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Hardrock abrasivity investigation using the Rock Abrasivity Index (RAI)

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ABSTRACT: The growing economic pressure on mining and tunnelling operations worldwide has led to an increasing demand for inexpensive and reliable investigation procedures in order to assess hardrock abrasivity. For such assessment a large variety of testing methods are possible. The "Rock Abrasivity Index" (RAI) introduced in 2002 represents an enhancement of the Equivalent Quartz Content (EQC). The RAI is calculated by multiplying a rock's UCS and EQC. Due to the wide availability of the input parameters and easy calculation, the RAI has since its introduction seen an increasing national and international use. Following 8 years of experience with this index, this paper summarises background information on abrasivity testing and remarks on the testing procedures used for RAI as well as experiences with and classifications for the RAI abrasiveness index.

1 INTRODUCTION

Regardless of whether we are dealing with conventional or TBM tunnel installation, blast hole drilling, anchor hole drilling or exploration drilling, the wear of tools used in rock cutting has always and will always represent a cost-intensive and performance-critical factor for rock excavation. Tool wear indeed does not only directly influence a project (e.g. tool and personnel costs related to changing worn tools) but will additionally influence the working cycle and the performance of the rock excavation process (Figure 1).

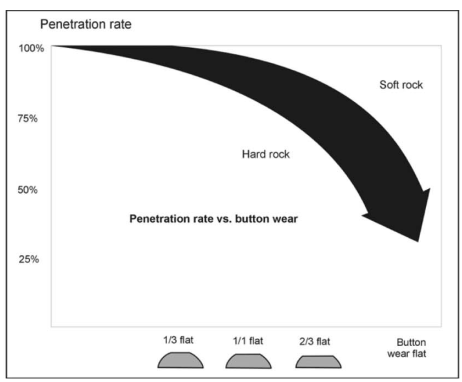


Figure 1. The wear of rock cutting tools represents a cost-intensive and performance-critical parameter. Left: inspection of roadheader cutter head. Right: Diagram showing the interaction of button wear and drill bit penetration (according to Atlas-Copco manual).

2 A SHORT DEFINITION OF ABRASIVITY

The term "abrasivity" describes the potential of a rock or soil to cause wear on a tool. Consequently, abrasivity is an important rock parameter to be determined and to be described in the course of any larger road, tunnel or mining project in order to allow the contractor to assess economical aspects of excavation methods.

As the potential to cause wear on a tool depends significantly on the specific circumstances of the observed system (e.g. involved tools, mechanisms of excavation, temperature, applied loads, etc.) it should nevertheless be kept in mind that rock abrasivity can never be an intrinsic physical parameter as for example rock strength.

3 OVERVIEW OF ABRASIVITY TESTING METHODS

Abrasivity investigation can be based on a wide variety of testing procedures and standards. For the estimation and discussion of such methods it is important to understand that the procedures cover a wide span of scale, ranging from on-site real-scale drilling tests to model tests with simplified tools and microscopic and chemical analysis of rocks and minerals (Figure 2). Depending on its individual scale and testing setup, each method is able to take different factors into account while disregarding others.

The focus of this paper is put on the Rock Abrasivity Index (RAI) in the context of geotechnical wear indices. For an up-to-date overview of other wear relevant procedures and

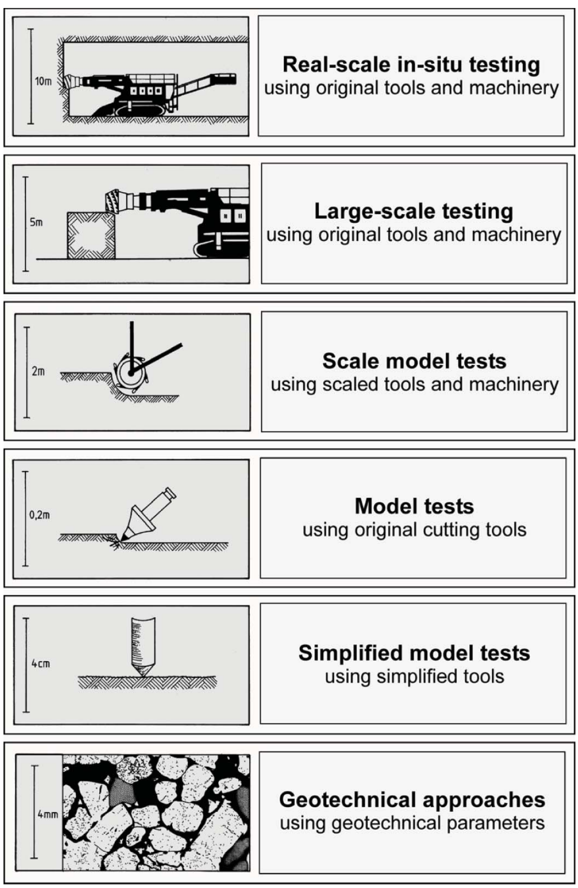


Figure 2. Scales of abrasivity investigation, shown for the example of roadheader operation.

indices including model testing setups like the CERCHAR or LCPC test. (Plinninger & Restner 2008).

4 A BRIEF HISTORY OF GEOTECHNICAL WEAR INDICES

Geotechnical wear parameters, based on simple rock and soil parameters represent a very common approach of engineering geologists to this topic. The role of quartz as a very common wear-relevant mineral was discovered early and the quartz content of a rock has to date remained a significant parameter for hardrock description. The use of hardness values, for weighting different minerals and their specific hardness, allowed inclusion of more minerals than just quartz into abrasiveness determination. Some of these hardness determination systems, developed in the early 20th century are still in use today: Mohs' scratch hardness (Friedrich Mohs, 1912–1924), Rosiwal´s grinding hardness (August Karl Rosiwal, 1896–1916) or Vicker's indentation hardness, developed in 1925 by Smith & Sandland and named after the British airplane company Vickers.

Widely used geotechnical wear indices based on these systems are for example the Abrasive Mineral Content (AMC), also referred to as "Mean Hardness", which uses Mohs hardness, the Equivalent Quartz Content (EQC), that uses Rosiwal grinding hardness and the "Vickers Hardness Number of the Rock" (VHNR), which is very common in Scandinavia and refers to Vickers indentation hardness.

Nevertheless the use of these indices, which are based on the rock's mineral content alone, reveal some weaknesses as other wear relevant rock features, such as grain size, grain shape and rock strength, are neglected. In order to understand the effect of this, one may compare the hypothetical abrasiveness of a loose quartz sand, a medium strength sandstone and a high strength quartzite with the same mineralogical composition—all three sediments would be described by the same EQC, VHNR or AMC value even if it is obvious that they will cause widely differing wear rates to the same tool!

As an example of how researchers have dealt with this problem, Figure 3 shows a diagram by Thuro (1997), where the drill bit lifetime of 45 mm button drill bits is plotted against the Equivalent Quartz Content of different rocks. In order to deal with the effect of widely

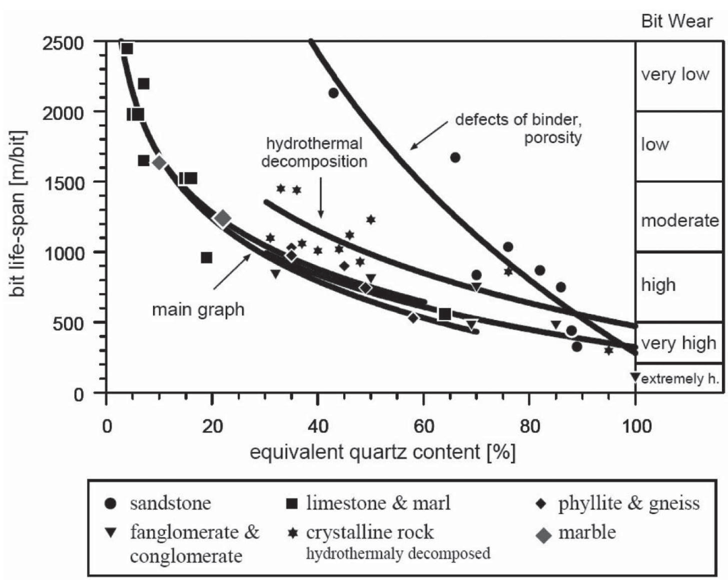


Figure 3. Drill bit lifetime plotted against the Equivalent Quartz Content for different rock types (Thuro, 1997, Fig. 10, p. 108).

differing drill bit lifetimes, different rock types have been identified and comprised to different graphs.

The main difference between the rock types selected for different graphs in Figure 3 is the differing binding, i.e. rock strength of the rocks. The medium to high strength rock types (crystalline rocks, phyllites, gneiss, limestone) form the "main graph" of highly abrasive rocks, while the other graphs, describe rock types that cause only moderate to low level abrasive wear, are formed by weak and decomposed rock types.

5 THE ROCK ABRASIVITY INDEX (RAI)

In order to overcome the weaknesses identified for conventional geotechnical wear indices like those presented in Section 4 below, the Rock Abrasivity Index (RAI) was introduced in 2002 (Plinninger, 2002) and first presented in the course of the 9th IAEG Congress in Durban, South Africa (Plinninger, Spaun & Thuro, 2002).

The RAI represents a modification to the Equivalent Quartz Content and is applicable mainly to hardrock but also suitable to weak rock types. Based on laboratory investigations in the scale of minerals and rock, the RAI is calculated for relevant rock types by multiplying the rock's Unconfined Compressive Strength (UCS) and Equivalent Quartz Content (EQC) according to equation 1.

$$\mathrm{RAI} = \sum_{i=1}^{n} \mathrm{A}_i \cdot \mathrm{S}_\mathrm{i} \cdot \mathrm{UCS} \qquad (1)$$

where RAI = Rock Abrasivity Index; UCS = Unconfined Compressive Strength [MPa]; A_i = specific amount of mineral [%]; S_i = Rosiwal grinding hardness referred to quartz = 100; n = number of all minerals.

When using these two core parameters, the RAI takes into account the content of abrasive minerals (which is especially relevant for abrasive wear) and the strength of the rock (which has found to be relevant for both, abrasive wear and wear due to breaking of tool parts (see Plinninger, Spaun & Thuro, 2002 for details).

In the context of geotechnical wear indices it should be pointed out that the basic principle of the RAI–the combination of mineralogical and mechanical rock parameters—does not represent a new approach. Quite similar approaches have been presented in the past with Schimazek's wear index (Schimazek & Knatz, 1970, 1976), which is calculated from quartz content, mean quartz grain size and Brazilian Tensile Strength or with the modified Schimazek wear index (Ewendt, 1989), which uses Equivalent Quartz Content, Point Load Index I_{50} and equivalent quartz grain size. Nevertheless, these two indices have only seen limited national and international use which might be related to the use of more difficult-to-obtain parameters like grain sizes or Brazilian Tensile Strength.

6 PRACTICAL ASPECTS OF DETERMINING THE RAI

The use of UCS and EQC as input parameters is one of the main reasons why the RAI has found a relatively fast and broad application since its introduction in 2002. These standard geotechnical parameters are available worldwide, in most cases already known from basic investigations (e.g. on the topic of stability assessment for underground openings) and are subject of various testing standards and recommendations which also assures their reliability. Additionally, the use of standard parameters allows what a special model test does not allow. That is the use of experiences and empirical estimations where no measurements are available and the possibility for empirical judgement on how representative a chosen value is.

The following discussion is intended to give background information and practical experiences for the laboratory investigation methods for the RAI input parameters.

6.1 *Investigation of mineral content by use of thin section analysis*

The qualitative and quantitative investigation of petrographical thin sections represents a very common investigation procedure for hardrock, also covered by an ISRM Suggested Method (ISRM, 1978a). Typical thin sections measure about 25 µm in thickness and 28 mm × 48 mm in size so that even very small hand specimen or TBM-chippings are suitable for testing. By use of special measures, e.g. impregnation with special resin even weak and non-durable rock types can be investigated. Limits to the application of this method are encountered when there are no sufficient samples available (e.g. from destructive DTH drilling) or if the rock fabric is too fine for qualitative and quantitative identification (especially fine grained igneous rocks or mudstones, claystones, siltstones). In such cases it can useful to rely on X-ray diffractometer techniques as alternative investigation methods as described in the following section 6.2.

6.2 *Investigation of mineral content by use of X-Ray Diffractometer Analysis (XRA)*

The identification of minerals by use of X-Ray Diffractometer Analysis (XRA) represents a technically different approach compared to petrographical thin section analysis. Instead of mineral identification by optical means, this method measures and identifies the diffraction of X-Ray radiation at the surface of mineral crystals in a powder sample. Modern diffractometers are capable of relatively fast and reliable identification and quantification of the mineral content by use of PC-guided systems. Thus XRA represents a good supplementary method for determining mineral content, especially when no thin section analysis can be performed.

6.3 *Unconfined Compressive Strength testing*

Unconfined Compressive Strength (UCS) represents one the most common parameters for describing intact rock strength in the field of engineering geology and rock engineering. In an international context the testing itself is subject to various testing standards such as the ISRM Suggested Method (1979). Additionally it should be mentioned that the data presented in this paper relates to UCS specimen with a length-diameter-ratio of 2:1.

Besides well known technical aspects which relate to UCS testing (like accuracy of the testing setup, loading rate or sample geometry) there are also a number of geotechnical influences (like the orientation of anisotropic rock types or the water content of weak rock types) that can play an important role for the resultant parameter. Additional information on those topics can be found in the paper by Plinninger, Bruelheide & Nickmann (2010) on representative sampling.

The high demands on the number and quality of samples for UCS testing represent some limitation for this method, especially when broken, jointed or anisotropic rock types have to be investigated. In such cases it can useful to rely on alternative methods as described in the Section 6.4 below.

6.4 *Indirect strength determination*

The use of indirect testing methods to determine rock strength may be useful if UCS tests cannot be performed in the necessary quantity or quality. Testing principles applicable for this purpose are for example the Point Load Test, (ISRM, 1985) or the Schmidt Hammer Test (ISRM, 1978b). The Point Load Test especially represents an easy-to-use method which can also be conducted on site due to relatively small testing equipment and little demands regarding test specimen. Pieces of drill cores and blocks can be tested as well as irregularly shaped hand specimens ("irregular lump tests"). Especially when advanced test result evaluation methods (see Thuro & Plinninger, 2001) are used to calculate the average Point Load Index (PLI) from a larger number of point load tests and site and rock type-specific conversion factors are used for assessment of UCS from the PLI, such statistically derived parameters may give a better understanding of the rock's strength than a small (non-representative) number of UCS tests.

7 CORRELATIONS WITH OTHER WEAR-RELEVANT INDICES

A correlation between the Rock Abrasivity Index (RAI) and the widely used CERCHAR Abrasivity Index (CAI) are derived from a model test shown in Figure 4. Besides the graphical solution shown in Figure 4, Schumacher (2004) derived a practically useful square function as given in equation 2.

$$CAI = 0.9 \cdot \sqrt[3]{RAI} \quad (2)$$

where CAI = CERCHAR Abrasivity Index; RAI = Rock Abrasivity Index.

8 EXPERIENCES

Based on the experiences gained with the RAI since 2002, Figure 5 gives typical values and value ranges for some of the most important types of sedimentary, metamorphic and igneous rocks.

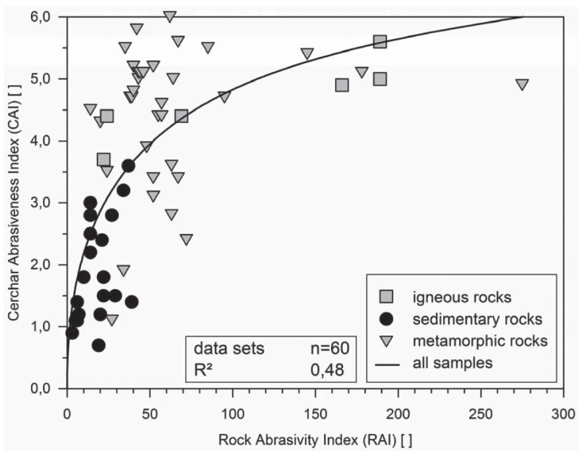
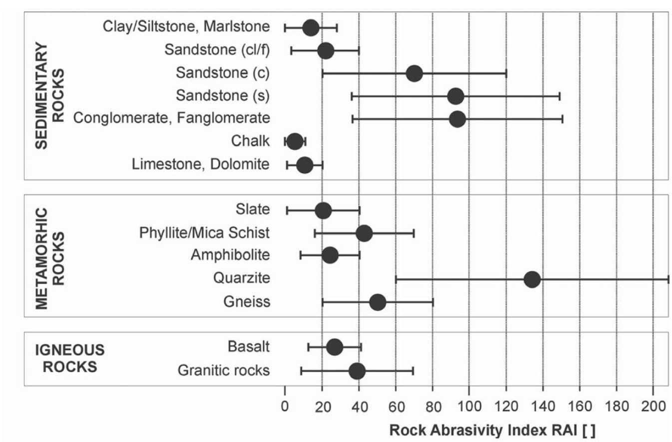


Figure 4. Empirical correlation between CAI and RAI, gained from 60 rock types tested with both methods.



(cl/f) – clay/ferritic binder; (c) – carbonatic binder, (s) – siliceous binder

Figure 5. Typical RAI values and value ranges for different rock types.

The maximum RAI values determined by the author so far were measured for Ordovician quartzites: Table Mountain Quartzites of Port Elizabeth, South Africa with RAI values of about 360 and quartzites of the so called Frauenbach Formation in Thuringia, Germany with RAI values of up to 200. Values of up to RAI = 400 seem possible for technically relevant rock types. There is no lower limit for RAI from definition, but effectively the lower limits are technically defined by the possibility to gain strength values from weak to very weak rock types.

9 RAI CLASSIFICATION

A classification for rock abrasivity was first published in Plinninger (2002) and has since proved suitable for the verbal description of rock abrasivity by use of the RAI (Table 1).

10 PREDICTING TOOL WEAR WITH RAI

The RAI has shown good results for the estimation of button bit wear. Based on numerous case studies for conventional drill and blast tunnelling projects in Western Europe, the prediction diagram given in Figure 6 was developed for ∅ 38–56 mm button drill bits (Plinninger, 2002).

Even if there is no sufficient database available to date for similar correlations of RAI and the specific wear of point attack picks (roadheader excavation) or cutter discs (TBM tunnels), a growing number of contractors have begun using the RAI in the field of their activities. One recent example is the use of RAI for the assessment of drill tool consumption for large diameter (∅ 900–1200 mm) bored piles by German drilling equipment manufacturer and geotechnical engineering contractor Bauer Spezialtiefbau (Beckhaus & Thuro, 2008).

Table 1. Classification of Rock Abrasivity from RAI.

RAI	Classification
<10	Not abrasive
10–30	Slightly abrasive
30–60	Abrasive
60–120	Very abrasive
>120	Extremely abrasive

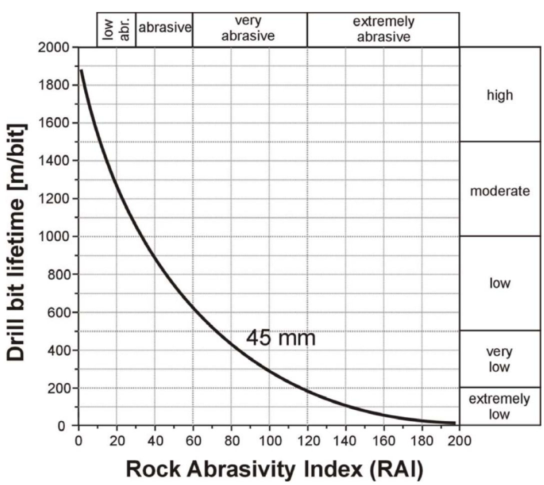


Figure 6. Drill bit lifetime for ∅ 45 mm button drill bits, plotted against the RAI.

11 CONCLUSION

Since its introduction in 2002 the Rock Abrasivity Index (RAI) has proven its value as an easy-to-use parameter for the description and classification of hardrock abrasivity. The input parameters (UCS and EQC) are very common and subject of various testing standards and recommendations which also assures international reliability of the these parameters. Even if problems in the determination of UCS or thin section analysis are encountered, there are well known alternatives available (like X-Ray Diffraction Analysis or Point Load Test).

Nevertheless it should be kept in mind that the RAI value is a geotechnical wear index, derived from laboratory tests from small scale samples and mineral/rock scale investigations. The representative assessment of RAI value distribution for a whole rock series or project as well as the assessment of other wear-relevant rock mass scale influences remain a challenging task for engineering geologists and rock engineers.

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