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Sampling and testing of anisotropic non-durable rock

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Abstract

Rock mechanical parameters gained from laboratory investigation (i.e. unconfined compressive strength, tensile strength, shear strength or abrasivity) are key values for the mechanical description and classification of any hardrock type. Consequently, such investigation is of crucial importance in the course of any preliminary site investigation conducted for infrastructure projects. Anisotropic or non-durable features are common for a variety of sedimentary and metamorphic rock types. However, such properties do indeed represent special tasks for appropriate laboratory investigation which might require preliminary assessment, carefully planned sampling and testing procedures, special methods (like block sampling, waterless sample coring) or special treatment (like sample sealing) throughout the whole work flow from sampling to testing.

For anisotropic rock types (for instance schists, phyllites, gneiss) it is evident, that sample size and orientation may have a much higher impact on the gained rock parameters than the testing setup and testing conditions itself. Consequently, the testing of samples with defined orientation regarding lamination, foliation or weak discontinuity planes are of crucial importance. Realistic predictions of the rock mass behaviour may also require larger sample dimensions. For non-durable rock types (for instance claystones, siltstones, marl) the mechanical behaviour of the rock may significantly be changed if the natural water content of the samples is changed during sampling, transportation, storage or trimming due to wetting and/or drying. Here, the fast and reliable identification of such rock types and choice of appropriate sampling methods and careful sample preparation procedures are of crucial importance for gaining of representative rock parameters. The selection of broken material blocks may also require the consideration of anisotropy and scale effects.

The presented paper gives an overview of the theoretical background of anisotropic and non-durable rock characteristics and resumes on practical experiences and solutions as applied for numerous demanding tunnelling projects in such rock types in Germany. The focus of this paper is limited to strength rather than to stiffness parameters.

Keywords

Laboratory testing, sampling, non-durable rock, anisotropic rock

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1 Background

Rock mechanical parameters gained from laboratory investigation (i.e. Unconfined Compressive Strength, Tensile Strength, Shear Strength or Abrasivity) are key values for the mechanical description and classification of any hardrock type. Consequently, such investigation is of crucial importance in the course of any preliminary site investigation conducted for infrastructure projects.

Anisotropic or non-durable rock behaviour can have a significant impact on rock sampling and testing procedures. Both features can occur in the same rock, but are not necessarily linked to each other. As further explained in the course of the following chapters, anisotropic features are a common phenomenon of sedimentary and metamorphic rock, while non-durable properties are usually limited to fine-grained, non-metamorphic sediments.

2 Defining “anisotropic” and “non-durable” rock behaviour

2.1 Anisotropic rock 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 defined (theoretically infinitely dense) spacing.

Mechanically anisotropic behaviour of rock is a result of the rock´s mineral composition and fabric, which depend on 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 structurally distributed and orientated. Common minerals, which might cause geomechanical anisotropy, are layered silicates, like clay or mica minerals, which may primarily be orientated by sedimentation (→ lamination, weak discontinuity planes) or secondarily be orientated under a specific stress regime during metamorphosis (→ schistousity / foliation, see Fig. 1, left). As a matter of this, sedimentary rocks and metamorphic rock types do quite commonly feature anisotropic properties.

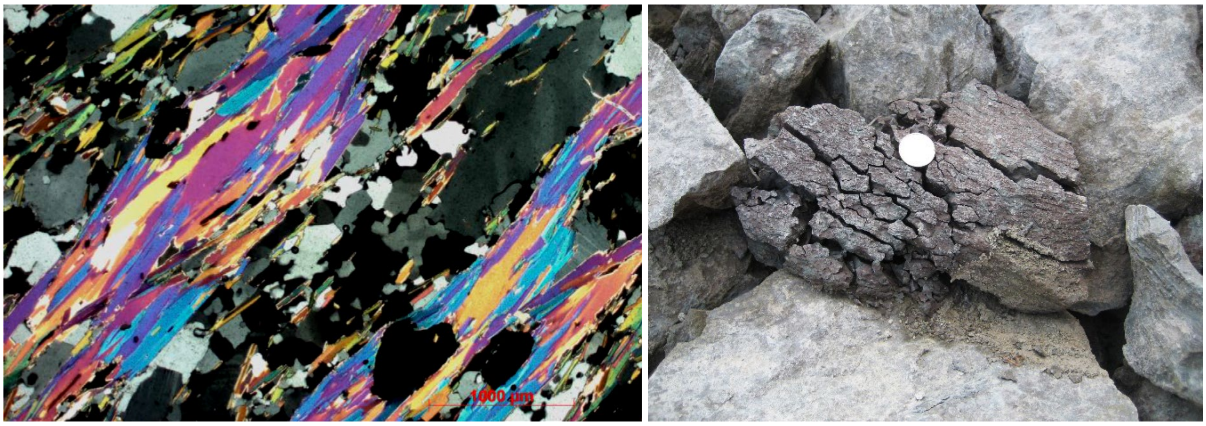

Fig. 1 Left: Thin section of a foliated schist under polarized light. Orientated mica minerals, which might cause significantly anisotropic mechanical behaviour appear as multicoloured “fibres”; Right: Decay of a tertiary sand-siltstone in the muckpile of a tunnel project within some weeks of atmospheric exposure.

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).

2.2 Non-durable rock behaviour

In the context of engineering geology and geotechnical engineering, non-durable rocks might be characterized by the following key properties:

1. strength: non-durable rocks feature an amount of mineralogical binding, that distinguishes them from soil and exclude them from the application of soil mechanical investigation procedures;
2. sensitivity to water: non-durable rocks react to changes in water content with irreversible weakening of the mineral structure, ranging to the complete disintegration (see Fig. 1, right);
3. relevant reaction time: weakening/decay takes place in a relevant, short period of time, usually some hours to a few years.

This kind of behaviour is usually found in fine grained diagenetic sediments, such as claystone, siltstone or marlstone. It is caused by clay minerals, such as smectites, illite or caolinite. With regard to their properties, non-durable rocks thus might be allocated at an intermediate position between (cohesive) unconsolidated soils and durable solid rocks.

3 The impact of anisotropy and durability on rock testing

For laboratory investigations of **anisotropic rock types**, such as Triaxial and Unconfined Compressive Strength Tests, Point Load Tests, Brazilian Tensile Strength Tests or Abrasiveness Tests, like CERCHAR Testing, it is evident, that sample size and orientation may have a much higher impact on the gained rock parameters than other aspects of testing setup and testing conditions. Theoretically the overall strength of an inhomogeneous sample depends on the inclination of weak discontinuities and can be calculated with the following equations (equ. 1 and 2) according to the Mohr-Coulomb failure criteria. For fractured rock (see Fig. 2) applies:

$$\sigma_1 = \frac{\sigma_3(\sin(2\alpha-\varphi_k)+\sin(\varphi_k))+2c_K\cos(\varphi_k)}{\sin(2\alpha-\varphi_K)-\sin(\varphi_K)} \qquad (1)$$

where α inclination angle
φ_k friction angle in the weak discontinuity
c_K cohesion in the weak discontinuity
σ_1, σ_3 principal stresses.

For intact rock applies:

$$\sigma_1 = \frac{1+\sin\varphi}{1-\sin\varphi}\sigma_3 + \frac{2c\cos(\varphi)}{1-\sin(\varphi)} \qquad (2)$$

where φ friction angle of the intact rock
c cohesion of the intact rock

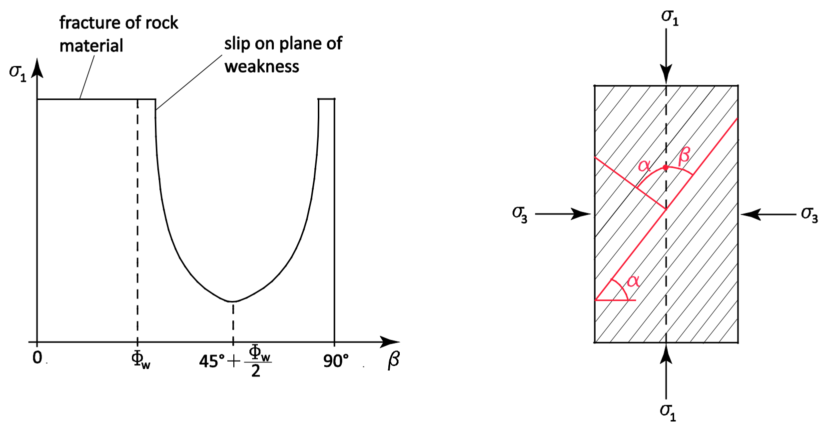

Fig. 2 Theoretical influence of weak discontinuity inclination on the UCS strength of rock (after Brady and Brown, 2004)

The diagram in Fig. 3 illustrates the practical impact of the theory. It resumes UCS results on 11 rock types of varying anisotropic behaviour (see Plinninger & Alber 2015 for details). The data lucidly depicts the impact of anisotropic features on measured UCS values with reference to the angle ß between loading axis and anisotropic plane. Depending on the specific mineralogy and fabric of the rock, this data shows an impact on UCS of up to 96 %!

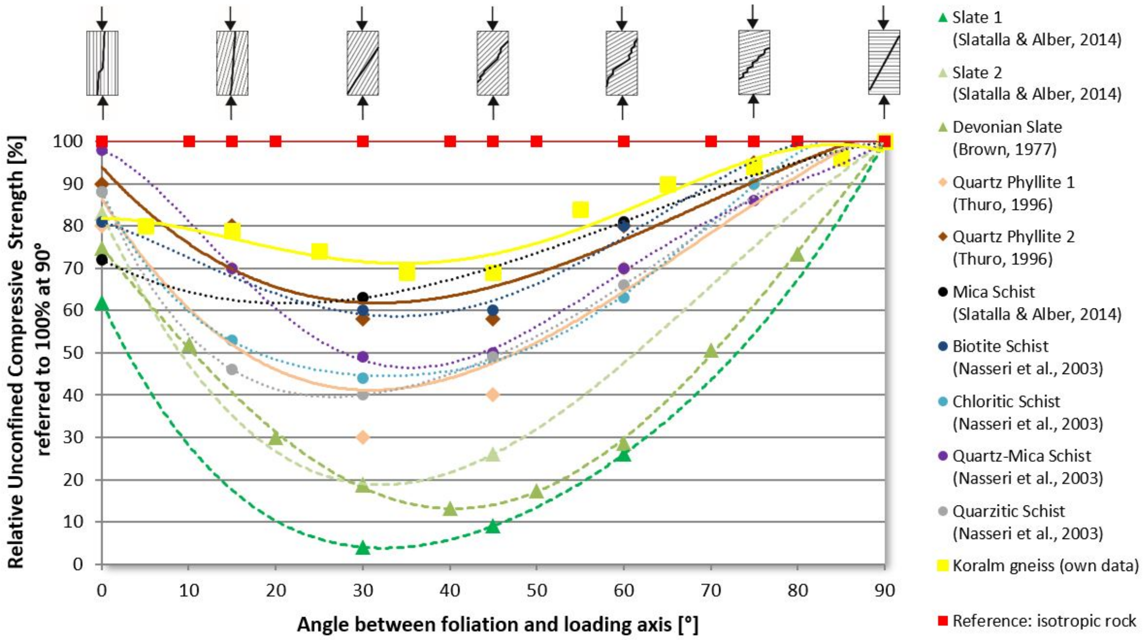

Fig. 3 Compilation of empirical UCS testing results showing the variation of relative UCS (y-axis) with varying angles between loading axis and orientation of the anisotropic features (x-axis). Plotted are results from 10 rock types which are described by polynomial regression lines.

Several studies found, that the strength of a rock sample generally depends on the sample size, i.e. that smaller samples achieve higher strength. Especially for the investigation of anisotropic and heterogeneous rock types, this so-called "size effect" plays an important role, making it mandatory to choose sample sizes according to the specific rock mechanical question. If the weak discontinuity orientation is not visible in the rock or the spacing of discontinuities is sufficiently small, it is possible to test small samples, e.g. with a diameter of 50 mm. This works well, however, only if the typical discontinuity or sequence of material layers is already represented in the sample of chosen size. Especially for stability assessment (i.e. slopes or underground openings), the aim should therefore be to recover large samples (see chapter 4.2) in order to establish appropriate strength parameter.

As stated in the definition before, the fundamental feature of **non-durable rock types** is, that their mechanical properties are influenced by their moisture content and its variation, i.e. wetting or drying. Such changes might take place during sampling, transportation, storage or trimming, especially if such effects are not sufficiently considered and no countermeasures are applied. Experience shows, that even if macroscopically intact, samples, that are "distorted" in such way might deliver strength or abrasivity values, which are significantly lower than the rock´s in-situ properties (Fig. 4).

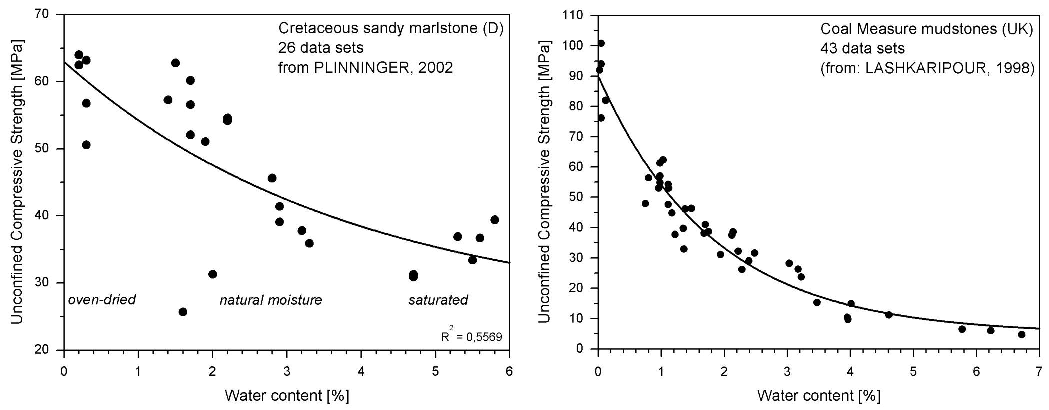

Fig. 4 Examples for the dependency of rock strength (UCS) from water content for cretaceous marlstone (Plinninger et al. 2010, left) and mudstones (Lashkaripour 1998, right).

While this circumstance might still be tolerated as a kind of "worst case" scenario for stability questions – for such purpose, the lower parameters are on the "safe side" for assessment – numerous problems have arisen in the past when it comes to the prediction of excavation performance and tool wear, for which low values might lead to estimates, that are too optimistic.

4 Dealing with anisotropic rock

4.1 Identification

An appropriate identification of mechanical anisotropy / isotropy will require laboratory testing, for instance strength tests or dynamic sounding in differing directions. However, as a rule of thumb, anisotropic behaviour should be presumed for any rock types that feature macroscopically recognizable discontinuities or foliation or show obviously parallel orientation of minerals unless isotropy is proven.

4.2 On-site Sampling

The identification of anisotropic features will inevitably require a set of samples with defined orientation between loading axis and anisotropic plane. As indicated in Section 3, also scale effects might play an important role for the testing results, so adapted sampling procedures have to be carried out.

Under such circumstances, **block samples (**usual size ≈ 0.3 x 0.3 x 0.2 m) represent a very effective, fast, easy and economical sampling method. It can be conducted in any location where a relevant rock type is exposed at a surface (e.g. natural outcrops, investigation pits or shafts, slopes, quarries, mines or conventional tunnel drivages). If such block samples can be gained, specimen of defined orientation can easily and precisely be formatted by overcoring on site (see Fig. 5, left) or in the laboratory. This preparation is supported by the fact that on large samples even fine weak discontinuity or anisotropic elements of larger spacing can be recognized much more easily than on small scale cores.

If samples must be gained by **core drilling**, two procedures might be applied:

4. 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 weak discontinuity planes during depth of drill hole);
5. 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 Fig. 5, right)

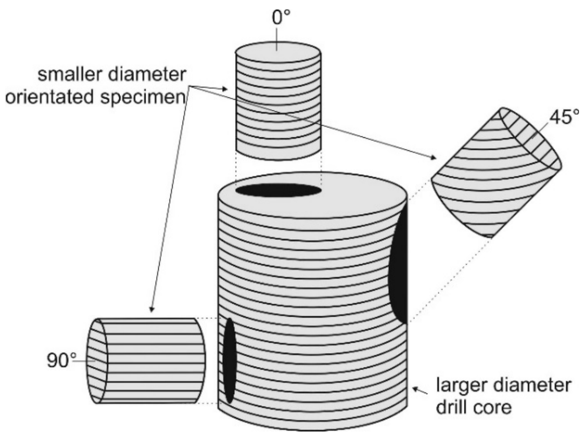

Fig. 5 Left: on-site overcoring of rock blocks in order to gain orientated samples; Right: Concept drawing for overcoring of a larger core sample in order to gain orientated specimen of smaller diameter.

For **large diameter core drilling,** KIT uses a special drilling rig which acquires a core of 600 mm diameter and 1200 mm length (see Fig. 6). Using a high-performance cutting bit with compressed air flushing, a gap of abt. 20 mm is created around the sample in which a tinplate casing is lowered and fixed force-fit to the rock sample by grouting with a rapid-setting plaster. The tinplate-stabilized rock core is broken away from its subface using a chisel and finally pulled out.

For transport and storage, the tinplate may be supplemented by wax, plaster or even a steel plate at both ends. Prior to testing large samples in the lab, the end planes are trimmed or lined with plaster, the tinplate is replaced carefully by a rubber envelope and the sample is placed in a large triaxial cell. This procedure is rather cost- and time-intense, but is has proven useful for the design of tunnel cut slopes of the Nuremberg-Erfurt highspeed railway (Vergara et al. 2014).

Fig. 6 Left: Coring of large diameter samples, Centre: drillhole after pullout; Right: sample after removal of tinplate

4.3 Preparation of specimen

When **block samples** are delivered to the lab, the weak discontinuity orientation must be determined by visual inspection before the sample is cored. If the water content of the rock is very low and the rock is stratified it may be very difficult to get an intact specimen by coring perpendicular to the weak discontinuity planes because of core disking (see Fig. 7, left). In this case it is often more promising to core parallel to the weak discontinuity planes, even though this direction is not preferred in view of the interpretation. Very low penetration speed should be used, in order to minimize disking effects.

For taking core samples from smaller blocks or intact cores of larger diameter a special technology is recommended: The material is covered with a wax/paraffin coating to preserve its humidity, then embedded in a special high-strength plaster with a glass fiber or geotextile mesh reinforcement before the samples are gained by overcoring (see Fig. 7, right).

Fig. 7 Left: unsuccessful attempts to core a block sample, Right: overcoring technology with plaster embedding

As already mentioned, the size-effect has to be considered in the selection of the sample size, especially for anisotropic rocks. In the selection it is important to consider the usage of the parameters. In case the uniaxial strength is used for the design of an underground construction it is important to get the minimum strength of the rock. But for the rating of the tool wear of an excavator bucket or ripper tooth it might be more important to get information about the strength maximum and hence to choose smaller sample sizes for the tests.

5 Dealing with non-durable rock

5.1 Identification

The identification and quantification of the specific sensitivity of a rock based on mineralogical investigation or rock properties, like UCS testing, might not lead to satisfactory results. Thus, index tests like wetting-drying cycles (Nickmann et al. 2010) or the slake durability test (ISRM 1977) are applied commonly to identify and classify non-durable rock behaviour.

5.2 On-site Sampling

The core issue of sampling non-durable rock types must be the best possible preservation of the natural moisture content, i.e. to prevent drying / wetting processes. Besides any technical measures, time will be the most critical aspect when it comes to the preservation of weak rocks in their natural moisture state, which should be taken into account before sampling. Additionally, there are a number of practical measures in order to preserve weak rocks samples and to avoid additional disintegration:

- choosing a sampling method that prevents the sample from artificial contact with water (block sampling, use of plastic inliners, use of air flushing where possible);
- immediate sample documentation and sample choice on site;
- immediate sealing by use of aluminium/plastic foils, wax or silicone plugs, etc.;
- padding and isolation of samples with wood chips, Styrofoam, PU-foam or similar in order to avoid mechanical damages to the samples during transport;
- for the transport of long core runs over large distances (i.e. using shipping companies or airfreight) it has proved useful to insert the core in a sound steel tube completely sealed with wax (Fig. 8)
- immediate and horizontal transportation to the laboratory;

As for anisotropic rock, sampling of **block samples** and coring in the lab represents an effective method for testing of non-durable rock, because the large volume contributes to the preservation of the natural water content inside the block. However, even for such large block samples, proper sealing (i.e. by foil wrapping) and insulation is mandatory. Adding wet cloth or a can of water can help to prevent drying if the store room or lab is not climatized, but water absorption from humid atmospheres must be avoided.

5.3 Preparation of specimen

After arrival in the lab, the material should be tested as soon as possible or otherwise remain unopened in the transport insulation. The water content has an important influence on the strength and the elastic properties of rocks and hence the water content shouldn't be changed by using flushing fluid for the cooling of the drill bit. Air cooling, however, may prove insufficient in hard rocks and cannot avoid that the drill bit heats up. In this case the water content can also be changed due to the heating and the coring must be executed in intervals to limit the temperature increase.

Fig. 8 Non-durable rock samples sealed in wax and in additional steel tubes (left)

Coring, sawing and trimming are again to be carried out without water, or in the case of very hard materials, at least with as little water as possible. Between the final preparation of the test specimen and the test itself, the sample is again stored in sealed - or better vacuumized - plastic bags. Measuring the water content after each processing step helps to track any possible changes. Another point is crucial for samples from larger depths or deep tunnel excavations: The sudden relief of the in-situ pressure in pre-stressed samples often leads to disintegration effects which may enhance disking and early failure. To our knowledge there is no practicable measure to mitigate this effect except a costly transport in a pressure container under estimated in-situ stress conditions.

5.4 Testing

Special measures against desiccation like coatings with rubber or metal foil are required for long-time tests like creep tests. For UCS and triaxial testing it is normally sufficient to determine the water content after the preparation on a parallel sample and on the sample material itself immediately after the test. In this way it is possible to capture the influence of the sample preparation on the water content. Caution is required with materials which have high initial water contents due to high porosity. It is possible that pore water is not homogeneously distributed after storage, handling or atmospheric exposure.

The test procedures themselves do not imply special requirements for non-durable rock. The usually smaller strength and stiffness combined with a higher ductility of these materials opens the possibility of observing the post-failure behaviour. Materials failing under brittle fracture cannot demonstrate any post-failure strength reserves because the elastic energy stored in the testing frame when released destroys the sample immediately.

6 Conclusions

Anisotropic rock behavior and non-durable rock behavior do represent geotechnically relevant features that originate from the specific composition and origin of a rock. Both features can occur in a rock, but are not necessarily linked to each other. While anisotropic features are a common phenomenon of sedimentary and metamorphic rock, non-durable properties are usually limited to fine-grained, non-metamorphic sediments.

Based on the background and experience presented in this paper, the key issues for a proper characterization of **anisotropic rock** can be summarized as follows:

1. Top priority should be to perform a majority of UCS tests perpendicular to the foliation or weak discontinuity (ß = 90°) in order to derive the maximum intact UCS (σc_{max} / σc_{90}). These tests are irreplaceable, since it is impossible to reliably extrapolate this property from other tests;
2. 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 (σc_{min}) which might be used to characterize the rock specific degree of anisotropy, for instance by use of the AI index as described by Plinninger and Alber, 2015;
3. 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.

Based on the background and experience presented in this paper, the key issues for a proper characterization of **non-durable rock types** can be summarized as follows:

1. to reliably identify such material properties,
2. to preserve the natural moisture content of samples, i.e. prevent drying / wetting processes throughout the whole procedure of sampling, transportation, storage, formatting and testing.

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