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Geological limits in roadheader excavation - Four case studies

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ABSTRACT: The prediction of tunnel stability is usually the main subject in preliminary site investigations prior to tunnelling projects. During the last few years in mechanical excavation, problems have occured also connected with the accurate prediction of excavation rates in soft and hard rock. Every now and again problems have been encountered leading to high bit consumption and low cutting performance of roadheaders. In this paper the connection between some geological features, cutting performance and bit wear are presented by means of four German case histories in different geological settings.

RESUMÉ: D´ordinaire lors d´études préliminaires aux grands projets de percement de tunnel, les pronostics sur la stabilité de l´excavation se trouvent au premier plein d´intérêt. Ce pendant ces dernières années les difficultés de prévoir correctement la résistence des roches lors de percement méchaniques. Encore des problèms revenaient en connexion avec la consommation des ciseaux et avec le progrès de couper de bas avec des machines de percement. Dans cet bulletin, sont exposées les corrélations fondamentales entre quelques propriétés géologiques, le progrès de couper et l´usage des ciseaux, utiliser l´assistance des études allemandes en différentes entourages géologiques.

1 INTRODUCTION

In the past few years the development of tunnel roadheaders has reached a level, at which they are used to an increasing extent, not only in soft rock but also in hard rock. The increasing use of this tool in tunnelling also demonstrates some specific problems and limits - in hard and abrasive rock as well as in soft rock conditions. The accurate assessment of the geological rock conditons and the geomechanical properties of rock mass is of crucial importance for cutting performance and bit wear. Although many machine manufacturers have invested a great deal of time and money in studies for the prediction of rock excavation rates, tool wear and derived costs, geological conditions seem to be too variable to keep up with.

The prediction of tunnel stability is usually the main subject in preliminary site investigations prior to tunnelling projects. While the choice of an economic tunnelling method is normally admitted a certain priority, special investigations for rock fragmentation - e.g. the cutting performance or the wear of the cutters - are carried out quite rarely. For this reason arising problems often have to be solved during tunnel excavation rather than in the design period.

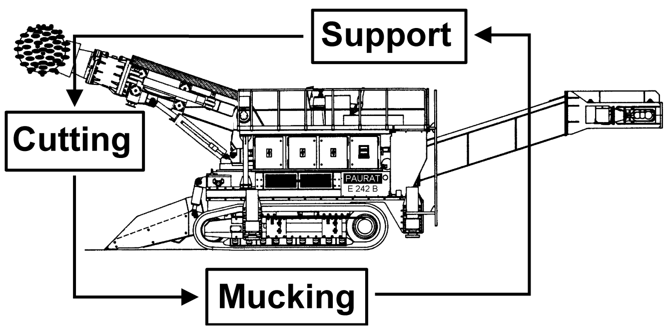


Fig. 1: Illustration of the main problems in roadheader excavation.

Table 1: Main Problems in roadheader excavation.

Process	Problem
Cutting	poor cutting performance
	high bit consumption, high tool wear
	no cutter head penetration, smudging of the cutter head
Mucking	soft soil behaviour & water (⇨ water-saturated mud)
	excavated blocks too big for haulage / conveyor belt

Table 1 and Fig. 1 give an idea of the kind of main problems in the different processes of roadheader excavation.

2 SCOPE

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 drill and blast tunnelling (Thuro 1996, Thuro 1997 a, b).

While performance is mainly influenced by macroscopic qualities such as rock strength, toughness (deformability), anisotropy, jointing or the weathering stage of rock mass (Gehring 1997, Thuro & Spaun 1996 a, b, Verhoef 1997) tool wear is predominantly affected by microscopic rock properties such as equivalent quartz content and the degree of mineral interlocking (Deketh 1995). Apart from conventional rock properties some special effects may hit the excavation process quite badly. For example in apparently good rock conditions with easy cutting of soft sandstones and clay-siltstones, even a low water inflow can lead to a total disaster: In one case, the cutter head has been smudged by clay and in another the mucking of the excavated material was nearly impossible due to the behaviour of the mud.

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 performance and bit consumption on the other. For that reason four tunnel projects in Germany in different geological settings have been followed more or less extensively: Altenberg tunnel, Idar-Oberstein (Permian fanglomerates), Bad Wildbad bypass, Black Forest (Permian fanglomerates and sandstones), Zeulenroda sewage tunnel, Thuringia (Ordovician slates and quartzites of the Thuringian Slate Mountains) and Underground Nuremberg, Bavaria (Triassic sandstones and clay-siltstones with calcrete layers).

3 CASE STUDIES

3.1 Altenbergtunnel, Idar-Oberstein

3.1.1 Project background and geological setting

In 1990 the 320 m long “Altenberg tunnel” was built in the vicinity of Idar-Oberstein, cutting through a river meander of the Nahe and making a short cut for the federal highway B 41. All along the tunnel section, Permian fanglomerates of the Saar-Nahe-Basin have been encountered with the composition illustrated in Fig. 2. The fanglomerate - a typical alluvial fan deposit - consists of subangular to well rounded components with diameters of up to 1 m (typical 20 - 50 cm) such as very hard and dense quartzites and vein quartz, argillaceous slates and volcanic rock in different stages of weathering.

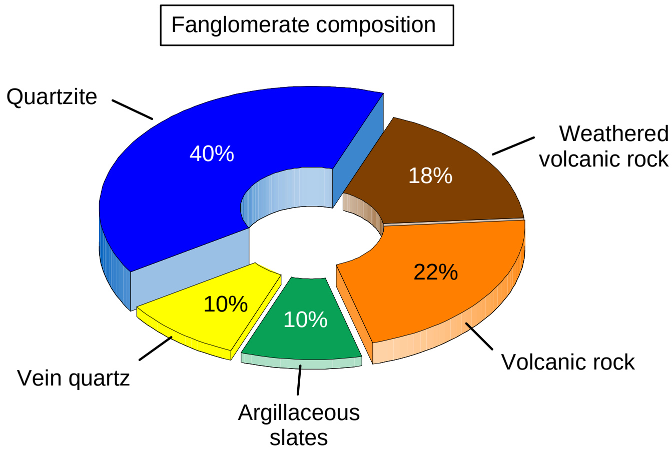


Fig. 2: Composition of the permian fanglomerate of the Waderner Formation, Idar Oberstein.

3.1.2 Occuring problems: performance & tool wear

In order to choose an economic tunnelling method, a test excavation with a 300 kW roadheader with a cross cutter head was performed. The result can be seen in Fig. 3. The outer bits of the cutter head were rased off immediately when penetrating the hard quartzite-bearing rock mass. Of course, the roadheader suffered not only from an enormous bit consumption but also from an exceptional poor penetration and cutting performance. Subsequently, the roadheader was removed from the site and drill and blast tunneling was used instead. The special problems of drilling performance and its influence on the working cycle are discussed in Thuro 1997 b.

Fig. 3: Typical asymmetric wear (type 3 ⇨ Table 2) of the outer cutter head bits of the used 300 kW roadheader.

3.1.3 *Causes*

The uniaxial compressive strength of the fanglomerate and its components is plottet in Fig. 4. The figure shows quite clearly that the range of the compressive strength of the fanglomerate is about 20 to 80 MPa, whereas the hardest components (quartzites) reach up to 230 MPa. During the site investigations only samples of the whole fanglomerate but not single components were tested.

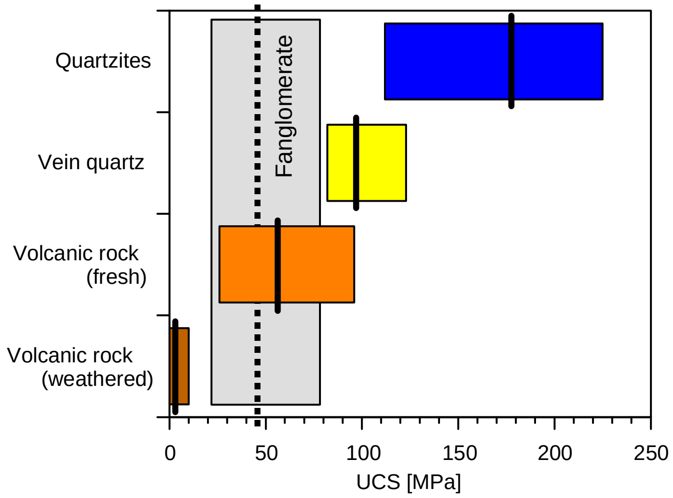


Fig. 4: Compressive strength of the fanglomerate and its components (by point load tests). Quartzites reach up to 230 MPa!

To be able to predict the cutting performance in connection with compressive strength a diagramm of the machine manufacturer like Fig. 5 is usually used. For the mean UCS of 50 MPa, the cutting performance would have been economical, but for the highest values of more than 200 MPa the machine was insufficent.

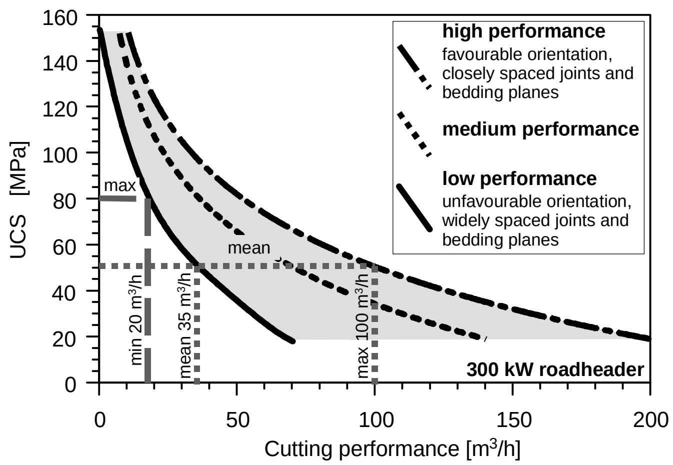


Fig. 5: Cutting performance of the 300 kW roadheader versus compressive strength. On dashed grey lines: estimation for the UCS of the fanglomerate, mean cutting performance estimated with approx. 35 m³/h.

3.2 *Meisterntunnel, Bad Wildbad*

3.2.1 *Project background and geological setting*

In 1994 to 1996 the 1684 m long "Meisterntunnel" was built as a traffic bypass for Bad Wildbad, a health resort located in the Northern Black Forest (Baden-Württemberg, Plinninger 1997). Throughout the tunnel´s total length the excavation works encountered fanglomerates, sandstones and clay-siltstones of the Upper Permian (Upper "Rotliegend", "Zechstein", Fig. 6).

Layers of calcrete were encountered which had a thickness of up to several decimeters. These crusts consisted of both dolomite and light yellow-coloured „Karneol" (cryptocrystalline silica). The scanning electron microscope photo (Fig. 7) gives an impression of the extremely dense texture that leads to a compressive strength of up to 150 MPa.

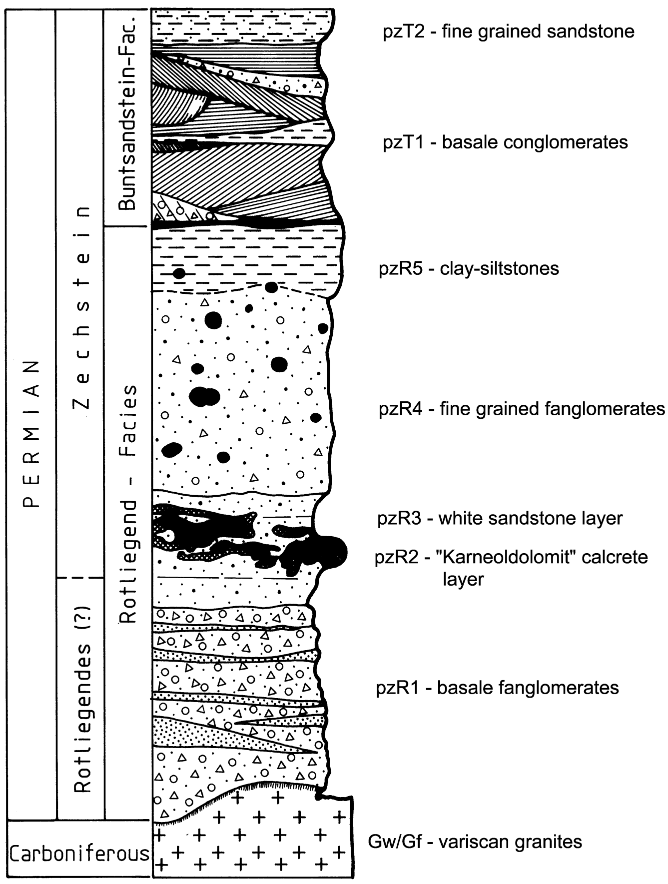


Fig. 6: Generalised scheme of the Permian rocks, encountered during the excavation works for the Meisterntunnel, Bad Wildbad.

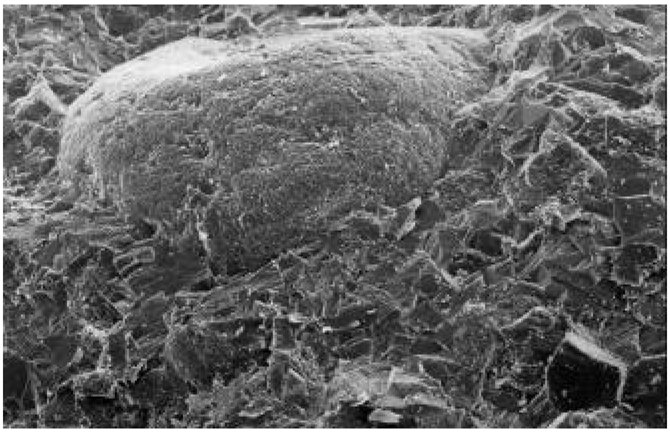


Fig. 7: Dolomitic calcrete - within the very dense dolomitic binder few rounded grains of quartz are visible. Picture´s width app. 1,6 mm.

3.2.2 Occuring problem: performance

During this project performance was not the only criterion for the choice of an appropriate excavation method. The health resort itself required best possible protection from immissions which were caused by the excavation works. Excavation with a roadheader was supposed to meet both requirements, so a Paurat E 242 B roadheader with 300 kW power and 120 t total weight was brought to the site. After assembly two cutting tests were carried out in December 1994. Even after the cutter head had been improved, the machine achieved only low performance of about 13 m³ (solid) per hour. The roadheader was removed from the site and drill and blast tunneling was used instead (Thuro & Plinninger 1998).

3.2.3 Causes

A detailed geotechnical investigation was subsequently carried out to reveal the causes for this financial disaster. The program included not only field investigations such as documentation of the geological situation, but also a large variety of laboratory work such as tests on the unconfined compressive strength, the rock abrasivity or thin section analyses. Fig. 8 shows the results of a series of point-load tests. Although the mean value is 59 MPa, the typical UCS for the hard and therefore difficult-to-cut layer is 90 MPa and the highest values climb up to over 150 MPa!

After all data had been analysed it became evident that the unfortunate combination of high compressive strength (up to 150 MPa in calcrete layers, up to 90 MPa in pzR4 fanglomerates and pzR5 clay-siltstones) and very widely spaced joints and bedding planes together had brought the roadheader "down to its knees" (Cutting performance diagramm in Fig. 9). For the typical UCS of 90 MPa, the cutting performance was not economical!

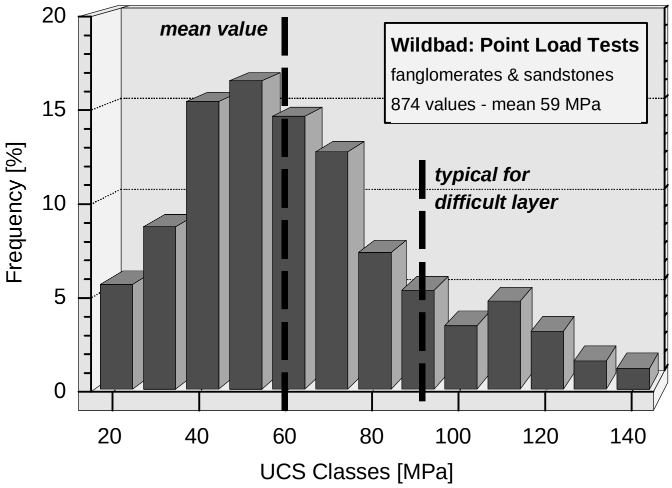


Fig. 8: Frequency of Point Load Test (UCS) values in Permian fanglomerates and sandstones of the Meisterntunnel, Bad Wildbad.

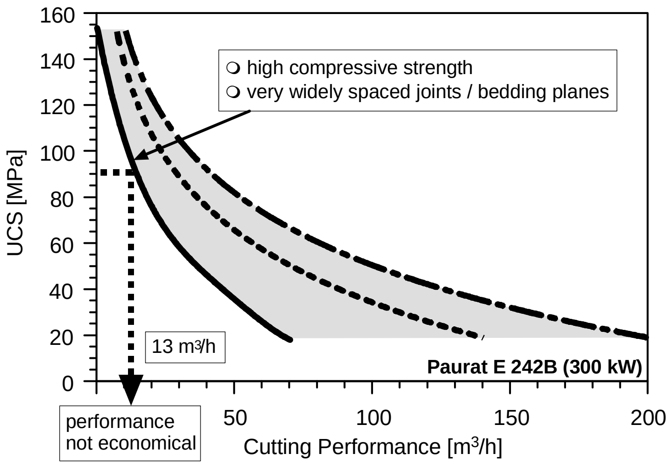


Fig. 9: Cutting performance of Paurat E-242B (300kW) roadheader versus compressive strength. Actual performance in the Meisterntunnel plotted in dashed line (13 m³/h).

3.3 Sewage Tunnel, Zeulenroda

3.3.1 Project background and geological setting

In 1994 to 1995 a 2.4 km long sewage tunnel was built in the vicinity of Zeulenroda, Thuringia. The rock conditions were characterised by Ordovician slates and quartzites of the Thuringian Slate Mountains called Phycodenschiefer, Griffelschiefer and Lederschiefer. The slates were typically black to grey, seldomly coloured, laminated to massive, sometimes closely folded and frequently mica bearing. The slates were alternating with hard grey quartzites of high compressive strength.

During excavation works, a large fault zone - the Weissendorf fault - was crosscut by the tunnel, with typically faulted and fractured material, fault gauge and heavy jointing of the related vicinity.

3.3.2 Occuring problems: performance & tool wear

Although the cross section of the tunnel was only 11 m², a 132 kW - roadheader could be installed (Atlas Copco Eickhoff ET 120). In the first 800 m the quartzites dominated the slate- quartzite interstratification, so the cutting performance dropped down from 22 m³ per hour to a minimum of below 5 m³ per hour (see Fig. 10).

At first the cutter head had to be changed from a longitudinal to a cross cutter. Subsequently the cross cutter had to be repaired several times due to damage of the bearing. The bit consumption was extremely high - rising from about 0.1 bits per m³ to over 5 bits per m³ (extreme value 15 bits per m³ - 150 bits in 11 m³!).

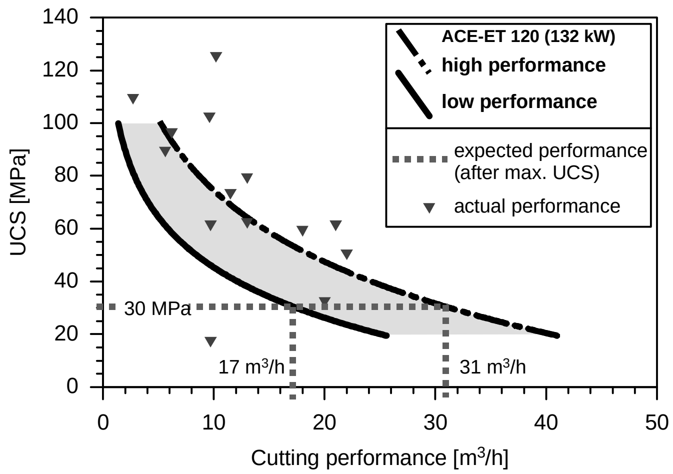


Fig. 10: Cutting performance of the Atlas Copco Eickhoff ET 120 (132 kW) roadheader versus compressive strength. Expected and actual performance in the Zeulenroda sewage tunnel.

3.3.3 Causes

Of course, the compressive strengths were far from expected. The performance according to the maximum compressive strength of 30 MPa was estimated with 15 to 30 m³/h. The actual values ranged from below 10 MPa (slates) to over 120 MPa (quartzites) causing the low cutting performance mentioned above.

Additionally the quartz contents were much higher than expected, especially in the hard quartzites, which were much more dominant than expected. In order to prove the influence of the quartzites, a wear characteristic of the used bits was made. The bit wear characteristic table given in Table 2 is based on several field studies in Germany, Austria and Switzerland. This bit wear characteristic may be used like a fingerprint to identify both abrasivity of rock and problems of cutting. Fig. 11 shoes quite clearly that breakage and damage of bits were common (types 2, 4, 5 & 6).

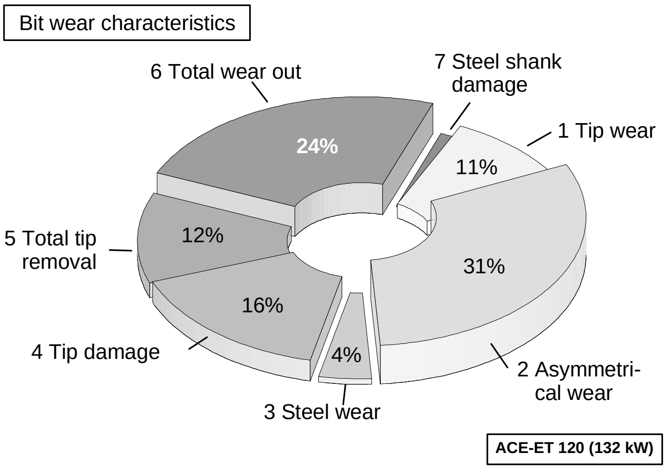
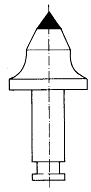
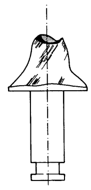
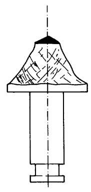
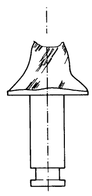
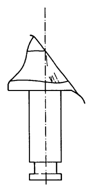
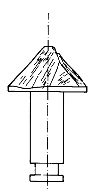
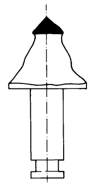
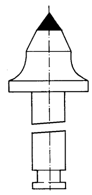


Fig. 11: Bit wear characteristic of 274 bits of the Zeulenroda sewage tunnel.

Table 2: Bit wear characteristic. Seven wear types can be distinguished.

Bit Wear Types		Bit Wear Types	
	**New Bit:** Perfect hard metal tip (insert of tungsten carbide with a cobalt binder) in a steel body	4 	**Tip damage**: Brittle fracture of the hard metal insert because of high shear stress
1 	**Tip wear:** Symmetrical wear of the hard metal (tungsten carbide) insert	5 	**Total tip removal**: The whole hard metal insert has been pulled out of its steel body
2 	**Asymmetrical wear**: Bits which are worn down on one single side	6 	**Total wear out**: The bit has been worn down to a certain level, where no parts of the hard metal insert are left
3 	**Steel wear**: Wear of the steel calibre in diameter as a result of chip grinding	7 	**Steel shank damage**: The bit was broken below the steel body in the tool shank and above the tool pockets

The investigations prove not only the abrasivity of the quartzite but also the jerkily movement of the cutter on the tunnel face (brittle, micro-chipping, tip damage & removal). Furtheron, when the rock is that hard, scraping of the rock surface leads to high temperatures, which has an unfavourable influence on the steel and the tungsten carbide: The hardness of tungsten carbide drops rapidly with increasing temperature, so that between 600°C and 800°C quartz is harder than tungsten carbide (Osburn 1969 in Deketh 1995). Therefore the wear resistance decreases at high temperatures!

The problem of the site investigations was apparently an insufficent sample rate and subsequently an insufficent number of rock tests.

3.3.4 Influence of joint spacing and fault zone material

The further excavation works were affected by a thick fault zone (Weißendorf fault), so that support works dominated the excavation rate (per day). However net cutting rates increased with decreasing spacing of discontinuities - joints and cleavage.

Fig. 12 indicates that at least two processes are taking place during cutting: As long as the rock is massive, scraping and cutting of material is dominant. There is much energy needed to carve the rock - resulting in a relatively low cutting performance. With closer joints the cutter head is able to rip out blocks or at least larger pieces of rock which are already precracked by small attending fissures. This process consumes less energy and the cutting performance is much higher. Similar observations were made in trench cutting by Deketh et al. 1996. Although the net cutting rate in the fault material was excellent, the time spent by installation of the support increased much more, so that the advance per day dropped necessarily.

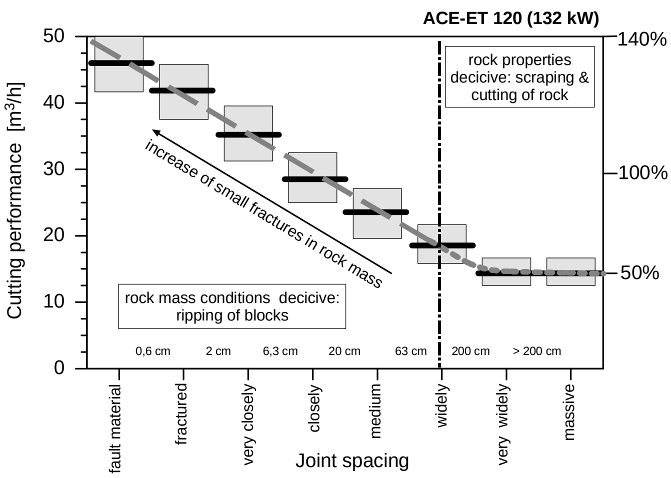


Fig. 12: Cutting performance of the AC-ET 120 versus joint spacing in argillaceous slates of the Zeulenroda sewage tunnel.

3.4 Underground Nuremberg

3.4.1 Project background and geological setting

For a better connection to the city´s airport, the underground system of Nuremberg (Bavaria) had to be extended. Thus in 1995 the excavation works for 3.3 km of new underground tunnels was begun.

The tunnels are built within sandstones and clay-siltstones of the upper triassic (Keuper, Fig. 13). Very hard dolomitic and calcitic calcretes ("Quacken") appear in some horizons.

Atlas Copco Eickhoff ET 380 L/Q roadheaders (200 kW power, 105 t total weight) were used on various lots of the new underground line. The excavation method was mostly successfull, but in some areas the roadheader excavation system suffered from severe problems with bit consumption or mucking, so that in these cases the whole excavation process was brought to the limit of its effectiveness.

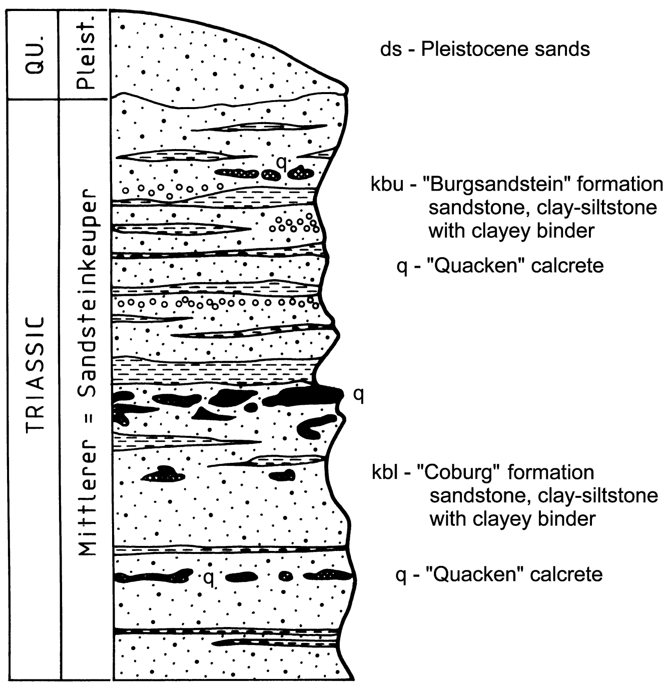


Fig. 13: Generalised scheme of the Keuper sediments encountered during the excavation works for the new underground system in Nuremberg.

3.4.2 Occuring problem: mucking

In one lot the performance of the roadheader proved to be far behind from what had been expected. Field studies soon discovered that this was not effected by poor cutting performance, but was indeed a problem of the roadheader´s mucking system. Due to the soft soil behaviour the muck haulage could not transport as much material as excavated by the cutter head. From time to time the cutting process had to be interrupted, so that the workers had time to shovel the forming mud into the haulage device.

3.4.3 Causes

The geological situation was consequently mapped throughout the excavation works. The geotechnical investigation program on both excavated material and undisturbed samples from the tunnel face included - among others - grain size analysis, water permeabilty tests, thin section analyses and powder swelling tests.

It was revealed that the mucking problem was clearly related to the amount of clay and silt in the excavated series. As shown in Fig. 14 the roadheader performance generally decreases with an increasing percentage of clay and silt. During the excavation process the clay- and siltstone-layers were cut to small debris by the roadheader. They were mixed together with sand from the sandstone-layers, that - unfortunately - are highly water permeable. In combination with the encountered water inflow of 2 - 5 l/sec this seemed to be the right mixture to form a water-saturated mud. This material could no longer be mucked by the roadheader´s muck haulage.

This model can also explain the flattening of the curve at higher amounts of clay and silt, which can be seen in Fig. 14: With an increasing percentage of clay and silt the amount of sand in the excavated material decreases and for this reason the material becomes less permeable for inflowing water.

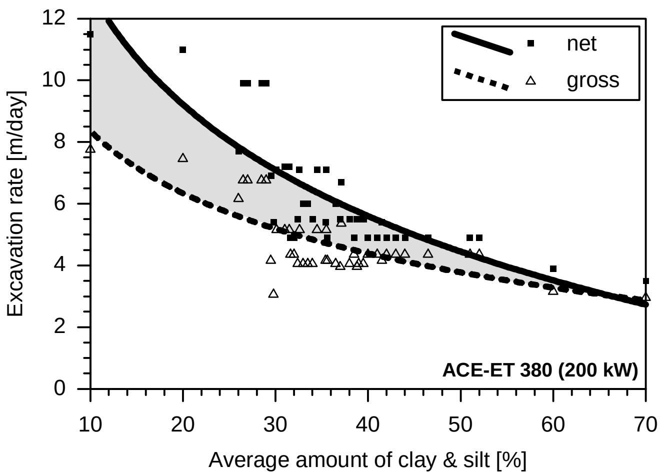


Fig. 14: Net and gross excavation rates versus average amount of clay and silt in the Keuper formation (“sandstones”) of the Underground Nuremberg.

3.4.4 Occuring problem: bit consumption

During the excavation work of another lot, the roadheader suffered from an immense bit consumption that reached amounts of up to 508 bits per day. Related to the excavated rock mass quantitity (solid) the specific bit consumption reached values up to 4 bits per m³.

3.4.5 Causes

A standard abrasivity testing program was carried out, including documentation of the bit wear characteristic, thin section analysis, analysis with the scanning electron microscope and laboratory tests of the rock´s compressive strength. Another valuable source data was found in the detailed notes and drawings of the tunnel face made by the roadheader´s engineer.

The assessment of about 100 used bits showed, that in most cases the hard metal bit was broken or even broken out of the bits steel body (wear type 4 and 5). This pointed at highly abrasive rock with a high compressive strength. Indeed there was a clear connection between enormous bit consumption and appearance of thicker calcrete layers. The highest wear of bits was achieved in an area, where two unjointed layers of calcrete were encountered with a thickness of 0.9 m and 0.5 m.

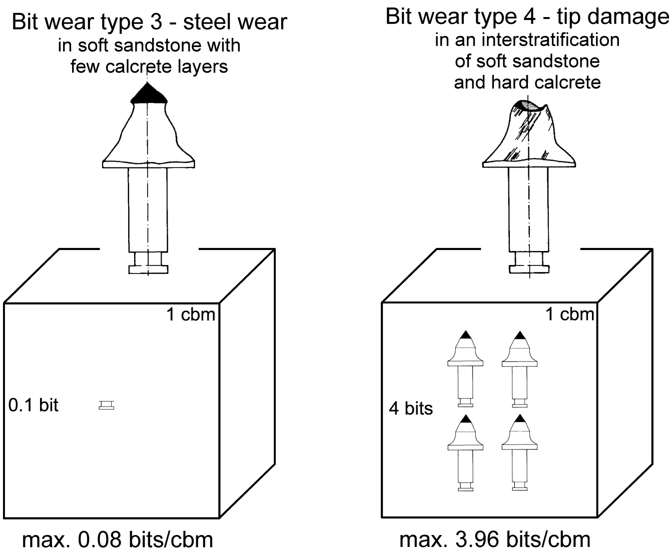


Fig. 15: Bit consumption per cubic meter in conditions with only few calcrete layers (left cube, steel wear) and with some thick, hard “quacken”-layers (right cube, tip damage & tip removal).

Although the investigations gave evidence of a high quartz content (up to 60 %) and a compressive strength of up to 180 MPa in these concretions, the immense bit consumption was not only effected by the abrading properties of the calcretes alone. The interchanging series of relatively soft sandstones and calcretes with a compressive strength of up to 100 MPa led to an increased breaking of the bits´ hard metal inserts: While the insert - made of tungsten carbide - are relatively resistant to grinding, their brittle behaviour makes them susceptible to hits, as obtained when the cutting head leaves a more soft sandstone layer and moves into a hard layer of calcrete. Since the broken or even broken out inserts can no longer protect the bit´s steel body from abrasion, the wear of such bits increases rapidly. Fig. 15 shows the clear differences between two neighbouring lots in bit comsumption and bit wear type - one with only few calcretes, the other with thick “quacken”-layers.

4 CONCLUSIONS

Based on the presented case studies, some general observations may be concluded:

① *Survey of the hardest layer*
Especially in rock material of heterogeneous composition - such as fanglomerates with hard components (⇨ Altenberg), sandstones with hard calcrete layers (⇨ Bad Wildbad, Nuremberg) or slate-quartzite-interstratification (⇨ Zeulenroda) - not the mean value but the "hardest inclusion" dominates the cutting performance and the tool wear. Especially the average performance follows the maximum values of the UCS, bit consumption is unfavourably affected by a combination of hard and soft layers leading to abundant bit breakage.

② *Survey of the softest layer*
Sometimes the "delicate link" causes problems - especially together with water (⇨ Nuremberg). Soft clayey sandstone forms mud with a distinct amount of water and cannot be removed by the roadheader´s haulage system. The cutting performance is ruined by mucking problems ("shovelling by hand"). Just in these conditions roadheaders should have the best excavation rates!

③ *Representative sampling*
Strange to mention - but always right: An insufficient sample rate and an insufficent number of rock tests may give an incomplete rendering of the facts (⇨ Zeulenroda). Representative sampling should contain the average and the maximum values (see ①). Sometimes it is necessary to search for the hardest components or layers and test them with field methods such as the point load test (⇨ Altenberg, Bad Wildbad, Nuremberg).

④ *Size effect*
When regarding problems in tunnel excavation, size effects are of crucial importance. Site investigations in view of rock fragmentation - dealing with problems in the range of several centimeters - must be completely different from that concerning tunnel stability - dealing with ranges of about 10 - 20 m.

⑤ *Geological Diversity*
Investigations should be attended by an experienced geologist and should focus on geological conditions and problems. A geological phenomenon may cause much more trouble in excavation than "just" higher rock strength values. Both geological-petrographical and geotechnical aspects should be taken into consideration to raise the level of geological contribution to underground construction.

Nevertheless the description of the large variety of geological and geotechnical influences on the effectiveness of cutting works may help to improve the estimation of rock excavation rates and bit consumption in planning future tunnel excavations.

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