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Textural rock anisotropy as a result of load memory exemplified by Cergowa sandstones from Komańcza

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To a large extent, geomechanical rock massive properties depend on the tectonic regime within the region. The stress influence has its result inside rock in the distribution of anisotropy. The anisotropy indicator is, for instance, a directional cracking caused by pre-existing microcracks present inside the rock sample. These microcracks were initiated by paleostresses related to the Carpathian Mountains upthrust period. The investigations were made in order to find a correlation between the orientation of joint sets and the variability of the mechanical properties of flysch rocks.

Key words: joints, stress, anisotropy, longitudinal wave, transverse wave, tensile strength

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INTRODUCTION

From the mechanical point of view, rocks are non-homogeneous, discontinuous and anisotropic materials. Their structure and texture developed as a result of complicated sedimentation and diagenesis processes, and quite frequently these processes occurred stage-like. Besides structural and textural factors, anisotropy was also significantly influenced by the local tectonical regime which, depending on load layout and intensity, triggers either visible joints or a weakening of the internal structure. During the further relaxing or under a load, both features can become visible as cracks analogous to the joint sets. This fact is of a special importance because, even in a seemingly isotropic rock sample, the strength parameter values to be determined can vary largely depending on the testing direction.

Joint sets are groups of fractures, which are serial, penetrative, geometrically arranged, and spaced at least several centimetres from each other. Joint set surfaces are perpendicular to the bottom and top of the layer in which they are located (Mastella, 1972; Jaroszewski, 1972; Dadlez, 1994; Dune, Hancock, 1994). In the Outer Carpathians, which are flysch mountains, joint sets are the visible traces of historical stress fields created as a result of compression (horizontal compression mainly), which was related to the overlapping of nappes.

Tests were made to prove, by means of tensile strength and ultrasonic defectoscopy methods, the existence of spatial defects, microscracks causing a directional tensile strength reduction and a directional ultrasonic wave attenuation, as well as to prove that the orientation of these weakened zones is the same as the orientation of joint sets determined *in situ*.

Summary of geological structure

The rocks selected for the tests are Cergowa Sandstones of the Dukla unit. They were obtained from a well-known exposure located within a non-operating quarry at the Komańcza town in the Beskid Niski Mountains (Figs. 1, 2).

The group of sandstones accompanied with Cergowa Shales as well as the lower cherty sandstone series, Sub-Cergowa Marls, and menilite shales are ascribed to menilite layers. The term of Cergowa Sandstones was introduced by H. Teisseyre (1930) for a complex of thick-layered sandstones within menilite shales. The most complete profile thereof is seen in the edge part of the Dukla unit, and it is the biggest thickness thereof in the edge fold next to town of Wisłok Wielki (300 m) and in the so-called Pete's fold (350 m). The sandstone thickness reaches 200 and even 250 metres next to the town of Komańcza (Ślączka, 1971).

The Cergowa Sandstones from the Komańcza quarry were selected for tests due to their very well developed joints as well as because these rocks are homogeneous from the lithological and petrographic points of view and macroscopically anisotropic with respect to their texture.

Methodology of field tests and laboratory tests

Laboratory tests were preceded by observations and the measuring of joints in sandstone layer outcrops in the quarry. Angles were measured within ± 2°. Nearly 100 joint surfaces were measured. The crack analysis was made with the application of common rules for joint statistics (Mastella, Konon, Mardal, 1996).

Figure 3 shows diagrams of joint set position dominants. The joint sets show a high extent of orientation constancy. Two

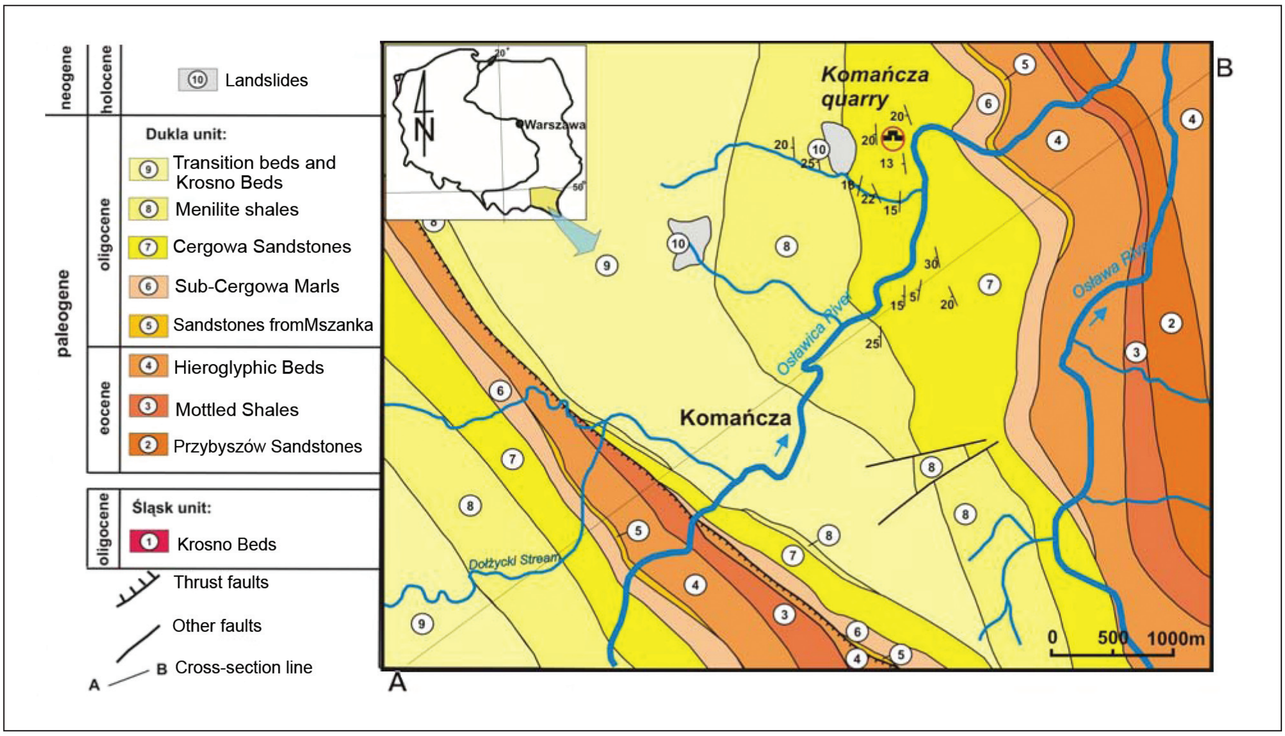

Fig. 1. Geological map of Komańcza (A. Ślączka, 1971, amended)

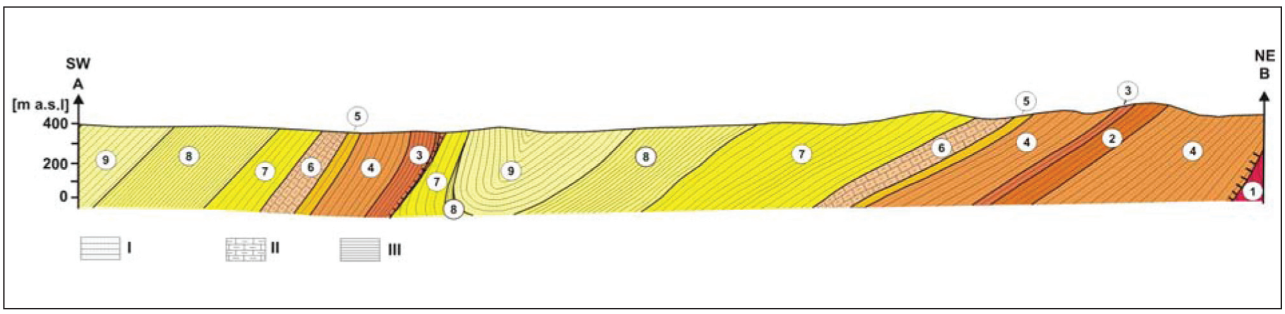

Fig. 2. Geological cross-section along the A–B line. I – sandstones, II – marls, III – shales; for the other terms, see Fig. 1 (A. Ślączka 1971, amended)

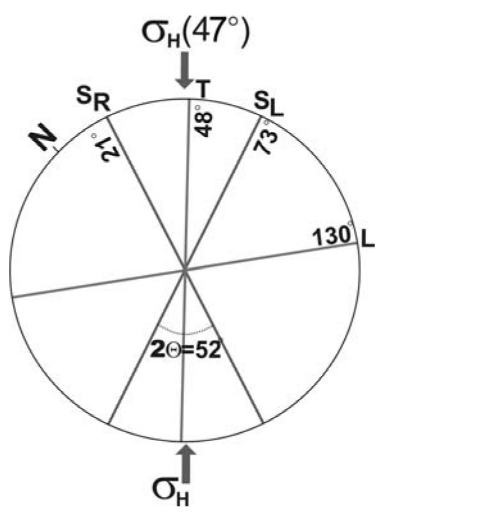

Fig. 3. Diagram of joint set dominants: S_R and S_L – slant sets; *T* – transverse set; *L* – longitudinal set; σ_H – axis direction for the highest compression; 2Θ – double shear angle

of the joint sets (S_R, S_L) are slant to the axes of folds in which they are located; the *T* set is nearly perpendicular to the axis of these structures, whereas the *L* set is nearly parallel to a varied extent. The acute angle between the S_R set and S_L set is called the double shear angle (2Θ). The bisector of this angle marks the position of the maximum compression axis, σ_H (Bucher, 1920, 1921; Ramsay, Huber, 1987) and has a nearly constant direction. Its average orientation in the Cergowa Sandstones from Komańcza is equal to 47°.

The rock monoliths selected for geomechanical tests were strictly oriented with respect to the main compression directions in the tri-axial field $\sigma_H > \sigma_V > \sigma_h$ under assumption of shear origin for S_R and S_L cracks (Dunne, Hancock, 1994; Mastella, Zuchiewicz, 2000). Besides, it was assumed (after Boretti-Onyszkiewicz, 1968) that in rocks with evident cracks (joint sets), hidden surfaces of easier division also exist. These hidden surfaces were memorised by the rock and are the initial origins for cracks featuring a spatial orientation similar to that of joint sets.

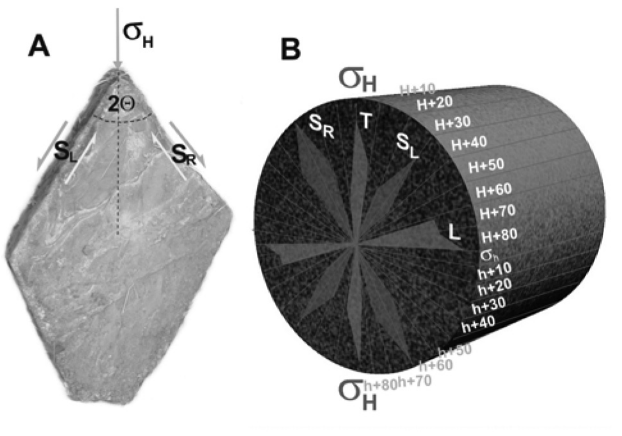

Fig. 4. *A* – monolith separated from the layer along surfaces of S_R and S_L joint sets. Marked features: displacement direction sense, double shear angle (2Θ), maximum compression axis direction σ_H; *B* – the designed measuring directions marked on a sample cut out from a monolith against a diagram of joint set orientation as determined *in situ*

In the rock monolith, the maximum compression axis, σ_H, was determined based on the bisector of the acute angle between S_R and S_L joint sets (Fig. 4A). The σ_H and σ_h compression axes are horizontal components, they are at right angle to each other. From the monolith, all samples were cut out in the direction complying with the σ_V axis (top–bottom). In total, 96 cylindrical oriented samples were prepared, each 5 cm in height and 5 cm in width. The number of samples used for tests was 90. In each sample, eighteen plane directions were marked in relation to the stress axis and to the joint set. The planes were oriented every 10 degrees. For this operation: σ_H – the plane parallel to the highest compression axis, H + 10 ÷ H + 80 – planes oriented stage-like; each next plane is inclined by 10 degrees more towards σ_H; σ_h – the plane parallel to the minimum compression axis, h + 10 ÷ h + 80 – planes oriented stage-like; each next plane is inclined by 10 degrees more towards σ_h (Fig. 4B). The longitudinal wave velocity was measured along each of the 18 directions; these were the forced failure plane directions as in tensile strength tests.

Ultrasonic test methodology. The applied methodology consisted in measuring the ultrasonic wave velocity in the sample along the directions as described above. Tests were made employing a Unipan UMT-12 defectoscope with Ultramet software, and fitted with 1 MHz test heads. As assumed in ultrasonic defectoscopy, any microcracks located at right angle or slant towards the ultrasonic beam at a specific angle attenuate or entirely eliminate the wave passage pulse which normally is present in a defect-free area. Therefore, defectoscopy is a very valuable tool which facilitates recording not only the microdefects, but also their spatial position in a sample. This fact allows to correlate the microcrack orientation with directions of the evident cracks observed *in situ*. On the other hand, the non-destructive character of this method provides for test repeatability.

Tensile strength test methodology. Samples were investigated by tensile strength tests (R_r) using the Brazilian method. For this method, when a cylindrical sample is loaded with a force at a right angle to the sample axis, the sample cracks along a plane which includes the cylinder axis; the cracking process is mainly caused by tensile forces. Therefore, this method is capable of modelling the processes that refer to the creation of joints because, after such tests, the obtained crack surfaces are extensive separation cracks genetically identical with cracks of the S_R and S_L sets which became evident as extension joints, though they were originated with a participation of shear forces (Dunne, Hancock, 1994; Mastella, Zuchiewicz, 2000).

The tests were made with the application of the MTS 815 testing system according to the procedure applied for rock behaviour and strain tests (Pinińska, 1994; 1995; 2003). Each sample was located in the testing machine so that the orientation of the forced-failure planes obtained after the test were compliant with the directions of the designed planes. In total, 90 samples were tested (5 samples for each of the 18 determined planes). Each sample was mounted in special brackets which facilitated locating the force application points directly above each other in one plane. Samples underwent loading with a constant load increment of 60 kN/min.

TEST RESULTS

Ultrasonic tests. A clear relation was observed between the measuring direction and the longitudinal and transverse wave velocities. This relation is graphically illustrated in A and B diagrams (Fig. 5) for average velocity values.

The highest longitudinal velocity values (V_p) are observed for the directions H + 30, h + 60 and H + 80 (Fig. 5A). These directions are related to the value intervals associated with joint sets, respectively S_L, S_R, L. The clear dependence, visible in the diagram, means that the rock samples feature an acoustic anisotropy which shows up as a longitudinal wave differentiation depending on the metering direction. In directions complying with the joint set directions, in particular S_L and S_R (and L to a lesser extent), the longitudinal wave (V_p) undergoes a significantly weaker dampening (i. e. reaches higher velocity values). In case of the transverse wave (V_s), there is also a visible relation between the wave velocity and the measuring direction (Fig. 5B). Due to the transverse character of the wave, with material particles oscillating at a right angle to the wave propagation direction, it is just the presence of microdiscontinuities with their surfaces located in space in the same directions as the joint sets, which causes a stronger attenuation of the wave in those directions.

The very clear relation allows to draw a conclusion that visible cracks spotted *in situ* have their analogs also on the microscale, in a seemingly isotropic sample, in the shape of sets of microcracks the spatial orientation of which can be approximated as certain planes, and the directions of those planes comply with the directions of the apparent joint sets.

Tensile strength. Like the longitudinal wave velocity, strength depends on the measuring direction (load orientation) to a varied extent. The lowest strength (R_r) values were obtained for the forced-failure planes the orientation of which complied with the orientation of the joint sets S_L (H + 30), S_R (h + 60), and L (H + 80). Therefore, tensile strength tests indicated that the Cergowa Sandstone strength differentiation depends on load direction (Fig. 6).

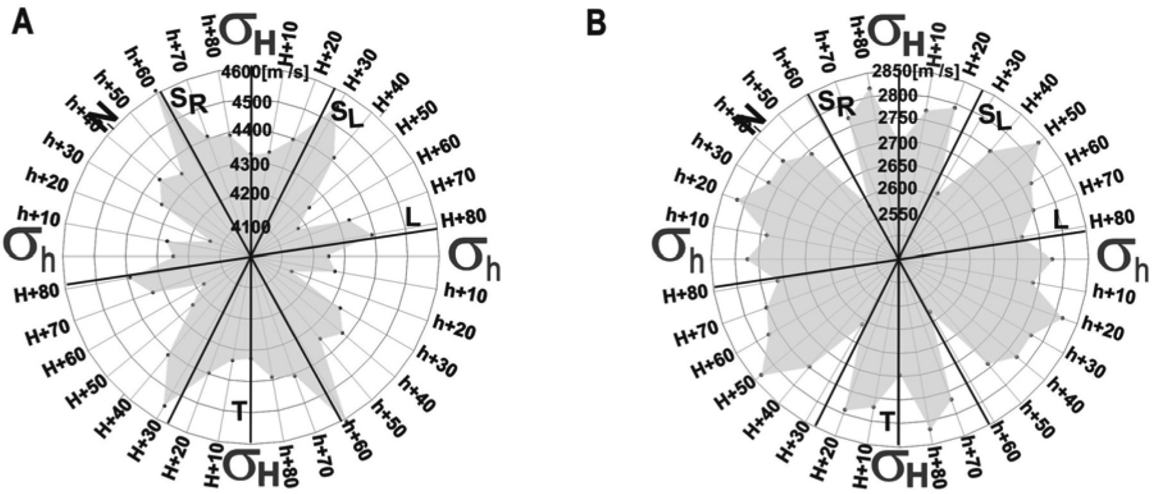

Fig. 5. Diagrams of velocity distributions for longitudinal wave (*A*) and transverse wave (*B*) depending on measuring directions against joint set dominants determined *in situ*

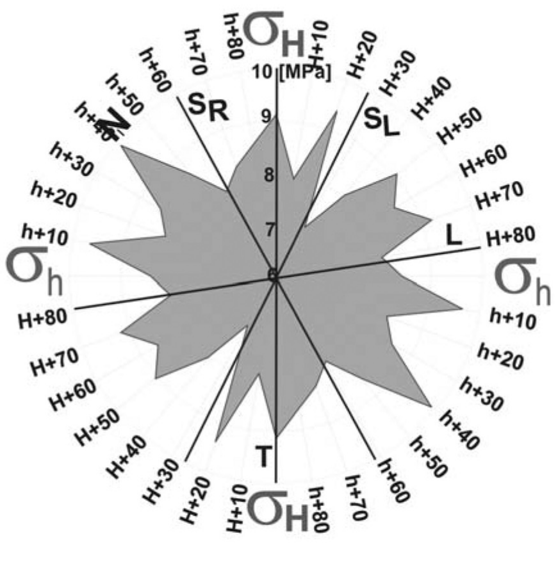

Fig. 6. Diagram of tensile strength (R_r) distribution versus the orientation of the forced-orientation plane

Thus, test results indicated that a higher crack susceptibility exists along the directions that comply first of all with the joint sets (S_R and S_L) and also with L.

CONCLUSIONS

A conclusion can be drawn from the lab tests that a strong anisotropy is present in the samples. The strongest factor for this anisotropy was the operation of the historical stress field. The field composition as recreated based on the surface orientation measuring for joint sets *in situ* finds its analog – on a sample scale – in the shape of spatially oriented weakenings, and is a sort of texture resulting from the defects (microdiscontinuities) accumulated in selected planes. This fact was confirmed by defectoscopy which has shown that the strongest longitudinal wave dampening takes place when the measuring directions are not the same as the joint area directions, i. e., in the case when the wave pulse directions are perpendicular or slant (at varied angles) to those planes. However, when the longitudinal wave direction is parallel to the planes featuring the same directions as directions of the joint set surfaces S_R, S_L and L, the dampening is at its weakest. An opposite relation is valid for the transverse wave: the strongest dampening occurs when the measuring directions are the same as the directions of S_R, S_L, L joint surfaces.

A similar correlation has also been noted for the tensile strength value distribution. The lowest R_r values are related to the forced-failure planes that have the same directions as the joint sets (S_R, S_L, L), thus clearly indicating the presence of weakened areas in the internal structure (sets of microdiscontinuities). Most probably, these spatially-oriented areas of easier division are joints in their initial stage, i. e., joint origin in the higher stress zone, and are responsible for the current anisotropy of the mechanical properties of the rocks.

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KOMANČNOS RAJONO „CERGOVSKIO“ SVITOS SMILTAINIO TEKSTŪRINĖ ANIZOTROPIJA − APKROVOS ATMINTIES REZULTATAS

Santrauka

Geomechaninės uolienos masyvo savybės priklauso nuo regiono tektoninio režimo. Tektoniniai įtempiai sukelia uolienų anizotropiją, pasireiškiančią kryptingu sutrūkinėjimu, t. y. mikrosuaižėjimu. Mikrosuaižėjimas siejasi su įtempiais, atsiradusiais Karpatų raukšlėjimosi procese. Panaudojant ultragarso defektoskopiją tempiamojo stiprio bandymu (braziliškas metodas) įvertinta mikrosuaižėjimo orientacija bei vidinės sandaros susilpnėjimo kryptys. Susilpnėjimo kryptys yra palygintos su matomais įtrūkiais uolienų atodangose.

Andrzej Domonik

ANIZOTROPIA TEKSTURALNA SKAŁ UWARUNKOWANA PAMIĘCIĄ OBCIĄŻENIA NA PRZYKŁADZIE PIASKOWCÓW CERGOWSKICH Z KOMAŃCZY

Streszczenie

W pracy przedstawiono wyniki badań nad wpływem paleonaprężeń na aktualny stan masywu skalnego. Na podstawie analizy wyników badań ustalono iż właściwości mechaniczne zbadanych skał w dużej mierze zależą od reżimu tektonicznego w regionie. Oddziaływanie naprężeń odzwierciedla się w postaci anizotropii właściwości geomechanicznych. Anizotropia przejawia się między innymi kierunkowym pękaniem powodowanym przez pierwotne mikrospękania obecne w próbce skalnej. Mikrospękania wywołane są paleonaprężeniami związanymi z wypiętrzaniem się Karpat. Określono przestrzenną orientację mikrospękań za pomocą defektoskopii ultradźwiękowej jak również kierunkowe osłabienia budowy wewnętrznej próbek skalnych za pomocą testów wytrzymałości na rozciąganie metodą brazylijską. Orientacja tych osłabień porównana została z kierunkami jawnych spękań ciosowych określonych w terenie.

Анджей Домоник

ТЕКСТУРНАЯ АНИЗОТРОПИЯ ПЕСЧАНИКОВ СЕРГОВСКОЙ СВИТЫ КОМАНЧНОВСКОГО РАЙОНА КАК РЕЗУЛЬТАТ ПАМЯТИ НАГРУЗКИ

Резюме

Геомеханические свойства массива пород зависят от тектонического режима региона. Воздействие тектонических напряжений определяет анизотропию пород, что вызывает направленную трещиноватость, которая в образцах породы проявляется микрорастрескиванием. Последнее явно связано с напряжениями, возникшими в процессе карпатского складкообразования. С помощью ультразвуковой дефектоскопии в процессе испытаний на растяжение (бразильский метод) установлена ориентация микрорастрескивания и направления ослабленности внутреннего строения пород. Направления ослабленности сопоставлены с наблюдаемыми нарушениями в обнажениях пород.