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Comparison of the Compressive and Tensile Strength Values of Rocks Obtained on the Basis of Various Standards and Recommendations

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Abstract: The objective of the current study was to compare results relating to the compressive and tensile strength of rocks obtained during research undertaken according to Polish Standards (as part of the European standards known as Eurocodes), American Society for Testing and Materials (ASTM) Standards, and the recommendations of the International Society for Rock Mechanics (ISRM). A total of 130 experiments for uniaxial compression on axisymmetric samples, point loads, and transverse compression (so-called Brazilian tests) were performed on rock samples comprising granite, limestone, and sandstone. Geometric properties of the samples were selected depending on the applied research method, and the relationship between the specimen's slenderness and shape, and the obtained values of compressive and tensile strength, were analyzed. The results of the study showed that values of compressive and tensile strength obtained in a laboratory depend significantly on specimen slenderness, different values of which are imposed by various ISRM standards and recommendations, wherein this sensitivity was much higher in the case of compressive strength. The study also raised doubt about the usefulness of the so-called point load test as a method for determination of the compressive strength of rocks and potential estimation of the tensile strength.

Keywords: compressive strength; tensile strength; regular axisymmetric specimen; irregular specimen; specimen slenderness; Polish Standard; Eurocode; ASTM Standards; ISRM recommendations

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1. Introduction

The recent development of road and railroad investments in south-eastern Poland has resulted in an increased demand for geotechnical laboratory studies of rock materials [1]. Geotechnical laboratory tests are also necessary, e.g., in the initial phase of designing facilities for underground storage of energy carriers, e.g., in salt caverns [2]. One of the problems that occurs is the correct determination of the mechanical properties of the rocks forming the rock mass in which energy carriers are stored [3]. Studies are usually aimed at determining the strength values of material constants, usually of compressive strength and, more rarely, of tensile strength. Stakeholders often require the determination of deformation constants (the longitudinal deformation modulus and the transverse deformation coefficient) and the Coulomb–Mohr tensile stress hypothesis parameters, namely, cohesion and the angle of internal friction.

The increased demand for laboratory studies [4] and the expansion of the desired scope of these studies [5] appears to indicate that investors require designs with greater emphasis on economic considerations, while retaining high values of safety coefficients. However, investments are also being demanded in areas with increasingly difficult geological conditions, in which geotechnical works are impossible without a thorough geological survey and determination of mechanical properties of the substrate.

As a result, laboratories are obliged to perform the required studies and tests in an extremely conscious manner. In the current paper, the term “conscious” is understood by

the authors to be a situation in which the laboratory staff do not act automatically, but control the study methodology at each step and modify it to ensure that reliable results are obtained. Such a process requires excellent knowledge of research procedures, and often requires execution of so-called calibration tests to become thoroughly familiar with the research equipment and the measurement track.

Another important factor related to the laboratory tests is standardization of research procedures. This standardization takes place, in parallel, within individual countries (e.g., Polish Standards PN, British BS, or German DIN standards), at the level of the European Union (so-called Eurocodes, which are labelled PN-EN in Poland), or through the activity of research associations, wherein recommendations formulated by the International Society for Rock Mechanics (ISRM) are of key importance in studies of rocks.

It should be noted that this standardization unfortunately contributes to the increasing disorder within the research market, because standards and recommendations prepared by individual decision makers often contain significantly different requirements. The greatest extent of these differences relates to the specimen slenderness λ , which is defined—in the case of a regular specimen—as the quotient of its longest and shortest dimensions. This means that in the case of a cylindrical specimen with height h and diameter d , slenderness is defined using the formula:

$$\lambda = h/d, \quad (1)$$

and in the case of a cuboid specimen with height h , the base of which is a square with side length a , slenderness is expressed using the following formula:

$$\lambda = h/a. \quad (2)$$

Numerous studies on the influence of a specimen's slenderness on its strength have been previously undertaken. It should be noted that the results of such studies were presented in the 20th century by [6–9] (p. 12). in Poland. In the current study, the authors decided to repeat these studies, selecting specimen slenderness according to the requirements of various standards and recommendations.

The goal of this study was to validate the current methods of determining compressive and tensile strength in terms of their interchangeability. In particular, it was important for the authors to determine the influence of the dimensions and shape of the tested sample on the obtained result. The conducted research shows that the analyzed methods are not interchangeable, and no value exists in determining the compressive and tensile strength of an irregular sample.

2. Determination of the Values of Compressive and Tensile Strength of Rocks—General Information

The goal of the current studies, the results of which are presented in this work, was to determine two material constants: the compressive strength R_c and the tensile strength R_t . This selection was dictated by the fact that investment stakeholders usually expect an appointed research team to determine these two material constants. The research procedures were selected using:

- the list of standards effective in Poland (in most cases representative of the 29 European countries that are bound to implement the European Standard);
- American Society for Testing and Materials (ASTM) Standards;
- the two-volume set of recommendations of the International Society for Rock Mechanics [10,11], which is hereinafter described as the “ISRM recommendations”.

2.1. Determination of Compressive Strength of Rocks— R_c

The compressive strength of a rock is usually the first quantity to be determined during studies on mechanical properties of rocks. This is partly a consequence of a certain, intuitive ease of understanding of this parameter, and is also due to the apparent simplicity of the experiment used to determine this quantity. This experiment is usually a uniaxial

compression test. The test can be characterized using the words “apparent simplicity”, which relates to the fact that its course is actually influenced by a large number of factors, which in extreme cases may result in significant differences in R_c values obtained for a single rock, as previously analyzed in the work by [12].

Depending on the specimen type used in the experiment, the compressive strength is determined using one of two possible methods:

- a test on a regular (cylindrical axisymmetric or cubic) specimen, using the uniaxial compression test; or
- a test on an irregular specimen, using the point load test, sometimes also known as the Franklin test.

The standard requirements and the ISRM recommendations formulated for these two strength tests are as follows:

(a) Uniaxial compression test

- PN-B-04110:1984 [13]—in Polish This is standard has been revoked in Poland. This means that procedures included in this standard are no longer formally effective, but the older generation of engineers still instinctively uses the R_c value determined according to this document in static calculations.
- PN-G-04303:1997 [14]—in Polish A standard from the Mining Sector, which should be considered to be effective; reference to the PKN (Polish Committee for Standardization) [15] source indicates it has not been withdrawn (29 April 2021).
- PN-EN 1926:2007 [16]—English version An effective standard, which should be used instead of PN-B-04110:1984.
- Ulusay and Hudson [17]—in English The ISRM recommendations are formulated on the basis of work presented by [18]. They contain—in addition to the methodology of compressive strength determination—a description of the method used to determine deformation-related material constants.
- ASTM D7012-14e1 [19]—in English A USA standard, for which the main content is identical to the ISRM recommendations.

Each of the aforementioned documents imposes its own requirements for the quantities and slenderness used in specimen testing [20,21]. These requirements, related to cylindrical samples, are summarized in Table 1. This summary indicates that the requirements for specimen diameters may be considered to be similar, whereas the requirements related to slenderness are significantly different. Thus, an identical diameter value was assumed for the tested samples, as $d \approx 44$ mm, whereas their height h was selected such that it met the slenderness condition according to Column 3, Table 1.

Table 1. Specimen diameters and slenderness required by individual standards and recommendations for the uniaxial compression test.

Document Title	Specimen Diameter d [mm]	Specimen Slenderness λ acc. to Formula (1)
1	2	3
PN-B-04110:1984 [13] (Poland)	$d = 50.0 \pm 3.0$ mm	$\lambda = 1.0$
PN-G-04303:1997 [14] (Poland)	$42.0 \text{ mm} \leq d \leq 54.0$ mm	$\lambda = 2.0$
BS EN 1926:2006 [22] * (UK)	$d = 70.0 \pm 5.0$ mm	
DIN EN 1926:2007-03 [23] * (Germany)	or	$\lambda = 1.0$
PN-EN 1926:2007 [16] * (Poland)	$d = 50.0 \pm 5.0$ mm	
Ulusay and Hudson [17] (ISRM recommendation)	$d \approx 54$ mm	$\lambda = 2.5 \div 3.0$
ASTM D7012-14e1 [19] (USA)	$d \geq 47$ mm	$\lambda = 2.0 \div 2.5$

* According to the CEN/CENELEC Internal Regulations, the national standards organizations of the following countries are bound to implement European Standard: Austria, Belgium, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, and United Kingdom.

- (b) Point load test If the material does not allow a regular specimen to be cut (as is often the case in, for example, rocks from the so-called Carpathian Flysch Belt), research procedures allowing an estimate of the compressive strength value for the tested material using irregular-shaped samples should be applied. Recommendations related to the methods of such experiments may be found in three documents:
- PN-G-04307:1998 [24]—in Polish A standard from the Mining Sector, which should be considered to be effective.
 - Ulusay and Hudson [25]—in English The recommendations of the International Society for Rock Mechanics, related to the methodology of the point load test and to the use of its results in determination of the compressive strength of the given material, are prepared on the basis of the works by Franklin et al. (1985) and Brook (1985).
 - ASTM D 5731-16 [26]—in English Among the three aforementioned documents, the PN-G-04307:1998 standard [24] should be considered obsolete due to reasons already discussed by [12] and which will not be repeated here. In contrast, Ulusay and Hudson (ISRM recommendations) [25] and ASTM D 5731-16 [26] distinguish—depending on the specimen shape and on the method of application of the loading force—four types of point load test:
 - i. the “core diameter” or “diametral” test;
 - ii. the “core axis” or “axial” test;
 - iii. the “block” test;
 - iv. the “irregular lump” test.

Figure 1 shows for an irregular specimen, according to the authors of the ISRM recommendations and ASTM Standards, how the loading force should be applied in each of the tests and the important geometric characteristics of the specimen in individual test types. According to these recommendations, irregular samples should meet the following conditions, depending on the test type:

- the “diametral” test: a specimen is understood to be a cylindrical rock fragment, for which the ratio of length to diameter is greater than 1.0;
- the “axial” test: a specimen is understood to be a cylindrical rock fragment, for which the ratio of length to diameter is greater than 0.3, but smaller than 1.0;
- the “block test”: a specimen is understood to be a fragment of rock with an approximately cuboid shape, as shown in Figure 1c, the edge dimensions of which are 50 ± 35 mm and which meet the ratios shown in Figure 1c;
- the “irregular lump” test: a specimen is understood to be a fragment of rock with a shape similar to that shown in Figure 1d, the edge dimensions of which are 50 ± 35 mm and meet the ratios shown in Figure 1d.

The aforementioned considerations show that the term “irregular specimen” has some limitations, which should be considered during sampling and material preparation for testing.

Figure 1. Point load test, specimen shape, specimen loading type and measured geometric characteristics: (a)—the “core diameter” test, (b)—the “core axis” test, (c)—the “block” test, (d)—the “irregular lump” test; reproduced from [27].

2.2. Determination of Tensile Strength of Rocks— R_r

The extremely high sensitivity to even small structural defects of rock is a peculiar feature of tensile strength. It should be noted that this feature provided the basis for the brittle cracking theory developed by the British engineer Alan Griffith (cf. [28]).

The existing methods of R_r value determination may be divided into two groups: direct methods—analogue to methods used in metal technology, which can be summarized as stretching of a regular specimen in a strength testing machine; and indirect methods—in which a rock material specimen is subjected to complex loads, generating stretching strain in specific cross-sections of the specimen. A wide overview of both direct and indirect methods is presented, e.g., by Vutukuri et al. [29] (pp. 87–130).

Because of the relative ease of its performance and simple calculations, the so-called transverse compression test developed in 1943 by the Brazilian engineer Fernando Carneiro (and thus also known as: the Brazilian test) is used in practice for geotechnical purposes [30,31]. In this test, the specimen subjected to the experiment has the shape of a cylinder with diameter d and height h , loaded on the side with force P . The method used to perform this experiment is regulated in three documents:

- PN-G-04302:1997 [32]—in Polish A standard from the Mining Sector, which should be considered to be effective.
- Ulusay and Hudson [33]—in English
- ASTM D3967–16 [34]—in English

Recommendations of the International Society for Rock Mechanics [33], prepared on the basis of the work by [35], related to determinations of tensile strength using both the direct method, by stretching cylindrical axisymmetric samples with high slenderness, and the indirect method, using the transverse compression test.

Each of the aforementioned documents imposes its own requirements for the quantities and slenderness used in specimen testing. These requirements, related to cylindrical samples, are summarized in Table 2.

Table 2. Specimen diameters and slenderness required by individual standards and recommendations for the transverse compression test.

Document Title	Specimen Diameter d [mm]	Specimen Slenderness λ acc. to Formula (1)
1	2	3
PN-G-04302:1997 [32] (Poland)	$42.0 \text{ mm} \leq d \leq 54.0 \text{ mm}$	$\lambda = 0.5$
Ulusay and Hudson [33] (ISRM recommendation)	$d \approx 54.0 \text{ mm}$	$\lambda = 1.0$
ASTM D3967-16 [34] (USA)	$d \approx 54.0 \text{ mm}$	$\lambda = 0.2 \div 0.75$

3. Accepted Methodology of Laboratory Studies

The laboratory studies included three tests: the uniaxial compression test and the point load test, which was used to determine the compressive strength, and the transverse load test, which was used to determine the tensile strength. The main information about the method used to perform individual tests is provided below.

3.1. Determination of Compressive Strength of Rocks— R_c

(a) Uniaxial compression test

The uniaxial compression tests were performed using a slightly different procedure than that suggested in the Polish Standards and in the ISRM recommendations, because the parameter controlling the loading was not the stress rate, but the specimen deformation rate. This operating mode of the press is less susceptible to phenomena caused by local non-uniformities of the samples and specimen treatment inaccuracies (mainly, the so-called pre-cracking), which allows for a narrower result distribution.

All regular samples (cylindrical axisymmetric) were compressed with the deformation rate of 10^{-4} s^{-1} . In the case of cylindrical samples with an identical diameter of $d \approx 45.0 \text{ mm}$ and slenderness values $\lambda = \{1.0; 2.0; 2.5\}$ the following rates of change of the height of the studied specimen $\Delta h / \Delta t$ were obtained:

- for samples with $\lambda = 1.0 \Rightarrow \Delta h / \Delta t = 0.0045 \text{ mm} \times \text{s}^{-1}$,
- for samples with $\lambda = 2.0 \Rightarrow \Delta h / \Delta t = 0.0090 \text{ mm} \times \text{s}^{-1}$,
- for samples with $\lambda = 2.5 \Rightarrow \Delta h / \Delta t = 0.0112 \text{ mm} \times \text{s}^{-1}$.

Using the value of the surface area of specimen cross-section A and of the specimen failure load P , the value of compressive strength R_c was determined using the commonly known formula:

$$R_c = P / A. \quad (3)$$

Figure 2 presents regular samples during the uniaxial compression test.

Figure 2. Samples during the uniaxial compression test; from the left: $\lambda = 1.0$, $\lambda = 2.0$, $\lambda = 2.5$.

(b) Point load test

The methodology used to perform the point load test used at the Rock Deformation Laboratory at Strata Mechanics Research Institute of the Polish Academy of Science (IMG PAN) was developed according to the ISRM recommendations prepared by Ulusay and Hudson [25]. The procedure is as follows:

- A. An irregular specimen with dimensions of 50 ± 35 mm is placed inside a press, between two conical standard hardened points (for simplicity, the “fang” term will be used hereinafter in the text) with a strictly defined shape and attachment, such as shown in Figure 3, in which:
 1. loaded specimen;
 2. conical fangs;
 3. nuts supporting the fangs;
 4. the shaft (top) and the seat (bottom) for fang attachment;
 5. guides ensuring axial application of the load;
 6. dynamometer.

The specimen orientation modes in relation to the loading direction, depending on its shape and the geometric characteristics of the specimen required during test result processing, are shown in Figure 1.

- B. The specimen is compressed until destroyed, and the value of strength corresponding to the exceeded rock strength (P) is recorded, in addition to the distance between conical compressing elements (D) at the time the specimen cracks. The W parameter is determined as the smallest specimen width orthogonal to the loading direction (Figure 1). Thus, the defined W value is then used in further calculations, regardless of the specimen cracking mode.
- C. The uncorrected point strength I_s of the specimen is determined according to the relationship:

$$I_s = P/D_e^2 \quad (4)$$

where D_e is the equivalent core diameter (for details, see the work by [36]) calculated for the diametral test according to the formula:

$$D_e^2 = D^2 \quad (5)$$

and for the test performed along the core axis, the block test, and the irregular lump test, according to the following relationships:

$$D_e^2 = 4A/\pi \text{ and } A = W \times D \quad (6)$$

The value of A defined in Formula (6) is considered to be the minimum surface area of the specimen cross-section passing through the load application points.

- D. The index of corrected point strength of the specimen $I_{S(50)}$ is calculated according to the following formula:

$$I_{S(50)} = F \times I_s \text{ and } F = (D_e/50)^{0.45} \quad (7)$$

where F is the so-called specimen size correction factor.

- E. The $I_{S(50)}$ index for the specimen determined using the method presented above provides the basis for R_c value estimation, wherein the recommendations by [25] suggest that the following relationship applies:

$$R_c = (20 \div 25) \times I_{S(50)} \quad (8)$$

Figure 3. The specimen during the point loading test.

The value of the multiplier in Formula (8) was accepted as 22 in the test performed for the purpose of this publication, according to Annex B to the PN-EN 1926 standard [16]. The authors of ASTM D5731-16 Standard [26] after Bieniawski [37] propose the assumption that the value of this multiplier, depending on the core size, ranges from 18 to 24.5.

It should be noted that the results of a point load test may be used to obtain an approximate estimation of the R_r value. Ulusay and Hudson [25] note that the point load test is a peculiar form of “indirect tensile” and suggest that the value of the $I_{S(50)}$ index is approximately equal to 80% of the R_r value obtained as a result of a direct, uniaxial tensile test or of a Brazilian tensile strength test. On the basis of this observation, the R_r value may be estimated according to the formula:

$$R_r = I_{S(50)} / 0.8 \quad (9)$$

It should be remembered, however, that the value of tensile strength R_r determined in this manner is a rough estimate and its use in design—and in particular, in any static calculations—should be undertaken with extreme care.

3.2. Determination of Tensile Strength of Rocks— R_r

As mentioned above, the tensile strength of the specimen was determined at the Rock Deformation Laboratory of IMG PAN on the basis of a transverse compression test performed according to ISRM recommendations contained in the work by Ulusay and Hudson [33]. A schematic view of loads in such a test and the view of a specimen during the test is shown in Figure 4a,b.

Figure 4. Transverse compression test: (a) schematically presented loads; (b) view of the specimen during the experiment (example).

More extensive, mathematical considerations related to the distribution of strain within the specimen during the Brazilian test may be found in the work by [38] (pp. 159, 225–227), and [39] (pp. 51–54) disclose how to use the Brazilian test to determine the tensile constants: Young’s modulus and Poisson’s coefficient.

For the purpose of this research program, Brazilian tests were performed on samples, for which $\lambda = \{0.5; 1.0\}$, wherein the experiments were performed with a constant piston speed of $0.0045 \text{ mm} \times \text{s}^{-1}$.

4. Samples Prepared for Testing

Three rocks obtained with the cooperation of the Geonics Institute, Czechia Academy of Sciences in Ostrava, were the subject of strength testing. These were:

- micritic limestone, Macoš formation, formed during Upper Devon and collected from a quarry located in Mokrá-Horákov (a detailed description is available on the website <http://kamenolomy.fzp.ujep.cz/index.php?page=record&id=160&tab=lom>) (accessed on 7 May 2021)—hereinafter referred to as the Mokrá-Horákov limestone;
- glauconitic godulian sandstone obtained from Silesian units of Outer West Carpathian Mountains, formed during Upper Cretaceous, collected from a quarry located in Řeka (a detailed description may be found in the work by [40])—hereinafter referred to as the Řeka sandstone;
- biotite granite, Silesian, collected from a quarry located ca. 1300 meters from Petrov (a detailed description may be found on the website <http://kamenolomy.fzp.ujep.cz/index.php?page=record&id=196>) (accessed on 7 May 2021)—hereinafter referred to as the Petrov granite.

In Tables A1, A3 and A5 for regular samples, and Tables A2, A4 and A6 for irregular samples (included in Appendix A), information about the samples prepared for testing may be found. The following designations are used in these tables:

h	—specimen height,
d	—specimen diameter,
m	—specimen mass,
V	—specimen volume,
ρ	—volumetric density of the specimen,
λ	—specimen slenderness,
D, W, L	—geometric characteristic of an irregular specimen, as in Figure 1c, “block” test.

To determine the uniformity of the tested rocks, average values and standard deviations were calculated for the prepared samples (only samples considered to be regular were taken into account). The results are summarized in Table 3.

Table 3. Average volumetric densities (ρ) of the samples prepared for testing.

	Limestone “Mokrá-Horákov”	Sandstone “Řeka”	Granite “Petrov”
ρ -mean [g $\times$ cm ^{−3}]	2.671	2.459	2.588
ρ -standard deviation [g $\times$ cm ^{−3}]	0.013	0.013	0.006
ρ -standard deviation [%]	0.47%	0.52%	0.23%

Values provided in Table 3 show, that in the case of the limestone and the sandstone, the standard deviation of volumetric density (ρ) is about 0.5%, in the case of granite is half this value (0.23%). This indicates that the uniformity of the tested rocks may be considered to be good.

5. Test Results

The results of the performed strength test are summarized below in Tables A7–A9 (included in Appendix B), where the following designations were used: λ —specimen slenderness, R_c —compressive strength of the specimen, R_t —tensile strength of the specimen, which was estimated according to Formula (9) in the case of the point load test.

It should be noted that the numbers of samples, and thus the numbers of experiments performed, are different for different studied rocks. This is a consequence of the quantity of material available for testing. As can be seen, the sandstone was available in the highest

quantity, whereas the quantities of limestone and granite were comparable and significantly lower than that of sandstone. If the quantity of material was inadequate, the number of irregular samples was reduced first.

6. Discussion of the Test Results

6.1. Compressive Strength Test Results

To facilitate the analysis of the obtained test results, the results were subjected to basic statistical analysis by calculating the average values of the respective material constants and their standard deviations. The results of this analysis are shown in Tables 4–6. First, we analyze the value of compressive strength R_c .

Table 4. The average values of compressive strength R_c and of tensile strength R_r and their standard deviations; “Řeka” sandstone.

“Řeka” Sandstone		Slenderness of the Specimen				Irregular Specimen
		$\lambda = 0.5$	$\lambda = 1.0$	$\lambda = 2.0$	$\lambda = 2.5$	
R_c	mean value [MPa]		169.41	177.47	177.21	94.23
	standard deviation [MPa]		43.00	24.47	22.66	11.78
	standard deviation [%]		25.4%	13.8%	12.8%	12.5%
R_r	mean value [MPa]	6.90	6.10			5.35
	standard deviation [MPa]	0.48	1.13			0.57
	standard deviation [%]	7.0%	18.5%			10.7%

Table 5. The average values of compressive strength R_c and of tensile strength R_r and their standard deviations; “Mokrá-Horákov” limestone.

“Mokrá-Horákov” Limestone		Slenderness of the Specimen				Irregular Specimen
		$\lambda = 0.5$	$\lambda = 1.0$	$\lambda = 2.0$	$\lambda = 2.5$	
R_c	mean value [MPa]		268.69	211.57	131.13	80.73
	standard deviation [MPa]		47.11	54.08	43.67	23.26
	standard deviation [%]		17.5%	25.6%	33.3%	28.8%
R_r	mean value [MPa]	7.16	5.68			4.59
	standard deviation [MPa]	1.04	1.53			1.32
	standard deviation [%]	14.5%	27.0%			28.8%

Table 6. The average values of compressive strength R_c and tensile strength R_r and their standard deviations; “Petrov” granite.

“Petrov” Granite		Slenderness of the Specimen				Irregular Specimen
		$\lambda = 0.5$	$\lambda = 1.0$	$\lambda = 2.0$	$\lambda = 2.5$	
R_c	mean value [MPa]		272.44	195.86	202.19	151.96
	standard deviation [MPa]		32.95	12.86	20.82	16.03
	standard deviation [%]		12.1%	6.6%	10.3%	10.5%
R_r	mean value [MPa]	7.51	7.33			8.63
	standard deviation [MPa]	0.75	1.07			0.91
	standard deviation [%]	10.0%	14.6%			10.5%

Limestone (Table 5) confirmed the rule that states that, in the case of samples for which the slenderness meets the condition

$$1.0 \leq \lambda \leq 2.5 \quad (10)$$

the compressive strength of the rock decreases with the increasing slenderness of the specimen. Qualitatively analogous results were presented, i.e., by Mogi [8], providing a partial basis for the formulation of the relevant requirement in the ISRM recommendations [25].

The results for granite (Table 6) are also qualitatively reflected in the literature. By studying rocks from the Upper Silesian Coal Complex, Kidybiński [9] concluded that the compressive strength of the specimen decreases with the decrease in its slenderness to the limit value of $\lambda = 2.0$, and then stabilizes. This was reflected in the requirements included in the PN-G-04303:1997 standard [14].

By comparison, the compressive strength values obtained for sandstone (Table 4) do not match any of the aforementioned rules, and the authors were unable to indicate a literature position containing a similar result. In this case, the average values of R_c for $\lambda = 2.0$ and $\lambda = 2.5$ are equal. In the case of samples in which $\lambda = 1.0$, this value is slightly lower. Thus, it appears plausible to assume that, in the case of sandstone, R_c does not depend on slenderness, but meets the condition:

$$R_c = \text{const.} = 174.70 \text{ MPa.} \quad (11)$$

Such a result would indicate that requirements related to the dimensions of a uniaxial compressed specimen, initially included in the PN-B-04110:1984 standard [13] and currently in the PN-EN 1926:2007 Eurocode [16,22,23], are well justified.

Here, the authors would also like to express an opinion regarding a certain recommendation included in the PN-G-04303:1997 standard [14]. This states that, given the values of compressive strength obtained for samples in which $\lambda = 1.0$ (let us designate these $R_{c,\lambda=1.0}$), the R_c values for samples in which $\lambda = 2.0$ (let us designate these $R_{c,\lambda=2.0}$) may be calculated using the formula:

$$R_{c,\lambda=2.0} = 8/9 \times R_{c,\lambda=1.0}. \quad (12)$$

By applying Formula (12) to the results contained in Tables 5 and 6, we obtain Table 7.

Table 7. A comparison of the re-calculation of the R_c values for samples in which $\lambda = 1.0$, to R_c values for samples in which $\lambda = 2.0$ using Formula (12) with values obtained from a uniaxial compression test (test, $\lambda = 2.0$) for samples in which $\lambda = 2.0$; the “Mokrá-Horákov” limestone and the “Petrov” granite.

	Formula (12)		Test, $\lambda = 2.0$
	$R_{c,\lambda=1.0}$	$R_{c,\lambda=2.0}$	
“Mokrá-Horákov” limestone	268.69	238.83	211.57
“Petrov” granite	272.44	242.17	195.86

The $R_{c,\lambda=2.0}$ values included in Table 7 differ from the corresponding values of R_c for $\lambda = 2.0$ included in Tables 5 and 6, such that the value of Formula (12) included in the PN-G-04303:1997 standard [14] appears to be dubious.

Finally, we should also compare the test results for the point load test and the uniaxial compression test. The reference of the average R_c values obtained as a result of the point load test, and indicated in Tables 4–6 as an irregular specimen, to the smallest average R_c values obtained as a result of a uniaxial compression test, indicates that:

- point load strength in the case of sandstone does not exceed 56% of the lowest average uniaxial strength;
- for limestone, point load strength R_c is not more than 62% of the lowest average R_c uniaxial strength;
- in the case of granite, point load strength is not more than 78% of the lowest average uniaxial strength.

These are significant differences and doubt exists about assigning them to non-uniformities of the tested material. Some solace may be found in this case because all of

these differences were biased in one direction, which means that the point strength was always lower than the uniaxial strength.

6.2. Tensile Strength Test Results

- The qualitative assessment of the tensile strength test results shown in Tables 4–6 can be reduced to two statements: the average R_r value or a specimen with lower slenderness is always slightly higher;
- the standard deviation of the average value R_r (expressed as a percentage) has a higher value for samples with higher slenderness in all cases.

However, quantitative assessment may be problematic. Although the influence of the slenderness value of the sample on the obtained R_r value can be considered to be small in the case of sandstone (Table 4) and granite (Table 6), for limestone (Table 5) the difference in the mean R_r values for both considered slenderness values amounts to 25%. The authors are not able to clearly indicate the reason for this difference, but would like to point out that, in the case of limestone, the calculated values of R_r standard deviations are significantly greater than the values of the corresponding standard deviations of R_r for sandstone and granite. This suggests that limestone is a highly heterogeneous material, which could be the main reason for the observed differences.

This is obvious because of two reasons: first, samples with greater slenderness have higher volumes, and thus they are characterized by a higher probability of non-uniformities occurring in the specimen and influencing the result distribution; second, samples with higher slenderness have longer sides, thus the possibility of non-uniformities at the junction specimen-press plate increases and the possibility of local strain concentrations weakening the specimen also increases.

Regarding the values of tensile strength, based on the results of the point load test using Formula (9), the average point R_r for the sandstone is equal to 88% of the smallest average Brazilian R_r . In the case of limestone, this ratio is 81%, and 118% for the case of granite. These differences are quantitatively smaller than the corresponding differences in compressive strength, but are significantly more troubling because they occur in both directions, that is, the point value of tensile strength may be smaller or greater than the “Brazilian” value.

We should also consider certain relationships that are characteristic of the point load test. Thus, accepting that, according to Annex B of the PN-EN 1926:2007 standard [16], the multiplier value in Formula (8) is 22, and comparing Formulas (8) and (9) for $I_{S(50)}$ we obtain:

$$R_r / R_c = \text{const.} \approx 0.057 \quad (13)$$

We now assess the effectiveness of this estimation for the R_c and R_r values obtained for rocks studied using, respectively, the uniaxial compression test and the transverse compression test (Tables 8–10).

Table 8. The values of the R_r to R_c quotient (quotient (13)) are calculated on the basis of the results of strength testing for the “Řeka” sandstone, provided in Table 4.

			$\lambda = 0.5$	$\lambda = 1.0$
			R_r [MPa]	
			6.90	6.10
$\lambda = 1.0$	R_c [MPa] =	169.41	0.041	0.036
$\lambda = 2.0$		177.47	0.039	0.034
$\lambda = 2.5$		177.21	0.039	0.034
the average value of quotient (13) for sandstone			−0.037	
standard deviation of that value			−0.003 (7.1%)	

Table 9. The values of the R_r to R_c quotient (quotient (13)) are calculated on the basis of the results of strength testing for the “Mokrá-Horákov” limestone, provided in Table 5.

			$\lambda = 0.5$	$\lambda = 1.0$
			R_r [MPa]	
			7.16	5.68
$\lambda = 1.0$	R_c [MPa] =	268.69	0.027	0.021
$\lambda = 2.0$		211.57	0.034	0.027
$\lambda = 2.5$		131.13	0.055	0.043
the average value of quotient (13) for limestone			−0.034	
standard deviation of that value			−0.012 (36.3%)	

Table 10. The values of the R_r to R_c quotient (quotient (13)) are calculated on the basis of the results of strength testing for the “Petrov” granite, provided in Table 6.

			$\lambda = 0.5$	$\lambda = 1.0$
			R_r [MPa]	
			7.51	7.33
$\lambda = 1.0$	R_c [MPa] =	272.44	0.028	0.027
$\lambda = 2.0$		195.86	0.038	0.037
$\lambda = 2.5$		202.19	0.037	0.036
the average value of quotient (13) for granite			−0.034	
standard deviation of that value			−0.005 (15.4%)	

It was found that, as required according to the PN-EN 1926:2007 standard [16], when the multiplier in Formula (8) is equal to 22, the average value of the quotient (13) does not exceed 0.037; namely, it is significantly lower than dictated by the ISRM recommendations by Ulusay and Hudson [25], i.e., 0.057.

7. Conclusions

The conclusions drawn from the results of the study presented and discussed above may be summarized by the following statements:

1. It appears that a clear determination of the optimal value of the specimen slenderness λ for determination of the compressive strength value R_c is impossible. Examples presented in Section 5 and discussed in Section 6 prove that results depend on the type of studied rock. Unfortunately, it is not possible to a priori draw a conclusion about the relationship of $R_c(\lambda)$ and the λ value at which it stabilizes for the given rock. It is usually assumed that for the designed structure, the stress values in the subsoil may not exceed its strength. It is also known (cf. [8,9]) that the R_c value obtained in the uniaxial compression test is inversely proportional to the slenderness of the tested sample. It follows that in uniaxial compression tests it is expedient to use samples with slenderness values that are as high as possible, which should decrease the R_c value to an extent and provide the designer with a wider safety margin. This approach means that uniaxial compression experiments should be performed according to the methodology written in ISRM recommendations—Ulusay and Hudson [17]. By comparison, the use of samples with such a high slenderness value increases the influence of disruptive factors on the results of the experiment, such as lack of specimen base parallelism (grinding errors and failure to maintain axisymmetric); lack of orthogonality between the base and the side of the specimen (core preparation errors); and inadequate precision of specimen placement inside the strength testing machine (eccentric loading force, then the phenomenon of asymmetry can be observed). Another problem relating to the use of samples with $\lambda \geq 2.5$ is

the quantity of the material available for studies. The stakeholders usually provide the material in the form of drilling cores, which are often fragmented. In practice, if tests are to be performed on samples with diameters of approximately 50 mm, which can be considered a standard value in such studies (cf. Table 1), a core section with a length of at least 150 mm is required. The experiences of the authors show that this is often impossible.

2. The significant difference between the results of the uniaxial compression and the point load tests is easily noticeable for all studied rocks. The numerical values provided in Tables 4–6 and Tables A7–A9 show that the average R_c values obtained as a result of the point load test comprise between 50% and 75% of such values obtained for uniaxial compression. This is a clear indication that the point load test should be used only if there are no other options available. Unfortunately, the limited quantity of the material for testing did not allow sufficient point load tests to be performed to evaluate the variants of this test (see above: Section 2.1, paragraph b), pp. (i)–(iv)) that yield R_c values closest to the values obtained from the uniaxial compression test. An attempt at such an evaluation was only able to be performed for the “Řeka” sandstone (see Table A8), and resulted in the following compressive strength values:

- the core diameter or diametral test—88.54 MPa;
- the core axis or axial test—96.02 MPa;
- the block test—102.05 MPa.

These results suggest that the block test results are the closest to the uniaxial compression test results; however, due to the number of tests performed for the sandstone (respectively: 4, 4, and 2) and the lack of respective results for limestone and granite, conclusions cannot be drawn.

3. Tensile strength R_t appears to depend on specimen slenderness only to a limited degree. By comparison, considering the results obtained for limestone, it may not be ruled out that it is much more sensitive to the local heterogeneity of the rock. In practice, this means adopting the following procedure for determination of R_t : if an adequate quantity of material is available, the R_t value should be determined using the transverse compression test as recommended by ISRM Ulusay and Hudson [33], using samples in which $\lambda = 1.0$; if the quantity of the material is small, then, to obtain as many samples as possible, the PN-G-04302:1997 standard [32] should be used with samples for which $\lambda = 0.5$. A remaining issue is the estimation of tensile strength on the basis of the point load test, i.e., using Formula (9). Quantitative analysis of the respective R_t values (see the second paragraph of Section 6.2) shows that differences compared to the average results of the Brazilian test are not significant in this case (approximately $\pm 20\%$). However, two main objections should be raised. First, the point value of R_t may be higher or lower than the Brazilian value; that is, using the jargon popular in mechanics, we do not know which side of the solution we are on and, in particular, whether we do not unacceptably increase the R_t value. Second, estimation of compressive strength according to Formula (9) means we assume in advance, based on the results from the value of quotient (13), that tensile strength comprises 5.7% of compressive strength. It should be noted that the value of quotient (13) equals 0.057 only when the multiplier in Equation (8) is 22, according to the PN-EN 1926:2007 standard [16]. Furthermore, the rules of analysis of results from point load tests, presented in the ISRM recommendations by Ulusay and Hudson [25], state that this multiplier may not be lower than 20 or higher than 25, as shown above in Formula (8). If the multiplier changes within these limits, the value of quotient (13) is inversely proportional to the multiplier and changes according to the curve shown in Figure 5. If the desired value of quotient (13) is 0.034 (the average value for limestone and granite, Tables 9 and 10) the multiplier in Equation (8) must equal 36.8. In the case of sandstone, for which the value of quotient (13) was 0.037 (see Table 8), the multiplier value is 33.8. These values were not foreseen by the method creators [27,35],

or in the PN-G-04307:1998 standard [24], the appropriate ISRM recommendations by Ulusay and Hudson [25], or the ASTM D5731-16 Standard [26].

Figure 5. Relationship between the value of the quotient (13) and the value of the multiplier in Formula (8).

To conclude, the authors would like to make an additional significant remark. They note that the purpose of this research project, the results of which are presented above, was not to argue with either Prof. Mogi or Prof. Kidybiński. The objective was only to highlight a certain degree of inconsistency in current laboratory testing of rocks, arising from documents of varying importance that establish laboratory testing procedures and often contain contradictory requirements. The authors wished to draw the attention of those examining widely understood rock mechanics to problems resulting from the current state of affairs, thus helping to clarify doubts and providing a warning of potential dangers.

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Appendix A

Table A1. Samples of the “Mokrá-Horákov” limestone prepared for laboratory testing (regular samples).

Specimen No.	h [mm]	d [mm]	m [g]	V [cm ³]	ρ [g × cm ^{−3}]	λ []
1	2	3	4	5	6	7
L1	22.23	44.48	91.57	34.5	2.65	0.5
L2	22.63	44.44	92.84	35.1	2.64	0.5
L3	22.12	44.44	90.52	34.3	2.64	0.5
L4	22.31	44.48	92.39	34.7	2.67	0.5
L5	22.41	44.39	92.97	34.7	2.68	0.5
L6	22.61	44.36	93.09	34.9	2.66	0.5
L7	22.64	44.39	93.11	35.0	2.66	0.5
L8	46.16	44.45	191.43	71.6	2.67	1.0
L9	46.18	44.41	192.20	71.5	2.69	1.0
L10	44.68	44.42	184.34	69.2	2.66	1.0
L11	45.88	44.40	190.31	71.0	2.68	1.0
L12	44.77	44.51	185.63	69.7	2.66	1.0
L13	46.29	44.50	191.75	72.0	2.66	1.0
L14	44.82	44.45	186.01	69.6	2.67	1.0
L15	46.05	44.48	191.62	71.6	2.68	1.0
L16	44.53	44.45	184.45	69.1	2.67	1.0
L17	44.87	44.50	185.87	69.8	2.66	1.0
L18	44.56	44.41	184.97	69.0	2.68	1.0
L19	46.10	44.50	191.15	71.7	2.67	1.0
L20	87.40	44.43	363.44	135.5	2.68	2.0
L21	88.29	44.46	367.10	137.1	2.68	2.0
L22	88.55	44.51	368.34	137.8	2.67	2.0
L23	88.46	44.45	367.16	137.3	2.67	2.0
L24	88.81	44.47	367.22	137.9	2.66	2.0
L25	88.19	44.41	366.18	136.6	2.68	2.0
L26	111.76	44.42	464.11	173.2	2.68	2.5
L27	111.77	44.44	465.36	173.4	2.68	2.5
L28	111.50	44.36	464.43	172.3	2.70	2.5
L29	111.80	44.40	463.65	173.1	2.68	2.5

Table A2. Samples of the “Mokrá-Horákov” limestone prepared for laboratory testing (irregular samples).

Specimen No.	D [mm]	W [mm]	$2L$ [mm]	m [g]	V [cm ³]	ρ [g × cm ^{−3}]
1	2	3	4	5	6	7
L30	34.57	48.68	58.49	243.80	98.4	2.48
L31	28.40	50.50	67.92	237.00	97.4	2.43

Table A3. Samples of the “Řeka” sandstone prepared for laboratory testing (regular samples).

Specimen No.	h [mm]	d [mm]	m [g]	V [cm ³]	ρ [g × cm ^{−3}]	λ []
1	2	3	4	5	6	7
S1	22.98	44.53	86.35	35.8	2.41	0.5
S2	22.83	44.51	87.07	35.5	2.45	0.5
S3	22.26	44.48	84.13	34.6	2.43	0.5
S4	22.70	44.49	86.18	35.3	2.44	0.5
S5	22.48	44.51	85.56	35.0	2.45	0.5
S6	22.47	44.50	86.01	34.9	2.46	0.5
S7	22.54	44.52	86.17	35.1	2.46	0.5
S8	22.36	44.46	85.45	34.7	2.46	0.5

Table A3. Cont.

Specimen No.	h [mm]	d [mm]	m [g]	V [cm ³]	ρ [g × cm ⁻³]	λ []
1	2	3	4	5	6	7
S9	22.44	44.46	85.64	34.8	2.46	0.5
S10	23.07	44.48	88.29	35.8	2.46	0.5
S11	22.38	44.47	85.28	34.8	2.45	0.5
S12	44.46	44.52	170.19	69.2	2.46	1.0
S13	45.86	44.54	173.61	71.5	2.43	1.0
S14	45.21	44.49	172.94	70.3	2.46	1.0
S15	44.52	44.52	170.10	69.3	2.45	1.0
S16	45.11	44.51	172.31	70.2	2.45	1.0
S17	45.64	44.49	174.07	71.0	2.45	1.0
S18	45.32	44.51	173.05	70.5	2.45	1.0
S19	44.83	44.53	171.09	69.8	2.45	1.0
S20	45.58	44.50	173.09	70.9	2.44	1.0
S21	45.34	44.51	174.28	70.5	2.47	1.0
S22	45.08	44.48	172.20	70.0	2.46	1.0
S23	45.31	44.52	172.99	70.5	2.45	1.0
S24	45.06	44.48	172.72	70.0	2.47	1.0
S25	45.47	44.50	173.64	70.7	2.46	1.0
S26	45.22	44.51	172.49	70.4	2.45	1.0
S27	45.27	44.50	173.50	70.4	2.46	1.0
S28	45.14	44.50	172.91	70.2	2.46	1.0
S29	44.92	44.49	171.09	69.8	2.45	1.0
S30	44.82	44.48	170.05	69.6	2.44	1.0
S31	44.76	44.50	171.70	69.6	2.47	1.0
S32	44.80	44.50	171.37	69.7	2.46	1.0
S33	90.10	44.50	346.01	140.1	2.47	2.0
S34	90.20	44.50	344.91	140.3	2.46	2.0
S35	90.20	44.50	346.68	140.3	2.47	2.0
S36	90.20	44.50	346.66	140.3	2.47	2.0
S37	90.20	44.50	346.20	140.3	2.47	2.0
S38	90.30	44.50	344.98	140.4	2.46	2.0
S39	90.00	44.50	345.99	140.0	2.47	2.0
S40	89.90	44.50	344.57	139.8	2.46	2.0
S41	90.00	44.50	346.65	140.0	2.48	2.0
S42	90.30	44.50	345.83	140.4	2.46	2.0
S43	112.00	44.50	429.86	174.2	2.47	2.5
S44	112.00	44.50	430.71	174.2	2.47	2.5
S45	112.00	44.50	430.37	174.2	2.47	2.5
S46	112.00	44.50	429.56	174.2	2.47	2.5
S47	112.00	44.50	430.40	174.2	2.47	2.5
S48	112.00	44.50	432.10	174.2	2.48	2.5
S49	112.00	44.50	430.43	174.2	2.47	2.5
S50	112.00	44.50	430.89	174.2	2.47	2.5
S51	112.00	44.50	431.33	174.2	2.48	2.5
S52	112.00	44.50	430.19	174.2	2.47	2.5
S53	120.00	49.20		227.8		2.4
S54	120.00	49.30		228.6		2.4
S55	121.00	49.20		230.2		2.5
S56	121.00	49.20		230.1		2.5
S57	35.30	49.10		66.7		0.7
S58	36.00	49.20		68.2		0.7
S59	36.30	49.20		68.9		0.7

Table A4. Samples of the “Řeka” sandstone prepared for laboratory testing (irregular samples).

Specimen No.	<i>D</i> [mm]	<i>W</i> [mm]	<i>2L</i> [mm]	<i>m</i> [g]	<i>V</i> [cm ³]	ρ [g × cm ^{−3}]
1	2	3	4	5	6	7
S60	43.25	53.20	127.00		292.2	
S61	44.70	51.90	128.00		297.0	

Table A5. Samples of the “Petrov” granite prepared for laboratory testing (regular samples).

Specimen No.	<i>h</i> [mm]	<i>d</i> [mm]	<i>m</i> [g]	<i>V</i> [cm ³]	ρ [g × cm ^{−3}]	λ []
1	2	3	4	5	6	7
G1	22.57	44.48	90.62	35.1	2.58	0.5
G2	22.40	44.48	89.76	34.8	2.58	0.5
G3	22.48	44.47	89.93	34.9	2.58	0.5
G4	22.53	44.44	90.33	34.9	2.58	0.5
G5	22.51	44.47	90.56	35.0	2.59	0.5
G6	22.47	44.49	90.38	34.9	2.59	0.5
G7	22.53	44.49	90.67	35.0	2.59	0.5
G8	22.54	44.48	90.56	35.0	2.59	0.5
G9	44.52	44.49	179.54	69.2	2.59	1.0
G10	44.46	44.50	179.21	69.1	2.59	1.0
G11	44.54	44.46	179.42	69.1	2.59	1.0
G12	44.38	44.51	178.58	69.1	2.59	1.0
G13	44.54	44.46	179.30	69.1	2.59	1.0
G14	44.33	44.53	177.80	69.0	2.58	1.0
G15	44.46	44.51	179.44	69.2	2.59	1.0
G16	44.28	44.46	178.05	68.7	2.59	1.0
G17	44.67	44.52	179.49	69.5	2.58	1.0
G18	44.67	44.49	179.75	69.4	2.59	1.0
G19	44.58	44.46	179.07	69.2	2.59	1.0
G20	43.80	44.50	175.91	68.1	2.58	1.0
G21	44.50	44.50	179.20	69.2	2.59	1.0
G22	89.40	44.50	360.12	139.0	2.59	2.0
G23	89.50	44.50	360.22	139.2	2.59	2.0
G24	89.70	44.50	361.69	139.5	2.59	2.0
G25	89.50	44.50	360.43	139.2	2.59	2.0
G26	89.70	44.50	361.14	139.5	2.59	2.0
G27	89.60	44.50	360.66	139.4	2.59	2.0
G28	89.00	44.50	359.34	138.4	2.60	2.0
G29	112.00	44.50	449.97	174.2	2.58	2.5
G30	112.00	44.50	451.40	174.2	2.59	2.5
G31	112.00	44.50	450.05	174.2	2.58	2.5
G32	111.00	44.50	449.52	172.6	2.60	2.5
G33	112.00	44.50	451.08	174.2	2.59	2.5
G34	112.00	44.50	449.26	174.2	2.58	2.5

Table A6. Samples of the “Petrov” granite prepared for laboratory testing (irregular samples).

Specimen No.	<i>D</i> [mm]	<i>W</i> [mm]	<i>2L</i> [mm]	<i>m</i> [g]	<i>V</i> [cm ³]	ρ [g × cm ^{−3}]
1	2	3	4	5	6	7
G35	34.30	45.40	63.60	302.62	99.0	3.06
G36	36.20	41.20	79.30	250.36	118.3	2.12
G37	37.70	40.90	69.90	269.81	107.8	2.50
G38	33.90	45.40	62.80	245.26	96.7	2.54

Appendix B

Table A7. The values of compressive and tensile strength were determined on samples comprising the “Mokrá-Horákov” limestone.

Specimen No.	λ []	R_c		R_r		Comments
		Uniaxial Compression	Point Loading	Uniaxial Compression	Point Loading	
1	2	3	4	5	6	7
L1	0.5			7.05		
L2	0.5			5.32		
L3	0.5			8.26		
L4	0.5			7.03		
L5	0.5			6.82		
L6	0.5			8.48		
L7	0.5			7.13		
L8	1.0			6.29		
L9	1.0			4.24		
L10	1.0			4.38		
L11	1.0			4.50		
L12	1.0			7.96		
L13	1.0			6.68		
L14	1.0	289.99				
L15	1.0	278.97				
L16	1.0	343.83				
L17	1.0	223.14				
L18	1.0	259.82				
L19	1.0	216.38				
L20	2.0	258.37				
L21	2.0	247.97				
L22	2.0	187.99				
L23	2.0	117.33				
L24	2.0	205.71				
L25	2.0	252.05				
L26	2.5	65.83				
L27	2.5	148.33				
L28	2.5	153.70				
L29	2.5	156.64				
L30			64.28		3.65	“block” test
L31			97.17		5.52	

Table A8. The values of compressive and tensile strength were determined on samples comprising the “Řeka” sandstone.

Specimen No.	λ []	R_c		R_r		Comments
		Uniaxial Compression	Point Loading	Uniaxial Compression	Point Loading	
1	2	3	4	5	6	7
S1	0.5			6.25		
S2	0.5			7.14		
S3	0.5			6.76		
S4	0.5			6.72		
S5	0.5			6.78		
S6	0.5			7.93		
S7	0.5			6.76		
S8	0.5			6.92		
S9	0.5			6.22		
S10	0.5			7.07		

Table A8. Cont.

Specimen No.	λ [°]	R_c		R_r		Comments
		Uniaxial Compression	Point Loading	Uniaxial Compression	Point Loading	
1	2	3	4	5	6	7
S11	0.5			7.38		
S12	1.0			6.28		
S13	1.0			6.41		
S14	1.0			6.13		
S15	1.0			5.78		
S16	1.0			6.57		
S17	1.0			7.25		
S18	1.0			5.87		
S19	1.0			7.22		
S20	1.0			6.31		
S21	1.0	204.92				
S22	1.0	200.69				
S23	1.0	155.50				
S24	1.0	189.85				
S25	1.0			data reading error		
S26	1.0	169.83				
S27	1.0		74.34		4.22	“axial” test
S28	1.0	142.20				
S29	1.0	79.12				
S30	1.0	223.63				
S31	1.0			3.21		
S32	1.0	158.99				
S33	2.0	194.76				
S34	2.0	174.52				
S35	2.0	189.75				
S36	2.0	181.39				
S37	2.0	207.43				
S38	2.0	122.16				
S39	2.0	181.86				
S40	2.0	172.59				
S41	2.0	153.83				
S42	2.0	196.36				
S43	2.5	185.66				
S44	2.5	165.98				
S45	2.5	205.38				
S46	2.5	140.49				
S47	2.5	144.95				
S48	2.5	173.13				
S49	2.5	192.51				
S50	2.5	189.62				
S51	2.5	205.06				
S52	2.5	169.35				
S53	2.4		88.87		5.05	
S54	2.4		78.68		4.47	“diametral” test
S55	2.5		94.71		5.38	
S56	2.5		91.89		5.22	
S57	0.7		92.27		5.24	“axial” test
S58	0.7		107.17		6.09	
S59	0.7		110.31		6.27	
S60			98.57		5.60	“block” test
S61			105.53		6.00	

Table A9. The values of compressive and tensile strength were determined on samples comprising the “Petrov” granite.

Specimen No.	λ []	R_c		R_r		Comments
		Uniaxial Compression	Point Loading	Uniaxial Compression	Point Loading	
1	2	3	4	5	6	7
G1	0.5			7.99		
G2	0.5			5.94		
G3	0.5			7.83		
G4	0.5			7.82		
G5	0.5			7.34		
G6	0.5			6.97		
G7	0.5			8.20		
G8	0.5			8.00		
G9	1.0			6.61		
G10	1.0			8.93		
G11	1.0			6.36		
G12	1.0	214.01				
G13	1.0	263.16				
G14	1.0	262.93				
G15	1.0			6.38		
G16	1.0			8.20		
G17	1.0	286.49				
G18	1.0	286.26				
G19	1.0	271.45				
G20	1.0	322.77				
G21	1.0			7.48		
G22	2.0	187.41				
G23	2.0	190.11				
G24	2.0	191.82				
G25	2.0			180.30		
G26	2.0	194.59				
G27	2.0	210.96				
G28	2.0	215.86				
G29	2.5	224.38				
G30	2.5	187.92				
G31	2.5	192.74				
G32	2.5	226.20				
G33	2.5	207.59				
G34	2.5	174.33				
G35			151.24		8.6	
G36			151.52		8.6	“block” test
G37			132.93		7.6	
G38			172.16		9.8	

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