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# Advances in the calculation of compressive strength from acoustic measurements of rock mass samples – examples of calculations

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## ABSTRACT

The properties of the rock mass, such as compressive strength and deformability of rocks, also have a direct impact on mining technology, the machinery used and its efficiency. For many years, work has been carried out on the widespread use of the ultrasonic method for determining rock strength properties. This method is characterized by simplicity of measurement and its accuracy increasing with the number of acoustic parameters. A very important advantage of this method is the possibility of multiple measurements, the short duration of the measurements and the almost immediate results, which can be presented in the form of a curve reflecting the relationship between compressive strength and the measured acoustic parameters. The article describes the development of research and the relationship between compressive strength and acoustic parameters such as volume density (p), longitudinal wave velocity (Cl), and acoustic modulus (H). The analyses demonstrated the accuracy of the calculations based on the value of the coefficient of determination ($R^2$). A new relationship between compressive strength and acoustic modulus was presented and it has with the highest accuracy. It was proposed that this new method can be used to calculate the compressive strength of all brittle materials using acoustic modulus.

**Keywords:** samples, compressive strength, acoustic parameters.

## INTRODUCTION

Mining engineers use uniaxial compressive strength of rock (UCS) in the design of rock mining parameters in Quarrys. The measurement of rock strength is standardized by the American Society for Testing and Materials (ASTM). Determining the compressive strength of samples is simple, but time-consuming and expensive. Indirect tests, such as speed of sound (SV), are therefore used to predict UCS. Samples for these tests do not require the same accuracy as laboratory tests and can therefore be easily used in quarries. Such tests are simpler, faster and more economical. UCS of rock also has a direct impact on mining productivity. Work has been carried out for many years on the feasibility and widespread application of non-destructive acoustic methods for determining the UCS of rock. Based on the literature UCS was determined using volume density (p) [7, 16], based on longitudinal wave velocity (Cl) [1–5, 8, 12–14, 17, 20–24, 26, 28, 31, 32, 35–37], and using (p×Cl) [15, 27, 29]. This paper proposes a new method for calculating the compressive strength of all brittle materials using acoustic modulus [H].

These methods are characterized by simplicity of measurement, and the accuracy of UCS determination increases with the number of measurements and the number of acoustic parameters taken into account. A very important advantage of these methods is the possibility of multiple measurements, short measurement times and almost instantaneous measurement results. These measurements can be presented in the form of a curve showing the relationship between USC and acoustic parameters.

For a given deposit, once determined, the compressive strength relationship based on ultrasonic (UT) measurements of acoustic modulus. The article analyses the increase in accuracy of UCS determination with an increase in the number of acoustic parameters measured. The article is original as it is based on Polish patents.

- Chrzan T. Patent RP, No. 119377. Method of measuring the compressive strength of rocks, $Rs = f(p)$. Date of receipt 12.10.1979.
- Chrzan T. Patent RP, No. 107172. Method for measuring the compressive strength of rocks, $Rs = f(Cl)$. Date of receipt 27.06.1979.
- Chrzan T. Patent RP, No. 157586. Method for measuring the tensile, compressive and impact strength of hard rocks, $Rs = f(H)$. Date of receipt 30.06.1992.

The paper proposes a new method for ultrasonic compressive strength testing of brittle materials such as rocks, bricks, cast iron and ceramics. The article provides an example of the application of the method for rejecting measurements that significantly differ from their mean value from a set of measurement data.

## BACKGROUND

Ultrasonic methods for determining the mechanical properties of rocks are based on the dependence of compressive strengths on acoustic parameters, i.e. longitudinal wave velocity, acoustic elasticity, etc. Based on the literature, the most commonly used formulae relating the uniaxial compressive strength of rocks UCS = Rs to their acoustic parameters are as follows:

- for sandstones, [19]

$$Rs = [a/(b - Cl)] - c \tag{1}$$

- for sandstones and dolomite-calcareous rocks [25, 30]

$$Rs = a + b \times Cl \tag{2}$$

- for sedimentary rocks; sandstones and shales, [19, 25, 31]

$$Rs = a \times Cl - b \tag{3}$$

- for sandstone [19]

$$Cl = a + b \times Rs \tag{4}$$

- for sedimentary rocks [25], sandstones [19]

$$Rs = p \times Cl \times b \tag{5}$$

- for sandstones and limestones [6], concrete [40]

$$Rs = p \times Cl^2 \tag{6}$$

- for limestones and dolomites [25], concretes [18]

$$Rs = a \times Cl^2 + b \times Cl + c \tag{7}$$

- for limestone [33]

$$Rs = a \times Cl^2 + b \times Cl \times \alpha - c \times \alpha - d \tag{8}$$

where: $a$, $b$, $c$, $d$ – correlation constants for rock type and type of relationship; $\alpha$ – longitudinal wave attenuation coefficient; $p$ – bulk density – apparent density (the one that takes into account the pores in the rock); $Cl$ – longitudinal wave velocity, $Rs$ – USC.

The relationships given have low correlation coefficients and coefficients of determination ($R^2$) and low accuracy for determining compressive strength. Increasing the number of acoustic parameters for the determination of UCS increases the accuracy of UCS calculations relative to the destructive measurements from the hydraulic press. The above relationships generally apply to sedimentary rocks. When the correlation is based on one acoustic parameter (Eqs. 1–7), then the square of the correlation coefficient $R^2 = 0.6$. With two acoustic parameters (Eq. 8), coefficient of determination $R^2 = 0.7$. When the correlation is based on a larger number of acoustic parameters (Eq. 16), then $R^2 = 0.96$.

When the rock structure is destroyed, there is a break in its continuity, which is reflected in the change in volume and shape of the crushed rock mass. The resistance to volume deformation is determined by the value of the longitudinal modulus of elasticity (E), and the resistance to shape deformation is determined by the value of the transverse modulus of elasticity (G). The destruction of rock samples on the press is caused by static loading. Excavation of rock by blasting causes dynamic loads to act on the rock. For this reason, the dynamic modulus of elasticity (H) should be used when describing a model of rock behaviour under dynamic loading.

According to Griffith's theory, the destruction of the cohesiveness of a medium is caused by an increase in stress around the heterogeneous part of the medium. As the porosity of a rock increases, its density decreases and the number of pores around which microcracks form increases. These microcracks combine to form larger cracks that lead to the destruction of the cohesion of the rock medium.

Taking into account the factors on which the UCS depends, a group acoustic parameter that takes into account these three important parameters has been chosen and has been named the acoustic modulus and denoted as *H*. It can be quickly and cheaply determined from ultrasonic measurements as the product of p×Cl×Ct.

It can be defined as:

$$H = p \times Cl \times Ct \ \ (\mathrm{N/m^2}) \tag{9}$$

where: *p* – bulk density ($kg/m^3$), *Cl, Ct* – longitudinal and transverse wave velocity in the specimen (m/s).

According to Mohr's theory, failure of the rock medium occurs as a result of the simultaneous action of normal and shear stresses and is the result of exceeding the allowable linear and angular deformations. During uniaxial compression, angular deformation occurs in the form of characteristic X-shaped cracks in the specimen. Given shear and normal stresses, the uniaxial compression strength of the specimen was assumed to be an unknown function *f* of their product $f\{[E \times \epsilon] \times [G \times \gamma xy]\}$ = UCS, which can be written as the product of 2 functions, $f1 \times f2$.

$$UCS = f1[E \times \epsilon] \times f2[G \times \gamma xy] \tag{10}$$

The elastic moduli E and G are functionally related to the acoustic parameters, given that b = Ct/Cl obtained:

$$G = b \times p \times Cl \times Ct,$$

and

$$E = (6b - 8b3) \times p \times Cl \times Ct = a \times p \times Cl \times Ct,$$

substituting that

$$H = p \times Cl \times Ct,$$

and given the above, obtained:

$$G = b \times H, E = a \times H$$

Substituting into Equation 10 yielded:

$$USC = f3[\mathrm{H}] \times f4[\epsilon \times \gamma xy] \tag{11}$$

Equation 11 shows that the value of the rock failure stress or UCS is a function of '*f*3' of the acoustic modulus and a function of '*f*4' of the product of linear and angular deformations. This product varies only slightly for a given deposit and is assumed to be constant. The empirically determined USC function for Equation 11 is hyperbolic, Equation 12. The function *f*1 and *f*2, *f*3, *f*4 are functions of the given products. Multiplying the numerator and denominator of the unit of acoustic modulus (H) by a metre gives the unit of energy (J) per ($m^3$) – the unit of rock workability, which can be defined as the relative rock workability index ($J/m^3$).

According to [9, 11]:

$$UCS = Rs = M/(N - H) \tag{12}$$

where: *M, N* – constants for rock type deposits, ($Pa^2$), (Pa); *H* – the value of the acoustic module of the tested rock sample, (Pa); *Rs* = UCS (Pa).

The relationships for (b) elastic-brittle (igneous) and (a) elastic-plastic (sedimentary) rocks are shown in Figure 1 [12]. It shows the transformed hyperbolic relation into a straight line relation. The straight line on the Y axis cuts the value of M and the tangent of the angle of inclination of the straight line is the value of N.

## EXAMPLES OF CALCULATIONS

### The use of statistical data processing software

For samples taken from the limestone deposit, examples are given of calculations of the relationship of the uniaxial compressive strength of the samples with their acoustic parameters. The measured data are summarised in Table 1 [10].

Based on the data summarised in Table 1, correlation relationships and $R^2$ values were calculated which describe the accuracy of the fit between the values calculated from the obtained relationships and the measured data, and what percentage of the y-value is calculated from the x-value. Uniaxial compressive strength of rock samples:

$$Rs = A + B \times x$$

a) as a function *f*(*p*),

$$Rs = f(p);\ Rs = -727.1 + 321.14 \times p;\ R = 0.794;\ R^2 = 0.63; \tag{13}$$

b) depending on *Cl*,

$$Rs = f(Cl);\ Rs = -127.5 + 43.06 \times Cl;\ R = 0.847;\ R^2 = 0.717; \tag{14}$$

c) depending on *p*×*Cl*,

$$Rs = f(p \times Cl);\ Rs = -95.7 + 14.5 \times p \times Cl;\ R = 0.866;\ R^2 = 0.75; \tag{15}$$

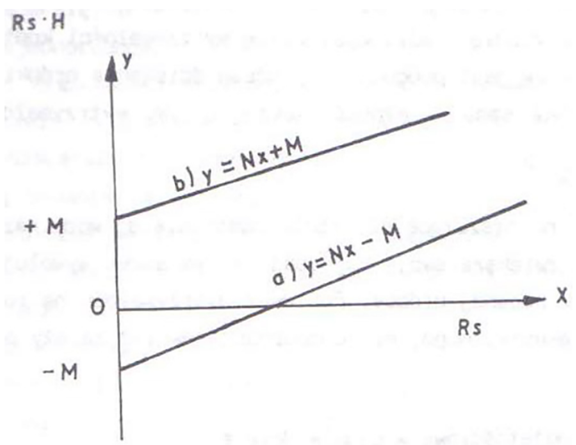


**Figure 1.** The hyperbolic relationship
Rs = USC = M/N – H transformed into a straight line
y = Rs × H = N × Rs – M

d) depending on $p \times Cl \times Ct$,

$$Rs = f(H),$$

$$Rs = 981.7/(38.2–H),$$

$$R = 0.978,\ R^2 = 0.956. \quad (16)$$

Increasing the number of acoustic parameters for the determination of UCS increases the accuracy of UCS calculations relative to the destructive measurements from the hydraulic press. This fact is confirmed by the calculated coefficient of determination values. The measuring points calculated for Equation 16 have the highest coefficient of determination. Relationships 13 to 15 are rectilinear, while relationship 15 is hyperbolic and better reflects the distribution of measuring points, which are the UCS values as a function of the acoustic modulus.

Figure 2 shows the distribution of measurement points around a straight line drawn according to the calculated correlation relation. The scatter of measurement points for one acoustic parameter $p$ is greater than the scatter of measurement points for two acoustic parameters $p \times Cl$ (Figure 4). Figure 3 shows the scatter of measurement points around a straight line drawn according to the calculated correlation relation. The scatter of measurement points for the acoustic parameter $Cl$ (Figure 3) is slightly smaller than the scatter of measurement points for the acoustic parameter $p$ (Figure 2). The scatter of measurement points for one acoustic parameter $Cl$ (Figure 3) is larger than the scatter of measurement points for two acoustic parameters $p \times Cl$ (Figure 4). Figure 4 shows the distribution of measurement points around a straight line drawn according to the calculated correlation relation. The scatter of measurement points for the two acoustic parameters $p \times Cl$ (Figure 4), compared to the scatter of measurements with one acoustic parameter Figures 2 and 3, is the smallest.

For the transformed hyperbolic relationship depending on ($p \times Cl \times Ct$) = $H$, $Rs = M/(N–H)$; $Rs \times (N–H) = M$; $Rs \times H = N \times Rs\text{-}M$ assuming that $Rs \times H = y$; and $Rs = x$, a rectilinear relationship was obtained: $y = -a + bx$. For limestone, a = -981.7; $b$ = 38.2; R = 0.978; $R^2$ = 0.956. Hence $Rs$ = 981.7/(38.2–$H$).

Figure 5 shows the distribution of measurement points around the straight line drawn according to the calculated correlation relation. The scatter of measurement points for the three acoustic parameters $p \times Cl \times Ct$ is smaller than the scatter of measurement points for one parameter, (Figures 2 and 3) and for two acoustic parameters (Figure 4).

## Measurement and testing methodology

Before taking rock blocks from the deposit to be sampled in the laboratory, it is necessary to establish a system of orientation in the deposit and in the rock blocks in the form of directions. For example, the horizontal direction coinciding with the Y axis is the line of blast holes, the direction perpendicular to the Y direction is the X direction. The vertical direction Z is perpendicular to the X and Y directions. The direction in which the compressive strength is to be determined, e.g. the X direction, is marked on a dozen blocks of at least 20×20×20 cm taken at equal intervals from the entire deposit. In the laboratory, the sample to be tested for compressive strength is cut with its longer axis in the X direction. Determination of the uniaxial compression strength (UCS) of rocks was performed according to the following guidelines International Society of Rock Mechanics (ISRM) [40]. The test involves applying a uniaxial compressive stress to a rock sample, usually a cylinder, until it fails and calculating the UCS as the maximum load divided by the cross-sectional area of the sample. ISRM suggests that the slenderness ratio (length to diameter) of the specimen should be 2.5–3:1.

1. Sample preparation – rock cores are prepared as cylinders with a slenderness ratio of 2.5–3:1, meaning that the length of the cylinder is 2.5 to 3 times its diameter.

**Table 1.** Data for calculations from the limestone deposit, [10] in the Z direction

| Lp | p [10]$^3$ kg/m$^3$ | [Xisv] Rs MPa | [Vxsv-Xsa]^² | H [10$^9$] Pa | Cl m/s | Ct m/s | H*Rs= H*UCS [10]$^{15}$ Pa |
|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 1 | 2.62 | 71.4 | 22.1 | 27.2 | 5250 | 1980 | 1942.1 |
| 2 | 2.63 | 153.0 | 5913.6 | 33.8 | 5720 | 2250 | 5178.8 |
| 3 | 2.62 | 112.1 | 1296.0 | 29.8 | 5500 | 2070 | 3340.6 |
| 4 | 2.46 | 66.1 | 100.0 | 13.6 | 3840 | 1440 | 899.0 |
| 5 | 2.46 | 87.2 | 132.2 | 25.5 | 5190 | 2000 | 2224.0 |
| 6 | 2.46 | 76.3 | 0.2 | 22.2 | 4820 | 1870 | 1692.0 |
| 7 | 2.40 | 32.1 | 1936.0 | 12.9 | 3640 | 1480 | 415.0 |
| 8 | 2.42 | 45.5 | 936.4 | 23.8 | 4450 | 2210 | 1083.0 |
| 9 | 2.41 | 41.3 | 1211.0 | 18.4 | 4140 | 1840 | 760.0 |
| 10 | n-9 | Xsal=Σ [[Xisv]:/9= 76.1 | Σ= 11538.5 Δ=[Σ]^½= 107.4 | . |  | m = [n-1]^½ = 2.83 | б = 37.96% |
| 11 | n=8 | Xsall=Σ 532/:/8= 66,5 | Σ= 5633,9 Δ=75 |  |  | m = 2.65 | б = 28.3% |
| 12 | n=16 | Xsa=1064/:/16=66,5 | Σ= 5633,9 Δ=75 |  |  | m = 3.87 | б = 19.4% |

**Note:** 1; column 1 – item number in Table 1, the last item is the number of measurements 'n', column 2 – volumetric density of the rock sample, 'p', from position 10 to 12 – the number of rock samples analysed, column 3 – the compressive strength value of the next rock sample, from position 10 to 12 – the average compressive strength value for the number of samples given in column 2, column 4 – the sum of the successive differences of the measured UCS value Xisv and the average value of the measured data Xa to the second power, for the number of samples given in column 2. Column 5 – the value of the acoustic modulus H in [GPa], Column 6– the value of the longitudinal wave velocity in the sample, Cl. Column 7– value of the velocity of the transverse wave in the sample, Ct, Column 8 – value of the product of the value of the acoustic modulus H and the value of the compressive strength [10^15 Pa] from position 10 to 12 the value of the average accuracy of the calculation for the number of samples given in column 2. Position 2 is the measurement that significantly deviates from the average value, position 10 is the calculation with the measurement that significantly deviates from the average value, position 11 is the calculation after discarding the measurement from position 2 for 8 measurements. Item 12 is the calculation for a set of 8 previous measurements with 8 measurements added equal to the mean value of the set of previous measurements.

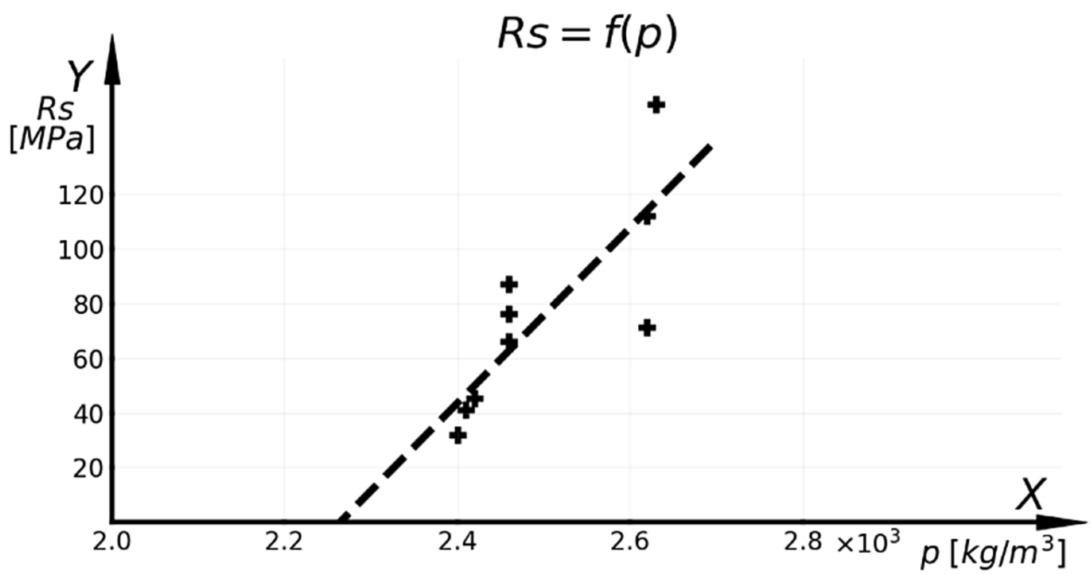


**Figure 2.** Relationship (a) UCS = Rs = f(p) and scatter of measurement points for UCS = Rs = -727.1 + 321.14 × p

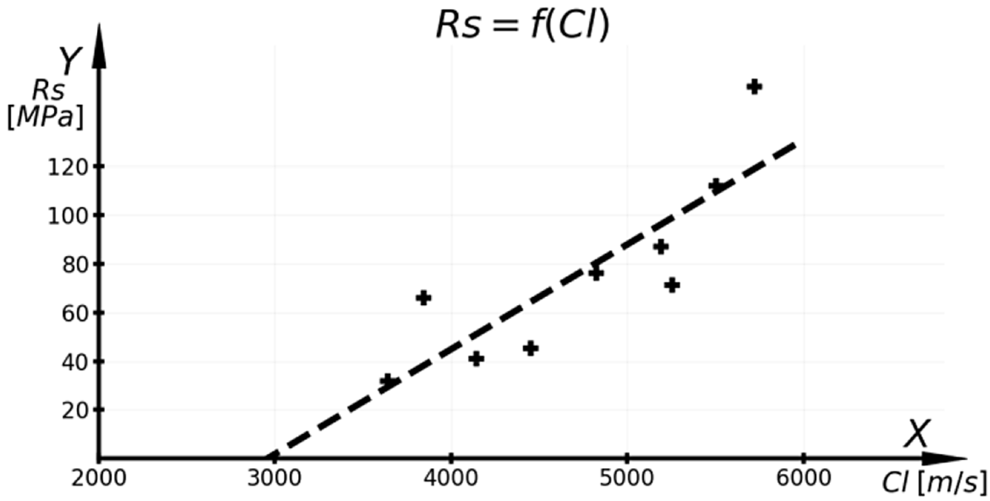


**Figure 3.** Relationship (b) UCS = Rs = f(Cl) and scatter of measurement points for UCS = Rs = -127.5 + 43.06 × Cl

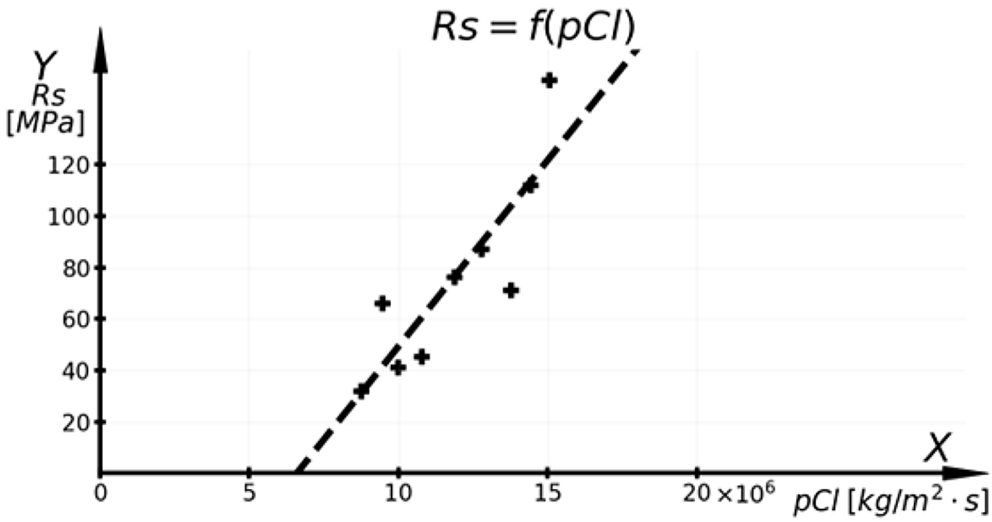


**Figure 4.** Relationship (c) USC = Rs=f(p × Cl) and scatter of measurement points for UCS = Rs = -95.7 + 14.5 × p × Cl

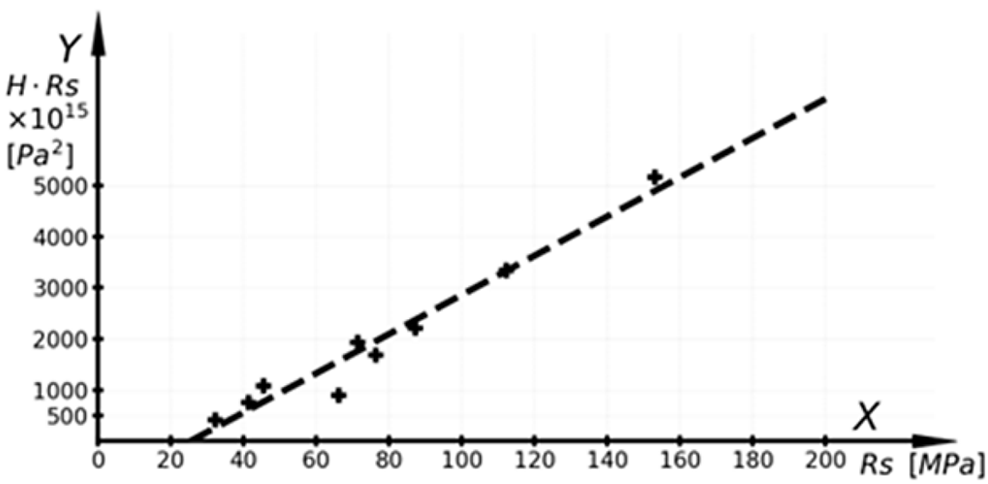


**Figure 5.** Relationship (e) UCS = Rs = f{(p × Cl × Ct) = H} and scatter of measurement points for Rs × H = f(Rs). UCS = Rs = 981.7/(38.2-H)

2. Testing – the cylinder is placed in a testing machine and subjected to a uniaxial compressive stress, which means that the force is applied axially (parallel to the length of the cylinder).
3. Load application – the load is applied gradually and continuously until the rock sample fails. The specimen is compressed in an air-dry condition with no visible cracks.
4. UCS Calculation – the uniaxial compressive strength (UCS) is calculated by dividing the maximum load the sample can withstand (the load at failure) by the sample's original cross-sectional area.
5. Reporting – the UCS is reported for each sample.

The ultrasonic longitudinal and transverse wave velocities are measured in the X direction of the sample. The volumetric density is determined for each sample. The sample is then compressed in the X direction on a hydraulic press and its compressive strength is recorded. A statistical processing computer programme is then used to determine the correlation constants and the value of the correlation coefficient R, which is used to assess the accuracy of the fit of the calculated relationship to the measured data. Given the dependence of the compressive strength on the acoustic modulus for a given deposit at any point in the deposit, it is possible to perform wave velocity measurements on rock fragments with two parallel surfaces and obtain the compressive strength as for cylindrical samples. The same procedure is used to determine the dependence of the compressive strength on the acoustic modulus in the Y and Z directions. The compressive strength in each direction is different, so the results of UCS measurements in the X direction should be given as UCSx. In the Y direction as UCSy and in the Z direction as UCSz.

## The mean standard error

The average standard error or average accuracy of б calculation for uniaxial compressive strength [UCS] measurements is calculated from the formula [11],

$$б = \{\Sigma[(Xisv–Xsa)]^2]/:/ (n–1)\}^{0.5} \quad (17)$$

where: $\Sigma[(Xisv–Xsa)]^2$ is the sum of consecutive differences between the UCS measurement value *Xisv* and the average value of the analyzed set of measurements *Xsa* to the second power, of all measurements, *n* is the number of measurement results.

The calculation was carried out in two steps:

- Step I: a) calculation of the average accuracy б, for a set of 9 measurements and their average value, b) analysis of measurements significantly deviating from the average value of the data set, c) rejection of the measurement significantly deviating from the average value of the data set.
- Step II: a) calculate the average accuracy б, for a set of 8 measurements and their average value, b) recalculate the average accuracy б, c) calculate the number of measurements for the assumed value of the sum of the difference of the measured value Xisv and the average value of measurements Xsa to the second power.

### *Step I*

Calculation of the average accuracy б. The value of the measurements for each sample Xisv is given in column 3. The average value of the measurements Xsa for the samples given in column 3 is summarized at the bottom of column 3. $\Sigma[(Xisv–XsaI)]^2$ the sum of the difference of the measured value of UCS and the average value XsaI = 76.1 MPa of the analyzed measurements to the second power for all measurements is summarized at the bottom in column 4 item 10 in Table 1. By substituting the data summarized in the table into the relation $б = \{\Sigma[(Xisv–XsaI)]^2]/:/ (n–1)\}^{0.5}$, б was calculated. Since it was assumed that $\{\Sigma[(Xisv–XsaI)]^2]\}^{0.5} = \Delta$, and $[n–1]^{0.5} = m$ then б = Δ/m, б = 107.4/2.83 = 37.96 = 38%. It has been verified that measurement 2 in Table 1, where UCS = 153 MPa, has too much error because it deviates significantly from the average value of the measurements. A method for removing measurements from a set of measurement data whose values deviate significantly from the average value is presented based on the set of measurements listed in Table 1. The measurement listed in Table 1 at position 2 has a value of Xisv =153 MPa. The calculated average accuracy (item 11 in Table 1) without this measurement is Δ = 75 and m = 2.65 hence б = 28.30%. From the formula t = [Xk-XsaII]/:/ б value' t' is calculated, where Xk - measurement significantly deviating from the average value, XsaII – average value of all measurements without taking into account the measurement significantly deviating from the average value, XsaII = 66.5 MPa.

If the calculated value "t" exceeds the critical value tk taken from Table 2 for 8 measurements with the assumed probability P = 0.95, the measurement 2 /Table 1/Xisv = 153 MPa can be rejected as containing a large error. Using the data from Table 1, we calculated t = (153–66.5)/28.3 = 86.5/28.3 = 3.06 The critical value of tk taken from Table 2 for 8 measurements and the assumed probability P = 0.95; tk = 2.51. Since the calculated value of t exceeds the critical value of tk, values of 153 MPa can be excluded from further calculations. The calculation error can be reduced by eliminating from the set of measurements those that deviate significantly from the average value, i.e. those in which the difference between the measured value and the average value is the largest. Only by adding to the set of measured data those whose value is equal to the average value of the analyzed data, significantly increased the value of calculation accuracy (item 12 of Table 1).

*Step II*

Calculate the average calculation accuracy б after discarding the measurement from item 2 of Table 1. The value of the measurements for each sample Xisv is given in column 3. The average value of the measurements XsaII = 66.5 MPa for the 8 samples in column 3 is given in item 11 of the table. Σ[(Xisv–XsaII)]$^2$ = 5633.9 the sum of the difference of the measured value of UCS and the average value of the analyzed measurements to the second power, of all measurements is given in column 4. By substituting the data summarized in Table 1 into the relation б = {Σ[(Xisv–XsaII)]$^2$/:/ (n-1)}$^{0.5}$, б was calculated, for 8 measurements. It was assumed that {Σ[(Xisv–XsaII)]$^2$]}$^{0.5}$ = Δ, Δ = 75 and (n–1)$^{0.5}$ = m, m = 2.65 is б = Δ/m, б = 75.0/2.65 = 28.3%. Checking the accuracy of the calculation of the number of measurements obtained from the above formula. Since Σ[(Xisv–Xsa)]$^2$ = Δ = 75; (n–1) = m ; obtained; m = Δ/ б$^2$. Hence, n = [Δ/б$^2$] +1 ; n = (75/8.0)+1 = 9.37 + 1 = 10 measurements (number of actual measurements = 8). Relative error Bwn, calculation of the number of measurements, Bwn = (nob/nr)–1, where "nob" – calculated number of measurements, "nr" – number of actual measurements. Bwn = [10/8]–1 = 1.25–1 = 25%. The relationship used gives measured values 25% higher than actual values. To make the value of Bwn equal to 0%, "nob" should be rounded and multiplied by B, B = 0.8. nob = 10 × 0.8 = 8, Bwn = [nob/nr]–1 = 8/8–1 = 1–1= 0%. To illustrate the calculation methodology, an example number of measurements was calculated for the average value of calculation accuracy, б = 15.0% and б$^2$ = 2.25 This value of б was taken to see how a change in the value of б affects the number of measurements. Б = {Σ[(Xisv–Xsa)]^2]/:/ (n–1)}$^{0.5}$. Assuming that; Δ = 22.5 it was obtained that n = 10 + 1 = 11. Δ = 45 it was obtained that n = 20 + 1 = 21. Δ = 67.5 it was obtained that n = 30 + 1 = 31. The analysis of the above calculations shows that the number of measurements for a given value of average calculation accuracy depends on the square of the sum of the difference of the measured value Xisv and the average value of the analyzed measurement data Xsa. For the same value of Δ, reducing the calculation accuracy twice from 15% to 28% results in an almost threefold reduction in the number of measurements from 31 to 8. Based on the real calculation example with Δ = 75 for the average calculation accuracy б, б = 10%, the number of measurements is 75 + 1 =76 measurements, nob = 76 × B = 76 × 0.8 = 61 measurements. Taking the average accuracy of calculation б, б =15% almost 2 times reduces the number of measurements and is n = (75/2.25) + 1 = 33.3 + 1 = 34 measurements, nob = 34 × B = 34 × 0.8 = 27 measurements. The results of adding 8 measurements with a value equal to the average value of the entire set of measurements analyzed are shown in item 12 of Table 1. Only in this case, increasing the initial data set by 100% resulted in an increase in calculation accuracy of about 10% from 28.3% to 19.4%.

**Table 2.** Critical tk values when excluding high error results from a data set [11]

| n | P = 0.95 | P = 0.98 |
|---|---|---|
| 6 | 2.78 | 3.64 |
| 7 | 2.62 | 3.36 |
| 8 | 2.51 | 3.18 |
| 9 | 2.43 | 3.05 |
| 10 | 2.37 | 2.96 |
| 11 | 2.33 | 2.89 |
| 12 | 2.29 | 2.83 |
| 13 | 2.26 | 2.78 |
| 14 | 2.24 | 2.74 |
| 15 | 2.22 | 2.71 |

**Note:** n-number of measurement data acceptable in the data set,P-probability of confidence

## CONCLUSIONS

The new method of determining the UCS of rocks based on ultrasonic measurements and using an acoustic module can be applied to a given deposit during its many years of exploitation. During the comprehensive assessment of the compressive strength of rocks, rapid ultrasonic measurements can complement the destructive testing method, and their accuracy can be increased by multiplying the number of measurements at a given site. This paper examines the increase in the accuracy of UCS determination as the number of measured acoustic parameters and the number of measurements increase.

From the analysis of measurements and calculation results summarized in the article, it is found that:

1. In each set of measurement results, about 10% are measurements with too much error, which should be discarded from the set of measurements before further statistical analysis.
2. If the average accuracy of the calculation is about 40%, there is at least one measurement with too much error in the set of analyzed data
3. If the average calculation accuracy is less than 30%, there is no measurement with too much error in the analysed data set.
4. For the same value, square, the sum of the difference of the measured value and the mean value of the analysed measurements, the number of measurements providing 10% of the mean value of the calculation accuracy is twice the number of measurements providing 15% of the mean value of the calculation accuracy.
5. For the same value of the square of the sum of the difference of the measured value and the mean value of the analysed measurements, a twofold reduction in calculation accuracy from 15% to 28% results in an almost threefold reduction in the number of measurements from 31 to 8.
6. The analysis of the article shows that the number of measurements for the assumed average value of accuracy depends on the square of the sum of the difference between the measured value Xisv and the average value of the analyzed set of measurements Xsa.
7. The calculation accuracy error can be reduced by eliminating from the set of measurements those that significantly deviate from the average value, i.e. those in which the difference between the measured value and the average value of the analyzed set of measurements is the largest.
8. The accuracy of calculations can be increased only by adding new measurements to the original set of measurements, the value of which is close to the average value of the original set of measurements.
9. It has been shown that the proposed use of the acoustic module increases the accuracy of determining the compressive strength of rock samples.
10. The compressive strength in each direction is different, therefore the results of UCS measurements in the X direction should be given as UCSx. In the Y direction as UCSy, and in the Z direction as UCSz.

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