rock material as opposed to of the excavated rock volume in cubic meters per working hour [9]. This allows for comparison to be made between different TBM types (eg. diameters, cutter geometry, power) in different rock materials [10]. Cutter wear is taken as the spooling distance of a disc cutter in kilometres or the consumption of disc cutters per cubic meter of excavated rock material (specific disk cutter consumption). Since the possible spooling distance of a disc cutter is reasonably high, the resolution with respect to geological and petrographical variations is quite poor and not applicable to rock mass characterization.

Basic excavatability: rock properties

For the investigation of excavatability there has to be distinguished the basic excavatability controlled by the intact rock and the general excavatability controlled by the rock mass properties. In other words, the general rock mass excavatability also takes into account the discontinuity pattern and characteristics, and water seepage/flow. If the rock mass is homogeneous and isotropic, rock properties could be directly correlated with excavation performance and petrographic properties (e.g. equivalent quartz content [11]) or index properties (e.g. rock abrasivity index [2, 12]) with tool wear.

Performance parameters

In earlier papers the suitability of different rock properties for correlation with drilling rates have been discussed in detail [3, 11]. Also when applying these techniques to other excavation processes, the best correlations were encountered using destruction work (strain energy [13]). From the physical point of view, the integral of the stress-strain-curve is a measure of energy (or work) related to the deformation volume. Because this is the work required for destruction of the rock sample, the newly defined rock property has been determined as ‘*specific destruction work* W_d [kJ/m^2]’ (in short: destruction work), which is also referred to as *strain energy*. As a product of both stress and strain, destruction work represents the work of shape altering of the rock sample including the post failure region.

Figure 2 shows the correlation between destruction work and cutting performance in roadheader excavation with R^2 = 89% (square of correlation coefficient). In contrast, the significance of the correlation with unconfined compressive strength (Figure 3) is not as good (R^2 = 62%).

A good correlation is also found with TBM performance, when specific penetration rate is plotted against destruction work (Figure 4, R^2 = 87%). To obtain better correlations, only TBM pulls in those tunnel sections were included where fracturing by joints was low and orientation of foliation was constant.

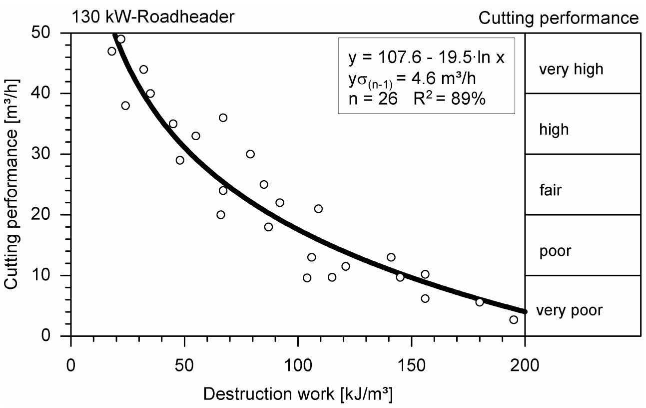

Figure 2. Roadheader cutting performance versus destruction work (slate and quartzite, Sewage tunnel Zeulenroda, Germany).

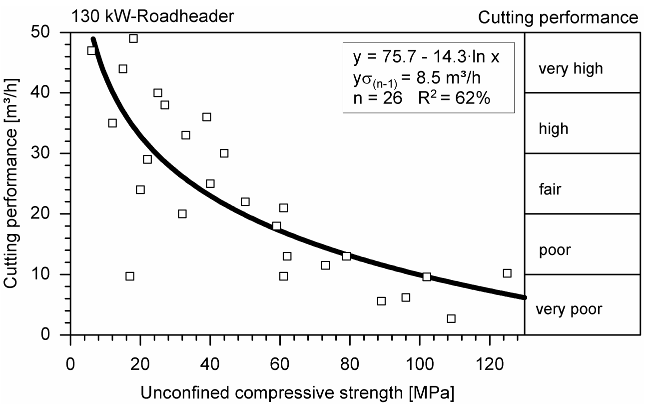

Figure 3. Roadheader cutting performance versus compressive strength (slate and quartzite, Sewage tunnel Zeulenroda, Germany).

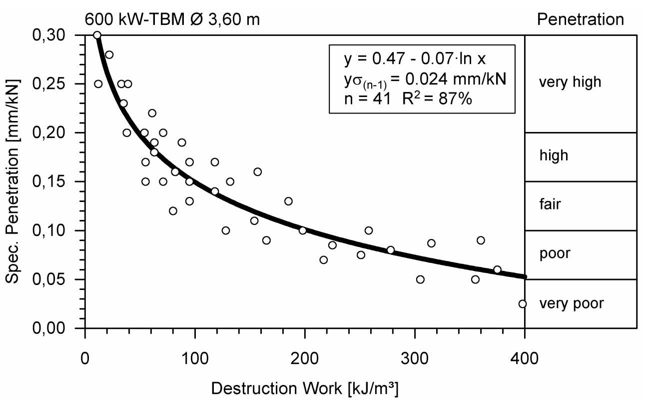

Figure 4. Specific TBM penetration rates versus destruction work (phyllite & carbonate schist, Schönberg pilot tunnel, Schwarzach, Austria).

In drill and blast tunnelling a fair correlation was encountered for the drilling performance (Figure 5) and for the specific consumption of explosives (Figure 6) with destruction work. The tested rock types included clay-siltstone, sand- and limestone, conglomerate, marl, marble, schist and different cristalline and igneous rock. The destruction work proved to be a highly significant parameter for correlation with the drilling performance. The chart indicates the close correlation between drilling rate and destruction work. In contrast to the described connection, correlations between the conventional mechanical rock properties (unconfined compressive and tensile strength, Young's modulus and the ratio of unconfined compressive strength and tensile strength 'toughness') and drilling rates show less significance [11].

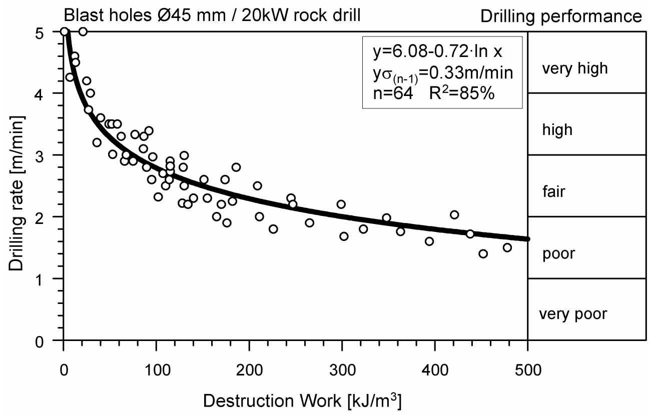

Figure 5. Drilling performance with 45 mm button bits versus destruction work (8 tunnel projects).

When correlating the specific consumption of explosives with destruction work (Figure 6), it is important to evaluate only homogeneous tunnel sections and explosives with comparable detonation characteristics (energy, velocity) and comparable blasting conditions (here: wedge cut, face profile & volume).

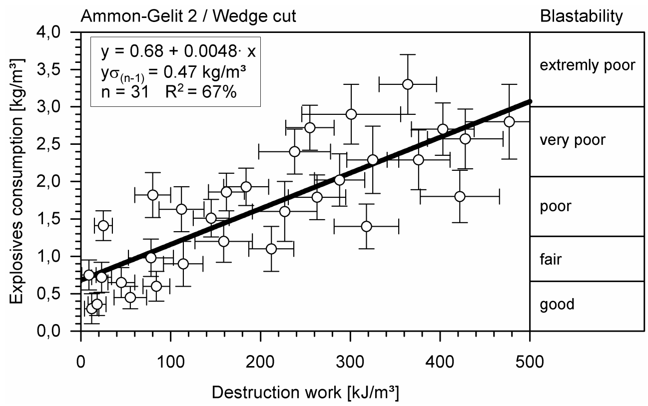

Figure 6. Specific consumption of explosives versus destruction work (31 case studies from 8 tunnel projects). Standard deviation as error margins.

In summary, mechanical rock properties, especially destruction work, can be used as a good measure for excavation performance and therefore provide useful information when carrying out site investigations in regard to excavatability. The limitation is that the prerequisites, homogeneous and isotropic rock mass sections without neous and isotropic rock mass sections without changing geological structures are only very rarely encountered.

Tool wear parameters

Having discussed some factors influencing performance rates, parameters for predicting the tool wear are now mentioned. Technical parameters and model tests have not proven to be really suitable for excavatability studies, although there are about 200 hardness tests for rock characterization [14, 15, 16, 17]. Much of them have been introduced for a special purpose and have not been developed further. Only few have gained international attention such as the drilling rate index DRI [18] or the Cerchar abrasivity index CAI [19, 20, 21]. The point is, that there is no single physical property in existence to quantify and describe 'rock abrasivity'. Also a lot of petrographic parameters such as rock texture and mineral fabric have been discussed to be used for predicting tool wear and drillability [22]. But the performed structural methods are very time (and cost) intemsive and thus have not been applied in practice.

It is clear, that the abrasivity of a rock type is at first a result of the amount of abrasive minerals with respect to the tool materials (steel; Mohs hardness ca. 5.5). Quartz (Mohs hardness of 7) represents the most common abrasive mineral. To include all minerals of a rock sample, the equivalent quartz content *eQu* has been determined in thin sections by modal analysis, meaning the entire mineral content referring to the abrasiveness or MOHS mineral hardness of quartz (Formula 1). Therefore each mineral amount A_i is multiplied with its relative ROSIWAL abrasiveness R_i to quartz (with quartz being 100% [23, 24]).

$$eQu = \sum_{i=1}^{n} A_i \cdot R_i \qquad (1)$$

An appropriate correlation between MOHS hardness and ROSIWAL abrasiveness is given in Figure 7. When the MOHS hardness is known, the abrasiveness of minerals can be estimated by this chart with satisfactory accuracy (within a half degree of Mohs hardness).

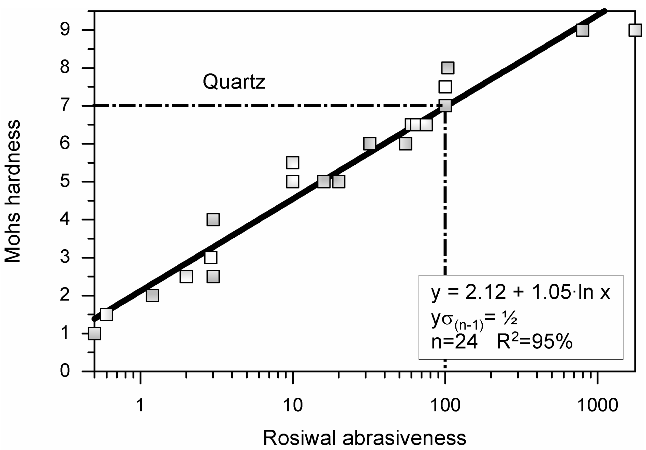

Figure 7. Correlation between ROSIWAL abrasiveness and MOHS hardness, enclosing 24 different minerals (excluding diamond).

The method of determining the equivalent quartz content is wide-spread among tool manufacturers, engineers and engineering geologists for preliminary site investigations prior to tool wear problems.

In Figure 8 the bit lifetime during conventional drill & blast tunnelling is correlated for different rock types. It is visible that bit wear raises mainly with increasing equivalent quartz content. Going more into detail, the given correlation shows another mainly influencing parameter for rock abrasivity: The grain binding: A very simple comparison may explain this: Both materials, a quartz sand and a silicic quartz sandstone may have a quartz content of nearly 100%. In the hypothetical case of drilling both materials, only the sandstone will cause mentionable tool wear, which is in this case (with identical mineral content) directly depending on the binding of the quartz grains.

In effect of this, some kinds of rock have their own curves: (a) sandstones, especially those with higher porosity, often corresponding with a defect in the silicic cementation; and (b) hydrothermally decomposed crystalline rock.

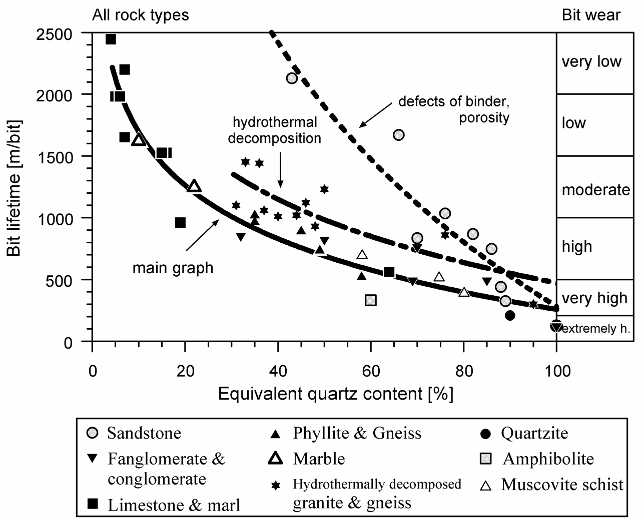

Figure 8. Drilling bit lifetime of different rock types versus the equivalent quartz content (42 case studies in 8 tunnel projects).

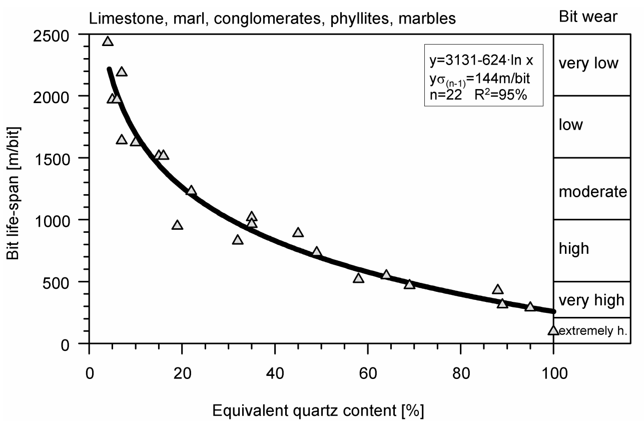

Figure 9. Drilling bit lifetime of rock types with grain-grain boundaries versus equivalent quartz content (8 tunnel projects).

In each of those special rock types the interlocking of the grains in the microfabric is 'disturbed'. Therefore, for purposes of prediction, each rock type must be discussed individually. In Figure 9 a group of rock types with grain-grain boundaries (limestone, marl, conglomerate, together with phyllite and marble) has been built to be described by a logarithmic regression curve. For the chosen rock group the relation is very close and may be used for a forecast of bit wear, when the equivalent quartz content is determined by a thin section modal analysis.

The Rock Abrasivity Index, RAI[25, 26] 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. Based on the 'mineral scale'- and 'rock scale'-investigations, the RAI is calculated for relevant rock types by multiplying the rock's unconfined compressive strength (as a parameter taking into account the grain binding and mineral interlocking of the material) and the equivalent quartz content. Rock mass scale information 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 10).

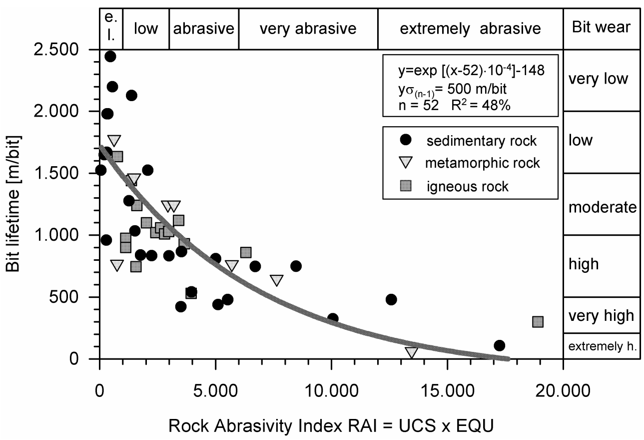

Figure 10. Drilling bit lifetime versus rock abrasivity index RAI.

General excavatability: rock mass properties

Although rock mechanical properties play a key role, geological parameters are rarely fully included in most projects. In some cases, the influence of geological features on rock fragmentation can be much higher than varying rock properties. Geological difficulties can have a high impact on the economics of an underground construction project, especially when the chosen excavation system turns out to be unsuitable for the conditions encountered. Thus it can be argued that the geological and petrological characteristics of the rock mass should be evaluated with the same degree of effort as that for the geotechnical prognosis. Furthermore, mechanical parameters are of limited value, if the rock mass is composed of anisotropic and inhomogenious material. Inhomogeneity and anisotropy obviously play a key role during the process of rock fragmantation.

Anisotropy

Of course, rock properties and excavation rates are also highly dependent on the orientation of weakness planes related to the direction of testing or advancing [3]. E.g. when the direction of penetation is at right angles to the orientation of foliation, rock material is compressed at right angles but sheared parallel to it. Although cracks will develop radial to compression, the cracks parallel to the bottom of the borehole will be used for chipping. Usually in this case the highest penetration rates in TBM excavation are obtained, because of the favourable schist orientation. The specific penetration is controlled by the shear strength of the foliated rock material (Figure 11). Here, the destruction work is a minimum and causes large sized chips and a maximum drilling performance.

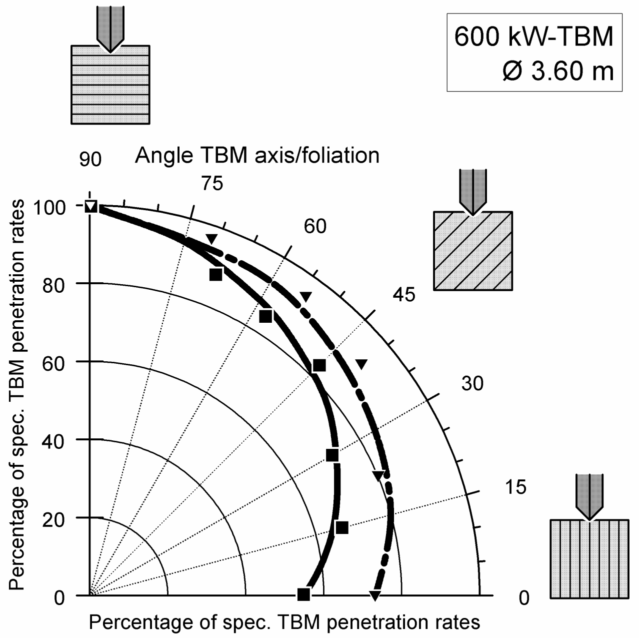

Figure 11. Mean values of specific TBM penetration rates in phyllite (full line) and phyllite – carbonate-schist interstratification (dashed line) versus angle of foliation. Schönberg pilot tunnel, Schwarzach, Austria.

If the penetration axis is oriented parallel to foliation, compression also is parallel but shear stress is at right angles. It should be clear, that fewer cracks will develop for reasons of higher strength at right angles to foliation. Penetration is controlled by the tensile strength parallel to the foliation producing small-sized fragments and a minimum drilling performance (see Figure 12 for comparison).

It is certain, that in the parallel case, rock properties are the highest and excavation rates are low. These correlations have been found for all studied excavation types (drilling, blasting, roadheader and TBM cutting) Thus, if the tunnel axis is parallel to the main foliation, excavation conditions are supposed to be very poor.

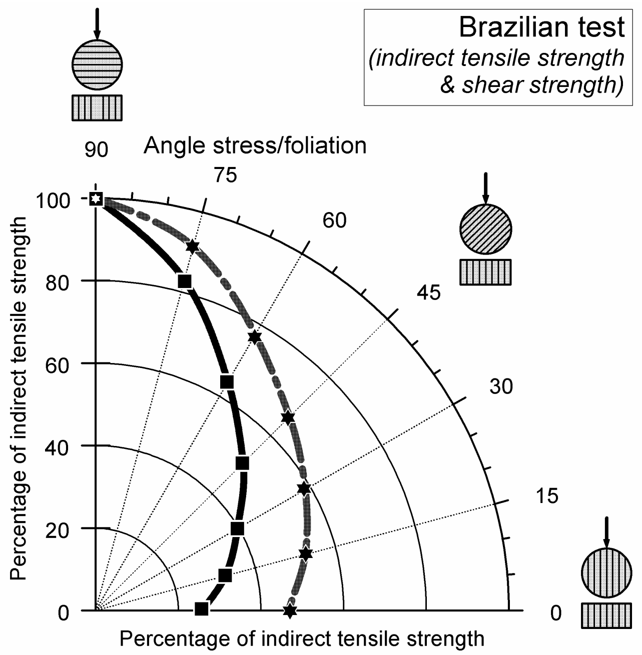

Figure 12. Mean values of Brazilian test results in two different quartzphyllites versus angle of foliation. Inntal tunnel, Innsbruck, Austria.

Spacing of discontinuities

Of course, excavation rates are also dependent on spacing of discontinuities in rock mass. Discontinuities are, as a law, weakness planes in rock mass - thus already Leopold MÜLLER talked about rock mass as 'broken rock'. The spacing of discontinuities could also be described as 'discontinuities per meter' and is another parameter for the precracking of rock.

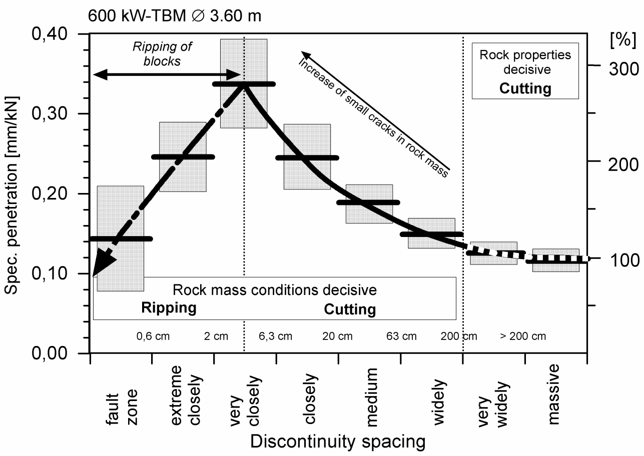

Figure 13. Specific penetration rate versus discontinuity spacing in phyllites (Schönberg pilot tunnel, Schwarzach, Austria).

In the chart of Figure 13 the influence of discontinuities is not visible, if the spacing is large against the dimensions of the tunnel or TBM. Here, the rock properties are decisive and performance is based on the cutting process only. With the discontinuities getting closer, the penetration rate increases significantly. This is caused by the increase of small cracks and fissures that accompany the major discontinuities. Here, the rock mass condition is decisive and the TBM starts to rip small blocks out of the tunnel face which first of all makes cutting more effective. Below a certain point (here about 5 cm spacing) the disc cutters rip more and more blocks out of the face, which can't be extracted quick enough by the mucking system. The result is a grinding and squeezing of the ripped rock blocks at the cutter head, what prevents the TBM to penetrate into the face. By this means, the efforts of fast penetration, especially in fault zones or zones with high *insitu* stresses (and therefore unravelling of the face), may be rendered useless very soon.

Conclusion

After all these observations, it is clear, that neither laboratory and field testing alone, geology alone, nor experience alone and equipment design and operation expertise alone can lead to the point where excavatability is anything like a clearly defined formula. Firstly, with the discovered correlation charts for mechanical and petrographic rock properties, it should be possible to predict excavation rates and tool wear for the examined rock types in a satisfactory manner. But besides rock properties, the main problem is the variety of geological phenomena, which cannot be put into figures and rock properties.

References

1. THURO, K., Geologisch-felsmechanische Grundlagen der Gebirgslösung im Tunnelbau. Habilitation Thesis, Münchner Geologische Hefte, Reihe B, Angewandte Geologie, B18, I-XIV, 1-160, 2002.

2. PLINNINGER, R.J., Klassifizierung und Prognose von Werkzeugverschleiß bei konventionellen Gebirgslösungsverfahren im Festgestein. PhD Thesis, Münchner Geologische Hefte, Reihe B: Angewandte Geologie, B17, I-XI, 1-146, 2002.

3. THURO, K., SPAUN, G., Drillability in hard rock drill and blast tunnelling. Felsbau, 14, 103-109, 1996.

4. DEKETH, H.J.R., The wear of rock cutting tools. Laboratory Experiments on the abrasivity of rock. Rotterdam, Balkema, 1995.

5. VERHOEF, P.N.W., Wear of Rock Cutting Tools - Implication for the site investigation of rock dredging projects. Rotterdam, Brookfield, Balkema, 1997.

6 THURO, K., PLINNINGER, R.J., Geological limits in roadheader excavation - four case studies. In: MOORE, D.P., HUNGR, O. (eds), Proceedings 8th Int. IAEG Congress, Vol. 5, Rotterdam, Brookfield, Balkema, 3545-3552, 1998.

7. THURO, K., PLINNINGER, R.J., Predicting roadheader advance rates. Tunnels & Tunnelling International, 6, 36-39, 1999.

8. THURO, K., PLINNINGER, R.J., Roadheader excavation performance – geological and geotechnical influences. In: VOUILLE, G., BEREST, P. (eds), Proceedings 9th Int. ISRM Congress, Rotterdam, Brookfield. Balkema, 1241-1244, 1999.

9. THURO, K., BRODBECK, F., Auswertung von TBM-Vortriebsdaten – Erfahrungen aus dem Erkundungsstollen Schwarzach. Felsbau 16, 8-17, 1998.
10. GEHRING, K., Classification of drillability, cuttability, borability and abrasivity in tunnelling. Felsbau 15, 183-191, 1997.
11. THURO, K., Drillability prediction - geological influences in hard rock drill and blast tunnelling. Geol. Rundsch. 86, 426-437, 1997.
12. PLINNINGER, R.J., SPAUN, G., THURO, K., Predicting tool wear in drill and blast. Tunnels & Tunnelling International 4, 38-41, 2002
13. THURO, K., SPAUN, G., Introducing 'destruction work' as a new rock property of toughness refering to drillability in conventional drill- and blast tunnelling. In: BARLA, G. (ed), Proceedings Eurock ´96 conference, Vol. 2, Rotterdam, Brookfield. Balkema, 707-713, 1996.
14. ATKINSON, H., Hardness tests for rock characterization. In: HUDSON, J. (ed), Comprehensive rock engineering. Principles, practice & projects. Vol. 3, Pergamon, Oxford, 105-117, 1993.
15. WEST, G., Rock abrasiveness testing for tunneling. Int. J. Rock Mech. Min. Sci. Geomech. Abstr., 26, 151-160, 1989.
16. BROOK, N., The measurement and estimation of basic rock strength. In: HUDSON, J. (ed), Comprehensive rock engineering. Principles, practice & projects. Vol. 3, Pergamon, Oxford, 41-81, 1993.
17. NELSON, P. P., TBM performance analysis with reference to rock properties. In: HUDSON. J. (ed), Comprehensive rock engineering. Principles, practice & projects. Vol. 4, Pergamon, Oxford, 261-291, 1993.
18. SELMER-OLSEN, R., BLINDHEIM, O.T., On the drillability of rock by percussive drilling. Proceedings 2nd Int. ISRM Congress, 65-70, 1970.
19. VALANTIN, A., Test Cerchar por la mesure de la dureté et de l´abrasivité des roches. Annexe de l´exposée présenté aux Journées de Information "Techniques de creusement", Louxembourg, 1973.
20. SUANA, M., PETERS, T., The cherchar abrasivity index and its relation to rock mineralogy and petrography. Rock Mech. 15, 1-7, 1982.
21. PLINNINGER, R.J., KÄSLING, H., THURO, K., SPAUN, G., Testing conditions and geomechanical properties influencing the CERCHAR abrasiveness index (CAI) value. Int. Journ. Rock Mech. & Min. Sci. 40: 259–263, 2003.
22. HOWARTH, D.F., ROWLANDS, J.C., Quantitative assessement of rock texture and correlation with drillability and strength properties. Rock Mech. Rock Eng. 20, 57-85, 1987.
23. ROSIWAL, A., Neue Untersuchungsergebnisse über die Härte von Mineralien und Gesteinen. Verhandlg d. kk. geol. R.-A. Wien, 475-491, 1896.
24. ROSIWAL, A., Neuere Ergebnisse der Härtebestimmung von Mineralien und Gesteinen. Ein absolutes Maß für die Härte spröder Körper. Verhandlg. d. kk. geol. R.-A. Wien, 117-147, 1916.
25. PLINNINGER, R.J., SPAUN, G., THURO, K., Prediction and Classification of tool wear in drill and blast tunnelling. In: VAN ROY & JERMY (eds), Proceedings 9th Int. IAEG Congress, 2226-2236, 2002.
26. PLINNINGER, R.J., SPAUN, G., THURO, K., Predicting tool wear in drill and blast. Tunnels & Tunnelling International 4, 38-41, 2002.