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An advanced assessment of sandstone uniaxial compressive tests

L. Vavro & M. Vavro
The Czech Academy of Sciences, Institute of Geonics, Ostrava, Czech Republic
leona.vavro@ugn.cas.cz (email of corresponding author)

P. Frantík & Z. Keršner
Brno University of Technology, Faculty of Civil Engineering, Brno, Czech Republic

Abstract

The compressive strength value is used in many technical fields as a basic mechanical resistance parameter to characterize various materials. The uniaxial compression test method is standardized for individual materials and is considered traditional, based on many decades of engineering experience. The uniaxial compressive strength (UCS) is usually determined on cubic or cylindrical test specimens of various dimensions. Its determination on rock core samples, for example, should follow the ISRM recommendation of keeping the length-to-diameter ratio (slenderness ratio) of the test specimen between 2.5 and 3.0. Perhaps the greatest advantage of the UCS testing is its speed and simplicity. UCS is easily measurable and requires no special laboratory equipment other than a compression testing machine. Therefore, it would seem that further research in this direction will not bring anything new; however, in this contribution the authors have tried to find some unusual insights into compressive testing. More specifically, some non-traditional parameters of dry and water-saturated sandstone were determined during uniaxial compressive testing on cylindrical test specimens with five different slenderness ratios ranging from 0.7 to 3.0. In addition to the UCS, parameters such as the effective compressive strength, dynamic bulk modulus, effective elasticity modulus and slope of the fracture surface were determined. The results obtained were correlated with the slenderness ratio of the tested specimens. In addition, the UCS determined on cylindrical and cubic test specimens was compared. Cretaceous medium-grained to coarse-grained arkose sandstone from the Božanov quarry in the north-east Bohemia, a well-known and long-used natural stone in the Czech Republic for construction, architecture and sculpture, was used in the experiment. The observed aspects of response of specimens from this quasi-brittle material to quasi-static loading can enrich the traditional ideas reflected primarily in the standard regulations regarding the recommended slenderness ratio to obtain relevant strength and stiffness characteristics.

Keywords

Sandstone, uniaxial compressive testing, cylindrical specimen, length to diameter ratio, effective mechanical properties

ISRM

NBG

1 Introduction

The uniaxial compressive strength (UCS) of rock is a basic mechanical property of intact rock determining the mechanical behaviour and failure characteristics of rocks under loading/unloading conditions. The UCS is also a key geomechanical parameter, which is widely used in mining and construction practice, for example in designing surface and underground structures, in rock mass engineering stability analysis and in a variety of problems encountered during blasting, excavation, and support in engineering works. Moreover, the UCS is crucial for rock mass quality classification, for example using RMR (Bieniawski 1976; Bieniawski 1989) or Q (Barton et al. 1974) classification systems and in predicting strength parameters of rock masses through Hoek–Brown failure criterion (Hoek and Brown 1980).

Although the standard direct method of determining the UCS of rocks is relatively simple in terms of conducting and evaluation of results, it requires a large number of precise prepared test specimens usually cylindrical in shape. Obtaining specimens of required quality is problematic in some cases, for example, preparing standard cylindrical rock samples in weak or weathered rock is quite difficult. For this reason, numerous other testing methods using other rock properties such as Schmidt hardness rebound number, point load index, density, porosity, ultrasonic wave velocity or abrasivity index are used for indirect estimation of UCS in engineering practice (Aladejare et al. 2021; D´Andrea et al. 1965; Kahraman 2001; Xie et al. 2024; Xu et al. 2023; etc.). Procedures for direct measurement of a precise rock UCS in laboratory have been standardized by both the American Society for Testing and Materials (ASTM 1995) and the International Society for Rock Mechanics (ISRM) (Bieniawski and Bernede 1979). In the case of the ISRM procedure, a diameter corresponding to the NX core size (54 mm) or larger and a slenderness ratio (length-to-diameter *L*/*D* ratio) of 2.5 to 3.0 are recommended. According to the ASTM procedure, the specimen shall have a *L*/*D* ratio of 2.0 to 2.5 and a diameter of not less than 1.85 inches (47 mm). In the field of natural stone testing, the procedure according to EN 1926 (ECS 2006) is standardized, which allows the use of both test specimens in the shape of a cube with an edge of 50 mm or 70 mm and a cylinder, the diameter and height of which are also equal to either 50 mm or 70 mm (*L*/*D* ratio = 1.0).

From the above, it is evident that several standardized or recommended procedures can be utilised for direct rock UCS testing, but these often vary considerably in the shape and size of the test specimens used. However, it is known that the shape of the tested material can have a significant effect on the outcome of the UCS measurements (Hoek and Brown 1980; Hawkins 1998; Thuro et al. 2001 and Tuncay and Hasancebi 2009). The aim of the research was therefore to compare the results of UCS determination on samples of different sizes and shapes, prepared from dried and water-saturated Božanov sandstone. Specifically, these were cubes with edges of 50 mm and 70 mm and cylindrical samples with a nominal diameter of 50 mm, but with different *L*/*D* ratios (0.7, 1.0, 2.0, 2.5 and 3.0). In addition, some non-traditional parameters of dry and water-saturated sandstone such as the effective compressive strength, dynamic bulk modulus, effective elasticity modulus and inclination of the fracture surface were determined during uniaxial compressive testing on cylindrical test specimens.

2 Rock material used for experiment

Upper Cretaceous arkosic sandstone, used for experiments, came from the open Božanov quarry (50.5054083N, 16.3364667E) in north-eastern Bohemia. This sandstone represents a well-known building, sculpture and decorative stone material that has been used on the Czech territory for many centuries, for example, at many historical monuments in Prague such as Prague Castle and/or Charles Bridge (Rybařík 1994).

Božanov sandstone is medium- to coarse-grained, greyish-white to beige psammitic rock with massive structure. It is predominantly (ca 70–80 vol. %) composed of quartz clasts with grain size from 0.2 to 1.5 mm. Other stable components are represented by clasts of fine-grained quartite and cherts. Non-stable fragments are mainly composed of feldspar grains (0.2–0.8 mm, ca 8–13 vol. %), represented by both K-feldspars (orthoclase > microcline) and plagioclase. All feldspars are at different stages kaolinised and sericitised. Micas (3–4 vol. %) are represented by small-scale flakes of biotite, less frequently muscovite. Accessory minerals are formed by tourmaline, zircon, apatite, and rutile. The rock matrix (about 5 vol. %) is composed of clay minerals (kaolinite > illite), rarely also of quartz and most often fills the inter-granular pores. Fe oxyhydroxides (“limonite”) are very finely dispersed in the matrix or rarely fill the pores. The degree of rock compaction is moderate.

The physico-mechanical properties of the studied sandstone are shown in Table 1.

Table 1 Selected physical and mechanical parameters of Božanov sandstone (according to own measurements and data published by Rybařík 1994; Rybařík 2008 and Vavro et al. 2025)

Material property	**Unit**	**Value (minimal–maximal)**
Specific (mass) density	kg·m^{-3}	2506–2630
Bulk density	kg·m^{-3}	2120–2210
Total porosity	vol. %	15.7–17.2
Open porosity	vol. %	9.4–10.2
Water absorption capacity	wt. %	4.3–6.5
Ultrasonic wave velocity (dry sample)	km·s^{-1}	2.73–3.06
Uniaxial compressive strength (dry sample)	MPa	47–75
Static Young's modulus (dry sample)	GPa	14.0–18.6
Poisson's ratio (dry sample)	–	0.15–0.25
Uniaxial compressive strength (saturated sample)	MPa	42–62
Softening coefficient in compression	–	0.81–0.87
Flexural strength (dry sample)	MPa	4.5–5.2
Grindability acc. to Böhm	mm	1.7–4.0

3 Methodology of the experiment

3.1 Test specimens

Two groups of test specimens were prepared in the laboratory from the sandstone blocks taken in the Božanov quarry. The first group was represented by cylindrical specimens with a nominal diameter of 50 mm, which were made using core drilling. The ends of the cylindrical cores were finally cut perpendicularly to the length, so that the length-to-diameter ratio (slenderness ratio) was 0.7, 1.0, 2.0, 2.5 and 3.0. A total of 60 cylindrical test specimens were prepared in this way, while each of the five subgroups differing in slenderness ratio contained 12 specimens. Subsequently, one half of the number of specimens in each subgroup was dried to a constant weight (dry specimens), the other half was immersed in water until the full saturation of the material was reached (wet specimens). This means that six dry and six water-saturated samples were tested in each subgroup. The second group of samples were cubic test specimens that were prepared using cutting by circular diamond blade. Specifically, 12 cubes with an edge of 50 mm and 12 cubes with an edge of 70 mm were prepared. As in the case of cylindrical specimens, in each of this two subgroups, half of the cubes were dried and the other was soaked in water until the weight was constant.

3.2 Experimental procedure

Before the UCS measurement itself, each test specimen was weighed and its dimensions were measured using a calliper. From the values of the weight and volume of the specimen, its bulk density was calculated. Furthermore, the ultrasonic wave velocity was measured on each test specimen using a Maruto CH-48S device. The dynamic elasticity (bulk) modulus was subsequently calculated from the value of bulk density and the ultrasonic wave velocity according to Eq. 1 (ÚNM 1981):

$$E_{dU} = \rho_0 \cdot V_u^{\,2} \tag{1}$$

Where E_{dU} Dynamic elasticity modulus
ρ_0 Bulk density
V_u^2 Ultrasonic wave velocity

The following compressive tests were performed on the ZWICK 1494 mechanical compression testing machine according to ISRM recommendation (Bieniawski and Bernede 1979), the loading rate was 0.5 MPa·s^{-1}. During the compressive tests the displacement u of the opposite loading plates in the direction of the cylindrical specimen axis was measured from which the effective compressive strength ($f_{c,eff}$) and effective elasticity modulus (E_{eff}) was calculated using following relationships (derived using standard engineering theory):

$$f_{c,eff} = \max(F(u))\frac{4}{\pi D^2}, \qquad E_{eff} = \max\left(\frac{\mathrm{d}F}{\mathrm{d}u}\right)\frac{4L}{\pi D^2} \tag{2}$$

Where $f_{c,eff}$ Effective compressive strength
E_{eff} Effective quasistatic elasticity modulus
F Loading force
u Loading plates displacement
L Length of the specimen
D Diameter of the specimen

Following the test, the average inclination of the fracture surface (Chakraborty et al. 2019; Supandi et al. 2020) was measured, provided it was distinctly formed by the failure. Variations in the slenderness ratio among different specimens led to a transition in the failure mode. This transition arises from the limited space available for the development of the failure mechanism, which in turn affects the inclination of the resulting fracture surface.

4 Experimental results

The results of the evaluation of all tests of dry/wet material are shown in Tables 2 and 3 and Fig. 1 to 5. Partial measurement results, as well as their arithmetic means and sample standard deviations, are plotted in each of the graphs.

Bulk density vs. slenderness ratio is presented in Fig. 1. The mean values are almost 7 % higher for wet sandstone compared to dry sandstone, the coefficient of variation is mostly below 0.5 % for both materials and, as could be expected, the values practically do not statistically depend on the slenderness ratio. The stated value of 7 % corresponds to the water absorption value of the Božanov sandstone, which is given in literature (Tab. 1).

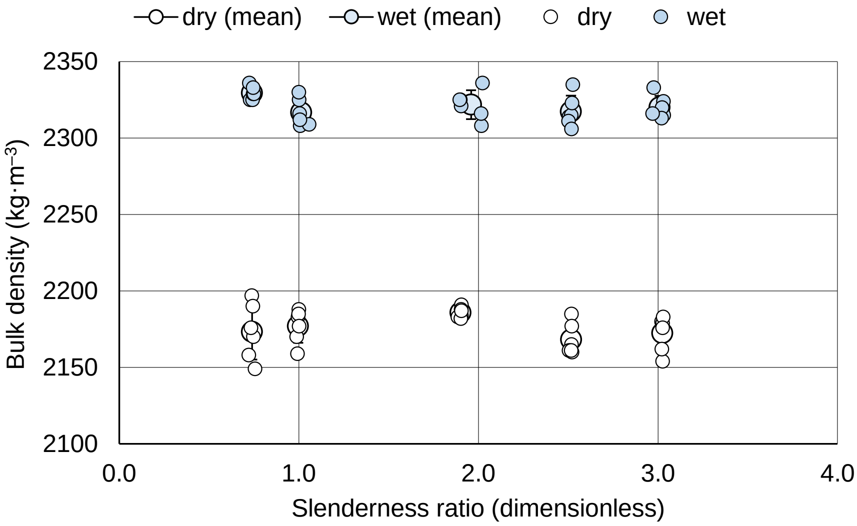

Fig. 1 Bulk density vs. slenderness ratio on cylindrical specimens

As can be seen from Tabs. 2 and 3, the compressive strength of wet Božanov sandstone is lower than that of dry samples, both in the case of cylindrical and cubic specimens. However, the strength softening due to water saturation is much smaller for cubic test specimens (ca 4 % and 8 % respectively) than for cylindrical ones (about 15 % to 39 %). At the same time, no clear difference in the compressive strength of cylindrical and cubic specimens, which is known for example in concrete (Neville 2011), neither in dry nor in water-saturated sandstone samples was found. In the case of dry cylindrical specimens, a noticeable decrease in the mean value of compressive strength with the increasing *L/D* ratio of the cylinders is visible. This reduction in compressive strength reaches up to 30% when comparing test specimens with *L/D* ratios of 0.7:1 and 3:1.

Table 2 Compressive strength on dried cylindrical and cubic test specimens

Parameter	**Unit**	**Cyl 0.7:1**	**Cyl 1:1**	**Cyl 2:1**	**Cyl 2.5:1**	**Cyl 3:1**	**Cub 50**	**Cub 70**
Arithmetic mean	MPa	64.3	62.7	52.6	44.5	44.4	46.7	54.6
Standard deviation	MPa	9.2	2.9	2.8	5.2	5.8	14.6	6.4
Coefficient of variation	%	14.2	4.6	7.1	11.6	13.1	31.1	11.7

Table 3 Compressive strength on water-saturated cylindrical and cubic test specimens

Parameter	Unit	Cyl 0.7:1	Cyl 1:1	Cyl 2:1	Cyl 2.5:1	Cyl 3:1	Cub 50	Cub 70
Arithmetic mean	MPa	45.7	48.3	32.2	37.6	36.9	44.9	50.2
Standard deviation	MPa	6.7	9.4	3.1	3.5	3.5	7.2	5.3
Coefficient of variation	%	14.7	19.4	9.4	9.2	9.4	16.1	10.5

Explanations to Tables 2 and 3: Cyl 0.7:1 – cylindrical specimens with slenderness ratio of 0.7:1, Cyl 1:1 – cylindrical specimens with slenderness ratio of 1:1, Cyl 2:1 – cylindrical specimens with slenderness ratio of 2:1, Cyl 2.5:1 – cylindrical specimens with slenderness ratio of 2.5:1, Cyl 3:1 – cylindrical specimens with slenderness ratio of 3:1, Cub 50 – cubic specimens with edge of 50 mm, Cub 7 – cubic specimens with edge of 70 mm.

The effective compressive strength of wet material was 15 to 40 % lower than that of dry sandstone (see Fig. 2), and the value of the coefficient of variation was between 6 and 18 %. The statistical dependence turned out to be much stronger for dry material.

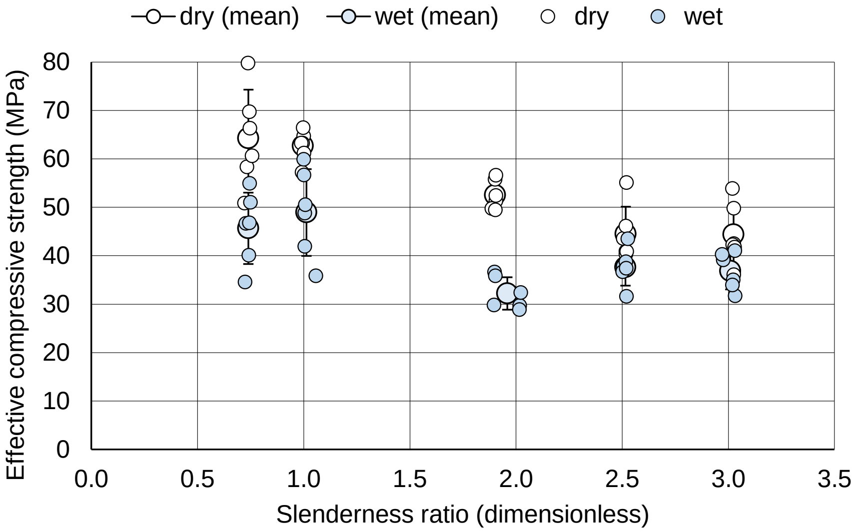

Fig. 2 Effective compressive strength vs. slenderness ratio on cylindrical specimens

The modulus of elasticity (Fig. 3) was in most cases 5 to 18 % lower for wet sandstone than that of dry sandstone, only in the case of a slenderness ratio of 2.5 it was 10 % higher. The coefficient of variation ranged from 5 to 12 % and 12 to 22 % in the case of dry and wet sandstone, respectively. The influence of slenderness on the values of the elastic modulus for dry and saturated material was at the level of medium and low statistical dependence, which can be considered adequate.

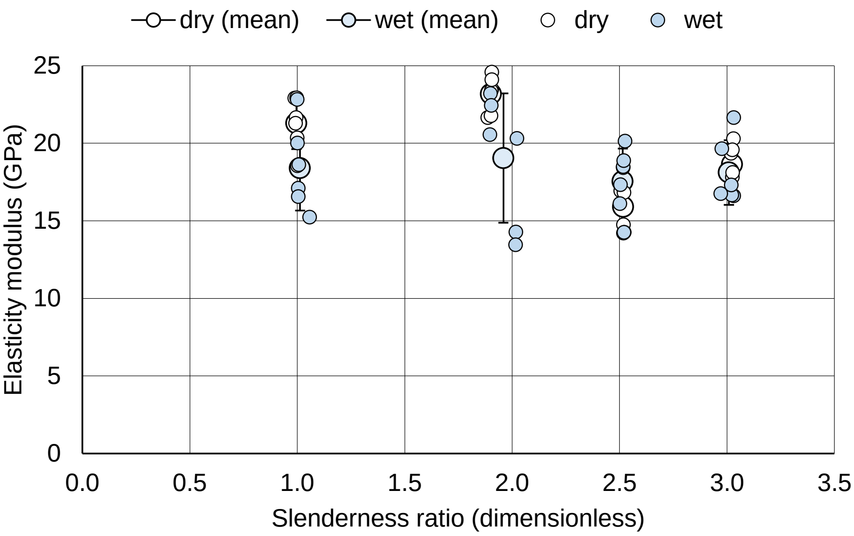

Fig. 3 Elasticity modulus vs. slenderness ratio on cylindrical specimens

In contrast, the values of the effective modulus of elasticity (Fig. 4) were shown to be totally dependent on the slenderness ratio for both dry and wet sandstone. The values of the effective modulus of elasticity were 6 to 27 % lower for the wet material compared to the dry sandstone. The coefficient of variation ranged from 2 to 12 % and 7 to 15 % in the case of dry and wet sandstone, respectively. Dependency of the effective elasticity modulus on slenderness ratio was expected due to additional elastic components included into the measurement. Due to higher stiffness of the shorter specimens the effect of additional elastic components is higher, resulting into lower effective modulus. As the slenderness ratio grows the quasistatic effective modulus E_{eff} should converge into a modulus close to the dynamic modulus E_{dU}, which is expected to be higher than static modulus (Fjaer 1999).

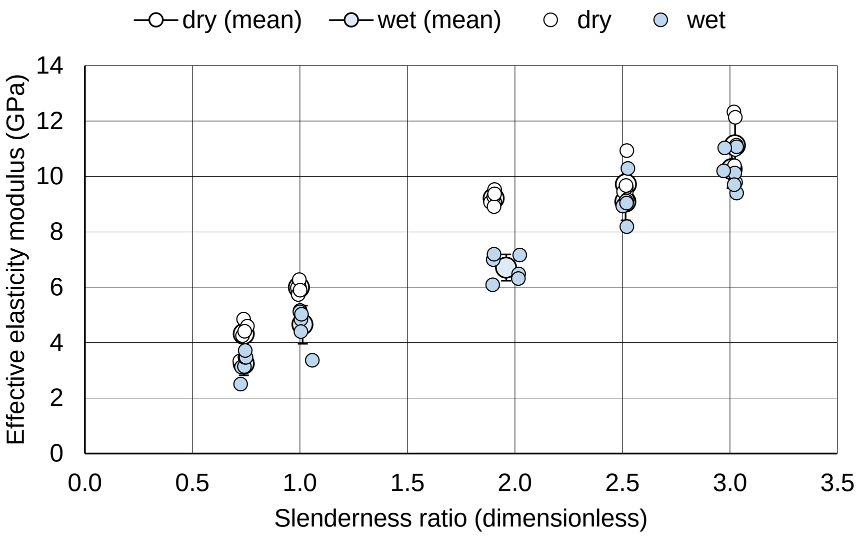

Fig. 4 Effective elasticity modulus vs. slenderness ratio on cylindrical specimens

The inclination of fracture surface was similar (Fig. 5) for dry and wet sandstone and with low values of the coefficient of variation (maximum 12 % for wet and 8 % for dry material). Both materials showed a high statistical dependence on the slenderness ratio.

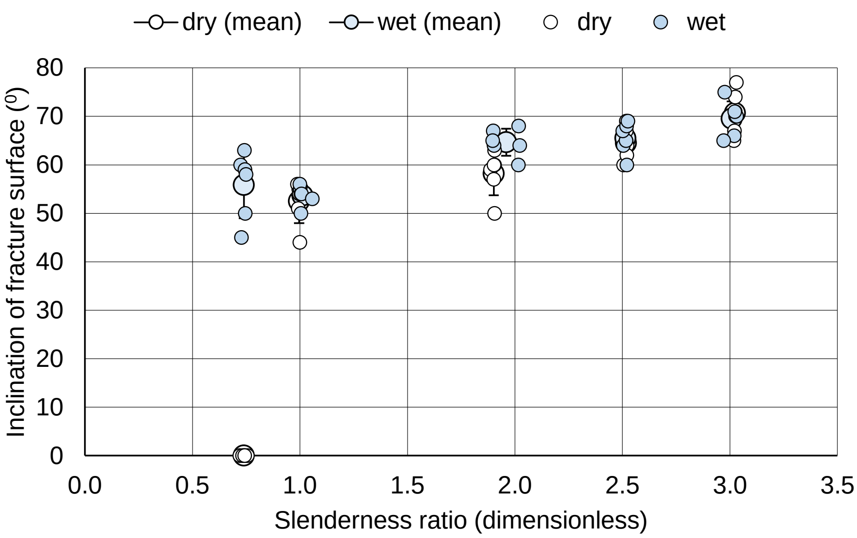

Fig. 5 Inclination of fracture surface vs. slenderness ratio on cylindrical specimens

5 Conclusions

This paper presents the strength and deformation parameters of dry and wet sandstone obtained in a large-scale experimental campaign of uniaxial compression tests with different cylinder slenderness ratios and different cube sizes. Most of these determined parameters can be described as non-traditional, i.e. those that are not commonly determined during rock compression tests. It showed that the observed aspects of response of specimens from this quasi-brittle material to quasi-static loading can enrich traditional ideas reflected primarily in standard regulations in relation to the recommended slenderness ratio for obtaining relevant strength and stiffness characteristics. The main conclusions are as follows:

1. As expected, it was found that the bulk density of both dry and water-saturated samples does not depend on the slenderness ratio of the test specimens. The difference between the bulk density of dry and wet test specimens corresponds to the water absorption capacity of Božanov sandstone. In the case of strength softening due to soaking, it was found that this parameter is significantly higher, approximately 4 times, for cylindrical specimens compared to cubic ones.

2. The highest values of dynamic elasticity modulus were found, both for dry and saturated sandstones, for specimens with *L/D* ratios of 1:1 and 2:1. Specimens with these *L/D* ratios also show the highest differences between the moduli of dry and wet rock (14 % and 18 %, respectively). For slenderness ratios of 2.5:1 and 3:1, the difference in elasticity moduli is negligible or even wet specimens have a higher modulus than the dry ones.

3. The stiffness of sandstones is practically independent of their water saturation, but it is strongly dependent on the slenderness ratio, and in addition, the values of the effective modulus of elasticity are completely unrealistic even around the slenderness ratio recommended by the standards. When calculating the effective elastic moduli, the determined displacement (u) can be affected by so-called loading effects, which cause deformations in the contact between the loading plates and the sample. In this way, the actual stress is overestimated and the elastic moduli tend to be underestimated. This fact is evident from the comparison of the values of the calculated effective elastic moduli and dynamic moduli.

4. The determined values of compressive strengths show that the suggested procedures, e.g. according to ISRM, are appropriate for estimating UCS. In the case of, for example, a shortage of rock material for the preparation of test specimens, the results for a slenderness ratio of 2.0 appear to be a very useful estimate of compressive strengths. The finding that the compressive strength obtained from test specimens with an *L/D* ratio of 2.0 or greater is about the same, while as the ratio decreases the strength increases is consistent with the conclusions published for sandstones, for example, by Hawkins (1998).

5. From the resulting inclinations of fracture surfaces (fracture angles) can be seen that the nature of the failure does not change practically in the entire range of the observed slenderness ratio, only the response of dry specimens at a slenderness ratio of 0.7 differs significantly. The values of the measured fracture angles (with the exception of the aforementioned dry specimens with *L/D* ratio of 0.7) correspond very well with the data determined for sandstone by Supandi et al. (2020).

It could be interesting to see how other parameters depend on the slenderness ratio, for example parameters quantifying damage and fracture of the studied sandstone, the fractal dimension of the fracture objects, etc. This is an area that the author team intends to focus on in the near future. The presented contribution should therefore be considered as an introductory study of the given issue.

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