Assessment of Intact Rock Strength in Anisotropic Rock - Theory, Experiences and Implications on Site Investigation

Ralf J. Plinninger
Dr. Plinninger Geotechnik, Bernried, Germany

Michael Alber
Engineering Geology / Rock Engineering, Ruhr-University Bochum, Bochum, Germany

ABSTRACT: Intact rock strength, usually determined by Unconfined Compressive Strength tests, represents one of the key parameters for performance and tool wear assessment in any hardrock excavation. An accurate assessment of this parameter during preliminary site investigation and undergoing operation is therefore of crucial importance in order to allow appropriate predictions as well as objective contractual discussions. Unfortunately, anisotropic rock behaviour may significantly influence UCS testing and interpretation of intact rock strength. The presented paper resumes the current knowledge regarding this topic, including empirical experience on specific anisotropic behaviour of different rock types, definition and experiences for the "Anisotropy Index" (AI) as well as experiences on sampling strategies and actual project application.

1 THE EFFECT OF ANISOTROPY ON ROCK STRENGTH ASSESSMENT

1.1 Defining "anisotropic behaviour"

In the context of engineering geology and geotechnical engineering "anisotropy" may be defined as directionally dependent geomechanical behaviour. The term is usually used in contrast to "isotropic" behaviour, which characterizes a material with uniform, directionally independent properties. In rock mechanicals literature, the term "anisotropy" is often traced back to the definition of Jaeger 1969, who used the term for the effect of a single plane of weakness on the strength of a cylindrical specimen. The models referred to nowadays do actually differ from this and usually refer to a specimen, that features a set of parallel discontinuities with theoretically infinitely dense spacing.

Mechanically anisotropic behaviour of rock is a result of the rock´s mineral composition and the geological processes that have formed it. If minerals with significant anisotropic properties are included in a rock, they might cause anisotropic rock behaviour when they are structurally distributed and orientated. Common minerals, which cause rock anisotropy, are layered silicates, like clay minerals or mica minerals, which may primarily be orientated by sedimentation (→ lamination, bedding planes) or secondarily be orientated under a specific stress regime during metamorphosis (→ schistousity / foliation, see Figure 1, left).

As a matter of this, sedimentary rocks and metamorphic rock types do quite commonly feature anisotropic properties. However, even if igneous rock types, like granite or diorite are common examples for isotropic behaviour, it should be kept in mind that for instance fluidal magmatic structures might also be existent in those rock types, which might cause anisotropy.

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 a mineral (few mm), rock (cm – dm) or rock mass scale (m – dam). According to the topic, the assessment of intact rock strength, the experience and data presented in this paper do in general relate to the “rock scale” in the size of usual UCS specimen.

1.2 The impact of anisotropic behaviour on intact rock strength assessment

Intact rock strength, usually expressed as Unconfined Compressive Strength (UCS) is a widely used key parameter for the assessment of performance and tool wear in almost any hardrock excavation method, for instance TBM tunnelling (Gehring, 1995), drilling (Thuro, 1996) or roadheader excavation (Thuro & Plinninger, 2002).

However, it is an incontrovertible fact, that anisotropic structure elements will have a significant impact on rock UCS, which is not only proven empirically (refer to Section 2), but can also be derived from rock mechanical theory or numerical models, such as the PFC models established by Schormair (Schormair, Thuro & Plinninger 2006, see Figure 1, right).

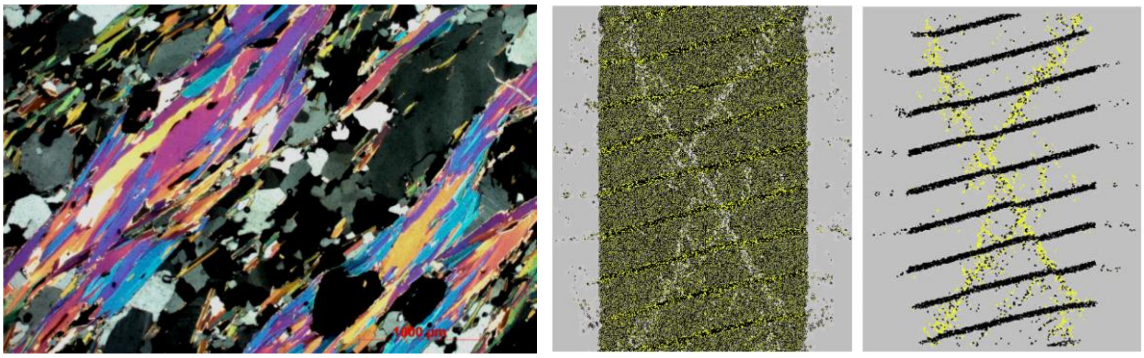

Figure 1. Left figure: Petrographical thin section of a highly foliated mica schist under polarized light, showing distinct layers of platy, multi-coloured mica (muscovite) and grey layers of quartz and feldspar at an 45° degree angle. Right figures: Example for Particle Flow Code (PFC) model of an Unconfined Compressive Strength Test on an anisotropic rock sample at 75° degree angle (from: Schormair, Thuro & Plinninger, 2006, Fig. 11, p. 10).

It is evident from these dependencies, that the interpretation of such results, the assessment of the rock-specific degree of anisotropy and the assessment of the maximum rock strength at a 90° angle between loading axis and anisotropic element is an important task during preliminary site investigation in order to obtain representative results for rock excavatability assessment.

Neglecting anisotropic effects during sampling, testing, reporting and data interpretation in relevant rock types inherits the risk of misleading (usually too low) rock strength values which might cause cost and time intensive misinterpretations regarding the application of excavation techniques or regarding estimations on excavation performance and tool wear.

2 EMPIRICAL RESULTS

2.1 Reference testing conditions and angle definition

The results presented in the following Section refer to UCS tests on cylindrical specimen with an length : diameter-ratio of about 2.0 to 2.5 according to ISRM 1979 / DGGT 2004 testing recommendations. 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.

The orientation of the anisotropic feature (angle ß) is usually defined either as the angle between the direction of loading and the orientation of the anisotropic features or as the angle between loading and the normal of the feature, the latter usually correlating with the angle between the anisotropic feature and a horizontal reference plane. In the course of the presented paper, all given angles are referred to the angle between loading axis and anisotropic features.

2.2 Empirical results for UCS tests on anisotropic rock

Figure 2 resumes testing results on 10 rock types of significantly varying anisotropic behaviour, including three types of slate (Brown, et al. 1977; Slatalla & Alber, 2014), two types of quartz phyllites (Thuro, 1996) and five types of schists with varying amounts of mica from several project locations (Slatalla & Alber, 2014; Nasseri et al., 2003). As reference, the hypothetical behaviour of an ideally isotropic rock is added to the diagram with data points and line in red colour.

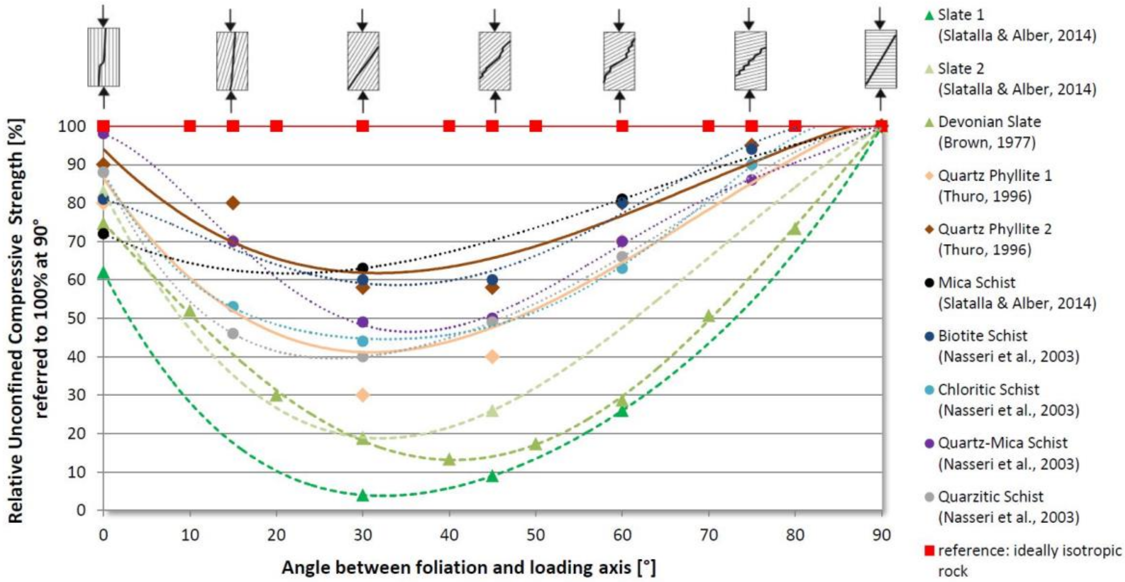

Figure 2. Compilation of empirical UCS testing results showing the variation of relative UCS (y-axis) with varying angles between loading axis and orientation of the anisotropic features (x-axis). Plotted are results from 10 rock types which are described by polynomial regression lines.

The data plotted in Figure 3 shows, that for all tested rocks the minimum compressive strength was found at an angle of 30° < ß < 50°, 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 (tests parallel to anisotropic structure elements) did reach levels of 60-98% of the 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 values of minimum 4 % (slate) to maximum 65 % (mica schist). It appears evident, that the minimum level of rock strength is able to characterize the mechanical relevance of the existing foliation.

3 CLASSIFICATION OF ANISOTROPIC BEHAVIOUR

In order to establish defined boundary criteria for distinguishing “isotropic” from “anisotropic” behaviour and to develop comprehensible baselines for widely used terms like “highly anisotropic” behaviour, a number of methods has been presented so far:

- Broch 1983 obtained a strength anisotropy index (Ia(50)) from point load test, which refers to the maximum and minimum Point Load Indices obtained from tests normal and parallel to the weakness planes.
- Singh et al. 1989 introduced the so-called “anisotropy ratio” (R_c), which was defined as $R_c = \sigma_{c\ 90} / \sigma_{c\ min}$, where $\sigma_{c\ 90}$ is the UCS measured at right angle to the foliation / bedding (Table 1).

Table 1 Classification of the “anisotropy ratio” R_c (Singh et al. 1989)

$R_c = \sigma_{c\ 90} / \sigma_{c\ min}$	Classification term	Example
1.0 – 1.1	isotropic	
1.11 – 2.0	low anisotropy	shale
2.01 – 4.0	medium anisotropy	
4.01 – 6.0	high anisotropy	slate
> 6.0	very high anisotropy	phyllite

- Unaware of the “R_c” approach, Plinninger 2002 used the same input parameters to calculate a reciprocal index value, the so-called “anisotropy index” (AI), which was defined as $AI = \sigma_{c\ min} / \sigma_{c\ max}$, where $\sigma_{c\ max}$ is the UCS measured at right angle to the foliation / bedding (Table 2). Given this definition, the AI is rated as an easy-to-apply and easy-to-interpretate index value for anisotropy quantification.

Table 2 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, massive limestone
0.8-1.0	slightly anisotropic	gneiss, quartzite, massive sandstone
0.6-0.8	moderately anisotropic	laminated sandstone
0.4-0.6	significantly anisotropic	mica schist, quartz phyllite
0.2-0.4	very anisotropic	phyllites, slates
< 0.2	extremely anisotropic	slates with excessive foliation

As an example for application, the empirical results presented in Section 2 of this report have been classified as presented in Table 3. It is obvious, that the classification terms derived from the AI application are able to distinguish the different degrees of anisotropic behaviour and are able to provide plausible verbal terms for their description.

Table 3 Example for the classification of the “anisotropy index” AI

rock type	UCS_{min} [%]	AI	Classification term
Slate 1	4 % at 30°	0.04	extremely anisotropic
Slate 2	19 % at 30°	0.19	extremely anisotropic
Devonian Slate	13 % 40°	0.13	extremely anisotropic
Quartz Phyllite 1	30% at 30°	0.30	very anisotropic
Quartz Phyllite 2	58% at 30°	0.58	significantly anisotropic
Mica Schist	63% at 30°	0.63	moderately anisotropic
Biotite Schist	60 % at 30°	0.60	moderately to significantly anisotropic
Chloritic Schist	44 % at 30°	0.44	significantly anisotropic
Quartz-Mica Schist	49% at 30°	0.49	significantly anisotropic
Quartzitic Schist	40 % at 30°	0.40	significantly to very anisotropic

4 EXPERIENCES ON ORIENTATED SAMPLING AND TESTING

In order to gain specifically orientated samples, three different sampling procedures might be used:

- to perform 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);
- to perform primarily non-orientated (i.e. usually vertical) on-site core drilling and then (secondarily) gain orientated samples by overcoring. 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 (see Figure 3, left scheme);
- to sample larger blocks on site and then (secondarily) overcore them on site or in the laboratory to gain orientated samples of any diameter (see figure 3, right photo)

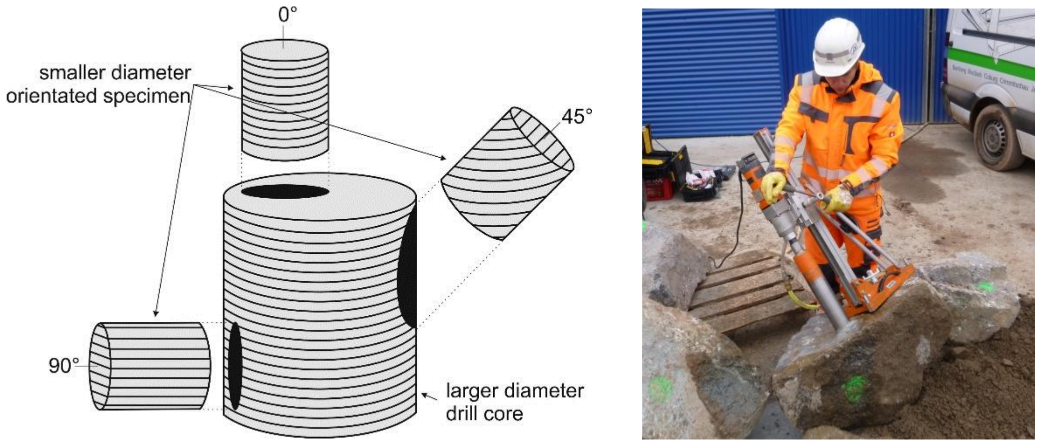

Figure 3. Left figure: Concept drawing for overcoring of a larger core sample in order to gain orientated specimen of smaller diameter. Right photo: Impression of Overcoring of block sample on site. This procedure allows an economical gain of orientated samples.

According to the referring testing standards and recommendations (for instance ISRM 1979, DGGT 2004) the documentation of the orientation of bedding planes, foliation, schistosity etc. in the testing protocol is mandatory for tests on anisotropic rock for obvious reasons. An additional photographic documentation before and after the test will allow a retrospective analysis, if necessary.

5 CONCLUSIONS AND RECOMMENDATIONS

Neglecting anisotropic effects during sampling, testing, reporting and data interpretation in relevant rock types inherits the risk of misleading (usually too low) rock strength values which might cause cost and time intensive misinterpretations regarding the application of excavation techniques or regarding estimations on excavation performance and tool wear.

The referring UCS testing standards and recommendations do not include specific references to the sampling and testing strategies regarding potentially anisotropic rock. However, regarding excavatability assessment, an appropriate investigation programme in anisotropic rock shall be carried out in a way, to at least derive the following rock properties:

- reporting of intact "normal" rock strength (i.e. $\sigma_{c\,max}$ / $\sigma_{c\,90}$ 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 basic requirements, the following practical recommendations can be concluded:

- Top priority should be to perform a majority of UCS tests perpendicular to the foliation or bedding (ß = 90°) in order to derive the maximum intact UCS ($\sigma_{c\ max}$ / $\sigma_{c\ 90}$). Note that these tests are irreplaceable, since it is technically impossible to reliably extrapolate this property from any other tests at differing angles.
- Second priority should be to perform a statistically sufficient quantity of tests at an angle of 30° < ß < 50° in order to derive the minimum intact UCS ($\sigma_{c\ min}$) which might 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 a minor role.

REFERENCES

Broch, E. 1983. Estimation of Strength Anisotropy using the Point-Load Test. *Int. J Rock Mech. Min Sci. & Geomech Abstr* Vol 20, No 4, pp 181-187.

Brown, E.T., Richards, L.R., Barr, M.V. 1977. Shear strength characteristics of the Delabole Slates. In: *Proc. Conf. Rock Engineering Newcastle upon Tyne*, pp. 35-51

DGGT - Deutsche Gesellschaft für Geotechnik e.V. *2004.* Neufassung der Empfehlung Nr. 1. des Arbeitskreises 3.3. „Versuchstechnik Fels" der Deutschen Gesellschaft für Geotechnik e.V.: Einaxiale Druckversuche an zylindrischen Gesteinsprüfkörpern. *Bautechnik*, 81, 10, pp 825 - 834.

Gehring, K.H. 1995. Leistungs- und Verschleißprognose im maschinellen Tunnelbau. *Felsbau* 13, 6, pp. 439-448.

ISRM – International Society for Rock Mechanics. 1979. Suggested Methods for Determining the Uniaxial Compressive Strength and Deformability of Rock Materials. *Int. Jour. Rock Mech. Min. Sci & Geomech. Abstr*., 16, 2, pp. 135-140 (Elsevier)

Jaeger, J. 1960. Shear failure of anisotropic rocks. *Geol. Mag*., 97, pp. 65-72.

Plinninger, R.J. 2002: *Klassifizierung und Prognose von Werkzeugverschleiß bei konventionellen Gebirgslösungsverfahren im Festgestein.* Münchner Geol. Hefte, Reihe B, 17 - Angewandte Geologie, XI + 146 p., 99 fig., 36 tab., Munich (Hieronymus).

Ramamurthy, T. 1993. Strength, modulus responses of anisotropic rocks. In: Hudson J.A., (ed.). *Comprehensive Rock Engineering* , vol. 1. pp. 313–29, Oxford (Pergamon).

Schormair, N., Thuro, K. & Plinninger, R.J. 2006. *The influence of anisotropy on hard rock drilling and cutting.* paper No. 491.- Engineering geology for tomorrow's cities - 10th IAEG Congress, Nottingham, United Kingdom, 6.-10. September 2006.

Singh, J., Ramamurthy, T. & Rao, G.V. 1989. Strength anisotropies in rocks. *Indian Geotech J*, 19, pp. 147–166.

Slatalla, N. & Alber, M. 2014. Failure behaviour and acoustic emission pattern of slate and mica schist in uniaxial loading. *Rock Engineering and Rock Mechanics: Structures in and on Rock Masses* – Alejano, Perucho, Olalla & Jiménez (Eds.), pp. 205-210, London (Taylor & Francis).

Thuro, K. 1996. *Bohrbarkeit beim konventionellen Sprengvortrieb.* Münchner Geol. Hefte, Reihe B, 1, - Angewandte Geologie, 45 p., 115 fig., 39 tab., Munich (Hieronymus).

Thuro, K. & Plinninger, R.J. 2002. Klassifizierung und Prognose von Leistungs- und Verschleißparametern im Tunnelbau. In: DGGT (ed.), *Taschenbuch für den Tunnelbau* 2003, 27, pp. 62-126, Essen (Glückauf).