ANISOTROPY OF MECHANICAL PROPERTIES OF GREYWACKE

Dagmar HAVLÍČKOVÁ, Martin ZÁVACKÝ and Lukáš KRMÍČEK
Brno University of Technology, Faculty of Civil Engineering, AdMaS Centre, Veveří 95, Brno, Czech Republic

e-mail: sujanska.d@gmail.com, zavacky.m@fce.vutbr.cz, krmicek.l@fce.vutbr.cz

ABSTRACT

The paper brings description of the mechanical properties of greywacke sampled in Kobeřice quarry (Lower Carboniferous Culm Basin, Drahany Uplands, Bohemian Massif). Anisotropy of mechanical properties was identified from series of laboratory tests of oriented samples using following procedures: (1) indirect tensile testing, (2) uniaxial compressive testing and (3) triaxial compressive testing. Parameters of Mohr-Coulomb and Hoek-Brown failure criteria were determined by evaluation of the obtained laboratory data. The tested greywacke performed relatively high uniaxial compressive strength, roughly 200 MPa. Better fitting by Mohr-Coulomb criterion was identified than by Hoek-Brown one within the investigated interval of confining stresses (0-15 MPa). In addition, Schmidt hammer test was carried out with comparison of several correlation relationships to uniaxial compressive strength which were compared with directly obtained value from laboratory tests.

Keywords: greywacke, uniaxial compressive strength, triaxial compressive strength, splitting tensile strength, failure criterion, Schmidt hammer, correlations

1 INTRODUCTION

Greywacke represents one of the most widespread rock types in Moravo-Silesian region of the Bohemian Massif. The rock is extensively mined in a number of quarries and used as a construction material. Therefore, it is important to know the mechanical properties of this rock type. Because of high strength typical for the focused rock type, slang expression of “Moravian granite” is often used in Moravia region as a name, despite the fact it is confusing from geological point of view.

Greywacke is a type of very compact (anchimetamorphic) sandstone with a matrix content of more than 15 %. The matrix material consists mostly of clay minerals, chlorite and silt. The sand-size grains correspond to quartz, feldspar, mica and rock fragments. Greywacke was formed in a marine environment in rapid subsiding basin. Greywacke rocks commonly alternate with layers of dark grey slates, argillites and conglomerates and typically occur together in thick sedimentary complexes. In the Bohemian Massif, they are mainly associated with deposition in Lower Carboniferous Culm basins in two main areas – the southern Drahany Uplands and northern Nízký Jeseník Mts. [1, 2] (Figure 1).

Material tested in our study was sampled in Kobeřice quarry, 10 km south from Prostějov (Figure 1). The rocks from this quarry are used for different construction applications, for example as aggregate in concrete. The base of the quarry is 230 metres above sea level. From the geological point of view, the studied area represents a tectonic fragment of Culmian rocks of Drahany Uplands, now located in the Carpathian Foredeep Basin of Miocene age.

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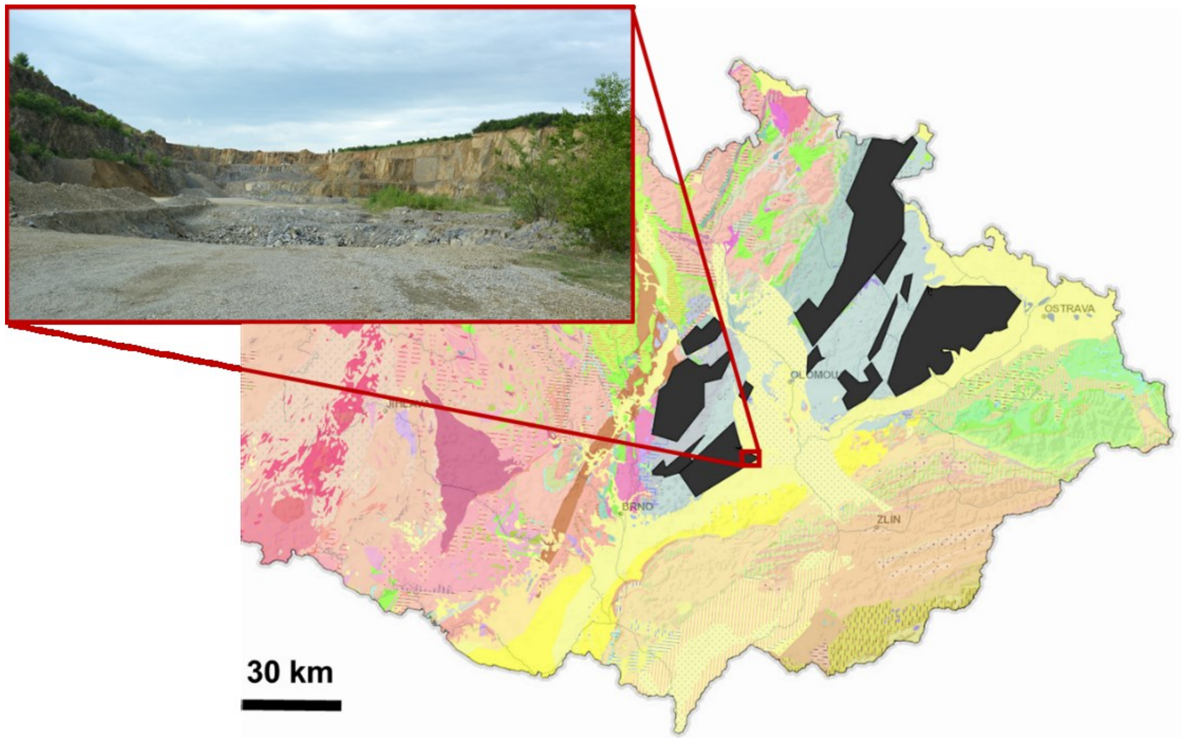

Figure 1. Geological map of the Czech part of the Moravo-Silesian region of the Bohemian Massif. Greywacke dominated lithologies are marked by black colour. Position of the studied Kobeřice quarry is highlighted by red square [3]

2 METHODS

Investigation of mechanical properties of the studied greywacke focused on the determination of the main parameters as tensile and compressive strength and shear failure parameters. Because of sedimentary origin of the rock, potential influence of bedding resulting in strength anisotropy was examined as well. Conducted testing program covered the following methods: Schmidt hammer test, splitting tensile test, uniaxial compression test and triaxial compression test. Specimens for laboratory testing were prepared by core drilling from irregular rock blocks sampled in the Kobeřice quarry. In order to avoid distortion of test results, weathered parts of the rock recognized close to blocks surface by brownish colour instead of grey - typical for fresh rock material in this case, were excluded from testing. Orientation of bedding planes was identified by flat fragments of the shales found in the rock.

Field testing of rock samples – blocks, was carried out by measuring of rebound hardness (using L-type Schmidt hammer). Series of 5 rebounds were conducted on each block. UCS was calculated from the obtained average rebound values using formula by Miller (1) [4] as well as using the formulas by Wang et al. (2) [5] and Yaşar and Erdoğan (3) [6]. The formulas (1) and (2) are considered as general for all rock types, while formula (3) was based on carbonate, sandstone and basalt rocks measurements.

$$\log_{10} UCS = 0.00088\, \rho R_L + 1{,}01 \tag{1}$$

where: *UCS* – uniaxial compressive strength [MPa]; ρ – unit weight [kN/m^3]; R_L – rebound hardness (average value for each block).

$$UCS = 4.52927\ e^{(0.05609 RL)} \tag{2}$$

$$UCS = 0.000004\ R_L^{\,4.29} \tag{3}$$

where: *UCS* – uniaxial compressive strength [MPa]; R_L – rebound hardness (L-type).

After preparation of regular shaped specimens, dry unit weight of the rock was calculated from measured volume and weight of the specimens. Splitting tensile test was carried out on 3 sets of specimens, each consisted of 5 pieces. Mutual orientation of bedding and imposed load during the tests is illustrated in Figure 2. Length to diameter ratio of the specimens was used in standard value of 0.5 with NX core diameter (54 mm) and load was applied in rate of 200 N/s [7].

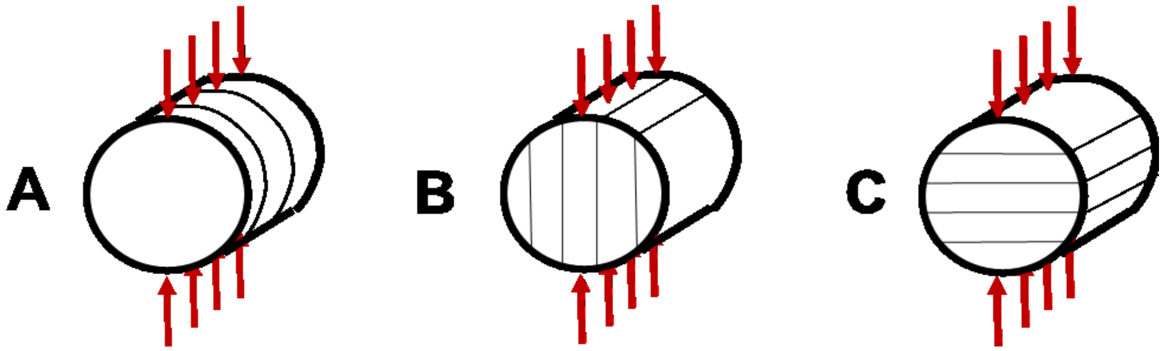

Figure 2. Orientation of imposed load on the specimens in consideration of bedding.

For uniaxial and triaxial compression tests were prepared cylindrical specimens with diameter of 38 mm and length to diameter ratio 2:1. Orientation of bedding in specimens for uniaxial tests is noted in the meaning: 0° – bedding planes parallel with specimen's axis and applied load; 90° – bedding planes perpendicular to specimen's axis and applied load. Uniaxial compression tests were carried out with inclination of bedding planes: 0°; 30°; 45°; 60°; 90° respectively and set of three specimens were tested in each case. Triaxial compression tests were conducted on three specimens with confining stresses: 5; 10 and 15 MPa respectively. More homogenous rock without visible bedding from the same locality was used in this type of test because of a limited amount of oriented samples. Additional uniaxial compression test was carried out on the same rock without obvious bedding planes for more consistent evaluation of failure criteria parameters. Axial load was applied in rate of 1.0 MPa/s during both testing procedures. In case of triaxial tests, confining stress was applied by Hoek cell with isotropic conditions up to required amount of the confining stress and then only axial load was increased until failure. Results from the triaxial tests were analysed in order to obtain parameters of failure criteria – Mohr-Coulomb (4) (MC) and Hoek-Brown (5) (HB) [8]. Determination of the parameters was done by the author's spreadsheet calculation according recommendations in [8].

$$\tau = c + \sigma \tan \varphi \tag{4}$$

where: τ – shear stress; c – cohesion; σ – normal stress; φ – friction angle.

$$\sigma_1 = \sigma_3 + \sigma_{ci} \left(m_i \frac{\sigma_3}{\sigma_{ci}} + s \right)^a \tag{5}$$

where: σ_{ci} – uniaxial compressive strength; m_i, s, a – empirical material constants.

3 RESULTS

The values in Table 1 are divided into two groups, with the designation "X", where the homogeneous finer Greywackes were measured and with the designation "II" for the coarser rock with the determined orientation of the layers. Average results of measuring Schmidt hammer (L-type) rebound hardness (RL) for "X" type of greywacke range from 45 to 56 with the average value 50, standard deviation 4 and coefficient of variation 8 % calculated as standard deviation divided by average. This corresponds to UCS values from 116 to 209 MPa according formula (1), 57 to 105 MPa according formula (2) and 49 to 126 MPa according formula (3). Values of rebound hardness of the second group noted "II" range from 43 to 48 with the average value 46, standard deviation 2 and coefficient of variation 4 %. This corresponds to uniaxial compressive strength values from 104 to 136 MPa according formula (1), 51 to 67 MPa according formula (2) and 41 to 65 MPa according formula (3). Value of dry unit weight used in the formula (1) was 2660 kg/m3 determined from prepared specimens for further laboratory tests.

Table 1. Average results of rebound hardness (R_L) and calculated UCS according to formulas described above. Note: "X" - finer Greywackes; "II" - coarser greywacke.

"X" samples	R_L [-]	UCS [MPa]		
		Miller (1)	Wang (2)	Yasar Erdogan (3)

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KO-X-01	51	160	79	85
KO-X-02	45	116	57	49
KO-X-03	46	122	60	54
KO-X-04	51	160	79	85
KO-X-05	53	178	89	100
KO-X-06	49	144	71	71
KO-X-07	48	136	67	65
KO-X-08	56	209	105	126
"II" samples	**R_L [-]**	**UCS [MPa]**		
		Miller (1)	**Wang (2)**	**Yasar Erdogan (3)**
KO-II-01	48	136	67	65
KO-II-02	46	122	60	54
KO-II-03	47	129	63	60
KO-II-04	43	104	51	41
KO-II-05	48	136	67	65

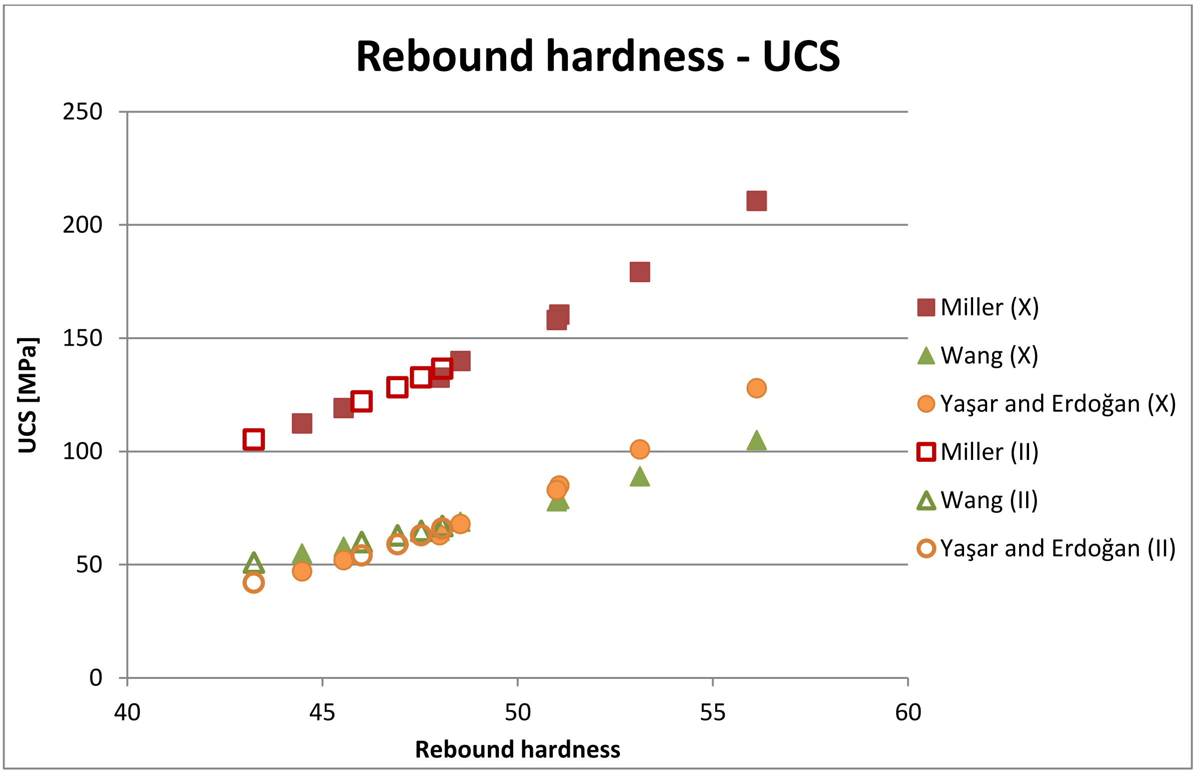

Figure 3. Dependence of the values of the Schmidt hammer (L-type) rebound hardness and estimated uniaxial compressive strength according to the formulas – Miller (1); Wang (2); Yasar and Erdogan (3). The data from each formula are marked with one colour, and they are grouped according to finer "X" and coarser "II" greywacke types, with marks to make clear the differences between fine grained and coarse-grained rock.

Results from splitting tensile tests (STT) are listed in Table 2. Average value of the strength, standard deviation and coefficient of variation were determined for each series of the test. Bedding orientation case "A" performed the highest strength, while orientation case "B" the lowest one. Variation of the results was relatively low in all cases; thus, the results could be considered as homogenous. The dependence of the STT on bedding orientation can be observed in Table 2.

Table 2. Tensile strength of greywacke determined by splitting tensile tests. Note: A,B,C – symbols of bedding orientation (Figure 2); Var – coefficient of variation (Std/Average).

Test type	Splitting tensile strength [MPa]					Average [MPa]	Std [MPa]	Var [%]
STT A	14.6	15.2	15.5	15.3	13.6	14.8	± 0.8	5
STT B	12.5	11.0	12.1	11.2	12.7	11.9	± 0.7	6
STT C	14.6	13.8	13.9	14.4	12.8	13.9	± 0.7	5

Uniaxial compressive strength (UCS) was tested on 5 sets of specimens, each consisted of 3 pieces, with different orientation of bedding to loading direction. Purpose of such testing was to investigate the influence of bedding on the strength of the rock. Results from the tests are plotted in Figure 4 where bedding orientation is on the horizontal axis and UCS is on the vertical axis with labelled average values for each orientation. Influence of the bedding on reached average UCS can be recognized where the highest strength was obtained in case of 90° orientations and the lowest UCS in orientation of 30°. Variability of the results is the highest in cases of 45° and 60°. Hence, the average values contain a considerable amount of uncertainty.

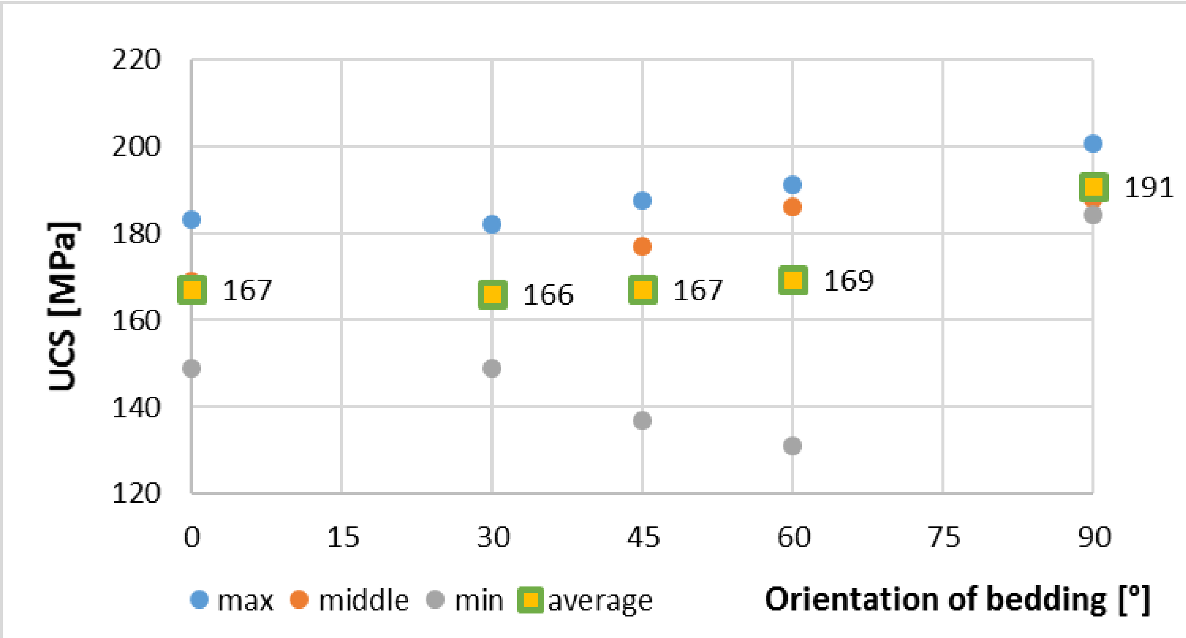

Figure 4. Influence of bedding orientation to UCS. Note: 0° means bedding planes parallel with applied loading.

Analysis of shear strength of the intact rock was done on a more homogenous type of greywacke from the same locality, where triaxial compression test was employed added by uniaxial compression test in order to widespread input data sets. Reached peak values of the main principal stress are in Table 3.

Table 3. Results from triaxial tests.

σ_3 [MPa]	0	5	10	15
$\sigma_{1,max}$ [MPa]	201	219	243	275

From the results in Table 3 we determined the values of MC and HB failure criteria parameters, which are outlined in Table 4. Fitting method of least squares was employed with error (sum of squares) for MC – 49 and for HB – 75. In case of HB criterion (see formula 5) were considered material constants s = 1.0 and a = 0.5 as it is typically used in case of intact rock [8]. Moreover, Table 4 contains extrapolated value of tensile strength, which was determined by HB criterion. Results of triaxial tests and plots of the both failure criteria are drawn in Figure 5. Tension cut-off was applied on MC criterion to avoid unrealistic overestimate of the tensile strength. Particular value of the strength limit was applied based on HB prediction of tensile strength in this case.

Table 4. Determined values of parameters for MC and HB failure criteria. Note: c – cohesion; φ – friction angle; σ_{ci} – uniaxial compressive strength; m_i – empirical material constant; $\sigma_{t,ext}$ – extrapolated tensile strength.

Mohr-Coulomb		Hoek-Brown		
c [MPa]	φ [°]	σ_{ci} [MPa]	m_i [-]	$\sigma_{t,ext}$ [MPa]
44.1	41.8	197	8.86	22

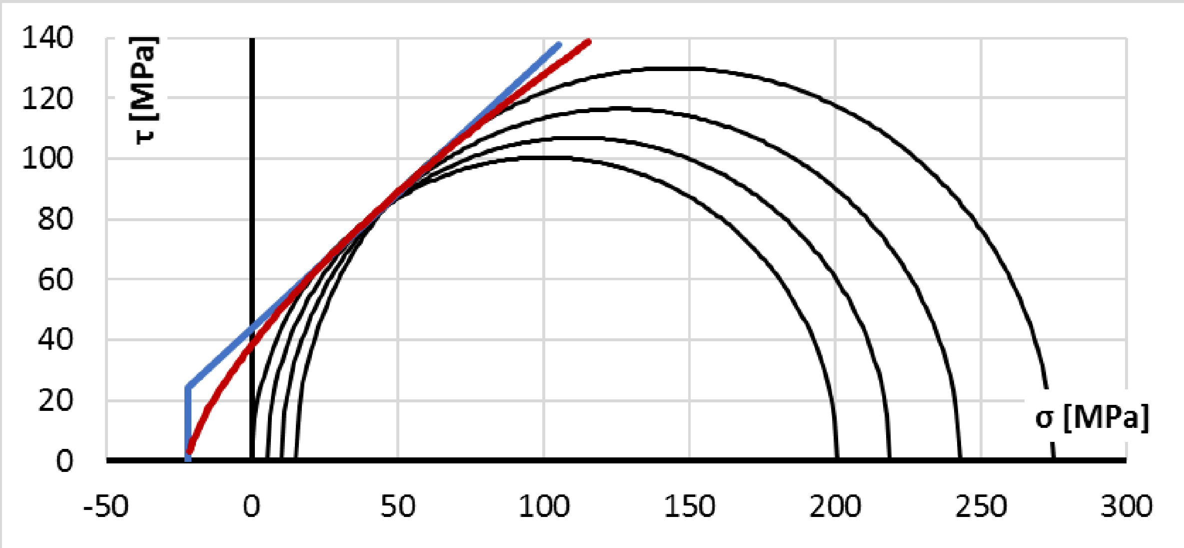

Figure 5. Plot of MC (blue) and HB (red) failure criteria in normal and shear stress coordinates. Result of each triaxial test is plotted by Mohr's circle.

4 DISCUSSION

Regarding the UCS values obtained using three different equations calculating with the R_L values, the one from Miller (1) [4] seems the most appropriate, while the newly derived equations from Wang et al (2) [5] and Yaşar and Erdoğan (3) [6] show significantly underestimated values.

We can see the differences in values of rebound hardness and UCS on fine-grained rocks "X" and coarse-grained rocks "II". The average value of R_L is 50 for "X" and 46 "II", the average UCS values obtained by equation (1) is 152 "X" and 125 "II". That means the fine-grained material is more compact and it performed also a slightly higher value of UCS than the coarse-gained rock. Considering larger grains contained in one group of the samples, another possible reason of rebound values variability can be found. Certain grains of minerals and original rock fragments can have lower hardness. Due to their larger dimensions within the impact area, the rebound value can be more affected by individual grain properties.

Tensile strength of the rock indicated dependence on mutual bedding and loading orientation during STT. Results from the testing showed relatively low variance, thus appreciable level of reliability has been reached (see Table 2). However, the extrapolated value of tensile strength by HB criterion (22 MPa) is roughly 50% overestimated when compared to the highest experimental result in case of "STT A". This could be explained by two reasons: some uncertainty in estimations always appears; the rock used for HB criterion was not influenced by bedding which usually decreases strength.

UCS obtained in tests focusing on strength anisotropy (see Figure 4) is 5% lower than UCS obtained in purpose of shear strength investigation (see Table 3). The reason could be the same as discussed above – absence of bedding in the second case. Estimate of UCS by HB criterion was 197 MPa, which means deviation of only 2%. UCS dependence on bedding orientation can be noticed according to the plot in Figure 4. The lowest strength was obtained in case of 30°, which is in accordance with previous publications, but the overall trend is not so clear [9], [10].

Regarding the shear strength of the rock and failure criteria evaluated based on triaxial tests, MC criterion performed better fitting (sum of squares 49) than HB criterion (sum of squares 75). This statement is probably correct only in a certain range of confining pressure (0-15 MPa investigated in this study). In tension area overestimating of strength by MC criterion (see Figure 5) appears and in case of high confining stresses more plastic behaviour should appear, thus the non-linear fitting should be better [11]. If we compare UCS of the rock and maximal applied confining pressure, only 7% of UCS was reached. There are technical limits as load capacity and loading frame stiffness of the employed testing equipment, and on the other side relatively high strength rock, which did not allow to approach the plastic behaviour region of the rock.

5 CONCLUSION

Greywackes as significantly widespread rock type in Moravo-Silesian region have been investigated in this study. Attention was paid to mechanical properties of the rock sampled in Kobeřice quarry with focus on strength anisotropy. The following conclusions can be drawn based on the obtained laboratory data:

- Influence of bedding on the strength anisotropy was identified in case of coarse-grained type of greywacke according to the results of uniaxial compression tests and splitting tensile tests.
- M-C failure criterion showed more appropriate fitting of the results obtained by triaxial tests within 0-15 MPa range of confining pressure than H-B criterion.
- Three previously published correlation relationships between Schmidt L rebound and UCS have been compared. The best prediction of UCS was obtained by Miller's correlation (1). However, all the correlations significantly underestimated the directly determined UCS of the studied rock.

Greywacke from only one locality was investigated within the presented study. Petrological variations of the rock are known within Moravo-Silesian region; thus, mechanical properties of the rock can be also variable. Hence, comparison of mechanical properties of the rock type from other localities could be interesting.

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REFERENCES

[1] VOZÁROVÁ, A. *Petrografia sedimentárnych hornín (Petrography of sedimentary rocks)*. Bratislava: Univerzita Komenského, 2000. ISBN 80-223-1427-7.

[2] VÁVRA, V. Multimediální atlas hornin (Multi-media atlas of rocks) [online], The Faculty of Natural Sciences of Masaryk University in Brno, 2013 [cit. 2018-08-30]. Available from: http://atlas.horniny.sci.muni.cz/index.html.

[3] ČGS, Mapové aplikace – Geovědní mapy 1:500 000 [online], [cit. 2018-08-30]. Available from: https://mapy.geology.cz/geocr500/

[4] MILLER, R.P. *Engineering classification and index properties for intact rock*. Urbana: University of Illinois. 1965. PhD Thesis.

[5] WANG, H. et al. Correlation of UCS Rating with Schmidt Hammer Surface Hardness for Rock Mass Classification. *Rock Mech Rock Eng.* 2017, 50, pp. 195–203

[6] YAŞAR, E. and Y. ERDOĞAN. Estimation of rock physicomechanical properties using hardness methods. *Eng Geol.* 2004, 71, pp. 281–288. DOI: 10.1016/S0013-7952(03)00141-8

[7] ULUSAY, R. and J.A. HUDSON. The Complete ISRM Suggested Methods for Rock Characterization, Testing and Monitoring: 1974-2006. Ankara: ISRM Turkish National Group. 2007. DOI:10.2113/gseegeosci.15.1.47

[8] HOEK, E. and E.T. BROWN. Practical estimates of rock mass strength. *International Journal of Rock Mechanics and Mining Sciences.* 1997, vol. 34, No 8, pp. 1165-1186. DOI: 10.1016/S1365-1609(97)80069-X

[9] GOODMAN, R.E. *Introduction to rock mechanics*. New York: Wiley, 1980. ISBN 0-471-04129-7.

[10] SALCEDO, D.A. Macizos Rocosos: Caracterización, Resistencia al Corte y Mecanismos de Rotura. In: *Proc. 25 Aniversario Conferencia Soc. Venezolana de Mecánica del Suelo e Ingeniería de Fundaciones*, Caracas. 1983, pp. 43-172.

[11] BEWICK, R.P. and P.K. KAISER. Discussion on "An Empirical Failure Criterion for Intact Rocks'' by Peng et al. (2013). *Rock Mechanics and Rock Engineering*. 2014, vol. 47, No 2, pp. 817-823.