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Non-destructive assessment of stone masonry elements' compressive strength

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ZADÁNÍ BAKALÁŘSKÉ PRÁCE

I. OSOBNÍ A STUDIJNÍ ÚDAJE

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Studijní program: Stavební inženýrství

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II. ÚDAJE K BAKALÁŘSKÉ PRÁCI

Název bakalářské práce: Nedestruktivní stanovení tlakové pevnosti zdicích prvků kamenného zdiva

Název bakalářské práce anglicky: Non-destructive assesment of stone masonry elements' compressive strength

Pokyny pro vypracování:
Na základě provedených experimentálních měření in-situ i v laboratoři bude sestavena kalibrační křivka pro nedestruktivní stanovení tlakové pevnosti zdicích prvků kamenného zdiva. Předpokládá se užití metody odrazového tvrdoměru, impulsní průchodové rychlosti a jejich kombinace metodou SONREB. Tlaková pevnost bude měřena na odebraných zkušebních tělesech z reálného kamenného zdiva z různých typů hornin, například pískovce, opuky, vyvřelých hornin, pro každou tuto skupinu bude kalibrační křivka zpracována individuálně.

Seznam doporučené literatury:

Jméno vedoucího bakalářské práce: Ing. Jan Zatloukal, Ph.D.

Datum zadání bakalářské práce: 18.2.2019 Termín odevzdání bakalářské práce: 26.5.2019
Údaj uveďte v souladu s datem v časovém plánu příslušného ak. roku

Podpis vedoucího práce Podpis vedoucího katedry

III. PŘEVZETÍ ZADÁNÍ

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19.2.2019
Datum převzetí zadání Podpis studenta(ky)

Declaration

I hereby declare that thesis was written separately only under academic guidance of thesis advisor Ing. Jan Zatloukal, PhD.

I hereby declare that all used materials have been fully cited in list of used literature.

In Prague, 27.5.2019

……………………………………

Martin Jonáš

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Non-destructive assessment of stone masonry elements' compressive strength

Nedestruktivní stanovení tlakové pevnosti zdících prvků kamenného zdiva

27. 5. 2019

Abstract

Non-destructive test methods have widespread usage in civil engineering, due to their non-invasiveness, quickness and low price. They are commonly used for assessment of various physical properties. One of these properties is unconfined compressive strength. While these tests are not assessing unconfined compressive strength directly, calibration is needed. Calibration for concrete is commonly used, however calibration for rocks is not available. Task of this thesis was assessment of calibration relation for rock for three non-destructive methods. To fulfil task, a set of tests and measurements on rock samples was processed and calibration relations were developed and evaluated. Calibration relations were evaluated for three different methods and three different rock categories.

Keywords

NDT, Schmidt rebound hammer, ultrasonic pulse velocity, unconfined compressive strength, SONREB, rock, igneous rocks, opuka rock, sandstone

Abstrakt

Nedestruktivní metody testování materiálů mají široké vyžití v stavebním inženýrství, hlavně díky jejich neinvazivitě, rychlosti a nízké ceně v porovnání s metodami destruktivními. Jsou často užívány ke stanovení různých fyzikálních vlastností materiálů. Jednou ze zásadních vlastností je pevnost v prostém tlaku. Jelikož tyto metody nestanovují pevnost v prostém tlaku přímo, je nutné měření kalibrovat. Kalibrace pro beton je známá a využívána, ale kalibrace pro horniny není dostupná. Úlohou této práce bylo stanovení kalibračních vztahů pro horniny pro tři nedestruktivní metody měření pevnosti. Za účelem cíle práce byla realizována série měření na horninových vzorcích, na základě které byly vyhodnoceny a stanoveny kalibrační vztahy. Tyto kalibrační vztahy byly stanoveny pro tři různé skupiny hornin zvlášť.

Klíčová slova

NDT, Schmidtovo kladívko, rychlost přechodu ultrazvukových vln, pevnost v prostém tlaku, SONREB, horniny, vyvřelé horniny, opuka, pískovec

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List of used symbols

a	regression coefficient
A	loaded area
A_b	absorbability
b	regression coefficient
c	regression coefficient
e	Euler's number
E	dynamic modulus of elasticity
ε	permittivity
F	force necessary for sample destruction
m_d	weight of dry sample
m_s	weight of saturated sample
ν	Poisson's ratio
Q	rebound value from SilverSchmidt L
R, R_L, R_N	rebound value, rebound value Original Schmidt L, rebound value Original Schmidt N
R^2	coefficient of determination
ρ	mass density
s	displacement
t	time
UCS	unconfined compressive strength, measured
$\widetilde{UCS}$	unconfined compressive strength, estimation
UPV	ultrasonic pulse velocity
V	volume of sample

1 Introduction

Unconfined compressive strength (UCS) is one of the main characteristics, which is being assessed for various types of building materials. Standard approach is realization of destructive tests, which can offer most accurate results in assessing UCS. These tests demand preparation of samples, that have to be extracted from bigger block of tested building material.

For some applications destructive methods are not suitable for various reasons. Mainly the problem is a damage of part of structure. This damage, doesn't have to cause structural problem, but may be a problem for visual quality and durability of structure, or the historical value of object is too high, while extraction samples for destructive tests is not possible. Other disadvantage of destructive tests is, that the tests are processed in laboratory, which takes a lot of time to extract samples, prepare them for testing, perform the test itself and this is expensive. These reasons cause, that the need for non-destructive assessment of unconfined compressive strength (UCS) is getting higher, especially in structural diagnostics, which is highly associated with problems of destructive tests listed before.

In last years of economic growth, interest in reconstruction of older objects is getting higher. It is very often, that structural diagnostics need approximate information about compressive strength of stone masonry very quickly and cheaply, sometimes right in situ. NDT assessment of unconfined compressive strength can provide information in very short time, with minimal costs and its accuracy is reliable enough for these needs.

Non-destructive assessment of compressive strength of building materials is possible by using methods of Schmidt rebound hammer, ultrasonic pulse velocity test and their combination in SONREB method. All these methods are based on measurement of certain parameter, but not the compressive strength directly. Correlation between these parameters and unconfined compressive strength (UCS) is used to calibrate the NDT measurement to assessment of UCS. Standard building materials like concrete, mortar, bricks and others have these calibrations set for longer period.

Rocks have been used for building of structures for thousands of years, but calibrations for them are not satisfactorily set. This thesis is focused to set calibrations for specific local types of rocks (opuka rock) and preparing calibrations for common rock types, to compare them with other researches. Obviously range of bachelor thesis cannot cover this whole theme, it will take much more time and effort to get and process enough quantity of rock samples.

In this thesis, certain number of rock samples will be processed, for which the calibrations will be set, specific problems will be solved and the results will be discussed to set new targets in research.

2 Non-destructive-test methods

Non-destructive-test methods (NDT) are using various physical phenomena to obtain certain properties of material, which we want to examine. NDT methods can provide us data in very short time period, cheaply and without any significant visible damage. Principles of methods used in these thesis are described lower.

2.1 Schmidt rebound hammer

One of the most common non-destructive-tests (NDT) is Schmidt rebound hammer test, that is designed to easily measure Q or R parameter, which is proportional to surface hardness of material (concrete or similar materials). Thanks to correlation between hardness and unconfined compressive strength (UCS), unconfined compressive strength can be assessed using calibration curves for each material. [52]

Rebound hammer was invented by Ernst Schmidt, a Swiss engineer. Method is based on rebound of hammer mass in the body of instrument. Plunger of instrument, which has spherical tip, is pressed against the surface, while body of Schmidt hammer is pressed against the sample/material. While the body is being pressed against material, the impact spring is stretched. Then the spring is released, hammer mass is casted and it rebounds from the plunger. The rebound rate is measured as R-value. Modern digital instruments measure the difference between velocity of hammer mass right before and after rebound, which is interpreted as Q-value. [42] Relationship between R and Q value can be simplified into this equation, which is valid for horizontally led impact: [51]

$$R \approx 0.75 * Q$$

Principle is based on relationship between hardness and kinetic energy ratio before and after rebound of hammer mass. The harder the surface is, less energy is dissipated by the material and then the velocity after rebound is higher, or the rebound rate is higher. [51]

For its easiness and reliability, Schmidt hammer test is maybe the most common NDT method used in civil engineering. Approximate value of unconfined compressive strength can be obtained in few minutes, right at the place (in situ). For materials without known calibration curves, only the R or Q value is obtained. The test itself progress as follows: [34]

1. Find or prepare adequate surface area, which will be flat and without rough dirt
2. Perform certain number of impacts with Schmidt hammer (usually 9 or 13 impacts)
3. Record R-value for mechanical Schmidt hammer
4. Process the measurement, get the average R-value, modern instruments can process the measurement itself as the average Q-value

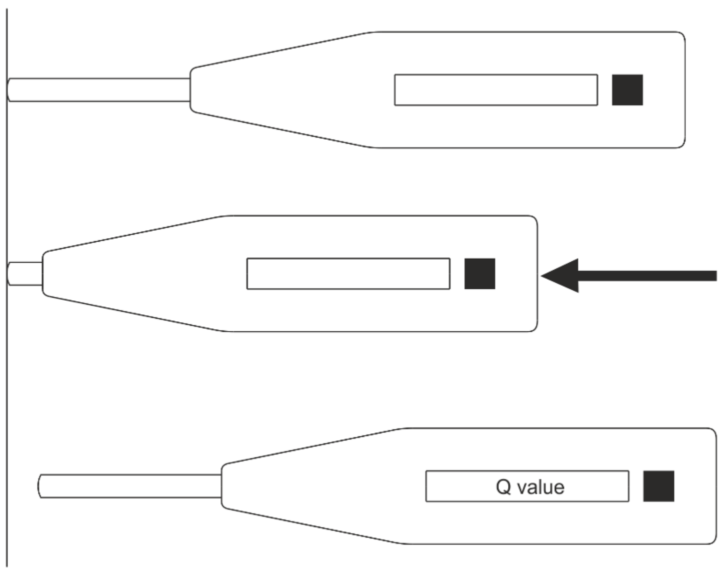

Fig. 1 Scheme of measurement with Schmidt rebound hammer (picture: M. Jonáš)

While only the surface hardness is measured, to assess the unconfined compressive strength, calibration curves must be used. These curves are known for concrete. For the test also depends the angle of measurement. The Schmidt hammer can be placed vertically up, horizontally, vertically down or in other angle. For mechanical Schmidt hammers, the influence of gravitation must be considered. This is contained in calibration curves, for each position is specified one calibration curve. Modern instruments compensate influence of gravitation to measurement itself, so measurement can be done in whatever position, as is needed. [34], [51]

Multiple other factors can influence measurement therefore results are then less accurate. Typical influences to measurement: [41], [51]

- Fineness of material surface, more rough surface gives higher results
- Size of sample, bigger sample is better
- Support of sample, if the sample can move, part of energy is dissipated by movement of sample
- Age of sample
- Moisture of sample, moisture lowers rebound
- Carbonation of concrete may increase rebound

Schmidt hammers are made in many variations, typical manufacturers in Europe are Proceq (Switzerland) and Matest (Italy). Most used types are these [34]

- Type N – Normal, for standard concrete testing, impact energy 2.207J
- Type L – Low, for testing of smaller samples or sensitive materials, impact energy 0.735 J
- Type LB – Low, Bricks, for brick testing, impact energy 0.735 J, difference between L and LB is in different radius of spherical plunger tip
- Type M – Massive, for testing massive concrete blocks, impact energy 29.43 J
- Type P – Pendulum, pendulum hammer for light materials or materials with low compressive strength, impact energy 0.833 J

Fig. 2 Schmidt hammer Type L (picture: M. Jonáš)

2.2 Ultrasonic pulse velocity (UPV)

Other commonly used NDT method is measurement of ultrasonic pulse velocity (UPV) in material. There are two most used options of measurement. First one is measurement of ultrasonic pulse velocity (UPV) on sample of known dimension. Second is measurement and comparison of wave transition time in the same distances on various samples of the same size, or in more directions on the same sample, which has more dimensions equal (cube). [29]

Ultrasonic pulse velocity method is based on emission and receiving of short ultrasonic pulse into material. Transmission of ultrasonic waves is possible thanks to properties of solids. Solids (opposite to liquids and gases) have higher atomic forces, so they can bear shear strains what is essential to transmission of ultrasonic waves in material. Ultrasonic waves are sonic waves with frequency 20kHz or higher. Types of waves are: longitudinal waves (P-waves), transverse waves (shear waves, S-waves) and surface waves (Rayleigh waves). P-waves are measured. [51]

Principle of method is measurement of time of transition of ultrasonic wave between 2 points of known distance on material sample. From time of transition t and displacement s, velocity UPV of ultrasonic waves can be easily calculated from equation: [44]

$$UPV = \frac{s}{t}$$

Velocity of waves in solids can be also described as a relation between dynamic modulus *E*, volumetric mass density *ρ*, and Poisson's ratio *v*: [51]

$$UPV = \sqrt{\frac{E}{\rho} * \frac{1-\nu}{(1+\nu)(1-2\nu)}}$$

For measurement of ultrasonic pulse velocity in rock samples used in this thesis, Proceq Pundit Lab unit was used. This unit consist of evaluation unit, transmitter, receiver and connecting cables. While transmitter (T) and receiver (R) are pressed against the rock sample, short ultrasonic pulses are transmitted. These short pulses are represented by longitudinal waves transmitted by transmitter and received by receiver, while transit time is measured. Proper acoustic coupling should be between sample and probes. This is ensured by using an ultrasonography gel, applied to ends of rock sample. [29], [51]

Ultrasonic waves are transmitted and received by using electroacoustic transducers, which are transducing electric energy to mechanical and vice versa. Probes can be divided to probes for longitudinal, transverse and surface waves. Also other divisions can be made, according to direction of transmission, working principle, material, they are dedicated to, own frequency and way of use. [51]

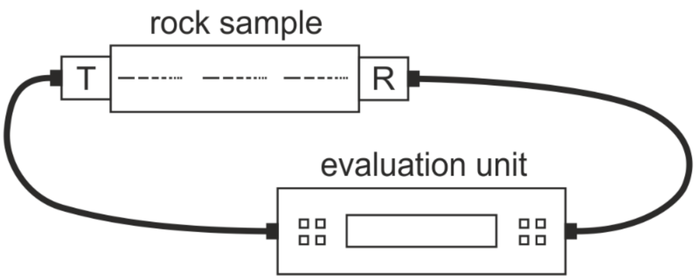

Fig. 3 Scheme of measurement with Proceq Pundit Lab unit (picture: M. Jonáš)

Process of ultrasonic pulse velocity (UPV) test using Proceq Pundit Lab unit is following: [29]

1. Device is switched on and calibrated using special plexiglass cylinder with defined pulse travel time.
2. Length of sample is measured in millimetres
3. Length of sample is set up to unit
4. Ultrasonography gel is applied to both ends of sample to transfer pulses from device to sample and vice versa.
5. Proper voltage and amplification is set up.
6. Transmitter and receiver are pressed against the sample sides.
7. Measurement is activated.

8. If the result is satisfying (right intensity of signal, expected velocity), measurement is recorded. If not, settings are changed and measurement is repeated until the result is satisfying. This phase requires experienced observer, who is able to detect systematic measurement error.

Ultrasonic pulse velocity (UPV) test has various uses in engineering. It can be used for easy and quick obtaining of dynamic modulus, evaluation of quality and uniformity, detection of defects, voids and tendon ducts, compressive strength estimation, crack depth estimation, location of pipes and lot of other applications. [29]

Fig. 4 PunditLab ultrasonic tester (picture: M. Jonáš)

2.3 Material humidity meter

Material moisture has inconsiderable influence to other material properties, so it is necessary to assess humidity of material. For this reason, various types of material humidity meters were invented. Humidity can be measured by destructive and non-destructive tests. Non-destructive tests provide less accurate results, but the advantage of quickness and easiness might be decisive for using these methods. Opposite to non-destructive tests are destructive tests, which can offer much more accurate results, but their disadvantage is in more complicated procedure, longer time period is needed and finally, part of structure or material must be removed. [14]

Non-destructive humidity sensors are based on several principles, these measuring devices are listed here: [14]

- Capacitive humidity sensor
- Resistive humidity sensor
- Microwave humidity sensor
- Radiometric moisture measurement system

2.3.1 Capacitive humidity sensor

For measuring humidity of rock blocks was used capacitive humidity sensor, mainly due to quickness of measurement and relatively good accuracy of results.

Capacitive humidity sensor works on principle of different permittivity (dielectric constant) ε of water and building material. Permittivity of water (ε=81) is much higher than permittivity of building materials (ε=2-5). Even small content of water significantly changes dielectric constant of medium. Change of permittivity is sensed by the capacitive transducer, measured in bridge circuit and then evaluated. Humidity is specified from permittivity of material, while certain relations between humidity of material and permittivity are used. [33]

This apparatus is very sensitive to quality of surface of measured material. If the surface is rough, between sensor and material can be a little gap. While the permittivity of air is very low (ε=1.00054), even a very little gap can cause significant influence to accuracy of measurement. [14] Due to this reason, making proper surface treatment is very important, if we want to obtain most accurate measurement. [14]

Fig. 5 Capacitive material moisture meter (picture: M. Jonáš)

3 Non-destructive assessment of unconfined compressive strength

While none of described techniques above can measure unconfined compressive strength (UCS) directly, all of these methods are using calibration relations between obtained property value and UCS. Process of calibration and compensation of moisture influence to Schmidt hammer test and ultrasonic pulse velocity will be determined.

3.1 Division of rock types

In this thesis, various rock types were examined. As these rocks have different physical properties, it is better to divide samples into groups according to similar properties. Division into groups should provide more accurate results and at the same time allow processing of more samples into one calibration than calibration for each rock type specifically. In this division, physical properties and geological origin of rock types were considered. We have divided rock samples from this thesis into three groups according to previously mentioned criteria. Description of these three groups follows in next sections.

3.1.1 Igneous rocks

Igneous rocks are extensive group of rocks, which are formed from magma or lava. They can be basically divided into intrusive and extrusive igneous rocks. Intrusive were formed under Earth's surface in huge masses, extrusive were formed from lava on Earth's surface. Usually, these rocks are very hard, durable and have high compressive strength. Differences between rock types of igneous rocks are in mineralogical composition, structure, crystal size and other properties. [21]

Igneous rocks are widespread as a building material thanks to their strength and durability, even while the workability is worse than soft rocks like sandstone or opuka (see chapter 3.1.2). Today are igneous rocks commonly used for paving (setts), retaining walls, fences, gabions, as a decorative stone and many of other uses. [21]

Fig. 6 Various intrusive igneous rocks (granite, granodiorite, quartz diorite) (pictures: M. Jonáš)

Variety of igneous rocks was processed in this thesis with similar results. For all of these rocks was typical high rebound value (Q), high ultrasonic pulse velocity and high unconfined compressive strength. According to this data, making a category for all igneous rock, independently to further division, was decided.

This category consists of samples of further rock types: granite, granodiorite, quartz diorite, syenite and basalt. Most samples were of three types, granite, granodiorite and quartz diorite.

3.1.2 Opuka rocks

Opuka rock is a very specific type of rock, typical for Czechia, especially in the surroundings of Prague. Opuka rock is sandy or silty marlstone, which was formed in Late Cretaceous in Czech massif. Opuka was widespread building material in Romanesque architecture in Czech lands, thanks to easiness of workability, great mechanical properties and durability of this material. We can find opuka mostly in historical objects, or as a decoration stone today. [27]

Opuka is set as a specific category in this thesis, due to its spread in structures in Czechia. Opuka has similar UCS as sandstone and it contains sand grains, but other properties are different to sandstone. Especially grain size is much different, what can significantly affect rebound value. [51] This was the reason not to join opuka rocks with sandstone into one calibration.

Fig. 7 Opuka rock (picture: M. Jonáš)

3.1.3 Sandstones

Sandstones are most famous building stone in history of Czechia. Since Gothic times, sandstones were the most popular material for masonry. Sandstones have relatively good durability and strength properties and perfect workability. This predestined them for construction purpose especially in times, when people had limited technologies. [28]

Sandstones are bonded clastic sediments with middle-size grains (0.063-2 mm). Bond is usually calcite or siliceous. Sandstones have three sub-types, quartz sandstone, arkose and greywacke. [28] Most of samples processed in this thesis were quartz sandstone, one sample was greywacke.

Fig. 8 Czech sandstone in structure, detail (pictures: M. Jonáš)

3.2 Schmidt hammer method

Schmidt hammer method is widespread method used to estimate compressive strength of stone elements. This method is dedicated to assess unconfined compressive strength (UCS) using two input parameters, Q-value from Schmidt hammer type L measurement and material moisture. Material moisture is not needed for igneous rocks.

For establishing relation between Q-value and UCS, data from measurements were used. These data inputs were Q-value, UCS and material moisture. Material moisture was background to adjust Q-value, which is influenced by humidity of material. After adjusting Q-value, graph with relation between Q-value and UCS was created. In next step this relation was evaluated into exact formula, using least square method in Microsoft Excel software. Formula might be in various forms, according to used regression. Best result is chosen pursuant to maximal coefficient of determination (R^2). Optimal result is reached, when R^2=1, then all the points lie on evaluated curve.

Assessment of calibration relation for unconfined compressive strength for three rock types listed in chapter 3.1 follows. For our results, two forms of regression were used. First one linear, which is dedicated to opuka rocks and sandstones, with formula of estimated UCS in form:

$$\widehat{UCS} = a * Q + b$$

Second one exponential for igneous rocks, with formula of estimated UCS in form:

$$\widehat{UCS} = a * e^{bQ}$$

Moisture effect to decrease of Q-value is compensated by adjustment of Q-value. This effect is visible for opuka rocks and sandstones. It is not necessary to adjust Q-value for igneous rocks. Compensation for opuka rocks and sandstones is following. If the material moisture is 0%, measured Q-value is valid. If the rock is saturated, measured Q-value is increased 1.05 times for opuka rocks or 1.15 times for sandstones. For intermediate values, increase is linearly interpolated between 1 and 1.05 times original Q-value for opuka rocks or 1 and 1.15 times original Q-value for sandstones.

3.2.1 Comparison of previous researches

As this method is the most widely spread, many of researches were done to calibrate relation of rebound hammer measurement (R or Q-value) to unconfined compressive strength. In table 1 are listed researches with their results and rock types, which are the results related to. This table has been taken over from Wang [46] and extended with data from Saptono [31].

Tab. 1 Comparison of researches in assessment of UCS by Schmidt hammer method. Table has been taken over from Wang [46] and extended with data from Saptono [31].

Researcher	Source	Fitting formula	R	Rock type
Aggistalis et. al.	[2]	$UCS=1.31R_N-2.52$	0.55	Gabbro and basalt
Aufmuth	[4]	$UCS=6.9*10^{(1.348\rho R - 1.325)}$	-	Rock type without specific expression
Aydin and Basu	[5]	UCS=1.45exp(0.07RL)	0.92	Granite
Deere and Miller	[10]	$UCS =6.9*10^{(0.0087\rho R + 0.16)}$	0.94	Rock type without specific expression
Dincer et. al.	[13]	$UCS=2.75R_N-36.83$	0.95	Andesites, basalts and tuffs
Kahraman	[15]	$UCS=6.97*exp(0.01*R_N*\rho)$	0.78	Carbonates
Katz et. al.	[16]	$UCS=2.21*exp(0.07*R_N)$	0.96	Maresha chalk, Cordoba-Cream limestone, Berea sandstone, Indiana limestone, Carrara marble, Gevanim syenite and MtScott Granite
Kayabali and Selcuk	[17]	$UCS=9.97exp(0.02R_L\rho)$	-	Gypsum, tuff, ignimbrite, andesite, sandstone, limestone, marble
Kidybinski	[19]	$UCS=0.447exp(0.045(R + 3.5) + \rho)$	-	Coal, Shale, mudstone
O'Rourke	[26]	$UCS=4.85R_L-76.18$	0.77	Sandstone, siltstone, limestone and anhydrite
Sachpazis	[30]	$UCS=4.29R_L-67.52$	0.96	Carbonate rocks (marble, limestone, dolomite)
Shalabi et. al.	[35]	UCS=3.20Hr-46.59	0.76	Shale, anhydrite, dolomite
Singh et. al.	[37]	$UCS=2R_L$	0.86	Sandstone, siltstone, mudstone, seatearth
Tugrul and Zarif	[43]	$UCS=8.36*R_L-416.00$	0.87	Granite
Wang, Hu and Lin	[46]	$UCS=4.52927exp(0.05609R_L)$	0.77	Rock type without specific expression
Xu and Mahtab	[47]	$UCS=exp(aR_L+b)$	-	Mica-schist, prasinite, serpentinite, gabbro, mudstone. Coefficients a and b depends on rock type.
Yagiz	[48]	$UCS=0.0098R^{2.584}$	0.92	Travertine, limestone, Schist and Dolomitic limestone
Yasar and Erdogan	[49]	$UCS=0.000004R_L^{4.29}$	0.89	Carbonate, sandstone, basalt
Yilmaz and Sendir	[50]	$UCS=exp(0.818+0.059R_N)$	0.91	Gypsum

From this table is apparent, that usually there are two variants of regression used, first one exponential, with formula of estimated UCS in form:

$$\widetilde{UCS} = a * e^{b*R}$$

And the second one linear, with formula of estimated UCS in form:

$$\widetilde{UCS} = a * R + b$$

Usually linear form is considered better, but as the relation between UCS and R or Q-value is exponential (can be seen in fig. 17, chapter 6.1, page 27), that could be a reason to choose exponential regression (except of maximal coefficient of determination). Also other forms of formulas are used, depends on every researcher.

As can be seen, problem of calibration of Schmidt hammer method was answered many times, lot of researches were published many years ago. Results of these experiments are pretty different, due to more reasons. As a first reason, difference between used regressions can be seen. The second reason, which might be essential, could be variety of used rocks in research. Some researchers were using specific calibration for each rock type, others combined more rock types to one calibration. But none of these approaches can be proven wrong without deeper study.

3.3 Ultrasonic pulse velocity (UPV) method

Second method used in assessment of unconfined compressive strength (UCS) is based on measurement of ultrasonic pulse velocity (UPV) on rock samples. Two input parameters are used, ultrasonic pulse velocity (UPV) and material moisture. Ultrasonic pulse velocity is basic parameter, which directly enters calibration relations. Material moisture influences measurement of ultrasonic pulse velocity, its value is used to adjust UPV value before entering UPV value into calibration.

Base of UPV method is very similar to Schmidt hammer method, only Q and UPV values are different. UPV value on dry samples enters the calibration with UCS value. If UPV value is not measured on dry samples, value is adjusted to compensate moisture effect. These data are inputs to chart and graph in spreadsheet calculator. Data are subsequently evaluated into calibration relation using least square method.

For all three groups of rocks (igneous rocks, opuka rocks, sandstones) is calibration relation in same, linear form. Its formula is:

$$\widetilde{UCS} = a * UPV + b$$

Material moisture influences measurement of UPV for sandstones and opuka rocks, therefore UPV value must be adjusted. For igneous rocks is this adjustment unnecessary. Water content in samples increases ultrasonic pulse velocity, so the UPV value measured on wet samples has to be lowered. For saturated samples, UPV value will be divided by 1.1 and for dry samples original value will be used. For intermediate values, factor is linearly interpolated between 1 and 1.1.

3.3.1 Comparison of previous researches

Similar to Schmidt hammer method, also for ultrasonic pulse velocity method there is a quantity of researches specialized to assess unconfined compressive strength. Results of these researches are listed below in table 2.

Tab. 2 Comparison of researches in assessment of UCS using ultrasonic pulse velocity (UPV) method

Researcher	Source	Fitting formula	R	Rock type
Altindag	[3]	$UCS=12.743*UPV^{1.194}$	0.76	Sedimentary rocks
Cobanoglu & Celik	[7]	UCS=56.71*UPV-192.93	0.67	Sedimentary rocks
Chary et. Al.	[6]	UCS=0.1564*UPV-692.41	0.8018	Sandstone
Chary et. Al.	[6]	UCS=0.0144*UPV-24.856	0.5099	Sandstone
Diamantis et. Al.	[11]	UCS=0.11*UPV-515.56	0.81	Serpentinite
Diamantis et. Al.	[12]	UCS=0.14*UPV-899.33	0.83	Peridotite
Kahraman	[15]	$UCS=9.95*UPV^{1.21}$	0.83	Various rock types
Khandelwal	[18]	UCS=0.033*UPV-34.83	0.871	Various rock types
Kilic & Teymen	[20]	$UCS=2.304*UPV^{2.4315}$	0.94	Sedimentary rocks
Kurtulus et.al	[22]	UCS=0.1581*UPV-643.2	0.87	Andesite
Martins, Francisco & Vasconcelos	[23]	$UCS=2*10^{-5}*UPV^{1.5343}$	0.931	Granite
Moradian & Behnia	[25]	UCS=165.05*exp(-4451.07/UPV)	0.7	Sedimentary rocks
Sarkar et. Al.	[32]	UCS=0.039*UPV-50	0.934	Various rock types
Sharma & Singh	[36]	UCS=0.0642*UPV-117.99	0.9022	Various rock types
Sousa et. Al.	[39]	$UCS=0.004*UPV^{1.247}$	0.72	Granite
Vasanelli et. Al.	[45]	UCS=0.0159*UPV-27.172	0.7282	Porous limestone
Yagiz	[48]	UCS=49.4*UPV-167	0.89	Various rock types
Yasar & Erdogan	[49]	UCS=31.5*UPV-63.7	0.8	Carbonate rocks

In these researches variety of used regressions is smaller, usually used regression is linear in form:

$$\widetilde{UCS} = a * UPV + b$$

Again as in chapter 3.2.1 results from these researches varies a lot. Main reason might be chosen group of rocks, which were used to research and form of regression. Commonly can be seen, that various rocks are used in one group together, what can influent final results, but they can be still reliable.

3.4 SONREB method

SONREB method is method developed to combine obtained Q-values and ultrasonic pulse velocity values, to get more precise result for assessment of unconfined compressive strength. The name means SONic REBound. [38]

Unconfined compressive strength is set as a combination of Q, UPV value and calibration constants. Calibration constants will be assessed for every rock group individually. SONREB formula for UCS is following:

$$\widetilde{UCS} = a * UPV^{b} * Q^{c}$$

Where *UCS* is estimated unconfined compressive strength, *UPV* is ultrasonic pulse velocity and *a, b, c* are calibration constants. [51]

Evaluation of SONREB method coefficients is processed by using a macro in Microsoft Excel software, which was released on Proceq website. This MS Excel macro is adapted to evaluate coefficients from at least 5 measurements and up to 20 measurements. [38]

Again, moisture effect to measurement have to be considered. Same compensations as in Schmidt hammer method and ultrasonic pulse velocity method are used. These compensations are used for opuka rocks and sandstones, not for igneous rocks, where moisture effect is negligible. If Q or UPV values are measured on dry samples, these values will be used without edition. If are samples during measurement saturated, Q-value will be multiplied by 1.05 for opuka rocks or 1.15 for sandstones. For intermediate values, multiplier is linearly interpolated between 1 and 1.05 for opuka rocks or 1 and 1.15 for sandstones. UPV value measured on saturated samples will be divided by 1.1 and for intermediate values, divisor is linearly interpolated between 1 and 1.1.

Comparison of results of other researches does not follow, due to lack of articles about this theme. SONREB calibration is available only for concrete and bricks, for rocks could not be found any, except of one source. Zatloukal [51] assessed calibration for opuka rocks. Some data from his research were used in this thesis to extend input data for SONREB method for opuka rocks.

4 Moisture influence to measurement

The main influence to measurement, which we cannot avoid by using correct procedure measurement, is material moisture effect. In cases, when measurement is processed in laboratory, rock samples are dried and whole testing is upcoming. If the measurement is processed outdoors, zero humidity of material is never reached. This metering is therefore influenced by material moisture and it is necessary to compensate this influence. In this chapter, reasons of moisture influence are discussed, approach to solve this problem and final compensation to measurements is specified.

4.1 Compensation of material humidity influence to Schmidt hammer measurement

It is well known, that rebound of Schmidt hammer test is influenced by material humidity for porous rocks. Water contained in voids of rock material dissipates energy of impact, therefore measured rebound is lower. However, as this fact is known, certain decrease of rebound values is discussed only in few researches. For purpose of this thesis, research of Sumner and Nel [41] was used.

Sumner and Nel studied decrease of rebound value caused by moisture on various rock types. Rock types used in research were basalt, quartzite, dolerite and sandstone They measured R-values first on dry samples, afterwards on saturated samples. Decrease of R-value was inquired. R-value decrease for igneous rock was relatively low. Cause might be seen in extremely low porosity, consequently humidity of rock material was very low too. Sandstones were significantly different. Decrease of R-value was up to 17.7 % of R-value measured on dry samples. [41]

Compensation of moisture effect to Schmidt hammer measurement for purpose of this thesis is divided into three groups according to rock types division.

First group are igneous rocks. As the decrease of R-value on basalts and dolerite was in Sumner's study [41] relatively low and measured values in this thesis are very high even for measurements performed outdoors, none compensation is used for Q-values measured on igneous rocks.

Second group are sandstones, which were also examined in Sumner's study [41]. Decrease of R-values on sandstones was maximally 17.7 %. Sandstone samples used in this thesis were relatively low quality (low UCS, high absorbability up to 20 % of dry mass), therefore the compensation was chosen higher. Q-values measured on saturated sandstone are increased 1.15 times of measured value. For intermediate values of humidity, multiplier of measured Q-value is linearly interpolated between 1 and 1.15.

Third group are opuka rocks. For this specific rock type, decrease of R-value was not assessed in any study. Compensation used for sandstone offers up, while opuka is relatively similar to sandstone in some properties (sediment, sand content, UCS). However, other properties are different and mainly Q-values measured on wet rocks outdoors were relatively high. Significant difference is also visible in absorbability, which was measured up to 6.5 % of dry mass (sandstones up to 20 % of dry mass). These reasons were considered and certain compensation of moisture effect was determined. Q-values measured on saturated opuka rocks are increased 1.05 times of measured value. For intermediate values of humidity, multiplier of measured Q-value is linearly interpolated between 1 and 1.05.

4.2 Compensation of material humidity influence to ultrasonic pulse velocity measurement

Material humidity influences also an ultrasonic pulse velocity (UPV) which is very important entry for this thesis. Ultrasonic pulses are transmitted by solid phase of rock material. Voids filled by air (or other gas) decelerate ultrasonic pulses in material, due to significantly lower velocity of passing waves. Speed of ultrasonic wave in air is around 340 m/s, while for solids it may reach up to 6000 m/s. If voids are filled by water, it can increase speed of ultrasonic wave due to higher speed of sound in water, than in gases. As is mentioned above, speed of ultrasonic wave in gas is about 340 m/s, in water it can reach about 1500 m/s. Increase of ultrasonic pulse velocity might be significant for porous rocks with higher absorbability. [40]

Part of rock samples of sandstones used in this thesis were dried and absorbability test was performed. While were samples dried, UPV was measured. After submerged samples reached stable weight (explained in chapter 5.3.2), they were declared as saturated. Now, UPV on saturated samples was measured. These data were evaluated into table 3.

Tab. 3 Difference between UPV measured on dry and saturated sandstone samples

Marking	Absorbability [%m_d]	UPV Dry [m/s]	UPV Saturated [m/s]	Increase [m/s]	Increase [%m_d]
S6	12.1%	3101	3082	-19	-0.6%
S7	13.8%	3028	3070	42	1.4%
S8	13.7%	2887	2996	109	3.8%
S9	17.2%	2663	2863	200	7.5%
S10	16.5%	2611	2769	158	6.1%
S11	18.6%	2192	2634	442	20.2%
S12	18.1%	1630	1897	267	16.4%
S13	16.7%	1623	2157	534	32.9%
S14	21.3%	2204	2595	391	17.7%
				Average increase [%m_d]	11.7%

Based on this table, compensation of moisture effect to ultrasonic pulse velocity was set. Again, this compensation differs for rock groups. Igneous rocks do not require adjustment of UPV value, due to their minimal absorbability (which is up to 1 % of dry mass, based on measurements).

Second group are sandstones, compensation of UPV for them is based on data from table 3. Average increase of UPV was 11.7 %. According to this value, divisor of saturated UPV value to obtain UPV value for dry sample is set to value 1.1.

Third group are opuka rocks. Data for this group are also unavailable. As they are similar rocks to sandstones and measured UPV value is almost in the same extent, compensation was set same as for sandstones. Divisor of saturated UPV value to obtain UPV value for dry sample is set to value 1.1.

5 Practical part

Practical execution of sample testing was the most extensive part of this thesis. Quantity of rock samples were processed and certain procedures are described in this part. From beginning with getting samples and preparation to tests to the end with testing.

5.1 Extraction of rock samples

Majority of samples came from diamond core drilling, which was performed mostly on bridges and retaining walls. These samples were extracted during structure diagnostics survey, serving as background for preparation of reconstruction of these structures.

Procedure of core drilling requires lot of time, effort and experience. Diamond drilling rig was used. The diamond drilling rig consists of mount, engine and diamond drilling crown. At first, anchorage of drilling rig is necessary, as the drilling rig is heavy and generates high forces and moments (higher than man can hold, downforce may reach 2-3 kN). After the drilling rig is anchored to structure, water supply hose is connected (water cooling of drilling crown and removal of cut material) and drilling may start. Drilling requires experienced operator, especially in cases of very hard or inhomogeneous material, when the drilling must be carefully done.

After the drilling is done, core is pulled out from crown and marked (number and direction to the top of bore). This core is then stored in a box and ready for further handling.

Fig. 9 Extraction of sample using diamond core drilling at bridge near Louny (picture: M. Jonáš)

Two drilling rigs were used:

- HILTI DD 130
- HILTI DD 160

Few rock samples were made from paving setts. These setts were collected at two localities, Milovice (damaged old paved roads) and Dejvice, Praha (redundant setts).

5.2 Preparation of rock samples

Extracted cores were collected and stored in laboratories of Faculty of Civil Engineering, CTU. Selection was made and suitable cores were selected for further process of testing.

First step before testing was preparation of rock samples. Cores were cut in perpendicular direction on HILTI DS TS 20 diamond wall saw to make cylinder rock samples. Cutting was easy to perform, however it was necessary to obey safety instructions, as this job might be very dangerous. Cores were fastened to cutting table and cut was made by saw. Paving setts were cut from all sides, to make cubic rock samples. Cut sides of samples were not planar, so the adjustment of sides was needed, to make sides planar and parallel.

Fig. 10 Diamond saw cutting paving sett (picture: M. Jonáš)

Rock samples were therefore grinded on Formtest PSM 3/230 machine. Samples were fastened into grinder and grinding of one side was made. To grind the second side of sample, it had to be turned to the other side. Grinder is adapted for maximum parallelism of sides. Then the other side is grinded and rock sample is finished and ready for testing.

Fig. 11 Sample grinding (picture: M. Jonáš)

5.3 Accessory laboratory measurements

After the rock samples are prepared, few accessory measurements in laboratory are made. These measurements are: volumetric mass density ρ and water absorption A_b.

5.3.1 Volumetric mass density

Volumetric mass density is one of basic physical characteristics of materials. It is not a specific input for this thesis, but it was measured as an accessory parameter.

Weight of dry sample m_d is measured on scales, dimensions of sample are measured and volume V is evaluated. Volumetric mass density is then computed using following formula:

$$\rho = \frac{m_d}{V}$$

5.3.2 Water absorption

Water absorption or absorbability A_b was used for purpose of assessing moisture effect to ultrasonic pulse velocity measurement for sandstones and for compensation of moisture effect to measurement of ultrasonic pulse velocity and Schmidt hammer measurement.

Rock samples are dried in dryer at 70±5 °C to stable weight (difference from previous weighting 24 hours ago less than 0.1 % of weight) and then are weighted on scales, m_d value is found. Samples are then put into container, water access to sample from all sides is secured (putting on special grid) and water is added to submerge samples. Rock samples are submerged until stable weight is reached (difference from previous weighting 24 hours ago less than 0.1 % of weight). Samples are weighted to find saturated weight m_s and the experiment is evaluated using formula:

$$A_b = \frac{m_s - m_d}{m_d} * 100\%$$

5.4 Schmidt hammer measurement

Measurement of Q-value with Schmidt rebound hammer was performed in two typical situations. On site of core sample extraction or in laboratory on sample itself. Proceq SilverSchmidt L device was used.

Majority of measurements was performed outdoors, in time of extraction of sample. Q-value was always measured on the same stone block, from which was sample extracted. For one measurement, 9 impacts with hammer were done. Device evaluated measured values into one Q-value, which was recorded. For every rock sample, three measurements were made, average value was used. If the place of measurement was hardly accessible and measurement was dangerous (from ladder, few meter above ground), only two measurements were made.

Surface of rock had to be flat and without rough dirt. If is this was secured, measurement could had begun. If not, surface adjustment was necessary. For this purpose, surface grinding was done, then processed the measurement.

In case of sandstones and opuka rocks, Schmidt hammer measurements were performed without material moisture measurement. For this reason, measurement was repeated with moisture metering.

Fig. 12 Grinded rock surface prepared for measurement right next to borehole. Visible dots are caused by hammer impacts. (picture: M. Jonáš)

Few rock samples were not accessible from structure surface (rock blocks deeper in masonry), therefore Schmidt hammer measurement could not have been processed in situ. If the rock quality was high enough, measurement was processed in laboratory directly on rock samples. It required hard samples, that measurement could not damage, such as igneous rocks.

Laboratory measurement was performed by using load press. Rock sample was fastened into press, and loaded by uniaxial force, which could not have done any damage to sample (about 10 kN). Role of this force was to secure, that sample could not move. If the movement was possible, impact energy would dissipate and measurement would be useless. After the sample was fastened, two rebound hammer measurements were performed. Average value was used.

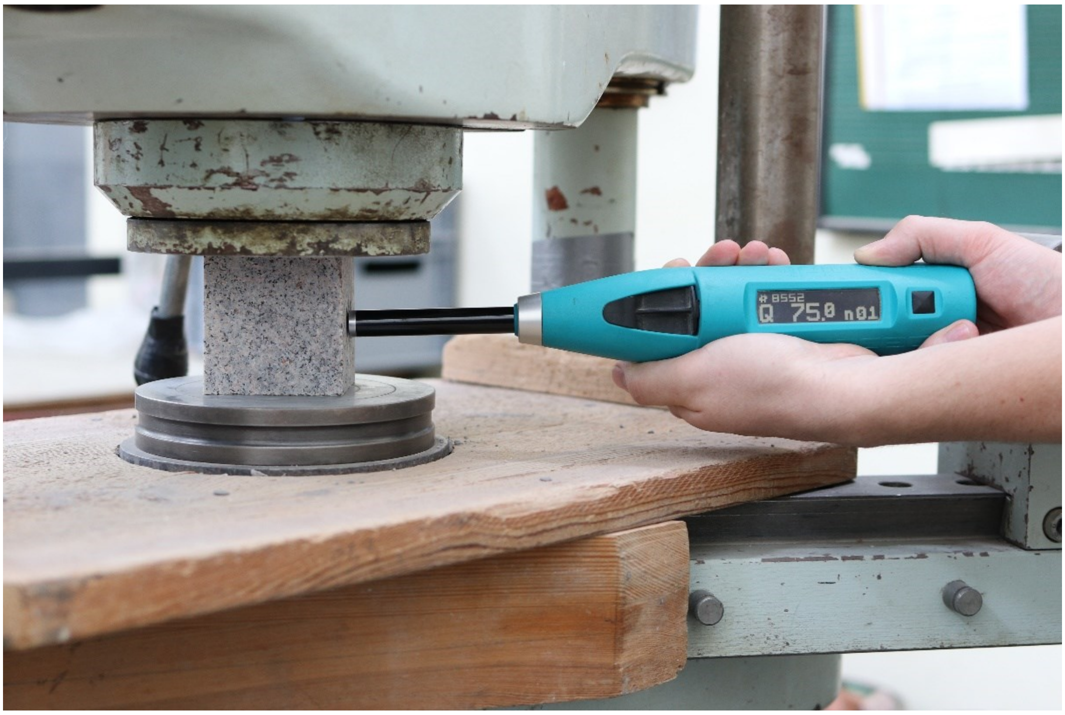

Fig. 13 Schmidt hammer measurement on rock sample fastened in press in laboratory (picture: M. Jonáš)

5.5 Ultrasonic pulse velocity measurement

Other laboratory measurement, essential for this thesis was ultrasonic pulse velocity (UPV) measurement. UPV was measured on dry or saturated samples. In case of part of samples on both dry and saturated samples, what was used for evaluation of moisture effect to measurement. For measuring, Proceq PunditLab unit was used.

Process of UPV measurement is quick and easy, but requires experienced observer, to detect measurement error. At first, device was calibrated. Length of sample was entered and ultrasonography gel was applied to the ends of sample. Then measurement could have been done. At least three measurements were made, if the result is stable, UPV value was recorded.

5.6 Material humidity measurement

Material humidity influences other measurements, therefore it was necessary to measure the moisture. These measurements were made only in situ, while samples in laboratory were dry or saturated only. Greisinger GMK 100 device was used. These measurements were processed only on opuka rocks and sandstones.

Humidity metering required flat surface, therefore gap between device and surface cannot be present. This gap could make the measurement useless. To adjust surface, portable diamond grinder was used. After the surface was adjusted, measurement began. Device was pressed against the surface and dragged to sides to detect the most reliable value. This value was then recorded and used for further processing.

Fig. 14 Surface grinding for humidity metering and Schmidt hammer measurement (picture: J. Zatloukal)

5.7 Unconfined compressive strength test

Following test of samples was destructive, therefore final, when unconfined compressive strength (UCS) was tested. These tests were performed in laboratories of Experimental Centre at Faculty of Civil Engineering, CTU. Two presses were used: VEB EU 40 and VEB EDB 400. VEB EU 40 was used for samples with lower compressive strength, which bore less than 400 kN in uniaxial pressure. VEB EDB 400 is high performance press, which can generate forces up to 4 MN, what stands for 400 tons. This press was used for samples with higher UCS, around 100 MPa or higher.

Before UCS test, it is necessary to obtain load area. Area of base of cylinder samples is computed from measured diameter. For cubic samples, area is computed from two dimensions of base. This area is considered as loading area, marked as A.

UCS test starts by putting dry sample into press. Loading plates have to be cleaned without rough dirt, which could discard the test. Sample must be situated into centre of loading plates, to secure only centric uniaxial pressure.

Fig. 15 Sample put in press before UCS test (picture: M. Jonáš)

Measurement is zeroed and sample is incrementally loaded until destruction. Force value at destruction is written down as F value. Then, the UCS is evaluated in MPa from formula:

$$UCS = \frac{F}{A}$$

This approach disregards size effect to unconfined compressive strength. Size effect should be considered into final result of UCS, however CSN EN 1926 [8], which is this UCS test based on, does not discuss size effect. It is due to certainly prescribed shape of samples. Adjustment according to size effect is regulated in standard CSN EN 12390-3 [9], which is regulating testing of hardened concrete. Size effect adjustment is derived for concrete samples, therefore cannot be used for rock samples, where size effect to UCS might be slightly different.

Fig. 16 Destructed sample after UCS test (picture: M. Jonáš)

6 Results

After extraction, preparation and testing of samples, results were evaluated. Results are divided into three sub-chapters according to used method, each sub-chapter is divided according to used rock types. As first, input values are shown for every method and rock type. Second, results are listed. Results are represented by calibration formula and graph, which were they evaluated from (except SONREB method).

6.1 Schmidt hammer method

Principle and process of calibration of Schmidt hammer method is described in chapter 3.2. For illustration, graph showing dependence between Q-value and UCS for all rock samples is shown. Relation between Q-value and UCS can be considered as exponential, what was discussed in chapter 3.2.1. This relation was not evaluated into calibration formula, it is listed only for illustration of relation between Q-value and unconfined compressive strength. Input values and results for every rock type are shown below.

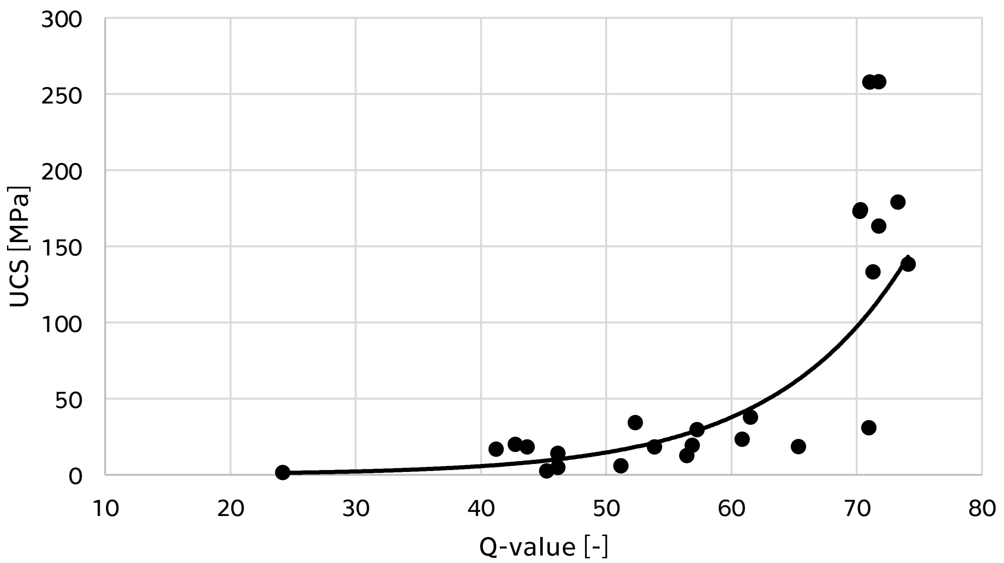

Fig. 17 Graph showing relation between measured Q-value and measured UCS on all samples together.

6.1.1 Igneous rocks

First evaluated group were igneous rocks. Compensation of moisture effect to measurement was unnecessary, therefore, humidity and absorbability are not listed. Then, Q-values were not adjusted.

Tab. 4 Input chart for igneous rocks. B - basalt, QD - quartz diorite, G - granite, GD - granodiorite, SY - syenite

Marking	Q-value [-]	UCS [MPa]
B1	71.0	258
QD1	71.8	163
QD2	71.8	258
G1	74.1	138
G2	70.3	174
G3	71.3	133
GD1	73.3	179
GD2	70.3	173
SY1	65.4	18.5
SY2	57.3	29.7

These values were plotted into graph of relation between Q-value and UCS, from which was relation formula evaluated. This formula is in form:

$$\widehat{UCS} = 5.60 * 10^{-3} * e^{0.143Q}$$

Coefficient of determination in this case is R^2=0.625. Amount of processed samples seems to be large enough to assess relatively reliable calibration relation. Measurement of UCS on samples is extremely sensitive to planarity and parallelism of loaded sides of sample. Some samples were destructed irregularly to standard [8], therefore these results were discarded and are not considered in data charts shown in thesis.

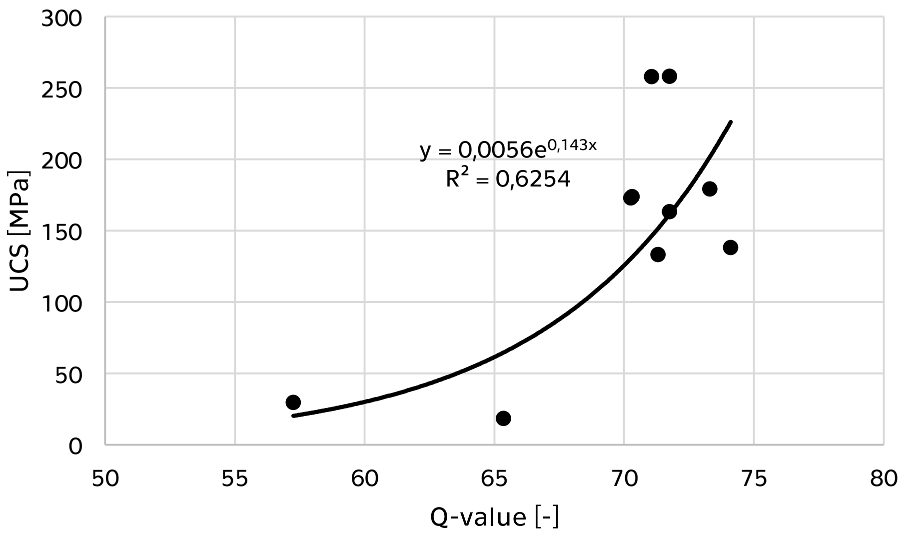

Fig. 18 Graph of relation between Q-value and UCS with evaluated relation. Used regression is exponential.

6.1.2 Opuka rocks

Second evaluated group were opuka rocks. Opuka rocks are rocks, where moisture can influence measurement, therefore compensation of moisture effect to measurement was necessary. Original Q-value, humidity and absorbability are listed. Q-values were adjusted according to approach described in chapter 3.2.

Tab. 5 Input chart for opuka rocks. O – opuka rock. Table shows data used for compensation of moisture effect to measurement and adjusted Q-value, which was subsequently used.

Marking	Q-value original	Humidity	Absorbability	Q-value adjusted	UCS
	[-]	[%m_d]	[%m_d]	[-]	[MPa]
O1	59.0	5.50%	6.43%	61.5	37.8
O2	52.2	4.20%	6.63%	53.9	18.4
O3	67.7	6.00%	6.14%	71.0	30.9
O5	43.7	0.00%	N/A	43.7	18.2
O6	41.2	0.00%	N/A	41.2	16.9

Evaluation of relation formula was made from graph of relation between adjusted Q-value and UCS. Evaluated formula is in form:

$$\widetilde{UCS} = 0.605 * Q - 8.39$$

Coefficient of determination in this case is R^2=0.639. Small amount of rock samples (only five samples) was processed, what influences accuracy of evaluated relation formula. However, R^2 reaches relatively higher value, thanks to linear division of values.

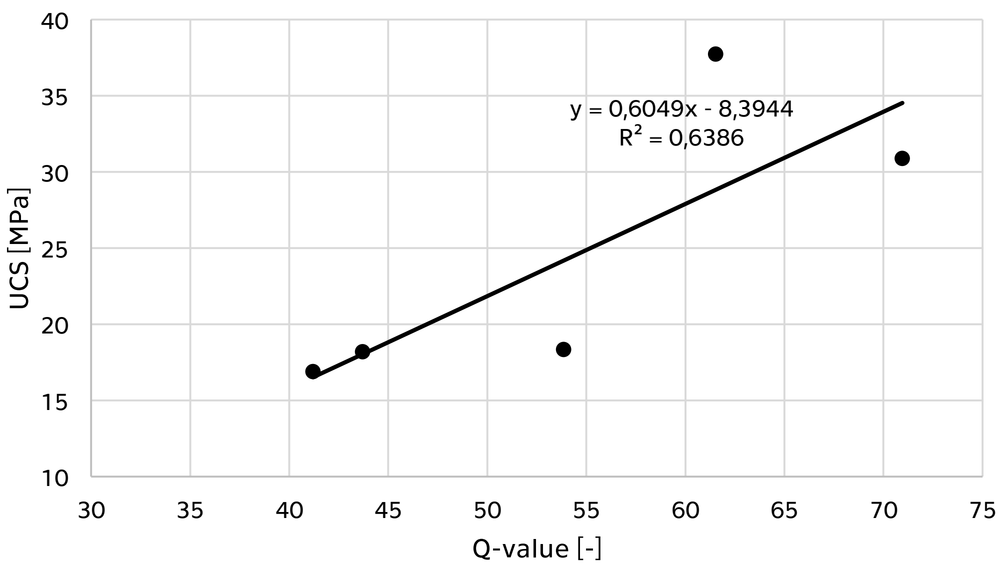

Fig. 19 Graph of relation between adjusted Q-value and UCS with evaluated relation. Used regression is linear.

6.1.3 Sandstones

Last evaluated group in Schmidt hammer method were sandstones. Sandstone might have very high absorbability (therefore humidity might be high too). Moisture can highly influence measurement, therefore compensation of moisture effect to measured Q-value was necessary. Original Q-values, humidity and absorbability are listed. Q-values were adjusted according to approach described in chapter 3.2.

Tab. 6 Input chart for sandstones. GR – greywacke, S – sandstone. Table shows data used for compensation of moisture effect to measurement and adjusted Q-value, which was subsequently used.

Marking	Q-value original	Humidity	Absorbability	Q-value adjusted	UCS
	[-]	[%m_d]	[%m_d]	[-]	[MPa]
GR1	42.8	0.00%	1.74%	42.8	19.9
S1	44.9	2.80%	14.7%	46.1	14.1
S2	44.9	2.80%	14.7%	46.1	4.90
S3	56.9	2.80%	5.98%	60.9	23.4
S4	52.6	4.50%	8.27%	56.9	19.3
S5	51.1	2.40%	14.7%	52.3	34.3
S6	52.8	5.50%	12.1%	56.4	12.7
S9	50.7	1.00%	17.2%	51.2	5.84
S12	23.8	2.10%	18.1%	24.2	1.46
S13	44.3	2.40%	16.7%	45.3	2.62

Same as for igneous rocks and opuka rocks, evaluation of relation formula was made from graph of relation between adjusted Q-value and UCS. Evaluated formula is in form:

$$\widehat{UCS} = 0.561 * Q - 13.2$$

Coefficient of determination in this case is R^2=0.299. Amount of processed samples is not small, but the variability of values is noticeable, therefore larger amount of samples should be processed. This variability is manifested in coefficient of determination, which reaches weak value and means lower reliability of result.

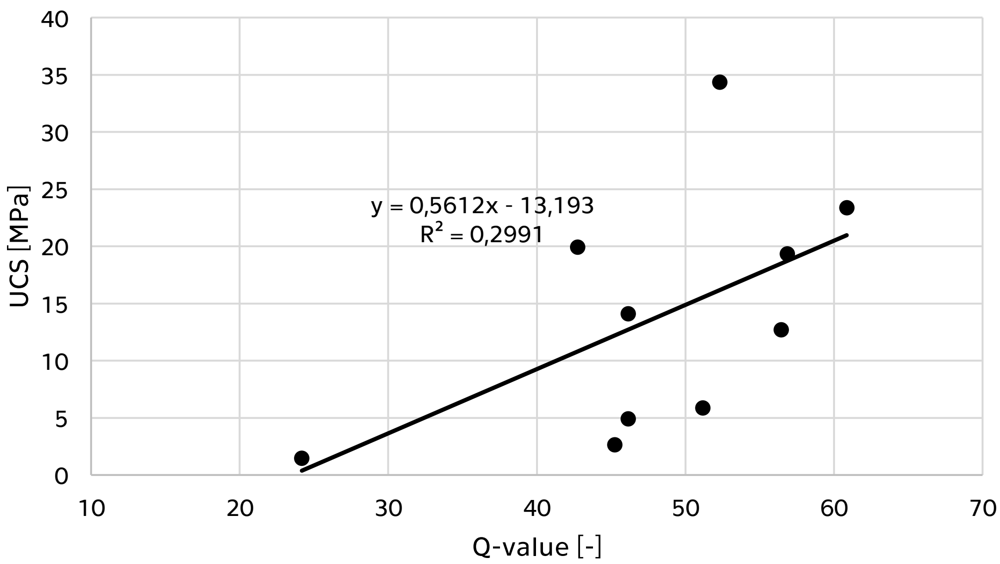

Fig. 20 Graph of relation between adjusted Q-value and UCS with evaluated relation. Used regression is linear.

6.2 Ultrasonic pulse velocity method

Ultrasonic pulse velocity method is based on relation between UPV and unconfined compressive strength. It's principle and process of calibration is described in chapter 3.3. Inputs and results are listed in following sub-chapters.

6.2.1 Igneous rocks

Calibration relation for igneous rocks was set using measured values of UPV and UCS at 10 rock samples. Samples were made of 5 different rocks from group of igneous rocks. UPV was measured on dry samples. However, if UPV was measured on wet samples, values would not vary a lot.

Tab. 7 Input chart for igneous rocks. B - basalt, QD - quartz diorite, G - granite, GD - granodiorite, SY - syenite

Marking	UPV [m/s]	UCS [MPa]
B1	5439	258
QD1	5698	163
QD2	5730	258
G1	5215	138
G2	5135	174
G3	5328	133
GD1	5130	179
GD2	4167	173
SY1	3510	18.5
SY2	3936	29.7

These values were input for graph of relation between UPV and UCS, from which was relation formula evaluated. This formula is in form:

$$\widetilde{UCS} = 0.0817 * UPV - 250$$

Data are distributed relatively evenly, therefore calibration can be considered as reliable, what confirms coefficient of determination, which is R^2=0.626. Relation can be seen in following graph.

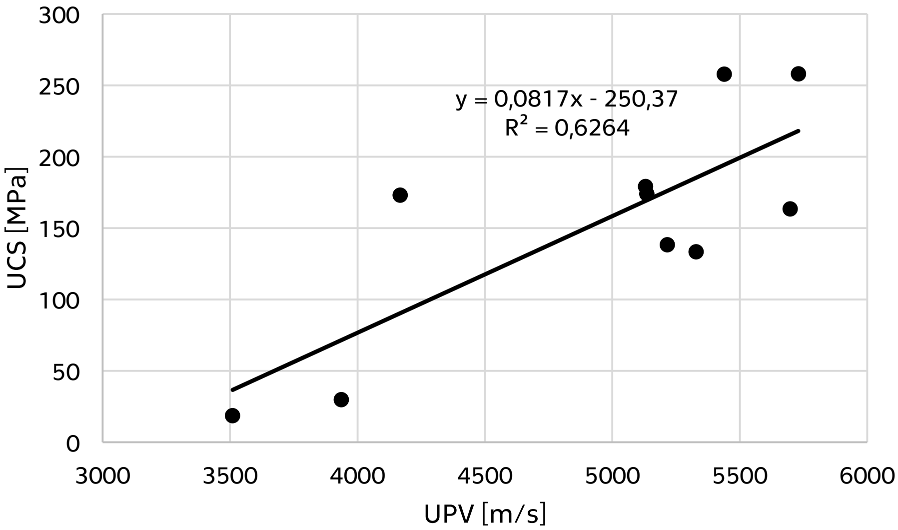

Fig. 21 Graph of relation between UPV value and UCS with evaluated relation. Used regression is linear.

6.2.2 Opuka rocks

Opuka rocks are second rock group in ultrasonic pulse velocity method. UPV was measured on dry or saturated samples. If UPV was measured on dry sample, this value would have been taken into evaluation. UPV values on saturated samples were adjusted according to approach described in chapter 3.3.

Tab. 8 Input chart for opuka rocks. O – opuka rock. Table shows UPV on dry samples, UPV on saturated and adjusted UPV-value, which was subsequently used.

Marking	**UPV dry sample** [m/s]	**UPV saturated sample** [m/s]	**UPV adjusted** [m/s]	**UCS** [MPa]
O1	N/A	3364	3058	37.8
O2	N/A	3345	3040	18.4
O3	N/A	3375	3068	30.9
O4	N/A	3246	2950	12.0
O5	2783	N/A	2783	18.2
O6	2694	N/A	2694	16.9

In tab. 8 are listed inputs into evaluation, adjusted UPV values and UCS values were considered. Relation between UPV and UCS is shown in graph at fig. 22. Evaluated calibration formula is:

$$\widetilde{UCS} = 0.0350 * UPV - 80.2$$

Coefficient of determination in this case is R^2=0.319. Only 6 samples were processed, what can highly influent accuracy of calibration formula. It is also obvious from weak value of R^2. Larger amount of samples should be processed.

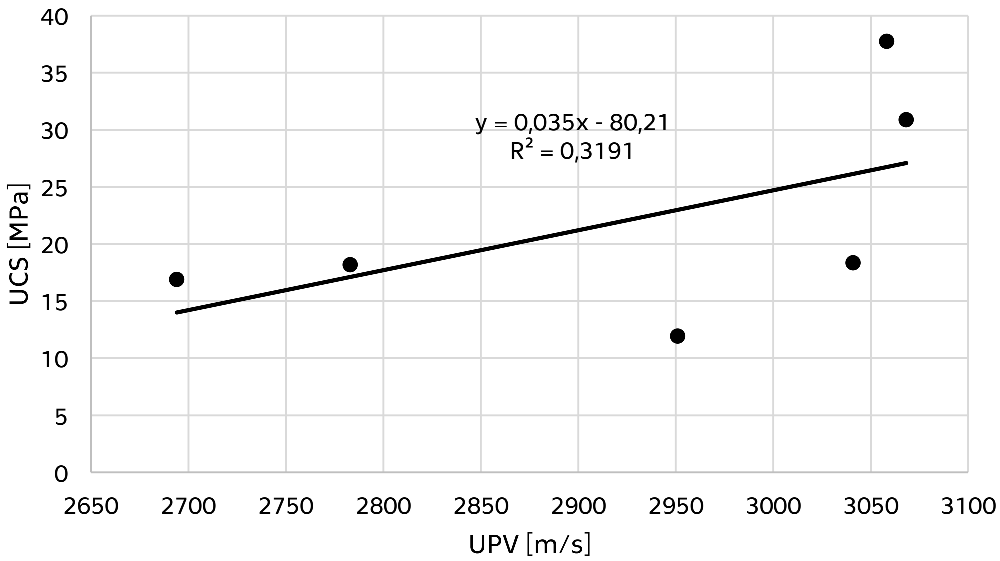

Fig. 22 Graph of relation between adjusted UPV value and UCS with evaluated relation. Used regression is linear.

6.2.3 Sandstones

Sandstones are last group of rocks in UPV method. Like opuka rocks, if UPV value measured on dry sample is unavailable, UPV on saturated sample must be adjusted. UPV values on saturated samples are adjusted according to approach described in chapter 3.3.

Tab. 9 Input chart for sandstones. GR – greywacke, S – sandstone. Table shows UPV on dry samples, UPV on saturated and adjusted UPV-value, which was subsequently used.

Marking	UPV dry sample [m/s]	UPV saturated sample [m/s]	UPV adjusted [m/s]	UCS [MPa]
GR1	N/A	3361	3055	19.9
S1	N/A	1881	1710	14.1
S2	N/A	1672	1520	4.90
S3	N/A	4199	3817	23.4
S4	N/A	3666	3332	19.3
S5	2746	N/A	2746	34.3
S6	3101	3082	3101	12.7
S7	3028	3070	3028	15.2
S8	2887	2996	2887	13.3
S9	2663	2863	2663	5.84
S10	2611	2769	2611	3.69
S11	2192	2634	2192	3.04
S12	1630	1897	1630	1.46
S13	1623	2157	1623	2.62
S14	2204	2595	2204	3.90

Data shown in tab 9. were used to assess calibration relation for sandstones using evaluation form graph (fig 23.) with UPV and UCS values. Evaluated calibration formula is:

$$\widehat{UCS} = 8.70 * 10^{-3} * UPV - 10.1$$

Coefficient of determination in this case is R^2=0.408. Fifteen rock samples were used, what had to secure more reliable result. Again, the coefficient of determination reaches lower value, therefore result might be not very reliable.

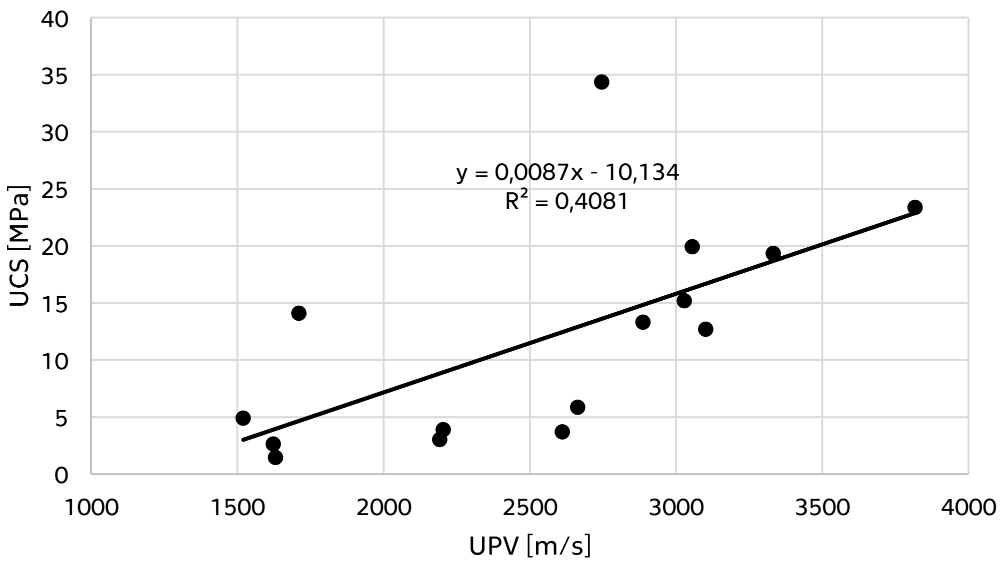

Fig. 23 Graph of relation between adjusted UPV value and UCS with evaluated relation. Used regression is linear.

6.3 SONREB method

Evaluation of SONREB method is using macro in Microsoft Excel from Proceq, manufacturer of Schmidt hammer and Ultrasonic pulse velocity tester. Due to high variability in order of coefficients, UPV is entered in km/s. Method is described in chapter 3.4.

6.3.1 Igneous rocks

In following table, input values for SONREB method are listed. Q-value and UPV did not have to be adjusted.

Tab. 10 Input chart for igneous rocks. B - basalt, QD - quartz diorite, G - granite, GD - granodiorite, SY - syenite

Marking	Q-value [-]	UPV [km/s]	UCS [MPa]
B1	71.1	5.44	258
QD1	71.8	5.70	163
QD2	71.8	5.73	258
G1	74.1	5.22	138
G2	70.3	5.14	174
G3	71.3	5.33	133
GD1	73.3	5.13	179
GD2	70.3	4.17	173
SY1	65.4	3.51	18.5
SY2	57.3	3.94	29.7

Calibration was evaluated in MS Excel macro. Result formula is in form:

$$\widetilde{UCS} = 1.87 * 10^{-8} * UPV^{3.21} * Q^{4.12}$$

Coefficient of determination in this case is R^2=0.798. Regression coefficient a is a=1.87*10^{-8}, what can raise questions, if this calibration formula can give us reliable results. It should be tested in praxis.

6.3.2 Opuka rocks

Input values for opuka rocks are listed in following table 11. Q-values and UPV were adjusted. Adjusted values are taken form tab. 5 and tab. 8, adjustment was done using approach described in chapter 3.4.

Tab. 11 Input chart for opuka rocks. O – opuka rock. Table shows only adjusted values, which were taken from chapter 6.1 and 6.2. These values were subsequently used.

Marking	**Q-value adjusted** [-]	**UPV adjusted** [km/s]	**UCS** [MPa]
O1	61.5	3.06	37.8
O2	53.9	3.04	18.4
O3	71.0	3.07	30.9
O5	43.7	2.78	18.2
O6	41.2	2.69	16.9

Calibration was evaluated and result formula is in form:

$$\widetilde{UCS} = 0.135 * UPV^{-2.04} * Q^{1.85}$$

Coefficient of determination is R^2=0.719, this value shows great correlation between used data and evaluated relation. However, small amount of samples means better coefficient of determination. Only five samples were used, therefore result can be unreliable.

6.3.3 Sandstones

Last evaluated group in SONREB method were sandstones, whose input values are listed in tab 12. Adjustment was done according to approach described in chapter 3.4., values are taken from tab. 6 and tab. 9.

Tab. 12 Input chart for sandstones. GR – greywacke, S – sandstone. Table shows only adjusted values, which were taken from chapter 6.1 and 6.2. These values were subsequently used.

Marking	Q-value adjusted [-]	UPV adjusted [km/s]	UCS [MPa]
GR1	42.8	3.06	19.9
S1	46.1	1.71	14.1
S2	46.1	1.52	4.90
S3	60.9	3.82	23.4
S4	56.9	3.33	19.3
S5	52.3	2.75	34.3
S6	56.4	3.10	12.7
S9	51.2	2.66	5.84
S12	24.2	1.63	1.46
S13	45.7	1.62	2.62

Calibration was evaluated and result formula is in form:

$$\widetilde{UCS} = 4.54 * 10^{-3} * UPV^{1.42} * Q^{1.67}$$

Coefficient of determination is R^2=0.661. Amount of processed samples might be large enough, result should be tested in praxis. Coefficient of determination shows higher value, correlation is therefore better than in Schmidt hammer method and UPV method.

7 Conclusion

According to available non-destructive tests, three methods of NDT assessment of unconfined compressive strength were calibrated. These calibrations were made for three defined rock groups (igneous rocks, opuka rocks and sandstones) for each method separately. A set of rock samples was processed to assess these calibration relations, according to certainly described approach.

Evaluated calibration relations might be used in engineering practice for assessment of rocks' compressive strength. Usage of these NDT methods should spare time and expenses, while the result should be relatively reliable. For assessment of UCS could be used only a Schmidt hammer measurement or ultrasonic pulse velocity measurement or combination of these two measurements into SONREB method. However, destructive UCS tests cannot be substituted, while none other exact simpler method exists.

Reliability of these relations is directly proportional to amount of tested rock samples. Less measurements are evaluated, reliability is lower. In three categories of rock types, various amount of samples was processed. While in igneous rocks amount seems to be sufficient and results seems to be usable, for opuka rocks it is disputable. In this category, only five (six for UPV method) samples were processed, therefore accuracy might be weaker. Group of sandstones was tested on 15 samples, but part of them was disengaged due to missing Schmidt hammer measurement (samples from deeper parts of structure, measurement could not be performed in laboratory due to low strength of material). However, variance of measured values on sandstones may be responsible for lower reliability of these relations.

For every rock group can be stated, that significantly higher amount of rock samples should be processed. However, acquiring of new samples in not a simple task. It requires objects, where samples could be extracted, time to process these extractions and also finances to pay expenses for these events. As a good option seems to be communication with Czech geologic survey, which could provide bigger amount of rock samples for purpose of calibration of NDT measurements of compressive strength.

Problem, which was met during measurements is moisture effect to measurements of UPV and Q-value. This problem is not very well described, only few partial researches were found about this problematic. Rather simple and easy tests could be made for specifying effect of material humidity to measurements. Again, amount of rock samples would be needed to measure on dry and wet samples and evaluating compensation of moisture effect.

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