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Semi-destructive determination of compressive strength of building and decorative stone based on its drillability

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Abstract

The uniaxial compressive strength (UCS) represents a basic material parameter of intact rock determining mechanical resistance and failure behaviour under loading conditions. Although the standard direct method for determining the UCS of rocks is relatively simple to perform and evaluate, it requires a large number of precisely prepared test specimens, usually cylindrical in shape. Obtaining samples of the required quality is problematic in some cases, for example, the preparation of standard cylindrical test samples in weak or weathered rock is quite difficult. Also in the case of historical constructions or works of art, the preparation of samples for destructive determination of UCS is essentially impossible. 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 utilized in engineering practice for indirect estimation of UCS value. The paper deals with the possibility of using the so-called Kučera's drill for semi-destructive testing of the strength of natural stone, specifically sandstones. These represent one of the most commonly used materials for stone masonry and historical architectural elements. In common construction diagnostic practice, the Kučera's drillis currently used mainly for determining the strength properties of brick masonry and mortars. The relationship between compressive strength and drilling resistance was verified on five types of sandstone with different strengths that are currently mined in the Czech Republic. In addition to the Kučera's drill, a Schmidt hammer was also used for non-destructive strength determination in order to compare the applicability of both methods. The results of the research can be applied in the diagnostics of building structures, e.g. in the reconstruction of historical buildings and in restoration work, but also in mining activities in a quarry, for example to select a sandstone material with the required properties.

Keywords

Sandstone, Compressive strength, Drilling resistance, Schmidt hammer, Semi-destructive measurements.

1 Introduction

Determining the mechanical properties of rocks, for example for the purposes of assessment the behavior, quality and stability of a rock mass, optimizing mining methods, desintegration of rocks or determining the usability of rocks in construction, is one of the basic types of tests in rock mechanics and rock engineering (Bieniawski 1974). The strength of rocks is usually determined in laboratory conditions using a compression testing machine (Hawkins 1998). However, these tests require the preparation of relatively large sets of test specimens of regular shape and defined dimensions. Destructive strength tests can therefore only be performed if a larger amount of intact rock can be taken. Unfortunately, this is not possible in some cases, for example in weathered rocks or rocks applied in historical monuments. For these purposes, a number of methods can be used for indirect determination of uniaxial compressive strength (UCS) of rocks using other physical and mechanical properties such as bulk density, porosity, P- and/or S-wave velocity, Schmidt hammer (SH) rebound number, hardness number, abrasivity index, drilling resistance, point load strength or impact strength (Aladejare et al. 2021; Kahraman 2001; Xie et al. 2024; etc.). In the presented research, rock drillability was used to indirectly determine the UCS of sandstones. In addition to drilling resistance, SH rebound hardness was also applied for the same objective to compare the applicability of both methods. The SH was developed in the late 1940s for non-destructive evaluation of surface strength of concrete in situ based on determination of rebound hardness (Schmidt 1951). Soon after, from the early 1960s, the SH began to be used also in rock mechanics practice mainly for indirect prediction of uniaxial compressive strength (UCS) and Young's modulus of rocks (Aydin 2009; Aydin and Basu 2005;Brabec and Krmíček 2023; Oderian and Bassagi 2014; etc.). Currently, the SH is commonly used in a wide range of applications not only in rock mechanics and rock engineering, but also in geomorphology and cultural heritage (for overview see e.g. Přikryl and Snížek 2023). The measurement of drilling resistance of rocks, developed in 1908, is currently mainly used in the field of assessing the quality of natural stone and its diagnostics, conservation and restoration. The resistance of the rock to drilling usually correlates well with the UCS (Pamplona et al. 2007, Siedel et al. 2010, Tiano and Vigiano 2000). In this research, the drillability of rocks was measured using Kučera's drill, which is used in common construction diagnostic practice primarily to determine the strength properties of brick masonry, mortars or structural timber.

2 Rocks used for the experiment

Five sandstones with different properties, long-term quarried and used in the Czech Republic, were selected for this study: (i) low strength Mšené sandstone (Koudelka et al. 2020; Kytýř et al. 2024), (ii) moderate strength Hořice sandstone (Vavro et al. 2019), (iii) moderate- to medium strength Božanov sandstone (Vavro et al. 2025), (iv) medium strength Kocbeře sandstone (Kytýř et al. 2024; Vavrik et al. 2021; Vavro et al. 2026), and (v) high strength Godula sandstone (Vavro et al. 2016).

Physical and mechanical properties of studied rocks are presented in Table 1.

Table 1. Average values of selected physical and mechanical parameters of sandstones used for experiment.

Rock property	Mšené	Hořice	Božanov	Kocbeře	Godula
Specific (mass) density [kg·m^{-3}]	2650	2640	2520	2660	2620
Bulk density [kg·m^{-3}]	1860	1940	2190	2250	2510
Total porosity [%]	29.6	28.3	15.7	14.8	5.4
Open porosity [%]	28.1	25.0	9.8	9.2	4.0
Water absorption capacity [%]	12.9	10.9	4.5	3.8	1.6
Uniaxial compressive strength [MPa]	15	33	52	80	126

UCS was tested on dried cubic (50 x 50 x 50 mm) specimens, water absorption was determined after 48 hours of soaking

3 Methodology, test samples and equipment used in the experiment

The sandstones used in the experiment were taken from active quarries in the form of irregularly shaped blocks with a side length of approximately 0.3–0.4 m. From these blocks, test specimens in the shape of cuboids measuring 150 x 150 x 50 mm were cut in the stonemason´s workshop using a diamond circular saw. Nine (in the case of the Mšené sandstone 10) such test cuboids were prepared from each tested rock, with the shortest dimension parallel to the rock stratification. A square grid was then drawn on the cuboids, showing their division into individual test cubes with an edge of 50 mm. A

total of nine cubes were created in this way in each of the cuboids, with the cubes in the corners being intended for non-destructive or semi-destructive testing (NDT) using a Schmidt hammer and Kučera's drill, and the other five cubes for destructive testing (DT) of UCS. This means a total of 36 cubes for NDT and 45 cubes for DT in the case of the Hořice, Božanov, Kocbeře and Godula sandstones and 40 cubes for NDT and 50 cubes for DT for the Mšené sandstone. First, NDT was carried out. Before testing, each test cuboid was dried to constant weight and then placed flat in a press and loaded to ca 20% of the expected compressive strength in order to its fixation. On the corner cubes of each cuboid, a total of 16 NDT measurements were performed, eight using a Kučera's drill and eight using a Schmidt hammer. The NDT measurements was carried out using: (1) a cordless Kučera's drill PZZ-01 (K.I.K., Czech Republic), primarily intended for testing brick masonry and mortars, and (2) an original Schmidt concrete test hammer, type NR (Proceq, Switzerland), with impact energy 2207 Nm and measuring range between 10 to 70 MPa of UCS, equipped with a recording device (Fig. 1). After performing the NDT tests, each cuboid was cut with a diamond saw into 9 cubes with an edge of 50 mm, which were dried to constant weight. The four corner cubes on which the NDT methods were applied were subsequently used to determine the physical properties. Five virgin cubes from each cuboid were then used for destructive testing (DT) of UCS. The compressive tests were performed on the computer-controlled ZWICK 1494 mechanical compression testing machine (Zwick/Roell, Germany) with the maximum loading force of 600 kN, the loading rate was 0.5 MPa·s^{-1}. The workflow of the entire NDT and DT testing procedure is schematically shown in Fig. 2.

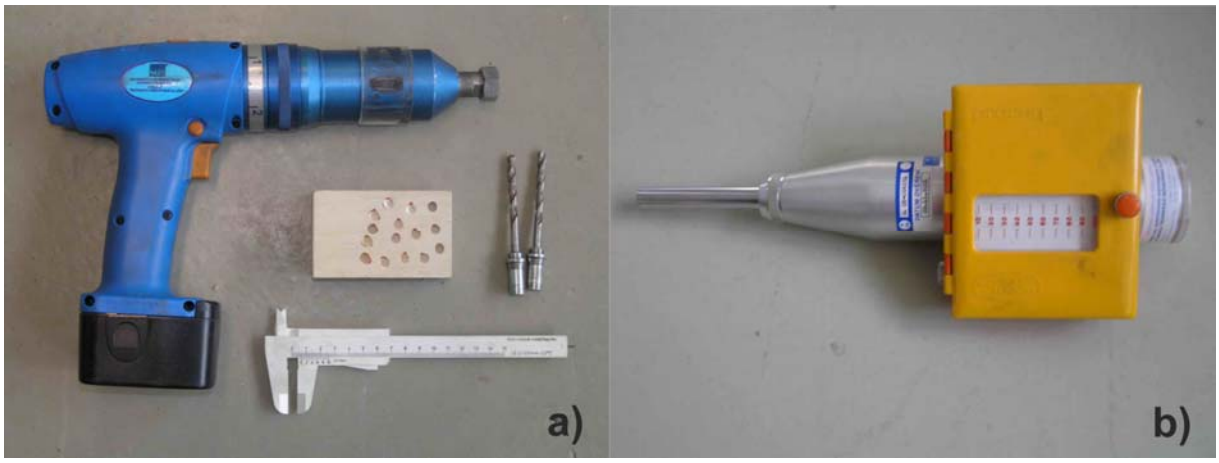


Fig. 1 NDT equipment used in the experiment: (a) Kučera's drill PZZ-01, (b) Schmidt hammer, type NR.

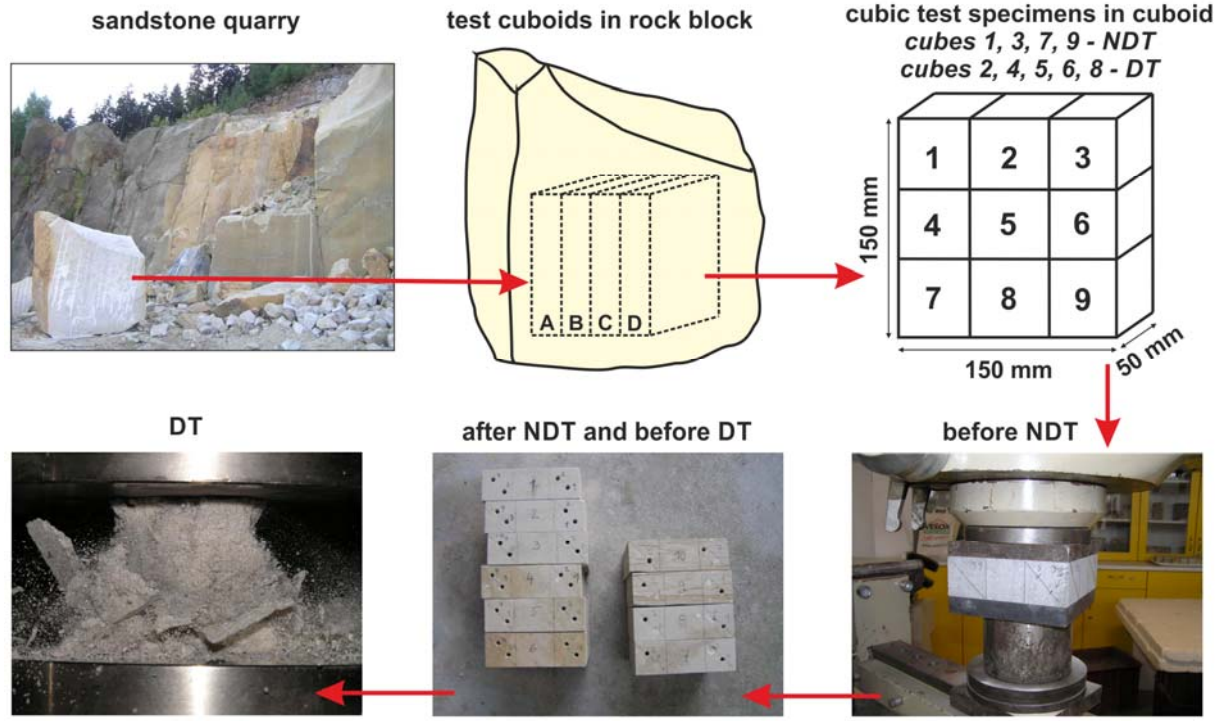


Fig. 2 Schematic framework of the experimental program.

4 Experimental results

The found relations of hole depth and rebound value with UCS are presented in Fig. 3. In the presented graphs, individual points correspond to the arithmetic means of partial NDT and DT measurement values within individual test cuboids.

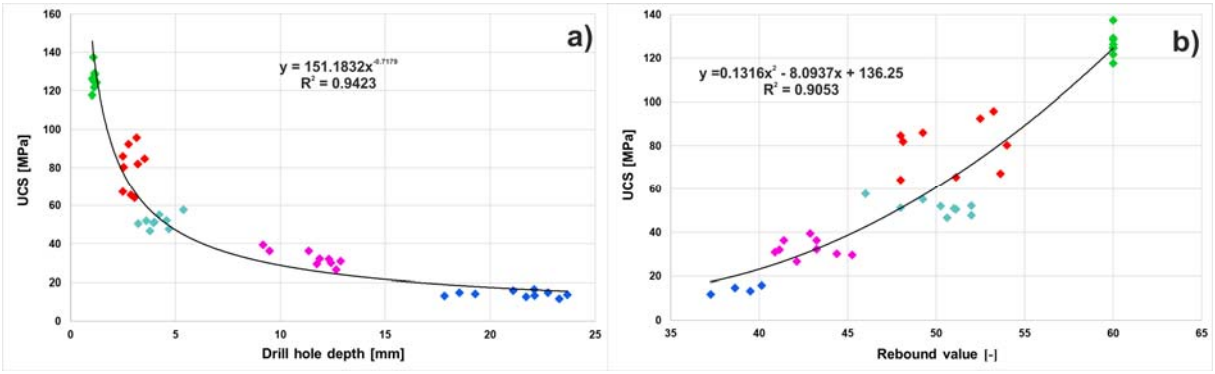


Fig. 3 Scatter plots showing correlations between drill hole depth and UCS (a) and rebound value and UCS (b); color marking for individual sandstones: light green – Godula, red – Kocbeře, teal – Božanov, violet – Hořice, dark blue – Mšené.

The relations between drill hole depth (DHD) and UCS is shown in the graph in Fig. 3a. The obtained regression equation of the power function from all measured values from five studied sandstones has the form $UCS = 151.1832DHD^{-0.7178}$, the value of the determination coefficient is $R^2 = 0.9423$. However, as can be seen from the graph, despite the high value of R^2, the power function does not completely accurately characterize the observed dependence, when, for example, the points representing the Hořice sandstone lie completely outside the fitted course of this function.

As can be seen from Fig. 3b, the relationship between Schmidt hammer rebound hardness (SRH) and UCS can best be described by a quadratic function with a regression equation of the form $UCS = 0.1316SRH^2 - 8.0937SRH + 136.25$ and with a coefficient of determination $R^2 = 0.9053$. However, it should be noted that the observed relation between SRH and UCS is undoubtedly influenced by the fact that for Godula sandstone the SRH value is equal to 60 in all cases. Also, the average SRH for the Hořice sandstone and the Kocbeřeone differ from each other by an SRH value of only ca 9, but the difference in the UCS of these two rocks is almost 50 MPa. It therefore appears that the Schmidt hammer testing method may have less sensitivity for estimating the UCS, especially for stronger types of sandstones.

For the reasons stated above in the commentary to Fig. 3a, the closest relationship between DHD and UCS was sought. This can best be expressed using a fifth-degree polynomial function in the form shown in Fig. 4. This relationship was then used to compile a calibration table for the approximate indirect determination of the UCS of dried sandstone based on the depth of the drill hole (Table 2).

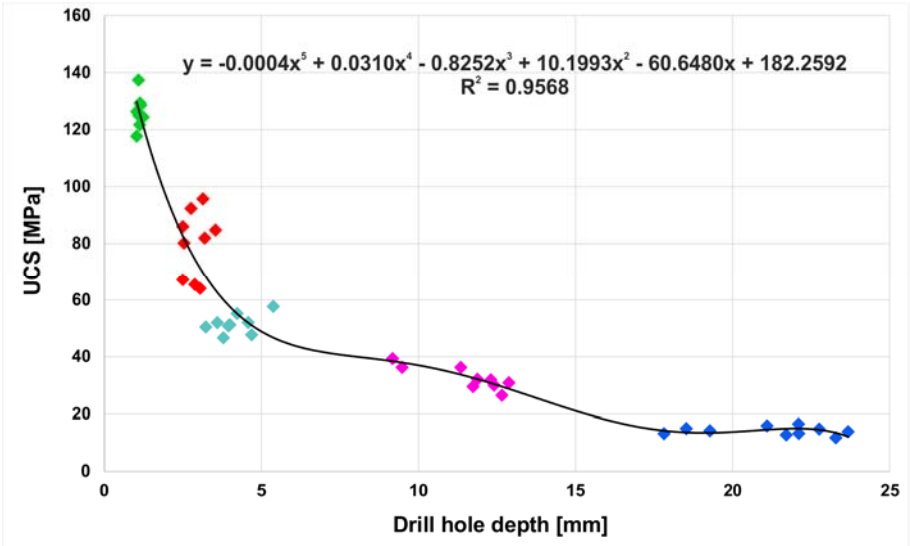


Fig. 4 The closest correlation found between DHD and UCS (all measured values) - fitting a fifth-order polynomial function; color differentiation of tested sandstones: light green points – Godula, red points – Kocbeře, teal points – Božanov, violet points – Hořice, dark blue points –Mšené.

Table 2. Demonstration of a part of the calibration table for estimation of the UCS of dried sandstone based on the DHD.

DHD [mm]	**UCS** [MPa]	**DHD** [mm]	**UCS** [MPa]	**DHD** [mm]	**UCS** [MPa]	**DHD** [mm]	**UCS** [MPa]
0.5	153.3	5.5	46.6	10.5	35.2	15.5	20.6
1.0	131.1	6.0	44.2	11.0	34.1	16.0	19.2
1.5	112.5	6.5	42.5	11.5	32.9	16.5	17.9
2.0	97.0	7.0	41.2	12.0	31.2	17.0	16.7
2.5	84.6	7.5	40.1	12.5	30.2	17.5	15.8
3.0	73.9	8.0	39.3	13.0	28.6	18.0	15.0
3.5	65.5	8.5	38.5	13.5	27.0	18.5	14.4
4.0	58.9	9.0	37.8	14.0	25.4	19.0	14.0
4.5	53.7	9.5	37.0	14.5	23.8	19.5	13.8
5.0	49.7	10.0	36.2	15.0	22.2	20.0	13.8

To convert the values obtained by NDT measurement with a Kučera's drill into UCS values, it was also necessary to determine the coefficient α. This coefficient is generally used in construction testing to express the ratio between NDT and DT parameters. An inverse relationship applies to the drillability of stone, i.e. with increasing UCS, the DHD decreases. The coefficient was therefore obtained by multiplying the UCS values by the corresponding DHD values ($\alpha = UCS * DHD$). In practical use, by dividing the coefficient by the DHD in a known sandstone, an approximate UCS value of this sandstone in MPa can be obtained. The determined values of the coefficient α for all five tested sandstones are given in Table 3.

Table 3. Coefficient α for estimation of UCS [MPa] from DHD [mm] for tested sandstones.

Sandstone	**Mšené**	**Hořice**	**Božanov**	**Kocbeře**	**Godula**
Coefficient α	300.660	371.914	215.301	231.975	141.552

5 Conclusions

The conducted research successfully verified the possibility of using the Kučera's drill for semi-destructive determination of the strength of natural stone as an alternative to other indirect methods of qualified estimation of the UCS, primarily the Schmidt rebound hardness testing.

In the case of comparative measurements using the Schmidt hammer, it was found that the dependence between rebound value (SRH) and UCS is not linear, but for tested rocks it can be expressed as a quadratic function in the form $UCS = 0.1316SRH^2 - 8.0937SRH + 136.25$. The relationship found is, however, evidently influenced by the fact that in the case of the strongest Godula sandstone, identical SRH values were consistently measured for all test cuboids. Also, the average SRH for the Hořice and Kocbeře sandstones differ by relatively small values, while the corresponding difference in UCS between these two materials reaches almost 50 MPa. This suggests that the Schmidt hammer may show lower sensitivity in estimating UCS, especially for sandstones stronger than ca 60 – 70 MPa.

The closest dependence found between hole depth (DHD) by Kučera's drill for the five tested sandstones of different strength can be described by a fifth-degree polynomial function in the form $UCS = -0.0004DHD^5 + 0.0310DHD^4 - 0.8252DHD^3 + 10.1993DHD^2 - 60.6480DHD + 182.2592$. From this equation and using the conversion coefficient α between DHD and UCS, a calibration table was subsequently derived for estimating the UCS of the natural porous stone. The defined relationship between drillability and compressive strength of rock corresponds to a very high degree of dependence, as evidenced by the value of the coefficient of determination R^2 of almost 0.96. Kučera's drill thus appears to be a very suitable alternative or supplement to Schmidt hammer technique.

The presented results represent an initial study on this issue. The found relationship between DHD and UCS will be further verified on a wider spectrum of clastic porous rocks and it is also planned to take into account the effect of moisture on the drillability of the natural stone.

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References

Aladejare AE, Alofe ED, Onifade M, Lawal AI, Ozoji TM, Zhang ZX (2021) Empirical estimation of uniaxial compressive strength of rock: Database of simple, multiple, and artificial inteligence-based regressions. Geotechnical and Geological Engineering 39(6): 4427–4455. DOI: 10.1007/s10706-021-01772-5.

Aydin A (2009) ISRM suggested method for determination of the Schmidt hammer rebound hardness: Revised version. International Journal of Rock Mechanics and Mining Sciences 46(3): 627–634. DOI: 10.1016/j.ijrmms.2008.01.020.

Aydin A, Basu A (2005) The Schmidt hammer in rock material characterization. Engineering Geology 81(1): 1–14. DOI: 10.1016/j.enggeo.2005.06.006.

Bieniawski ZT (1974) Estimating the strength of rock materials. Journal of the South African Institute of Mining and Metallurgy 74(8): 312–320.

Brabec M, Krmíček L (2024) Schmidt rebound hardness dependence on the core-size: A correction model presented and tested on greywacke. Journal of Testing and Evaluation 52(4): 2663–2673. DOI: 10.1520/JTE20230628.

Hawkins AB (1998) Aspects of rock strength. Bulletin of Engineering geology and the Environment 57(1): 17–30. DOI: 10.1007/s100640050017.

Kahraman S (2001) Evaluation of simple methods for assessing the uniaxial compressive strength of rock. International Journal of Rock Mechanics and Mining Sciences 38(7): 981–994. DOI: 10.1016/S1365-1609(01)00039-9.

Koudelka P, Fila T, Rada V, Zlamal P, Sleichert J, Vopalensky M, Kumpova I, Benes P, Vavrik D, Vavro L, Vavro M, Drdacky M, Kytyr D (2020) In-situ X-ray differential micro-tomography for investigation of water-weakening in quasi-brittle materials subjected to four-point bending. Materials 13(6): 1405. DOI: 10.3390/ma13061405.

Kytýř D, Koudelka P, Drozdenko D, Vavro M, Fíla T, Rada V, Vavro L, Máthis K, Souček K (2024) Acoustic emission and 4D X-ray micro-tomography for monitoring crack propagation in rocks. International Journal of Rock Mechanics and Mining Sciences 183: 105917. DOI: 10.1016/j.ijrmms.2024.105917.

Oderian OA, Bassagi M (2014) Preliminary field measurement of the uniaxial compressive strength of migmatite using N-type Schmidt rebound hammer. The International Journal of Engineering and Science 3(8): 11–17.

Pamplona M, Kocher M, Snethlage R, Barros LA (2007) Drilling resistance: overview and outlook. Zeitschrift der Deutschen Gesellschaftfür Geowissenschaften 158(3): 665–679. DOI: 10.1127/1860-1804/2007/0158-0665.

Přikryl R, Snížek P (2023) Critical assessment of the “non-destructiveness” of Schmidt hammer test on monumental sandstones: A microscopic and microstructural approach. Journal of Cultural Heritage 59: 247–254. DOI: 10.1016/j.culher.2022.12.011.

Schmidt E (1951) A non-destructive concrete tester. Concrete 59(8): 34–35.

Siedel H, Pfefferkorn S, von Plehwe-Leisen E, Leisen H (2010) Sandstone weathering in tropical climate: Results of low-destructive investigations at the temple of Angkor Wat, Cambodia. Engineering Geology115(3-4): 182–192. DOI: 10.1016/j.enggeo.2009.07.003.

Tiano P, Viggiano A (2000) A new diagnostic tool for the evaluation of the hardness of natural and artificial stone. Internationale Zeitschrift für Bauinstandsetzen und Baudenkmalpflege6(5): 555–566.

Vavrik D, Benes P, Fila T, Koudelka P, Kumpova I, Kytyr D, Vopalensky M, Vavro M, Vavro L (2021) Local fracture toughness testing of sandstone based on X-ray tomographic reconstruction. International Journal of Rock Mechanics and Mining Sciences 138:104578. DOI: 10.1016/j.ijrmms.2020.104578.

Vavro L, Malíková L, Frantík P, Kubeš P, Keršner Z, Vavro M (2019) An advanced assessment of mechanical fracture parameters of sandstones depending on the internal rock texture features. Acta Geodynamica et Geomaterialia 16(2): 157–168. DOI: 10.13168/AGG.2019.0013.

Vavro L, Vavro M, Nag A, Klichová D, Stolárik G, Gupta MK, Hloch S (2025) Erosive wear behavior of sandstone under low-pressure pulsating water jet. Tribology International 203: 110411. DOI: 10.1016/j.triboint.2024.110411.

Vavro M, Souček K, Vavro L, Georgiou L, Mrógala J (2026) Study of the microstructure and permeability of building stone using X-ray micro-tomography. Periodica Polytechnica Civil Engineering 70(1): 11–27. DOI: 10.3311/PPci.42434.

Vavro M, Vavro L, Martinec P, Souček K (2016) Properties, durability and use of glauconitic Godula sandstones: a relatively less known building stone of the Czech Republic and Poland. Environmental Earth Sciences 75(22): 1437. DOI: 10.1007/s12665-016-6248-3.

Xie WQ, Liu XL, Zhang XP, Liu QS, Wang EZ (2024): A review of test methods for uniaxial compressive strength of rocks: Theory, apparatus and data processing. Journal of Rock Mechanics and Geotechnical Engineering (article in press). DOI: 10.1016/j.jrmge.2024.05.003.