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# Anisotropic rock strength properties - an important issue for site investigation and excavation assessment

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ABSTRACT: Intact rock strength, usually characterized by Unconfined Compressive Strength (UCS), represents a key parameter for performance and tool wear assessment for any hardrock excavation methods, i.e. TBM, drill & blast, roadheader or other mechanical excavation. An accurate assessment of UCS and its variation is therefore of crucial importance in the course of any preliminary site investigation in order to allow for appropriate tender baselines and reasonable bid estimates. Although "intact rock" is usually understood as a small volume of rock material, that behaves as a continuum and shows no significant influence of discontinuities, many rock types, including a majority of sedimentary and metamorphic rocks, might still incorporate internal structural features like lamination, bedding or foliation, which might not be discontinuities by definition, but might cause directional dependent behaviour. If insufficiently considered during sampling, testing and interpretation, such features inherit the risk of artificially biassed strength results and unnecessarily broad value ranges which might even question the overall significance of UCS as input parameter. This paper includesexperimental test results on directional strength behaviour, presents approaches for the classification of anisotropy, displays examples for the practical impact of anisotropy on strength and states recommendations for sampling and testing of such rock types.

## 1 TERMS AND DEFINITIONS

This paper is intended to analyse practical aspects of anisotropic strength properties with regard to the assessment of intact rock strength. The relevant terms shall be defined as follows:

Intact rock: A smaller volume of ground, that behaves as a continuum and shows no influence of discontinuities and thus represents a smaller subset of a rock mass. However, intact rock may still incorporate internal rock structures („integral discontinuities") and can show either isotropic or anisotropic behavior.

Anisotropic behaviour: Directionally dependent geomechanical behavior of rock used in contrast to isotropic behavior. Such properties result from a rock´s mineral composition and fabric, i.e. if minerals with significant anisotropic properties (for instance phyllosilicates, like mica or clay minerals) are included in the rock´s composition, they might cause anisotropic behavior when structurally distributed and orientated by sedimentation (lamination, bedding) or metamorphosis (foliation).

Isotropic behaviour: Directionally independent geomechanical behavior of a rock. The term is usually used in contrast to anisotropic behavior.

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Additionally, it should be kept in mind, that it is mandatory to relate any assessment of anisotropic properties to a specific scale of investigation: A geological body may show significant variation in its directional dependent behaviour if related to mineral (few mm), rock (cm – dm) or rock mass scale (m – dam). According to the topic of this paper, i.e. the assessment of intact rock strength, the experience and data presented in general relates to the "rock scale" in the size of usual UCS specimen (i.e. Ø 30 mm – 120 mm).

## 2 EMPIRICAL RESULTS FROM ORIENTED UCS TESTING

Figure 1 summarizes test results from 26 rock types of significantly varying anisotropic behaviour, which have been compiled from testing data from the authors as well as numerous international publications. The data set comprises 5 sedimentary rock types (clayey limestone, limestone, sandstone, coal and travertine) and 21 metamorphic rock types (including several shale, slate, phyllite, schist and gneiss types). As a reference, the hypothetical behaviour of an ideally isotropic rock is added to the diagram with data points and line in red colour.

The orientation angle ß of the anisotropic feature (x-axis) refers to the angle between loading axis and anisotropic feature. On the y-axis, the relative UCS is plotted, referred to the maximum UCS measured in tests perpendicular to the axis of anisotropic features at ß = 90°. As far as could be determined from the referred publications, results refer to "usual" UCS tests on cylindrical specimen with a length: diameter-ratio of about 2.0 to 2.5 according to ISRM 1979 or similar testing standards. It should be noted in the context of testing conditions and sample geometry, that tests on cubic samples or cylinders with a l:d-ratio of < 1.0 will lead to significantly differing results.

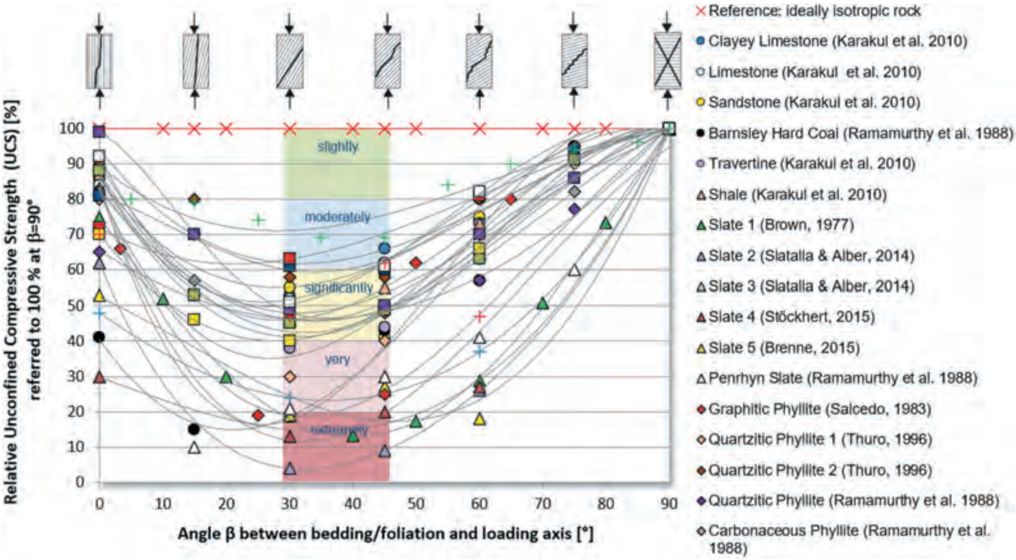


Figure 1. Compilation of empirical UCS testing results showing the variation of relative UCS (y-axis) with varying angles between loading axis and orientation of the anisotropic features (x-axis). Plotted are results from 26 rock types which are described by polynomial regression lines. Anisotropy classification according to the "anisotropy index" AI (see Section 3) is displayed in the background in the referring section between of approximately 30 - 45°.

The data plotted in Figure 1 shows, that for all tested rocks the minimum compressive strength was found at an angle of 30° < ß < 45°, while the maximum compressive strength was generally found at ß = 90° (used as 100% reference in the diagram). The relative UCS at a 0° angle (i.e. tests parallel to anisotropic structure elements) did reach levels of 30-99 % of maximum UCS, which leads to a distinctive asymmetrical shape of the polynomial regression curves.

The most striking impression from this compilation is the wide variation in minimum compressive strength, which covers a range of 4 % (slate) to 70 % (Koralm Gneiss). It appears evident, that the minimum level of rock strength is able to characterize the mechanical relevance of anisotropic behaviour as further displayed in the following Section 3. Figure 2 shows examples of the fracture pattern depending on the orientation of loading with respect to their anisotropic properties.


Figure 2. Examples of samples and fracture pattern in anisotropic samples.

## 3 CLASSIFICATION OF ANISOTROPIC BEHAVIOUR

In order to establish defined boundary criteria for distinguishing "isotropic" from "anisotropic" behaviour and to develop comprehensible baselines for terms like "very anisotropic" or "extremely anisotropic" behaviour, a number of methods has been presented (Broch 1983, Singh et al. 1989). Plinninger (2002) proposed the so-called "anisotropy index" (AI), which is defined as follows:

$$AI = \frac{\sigma_C \text{ min}}{\sigma_C \text{ max}} \tag{1}$$

where $\sigma_{c\ max}$ is the UCS measured at right angle to the anisotropic feature ($\beta$ = 90 °) and $\sigma_{c\ min}$ is the lowest value of UCS measured at 30° < ß < 50°.

A practical classification of anisotropy according to the AI is given in Table 1.

Table 1. Classification of the "anisotropy index" AI (Plinninger 2002), English terms added.

| $AI = \sigma_{c\ min} / \sigma_{c\ max}$ | Classification term | Example |
|---|---|---|
| 1.0 | ideally isotropic | granite, basalt |
| 0.8-1.0 | slightly anisotropic | quartzite |
| 0.6-0.8 | moderately anisotropic | gneiss, limestone |
| 0.4-0.6 | significantly anisotropic | mica schist, quartz phyllite, sandstone |
| 0.2-0.4 | very anisotropic | phyllite, slate |
| < 0.2 | extremely anisotropic | slate with excessive foliation |

## 4 POTENTIAL IMPACT OF ANISOTROPY ON PERFORMANCE ESTMATES

Actual UCS testing standards and recommendations do usually not include any suggestions for sampling and testing strategies in potentially anisotropic rock. Nevertheless, it is obvious, that neglecting anisotropic effects during sampling, testing, reporting and data interpretation in relevant rock types inherits the risk of misleading (usually too low) rock strength characteristics which might cause cost and time intensive misinterpretations regarding the application of excavation techniques or regarding estimates on excavation performance and tool wear.

Figure 3 presents the results of a simulation, which is intended to depict the potential impact of anisotropic behaviour on measured rock strength. The blue distribution shows the gauss-normal distribution of test results for a (hypothetical/ideal) rock with an average UCS of 100 MPa as derived from testing solely perpendicular (β = 90°) to the anisotropic features. This distribution is well-suited to describe the "intrinsic" properties of this rock type and to reflect the "natural" variation in intact rock strength.

Let´s now assume, that the considered rock features some kind of lamination or foliation, that causes "very anisotropic" behaviour (i.e. AI = 0.2-0.4) and testing is no longer performed in a strictly oriented manner, but with random orientation of β = 0° to 90° in each test. According to the findings displayed in Section 2 of this paper, this testing strategy now leads to a significant number of tests results, which deliver too low test results (according to the specific angle β in the specimen), so this testing setup adds an "artificial" (i.e. angle-related) variation to the already "natural" variation of rock strength. The resulting distribution - depicted with the red columns in Figure 3 - is obviously not suited to reasonably reflect the original intact strength properties of the tested rock. However, it should be noted in the context of this simulation, that the calculations for the "red" distribution were performed on the assumption of a "true random" orientation, i.e. each any angle being represented with the same number of tests. If testing is biassed towards one or another angle, literally any distribution can be obtained.

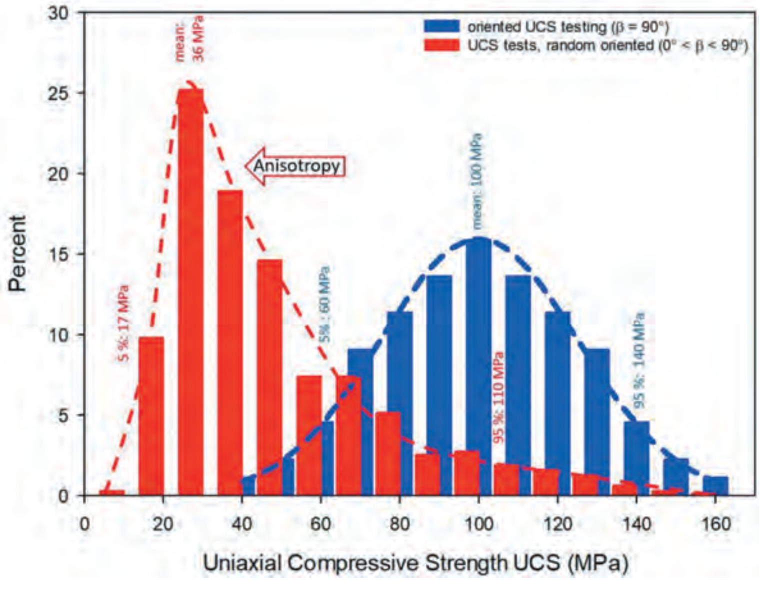


Figure 3. Results of a simulation of test results from oriented testing (blue) versus tests with random orientation (red) for a hypothetical rock with ideal gauss-normal strength distribution and "very anisotropic" behaviour.

The impact on practical aspects of tunnelling becomes evident when these two data sets are used as input for estimates on excavation performance, for instance for the assessment of Net Cutting Rate (NCR) of a heavy duty roadheader. As lucidly depicted in Figure 4, testing with random orientation has a significant impact on the performance estimates, leading to an (artificial) 5 times increase in bandwidth and an average NCR, which is 2.5 times higher than the (more reasonable) estimate, which is based on the average of oriented UCS tests.

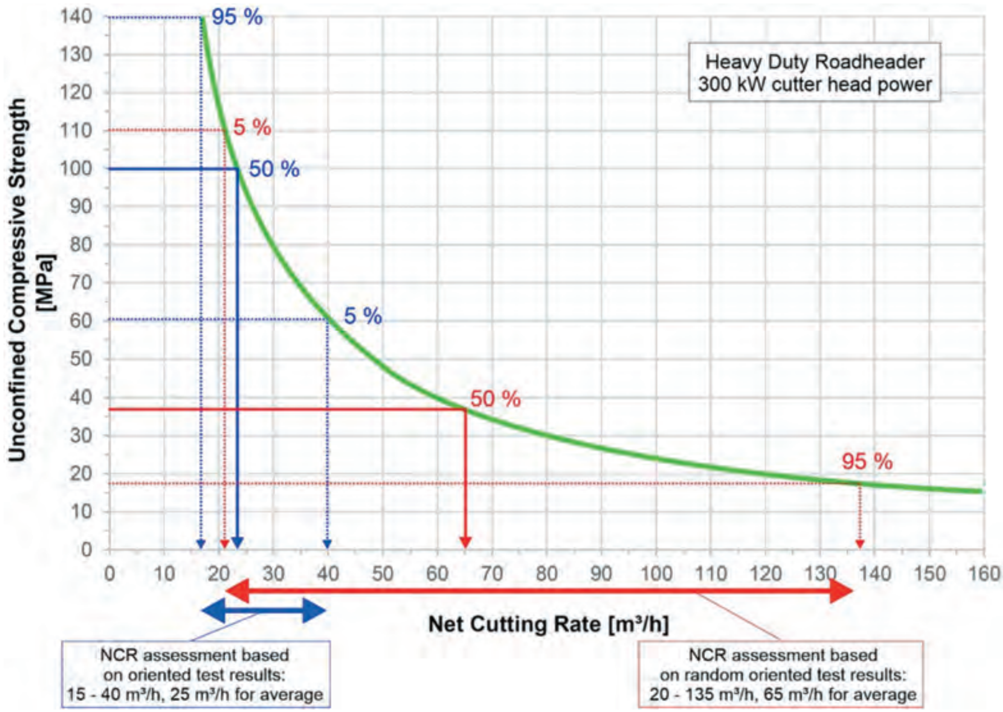


Figure 4. Impact of the two simulated test result distributions according to Figure 2 on the assessment of Net Cutting Rate (NCR) for a heavy duty roadheader. Blue arrows indicate NCR estimates for the results from oriented UCS testing (15-40 m³/h), red arrows indicate the (misleading) NCR estimates as can be derived from the results of randomly oriented UCS testing (20-135 m³/h).

## 5 SUGGESTIONS FOR ORIENTATED SAMPLING AND TESTING

As displayed in the previous sections, the assessment of potentially anisotropic rock behaviour and the implementation of strategies to overcome inherent problems are fundamental tasks in the course of any profound preliminary site investigation. In order to be able to reliably identify, classify and to assess anisotropic behaviour, oriented sampling and testing is mandatory for relevant rock types in order to at least derive the following rock properties:

- reporting of intact “normal” rock strength (i.e. σc max/σc 90 at ß = 90°);
- characterization and classification of the rock specific degree of anisotropy;
- optional reporting of the rock specific, full angle-dependent anisotropic characteristics.

In order to meet these requirements, the following recommendations can be concluded:

- Top priority should be to perform a majority of UCS tests perpendicular to foliation/lamination/bedding (ß = 90°) in order to derive the maximum intact UCS (σc max/σc 90). Such tests are irreplaceable, since it is technically impossible to reliably extrapolate this property from any other tests at differing angle.

- Second priority should be to perform a statistically sufficient quantity of tests at an angle of 30° ≤ ß ≤ 50° in order to assess minimum intact UCS (σc min) which can be used to characterize the rock specific degree of anisotropy, for instance by use of the AI index as described in Section 3 of this paper.
- Additional tests at other angles of 0° ≤ ß ≤ 90° might be also carried out in order to be able to derive a "full angle" rock specific curve for anisotropic behaviour. However, it might be kept in mind, that especially for hardrock excavation assessment; the knowledge of the full angle-dependent behaviour might play an only minor role.

In order to gain the required oriented samples, the following procedures can be carried out:

- performing orientated on-site core drilling in order to gain core samples with defined orientation in any diameter (note: problematically in formations with varying orientation of foliation or bedding planes during depth of drill hole);
- performing primarily non-orientated (i.e. usually vertical) on-site core drilling and then (secondarily) gain orientated samples by overcoring in the laboratory. From own experience, drill cores of ≥ 120 mm in diameter are sufficiently large for the preparation of cylindrical specimen of ≤ 50 mm in diameter of any orientation (Figure 5, left scheme);
- sampling of larger rock blocks and overcoring them on site or in the laboratory to gain orientated samples (see Figure 5, right photo)

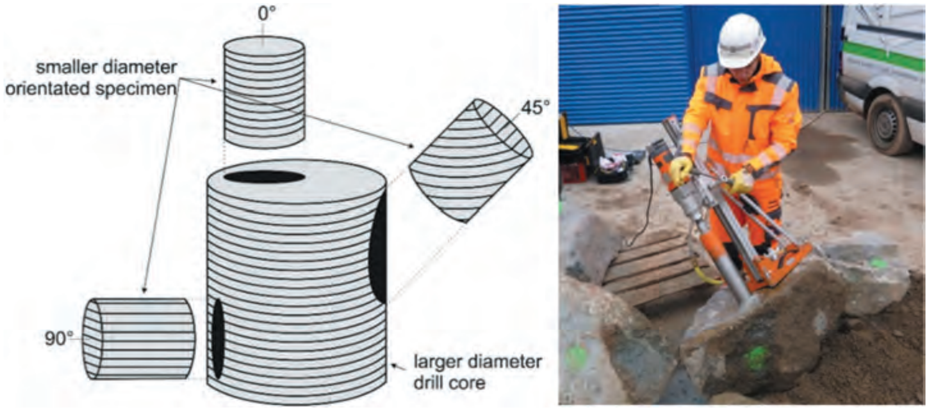


Figure 5. Left figure: Concept drawing for overcoring of a larger core sample in order to gain orientated specimen of smaller diameter. Right photo: Impression of Overcoring of block sample on site.

## 6 CONCLUSIONS

Many rock types exhibit anisotropic strength characteristics. Without any further knowledge, such behaviour should be expected for any type of metamorphic rock (foliation), but also for sedimentary rocks with obvious lamination or bedding structures. A compilation of experimental test data of rocks from all over the world shows that the specific degree of anisotropy, expressed by the anisotropy index AI (AI = σc min /σc max) varies significantly between 0.04 ("extremely anisotropic") to 0.7 ("moderately anisotropic") and there is no reason to assume, that values of 0 to 1 shouldn´t be geotechnically possible.

Neglecting the dependency of measured results from Unconfined Compressive Strength (UCS) tests on the orientation of test specimen might lead to biassed (i.e. significantly lower) strength measurements and artificially extended value ranges. It can be demonstrated, that the use of such erroneous UCS data might lead for instance to way too high estimates of the Net Cutting Rate of a roadheader. The same applies to other estimates, for instance on TBM penetration rates or drilling rates in anisotropic hardrock conditions. It is therefore mandatory to appreciate anisotropic strength characteristics by applying special care to the sampling and testing of relevant rock types and to perform oriented testing which is able to reliably identify maximum UCS (testing at orientation ß = 90°, i.e. perpendicular to foliation/lamination/bedding) and the specific degree of anisotropy.

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