Effect of sloppy sample preparation on results from uniaxial compressive strength tests

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Abstract. The requirements on sample geometry for strength tests are specified in standards and recommendations such as those provided by ASTM, ISRM and DGGT. Various circumstances may lead to deviations from these specifications, e.g., the nature of the rock material, lack of time, economic reasons, underestimation of the importance of precise preparation and inaccurate tools. We investigated the effect of sloppy sample preparation on the experimentally determined Young’s modulus and uniaxial compressive strength in conventional uniaxial compressive strength tests of two rocks, Ruhr sandstone and Solnhofen limestone. Both are known for their high uniaxial compressive strength > 100 MPa and Young’s modulus > 30 GPa. Six end face geometry categories were tested on cylindrical samples with a diameter of 30 mm and a nominal length of 65 mm: (1) two standard end faces with tolerances ± 0.01 mm and ± 0.005 mm, (2) one standard, one inclined end face with inclinations of 0.04°, 0.1°, 0.6° and 1.2°, (3) two inclined end faces with inclinations of 0.04° and 0.6° and three azimuth combinations, (4) two rough end faces, (5) two wedged end faces with wedge angles of 5° and 10°, and (6) two spherical end faces with radii of 35 mm, 40 mm, and 45 mm. At least two samples were tested for one geometry. The strength for standard end face geometries based on seven tests was 171±9 MPa for Ruhr sandstone and 232±38 MPa for Solnhofen limestone. Low tolerance standard end faces showed a slightly better reproducibility than high tolerance standard end faces. The strength of Ruhr sandstone reduced significantly by 61% from 181±20 MPa to 70±7 MPa when the inclination of one end face was increased. For the same geometries, the strength of Solnhofen limestone reduced by 71%. The full ranges of strength and Young’s modulus (excluding spherical geometries which were determined only for Ruhr sandstone) were 27 MPa to 266 MPa and 2 GPa to 48 GPa for Solnhofen limestone, and 70 MPa to 351 MPa and 3 GPa to 41 GPa for Ruhr sandstone. Our results show that low tolerance preparation increases reproducibility, and slight deviations from standard end face geometries and impurities significantly affect experimentally determined Young’s modulus and strength.

1. Introduction

A sloppy end face preparation of rock samples can lead to significantly smaller or larger values of uniaxial compressive strength (UCS) than for properly prepared samples according to standards and/or recommendations [1]. This has implications for contractual and rock engineering aspects. For almost any excavation work, the UCS defines a contractual class. Examples are given in the German standards DIN 18300 [2], 18301 [3], 18304 [4], 18312 [5], and 18313 [6], which cover surface excavation, drilling,
piling, subsurface and diaphragm wall works, respectively. The geotechnical description of rock, as set forth in DIN EN 14689-1 [7], distinguishes six intact rock strength classes. UCS is also the decisive value for all predicting equations for advance rates of hard rock TBM's, road headers, and drill works for bolts, anchors, and blast holes. For example, by stating a too low UCS, predictions about advance speed are overestimated and lead to claims when correct UCS tests are executed during the construction phase. From a rock engineering point of view, UCS is the starting value for estimating the rock mass strength by various scaling laws. A false UCS will always lead to a wrong estimate of the rock mass strength. The same is valid for Young's modulus, which is also altered when sample preparation is inaccurate, potentially leading to the design of an overly conservative or insufficient support system.

Because end face preparation is particularly important for the stress distribution within a tested sample [8], there are several national and international standards and recommendations defining requirements on end face geometry for UCS tests. The plane parallelisms defined in ASTM [9], ISRM [10] and DGGM [11] are 3.5 mm, 3.5°, and 3°, respectively, while the evenness is defined to be better than 0.01 mm, 0.02 mm, and 0.1 mm, respectively. To account for inaccuracies associated with end face preparation, it is recommended to use a spherical seat in the axial assembly. Hoskins and Horino (1968) [8] derived – from an experimental study on the effect of spherical seats on the experimentally determined UCS – a maximum tolerance for plane-parallelism of 0.25° when using a spherical cap corresponding to 0.13 mm deviation for a sample with a diameter of 30 mm. Hawkes and Mellor (1969) [12] recommend a tolerance of 0.06° (0.03 mm for a 30 mm diameter sample). In practice, deviations from these specifications can result from the nature of the rock material, lack of time, economic reasons, understimation of the importance of precise preparation and inaccurate tools.

We systematically investigated the effect of sloppy end face preparation on UCS and Young’s modulus by preparing defined deviations from evenness and plane parallelism and performing UCS tests on cylindrical samples that, apart from end face geometries, comply with the German recommendations defined by the DGGM [11].

2. Material and methods

Samples were prepared from one block of Ruhr sandstone and Solnhofen limestone, respectively. The Ruhr sandstone block showed no signs of macroscopic heterogeneity or anisotropy. The block of Solnhofen limestone appeared transverse isotropic with a visible bedding plane and no signs of in-plane heterogeneity or anisotropy.

2.1. Material

Ruhr sandstone (Figure 1 a) originates from the Oberste GmbH quarry in Dortmund (Germany) and is part of the Namur C to Westfal A within the upper Carboniferous (Junker et al. 2006). The sandstone is composed of quartz, feldspar, mica, carbonatic minerals and minor constituents with an average grain size of about 250 µm in a sericitic matrix. Solnhofen limestone (Figure 1 b) from Solnhofen (Germany) represents a quasi-monocrystalline carbonate rock without visible grain boundaries. The direction of drilling was orthogonal to the scale. Macroscopically, very fine layering sequences, small folds and filled fissures are visible. The fissures partially extend over the complete drill core with fracture widths of max. 0.1 - 0.2 mm. Care was taken not to use drill cores with visible fracture surfaces or folds.

Both rock varieties have been thoroughly characterized and mechanically investigated in previous studies [13],[14]. They were selected for their high uniaxial compressive strength > 100MPa and Young’s modulus > 30 GPa being particularly sensitive to geometrical deviations of end faces.

We deviated from ISRM [10] recommending a ratio of 2.5 ≤ L/D ≤ 3 on purpose to reduce the bending potential for samples with wedged end faces. The sample diameter was chosen at ~30 mm to account for common practice to reduce sample size for high-strength or fractured rock material. Yet, the diameter exceeded the size of the largest grains at least by a factor of 20 (Figure 1).
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Figure 1. Thin sections of a) Ruhr sandstone (left) and b) Solnhofen limestone (right) using crossed nicols. Ruhr sandstone is composed of quartz, feldspar, plagioclase, muscovite, and biotite. Solnhofen limestone is mainly composed of calcite.

After sawing, the end faces were prepared in various ways to simulate unintended deviations from parallelism and perpendicularity (c.f. section 2.2). We did not further treat the sides of the sample. No drilling marks were sensible owing to slow drilling with manually controlled rate of penetration. The samples were dried at 60 °C for at least 24 h until testing.

2.2. End face preparation
Six classes of end face geometries with different further geometrical specifications were prepared for both rock types (Figure 2). The top of a sample was defined by the direction in which the cores were drilled. At least two samples were prepared for each specific geometry.

A) Standard according to ISRM [10]
Seven cores were ground in accordance with the ISRM specifications (≤ 0.02 mm parallelism) to obtain reference values for the UCS. The grinding process lasted until the parallelism of end faces lay within 0.02 mm. The other four samples were ground on a surface grinder to keep the error of parallelism as small as possible and to evaluate the validity of the recommendations for end faces in comparison to the results from the cup wheel grinder. The sample holders of both machines are almost identical for a standard grind. On the cup wheel grinder, the sample cylinder is clamped between two angular prisms and fixed via a vacuum.

B) Single-ended wedged
Samples were bevelled in four angles between 0.04° and 1.2° at the top end face using the surface grinder and shims that were placed under the sample to produce a wedge. The smallest angle of 0.04° corresponds to a sheet thickness of 0.02 mm being the upper limit of parallelism according to ISRM [10]. The bottom end face was treated with a surface grinder according to end face class A).

C) Double-ended wedged
Samples were bevelled in two different angles, 0.04° and 0.6°, at the top and bottom end faces using the surface grinder and shims with different thicknesses. The dip directions of both end faces were varied in three different relative orientations.

D) Double-ended rough
Both end faces were sawn and then sandblasted to adjust the flatness and roughness of unground samples. We used slag tap granulate with a grain size of 0.2 mm to 1.0 mm and a Mohs hardness of 6 to 7. The abrasive was blasted for 15 s with 6.5 bar to 7 bar from a distance of 12 cm to 15 cm while slowly rotating the sample to ensure uniform material removal. After sandblasting, samples showed a JRC of 0 to 2 [15][16].

E) Double-ended double-wedged
To simulate a line source for stress application double-wedged end faces were prepared with identical angles and orientations of the wedges on both end faces. To investigate the effect of wedge shapes two different wedge angles were prepared at 5° and 10°.

F) Double-ended spherical
To simulate a point source for stress application with smooth stress distribution we prepared spherical end faces on both ends. For this purpose, a fourth axis was designed and manufactured in the form of a radius grinding frame. The sample holder was attached to a swivel axis, which could be adjusted manually via a hand wheel. To align the apex of the grinding wheel with the centre of the sample a steel plumb bob was used. A disadvantage of the radius grinding frame is the rigid seat of the sample cylinder. For spherical grinding, the sample must be continuously rotated in small increments. The grinding process is therefore time-consuming taking approximately 8 h to 9 h. Three different spheroid radii were prepared for each rock type, i.e., 35 mm, 40 mm and 45 mm.

![Figure 2](image)

**Figure 2.** End face classes (left) and examples of failure patterns (right): A) according to ISRM [10], B) single-ended wedged, C) double-ended wedged with different dip directions, D) double-ended rough, E) double-ended double-wedged, F) double-ended spherical.

2.3. Sample characterization
All samples were geometrically characterized after preparation using a measuring setup mounted on a granite surface plate with a grade AA accuracy (accuracy of 0.17). The profiles of the end faces were measured with a vertical resolution of 0.001 mm for 60 datapoints across the diameter of 30 mm (Figure 3). The physical properties of prepared samples are independent of end face geometry and confirm the homogeneity of sample material. Geometric density and P-wave velocity amount to 2516 ± 6 kg m⁻³ and 4794 ± 124 km s⁻¹ for Ruhr sandstone, and to 2578 ± 5 kg m⁻³ and 5656 ± 130 km s⁻¹ for Solnhofen limestone.
2.4. Uniaxial compressive strength tests

Samples were placed in a stiff 4000 kN loading frame and centered between the loading plates. Our assembly comprises a spherical seat. A radial strain chain was placed at the centre of the sample. The unconfined compressive strength test was conducted servo-controlled with grade 1 testing equipment. During testing, axial load was applied until failure occurred. The axial piston advanced with a constant velocity resulting in a nominal strain-rate of about $10^{-5}$ mm/mm/s. Experiments were conducted using an MTS TestStar II m controller. Axial load and axial displacement were recorded with a sampling frequency of 10 Hz using a calibrated load cell and calibrated LVDTs with a resolution of $10^{-7}$ m. Uniaxial compressive stress and axial strain were monitored and controlled with a frequency of 10 Hz.

Axial stresses and strains were calculated based on the cross-sectional area of the sample (disregarding effective contact points between piston and sample) and maximum sample length, respectively. UCS $\sigma_c$ was derived from the maximum in the stress-strain relation. The deformation modulus $V$ was determined at an axial stress in the range from 40% to 60% of the UCS using axial strains that were calibrated for system characteristics.

3. Results

Samples of Ruhr sandstone and Solnhofen limestone exhibited a wide range of UCS and Young’s moduli (Figure 1 and Figure 4). The minimum and maximum UCS determined for Ruhr sandstone were 62 MPa and 456 MPa, respectively. The supposedly "correct" UCS for low tolerance standard end faces was $166 \pm 2$ MPa. For Solnhofen limestone, the minimum and maximum UCS were 27 MPa and 266 MPa, respectively. The average UCS for low tolerance standard end faces was $240 \pm 36$ MPa. For both rocks, results for standard and low tolerance end faces were similar. Interestingly, the repeatability of samples with standard end faces was larger than for samples with low tolerance standard end faces (Ruhr sandstone: $176 \pm 12$ MPa vs. $166 \pm 2$ MPa; Solnhofen limestone: $220 \pm 44$ MPa vs. $240 \pm 36$ MPa).

For both rock varieties, the UCS systematically decreased with increasing inclination angle of single-ended wedged end face geometries by a factor of 2.6 (Ruhr sandstone) and 3.5 (Solnhofen limestone). Samples were less sensitive to inclination angle when both end faces were inclined, but when the dip directions of both end faces were at an angle of 90°, the UCS of both rock types decreased significantly.

UCS was significantly larger compared to standard end faces for double-wedged and spherical end faces of Ruhr sandstone samples. Larger UCS were not observed for double-wedged samples of Solnhofen limestone; spherical samples were not prepared from Solnhofen limestone.
Young’s moduli showed a dependence on standard and inclined end face geometries similar to that of UCS (Figure 4). The full range of Young’s moduli was 3 GPa to 42 GPa for Ruhr sandstone and 2 GPa to 48 GPa for Solnhofen limestone. Young’s moduli decreased systematically with increasing inclination angle of single-ended wedged end faces. Young’s moduli of samples with rough, double-wedged and spherical end faces were significantly reduced compared to those obtained for standard end faces.

![Young’s modulus and UCS values](image)

**Figure 4.** UCS (top) and Young’s moduli (bottom) for samples of Ruhr sandstone (diamonds) and Solnhofen limestone (circles) for different end face geometries.
The failure patterns differed significantly among the samples with different end face geometries (Figure 2). Samples with standard end faces failed by axial splitting, shear or a combination of both, with a more pronounced tendency of Solnhofen limestone to axial splitting. End faces showed signs of toppling for samples with inclined end faces. Rough end faces were associated with axial splitting. The spherical samples of Ruhr sandstone showed uniform triple junctions that were oriented at an angle of 120° to each other. Double-wedged samples of both rocks showed a single failure plane that was oriented subparallel to the direction of loading and initiated from the roof ridge. Notably, all failure planes of double-wedged samples bulged equally from their centreline. More experiments complemented by numerical simulations on the stress distribution in samples with different end face geometries are required to better understand the failure patterns and derive warning signs for sloppy sample preparation.

4. Discussion

According to the UCS and Young’s moduli for standard end face geometries we conclude that the tolerances for plane parallelism and evenness of the ISRM were sufficient for the investigated rock varieties. The differences in average UCS between standard and low tolerance standard end face geometries were small, but the UCS standard deviation improved for low tolerance standard end faces. More experiments are required to statistically validate these results.

Sloppy end face preparation may lead to significant deviations from the UCS and Young’s moduli targeted by standards and recommendations. The lowest UCS values were 37% and 11% of the UCS determined for low tolerance standard end faces for Ruhr sandstone and Solnhofen limestone, respectively, and determined for rough end faces. The lowest Young’s moduli values were 8% and 5% of the Young’s moduli determined for low tolerance standard end faces for Ruhr sandstone and Solnhofen limestone, respectively, and determined for double-wedged end faces.

Strength can also be increased significantly for specific end face geometries that were rather elaborate to prepare, i.e., double-wedged and spherical end faces, but the effect seems to depend on rock type and therefore needs to be further investigated to understand the underlying mechanisms.

The results obtained in this study would be less significant for lower strength and more compliant rocks than the two investigated rock varieties, but also more significant for higher strength and stiffer rocks. Generally, the sensitivity to end face geometry increases with increasing strength and stiffness, while the absolute measurement accuracy decreases. It may therefore be necessary to adjust recommendations for tolerances according to the mechanical properties of the investigated rock material.

In practice, sloppy end face geometries will usually lead to deviations from standard geometries that are associated with determining a too low UCS and Young’s modulus – with severe consequences for derived safety, depletion and economic concepts. The effort for sample preparation according to standards or better is justified in light of the risks and miscalculations associated with wrong results.

5. Conclusions

Based on UCS tests of 74 samples of Ruhr sandstone and Solnhofen limestone with different end face geometries we derived the following conclusions:

- UCS and Young’s modulus are strongly affected by end face geometry. UCS and Young’s moduli can be significantly decreased, but also increased, while the end face geometries typically associated with sloppy sample preparation led to a decrease in UCS and Young’s modulus.
- The maximum decrease in UCS was 37% and 11% for Ruhr sandstone and Solnhofen limestone, respectively, and in both cases determined in an experiment with rough end faces. The maximum decrease in Young’s modulus was 8% and 5% for Ruhr sandstone and Solnhofen limestone, respectively, and in both cases determined in an experiment with double-wedged end faces.
- The tolerances for plane parallelism and evenness of the ISRM were sufficient for the investigated rock varieties. In general, it may be necessary to adjust recommendations for tolerances according to the mechanical properties of the investigated rock material.
• Failure patterns may serve as warning signs for specific deficits in sample preparation, e.g., for end faces with an inclination angle. More experiments complemented by numerical simulations on the stress distribution within samples are required to better understand the failure patterns and their potential for diagnosing sloppy sample preparation.

Acknowledgments
The authors thank Claudia Brajer and Lucas Witte for their support in performing the laboratory experiments.

References
[1] Arzúa J, González J, Erazo I T, Canovas M, Alejano L (2019): Grinding or not grinding, that is the question. 14th International Congress on Rock Mechanics and Rock Engineering (ISRM 2019) - Rock Mechanics for Natural Resources and Infrastructure Development, ISBN 978-0-367-42284-4
[2] DIN 18300:2019-09: VOB Vergabe- und Vertragsordnung für Bauleistungen - Teil C: Allgemeine Technische Vertragsbedingungen für Bauleistungen (ATV) – Erdarbeiten
[3] DIN 18301:2019-09: VOB Vergabe- und Vertragsordnung für Bauleistungen - Teil C: Allgemeine Technische Vertragsbedingungen für Bauleistungen (ATV) – Bohrarbeiten
[4] DIN 18304:2019-09: VOB Vergabe- und Vertragsordnung für Bauleistungen - Teil C: Allgemeine Technische Vertragsbedingungen für Bauleistungen (ATV) – Ramm-, Rüttel- und Pressarbeiten
[5] DIN 18312:2019-09: VOB Vergabe- und Vertragsordnung für Bauleistungen - Teil C: Allgemeine Technische Vertragsbedingungen für Bauleistungen (ATV) – Untertagebauarbeiten
[6] DIN 18313:2019-09: VOB Vergabe- und Vertragsordnung für Bauleistungen - Teil C: Allgemeine Technische Vertragsbedingungen für Bauleistungen (ATV) – Schlitzwandarbeiten mit stützenden Flüssigkeiten
[7] DIN EN ISO 14689:2018-05: Geotechnische Erkundung und Untersuchung - Benennung, Beschreibung und Klassifizierung von Fels (ISO 14689:2017); Deutsche Fassung EN ISO 14689:2018
[8] Hoskins J R., Horino F G (1968): Effect of end conditions on determining compressive strength of rock samples. U.S. Bur. Mines Rept. Ivest. 7171: 22 pp
[9] ASTM D7012-14e1, Standard Test Methods for Compressive Strength and Elastic Moduli of Intact Rock Core Samples under Varying States of Stress and Temperatures, ASTM International, West Conshohocken, PA, 2014, www.astm.org
[10] ISRM 1979, Suggested methods for determining the uniaxial compressive strength and deformability of rock materials. Int. J. Rock Mech. Min. Sci. Geomech. Abs. 16(2), 135-140
[11] Mutschler T (2004), Neufassung der Empfehlung Nr. 1 des Arbeitskreises "Versuchstechnik Fels" der Deutschen Gesellschaft für Geotechnik e. V.: Einaxiale Druckversuche an zylindrischen Gesteinsprüfkörpern. Bautechnik, 81: 825-834
[12] Hawkes I, Mellor M (1969): Uniaxial testing in rock mechanics laboratories. Engineering Geology 4, 177–285
[13] Duda M, Renner J (2013): The weakening effect of water on the brittle failure strength of sandstone. Geophys. J. Int. 192 (3), 1091–1108
[14] Baud P, Schubnel A, and Wong T (2000): Dilatancy, compaction, and failure mode in Solnhofen limestone. J. Geophys. Res. 105( B8), 19289–19303
[15] Brown E T (1981): Rock Characterization, Testing and Monitoring: ISRM Suggested Methods. 200 p., Oxford (Pergamon Press)
[16] Barton N (2013): Shear strength criteria for rock, rock joints, rock fill and rock masses: Problems and some solutions. J. of Rock Mech. and Geotechn. Eng. 5, pp 249–261
[17] DIN 876-1:1984-08: Prüfplatten; Prüfplatten aus Naturhartgestein; Anforderungen, Prüfung