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Structural control on fracture toughness (brittle cracking) in the Krosno Sandstones of Mucharz, southern Poland

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The fracture toughness of the Krosno Sandstones of Mucharz, southern Poland, was analysed to determine, its relation to structural features of the rock, in particular as regards their orientation relative to the direction of the load applied. The critical stress intensity factor for fracture toughness K_{IC} was determined according to the rarely used chevron bend method, as recommended by the International Society for Rock Mechanics (ISRM). Tests were carried out at constant load increase, equal to 15 kN/min.12 sandstone specimens, cut out in three mutually perpendicular directions from 4 cubical rock blocks, were analysed. The mutually perpendicular failure planes, obtained in this way relate to structural features of the rock material, making it possible to evaluate the effect of structure on the fracture pattern of the rock analysed. Toughness tests were preceded by measurements of propagation ultrasound waves and analysis of dynamic features that enabled preliminary determination of the rock anisotropy. The research elucidated the structural controls on the fracture toughness of the Krosno Sandstones.

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INTRODUCTION

The quantitative description of changes occurring within fractured material as a result of external, mechanical or thermal factors, is one of the most important goals of rock mechanics. Permanent failure of the structure takes place as a result of increases in discontinuity surfaces, and it is important to determine the relation between the maximum permissible stress and the length and location of cracks (ISRM, 1988). This relationship has become widely recognised and analysed with regard to many artificial materials: metals, plastics, ceramics, and concrete (Ouchterlony, 1989), though it has been less studied in rocks. It can potentially play an important role in research into rock strength, however, since traditional laboratory methods do not provide a full spectrum of rock features with regard to strength and strain.

Rocks are inhomogeneous, quasi-continuous media with many, often small defects, which are the areas of stress concentration when external forces are applied (Griffith, 1920). When their boundary values are exceeded, crack growth occurs, which may lead to material failure due to fracture. Based upon the rock characteristics and the mode of operation of the external factors, we can distinguish brittle, plastic, quasi-brittle and fatigue fracture.

Quasi-brittle fracture, which is the main factor causing failure of rock material, is usually preceded by minor, permanent plastic strain. Elastic strains that precede fracture are significantly greater and they cause the creation of two congruent failure surfaces (Gustkiewicz, 1997). However, plastic strain should be taken into consideration, since its scale varies, depending upon the characteristics of a given rock.

The variable character of the internal rock structure can cause variability of the fracture process, depending upon the direction of load applied. The rock structure, which is a result of diverse processes of formation and diagenesis, significantly influences behaviour of the material under the influence of external forces. Archival results of rock strength tests show a significant diversity of parameter values. This diversity may reflect a variability of structural features, such as bedding or directionality in the arrangement of mineral grains. Segregation of specimens into groups with different orientations of structural fea-

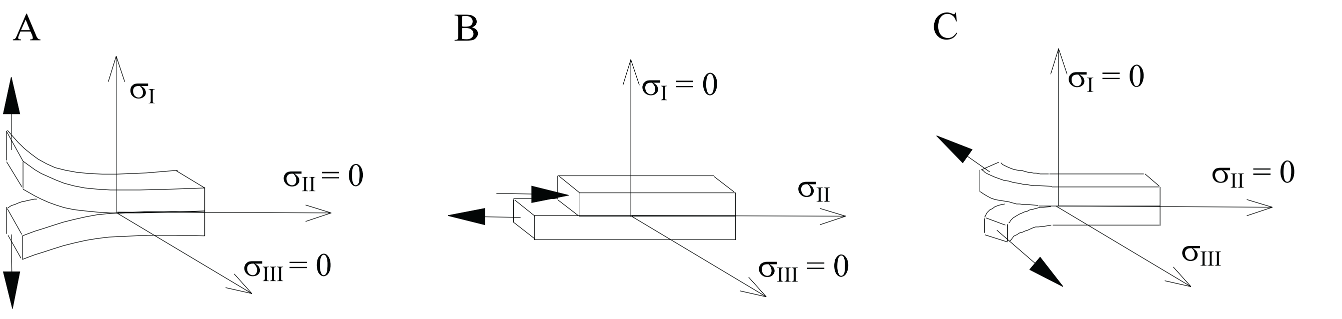

Fig. 1. Main components of stresses: σ_I — tension, σ_{II} — direct shear, σ_{III} — pure shear; occurring in places of their concentration: A — tension, B — direct shear, C — pure shear

tures in relation to the load applied rarely took place prior to strength tests. Strength tests performed on series of specimens of a given material are supposed to determine its resistance, but this can undergo quite significant changes.

At the propagating crack front, three main failure mechanisms can be distinguished: tension, direct shear and pure shear, with corresponding stresses: σ_I, σ_{II}, σ_{III} (Fig. 1). As the supplied energy increases, the crack front moves, following the emerged stress concentration field (Pinińska, 1995), measured by stress intensity factors. Their critical values, defined as: K_{IC}, K_{IIC}, K_{IIIC} provide the quantitative description of the material brittle fracture toughness and can be treated as constant values for this material.

According to Irvin's criterion, work needed for advancement of the crack by a given surface is equal to:

$$\sigma\Gamma = G \cdot \sigma_s$$

where: $\sigma\Gamma$ — fracture work needed to create crack surface σ_s; G — energy in crack front with regard to surface unit.

G energy stream is a function of stresses σ_I, σ_{II}, σ_{III} that are created around the crack edge and strain characteristics of rock material, described by Young's modulus and Poisson's ratio, while stress intensity factors indicate the stresses, and therefore it is possible to define the energy stream as:

$$G = \frac{1-\nu^2}{E}\left(K_I^2 + K_{II}^2\right) + \frac{1+\nu}{E} K_{III}^2$$

where: ν — Poisson's ratio; E — Young's modulus.

When the energy stream exceeds the critical value, the crack advances. Thus the stream value (G_c) can be described as:

$$G_C = \frac{1-\nu^2}{E}\left(K_{IC}^2 + K_{IIC}^2\right) + \frac{1+\nu}{E} K_{IIIC}^2$$

where: ν — Poisson's ratio; E — Young's modulus; K_{IC}, K_{IIC}, K_{IIIC} — indicators of brittle fracture toughness, respectively: for tension, direct shear and pure shear.

Determination of values of brittle fracture toughness indicators is very significant when attempting to fully describe the rock features with regard to toughness and strain. In laboratory conditions, various research methods are used. One of them is the chevron bend method, based upon the bending of a cylindrical specimen with an initial notch in a special yoke (ISRM, 1988; Dziedzic, 1999). The V-shaped initial notch is supposed to concentrate stress around the top and to cause propagation, ideally perpendicular to the direction of the load applied. This allows creation of a state of stress, in which tension stress (σ_I) — dominates. Such conditions make it possible to determine, through experiment, K_{IC} the indicator of brittle fracture toughness for tension.

Using this method, fracture toughness tests were performed on specimens of Krosno Sandstone, taken from Górka-Mucharz quarry, located in the eastern part of the Beskid Mały Mountains (Fig. 2). The objective of research was to determine the influence of the structural features of a rock to its resistance

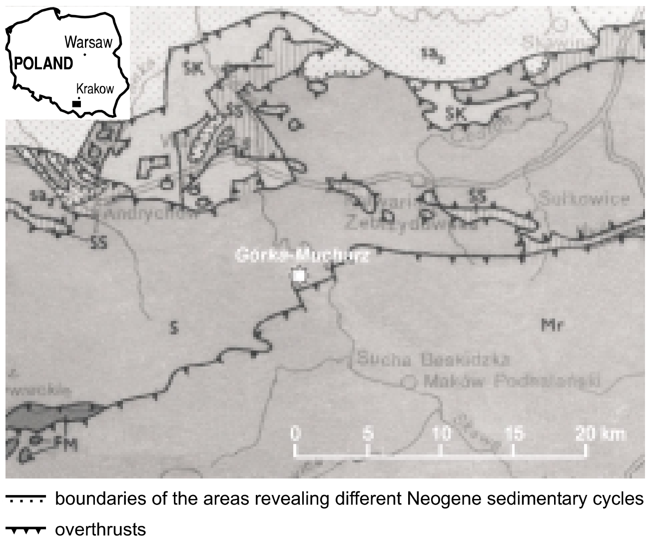

Fig. 2. Location of the Górka-Mucharz quarry on the map of Poprawa and Nemčok (1988–1989)

SK — Skole unit, SS — Sub-Silesian unit, SB — Silesian-Baška unit, S — Silesian unit, FM — Fore Magura unit, Mr — Magura unit (Racza sub-unit), sa_2 — areas of Early Badenian marine molasse sedimentation to tension, as well as to determine the anisotropy of this phenomenon. A level 1 research variant was applied, that is, the tests were performed at constant load increase, equal to 15 kN/min, measured at the same time as the opening of the propagating crack.

MACROSCOPIC DESCRIPTION AND PETROGRAPHIC ANALYSIS

The tested specimens were taken from roughly cubic rock blocks, supplied from the quarry, with side lengths of approximately 30 cm (Fig. 3). the necessary dimensions for valid testing. ISRM instructions (1988) state that the diameter of a sample must be at least 10 times more then maximum size of grains. The maximum observed length of quartz grains was 3 mm for samples from Mucharz. Therefore, the optimal sample size was evaluated as 5cm in diameter and 20 cm in length.

These samples were cut out, taking into consideration the macroscopically determined structural features. The Krosno Sandstones from Górka-Mucharz quarry form part of a Silesian nappe. Tectonic effects of this are seen as strong cracking showing various trends. Książkiewicz (1972) named this zone the Sawa dislocation, where there are many transverse depressions. This tectonic characteristic has a strong influence on stress distributions and fracture toughness. Effects of displacement and discontinuities are observed at macro-, meso-, and microscales. The Krosno Sandstones near Mucharz can be subdivided lithologically. Książkiewicz (1951) identified two units and Moroz-Kopczyńska (1976) four, with different proportions of shale. The Krosno Sandstones are fairly monotonous in mineral composition, but are strongly variable in texture. Mineral gically they are greywackes and wackes. Textural variants irregularly thick-bedded sandstones; thin-bedded and parallel-bedded sandstones; and convolute or cross-bedded sandstones. The porosity of the sandstones relates grain packing and textural type (Pinińska, 1980).

Fig. 3. Cubic blocks of Krosno Sandstones from Mucharz

Table 1

Mineral composition of Krosno Sandstones from Mucharz according to the classification of Pettijohn *et al*. (1972)

Building element		Content [%]	
3 minor elements	quartz grains	67	77
	micas	17	
	fragments of other rocks	16	
matrix	clay-carbonate bond	24	23
	other components (mainly feldspars)	6	

The Krosno Sandstones from Górka-Mucharz quarry are Oligocene in age. The rocks exploited comprise coarsely bedded (0.5–10 m) strata, of the lower, of the two Krosno units of Książkiewicz (1972), and of "complex II" of Moroz-Kopczyńska (1976).

In hard specimen the rock shows quartz, feldspar and mica grains in a calcareous cement. There is clear lamination, emphasised by dark iron compounds. There is some preferred orientation of mineral grains: in observation of polished sides of the cube using a binocular microscope, this lamination is clearly visible in two sides, but on one of them the elements that emphasize it are longer. On the third side, there is no lamination visible, but we can observe glistening quartz and feldspar grains, with cross sections much larger than along the other two sides. These structural features allowed determination of a plane, parallel to lamination, serving as a basis for determination of failure surface in toughness tests (Fig. 4).

Petrographic analysis confirmed the macroscopic observations with regard the weak preferred mineral orientation, to particularly picked out by feldspars and opaque minerals. The cement comprises clay minerals and calcium carbonate with fine quartz grains, and the overall sorting is good. There are minor lithic grains of metamorphic and carbonate rocks. The grains are slightly rounded, indicating minor transport. Sporadic grains of glauconite indicate local early diagenesis. The rock typically shows numerous intergranular fractures, as well as non-rebuild fractures in quartz grains. A > 15% content of fine matrix (quart, feldspar and other grains) indicate that these rocks belong to the wacke group (Table 1). According to Pettijohn's classification (Pettijohn *et al*.,1972) it is a moderately granular lithic or arkose wacke.

METHODICAL GUIDELINES

As mentioned previously, the research methodology assumed performance of fracture tests in three, mutually perpen-

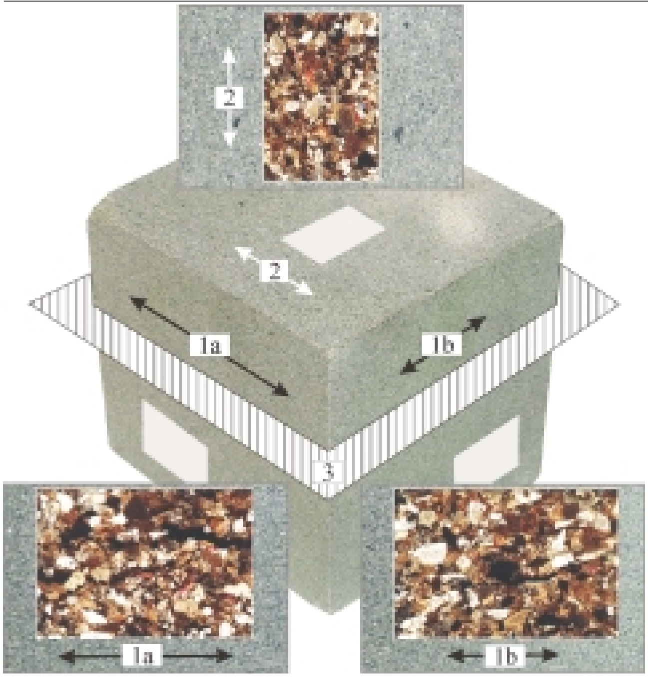

Fig. 4. Macroscopic and microscopic image of three mutually perpendicular sides with marked structural elements: 1a, b — elements emphasizing lamination (the size of arrows symbolises the difference in their length), 2 — direction of arrangement of longer mineral axes, 3 — marked of lamination surface

dicular planes. The failure surfaces thus obtained may be related to structural features and enable monitoring of the fracture process. In accordance with the assumptions made, three mutually perpendicular fracture planes were specified, together with related directions of measurement of ultrasound wave speed (Fig. 5). Adequate symbols for marking of specimens, failure planes and directions of measurement ultrasound waves were adopted:

— failure planes: H — parallel to lamination, Vr — perpendicular to lamination and parallel to the longer mineral axes, Vp — perpendicular to lamination and perpendicular to the longer mineral axes,

— specimens: s-V — cut out perpendicular to H plane, s-Hr — cut out perpendicular to Vp plane, s-Hp — cut out perpendicularly to Vr plane,

— directions of measurement of ultrasound waves (main: k-V — perpendicular to lamination, k-Hr – parallel to lamination and parallel to the longer mineral axes, k-Hp – parallel to lamination and perpendicular to the longer mineral axes; auxiliary: k-Ha, k-Hb — measurements in H plane, k-Vra, k-Vrb — measurements in Vr plane, k-Vpa, k-Vpb — measurements in Vp plane).

The cycle of laboratory research included ultrasound tests, aimed at preliminary determination of the anisotropy of the rock material, and the actual toughness tests.

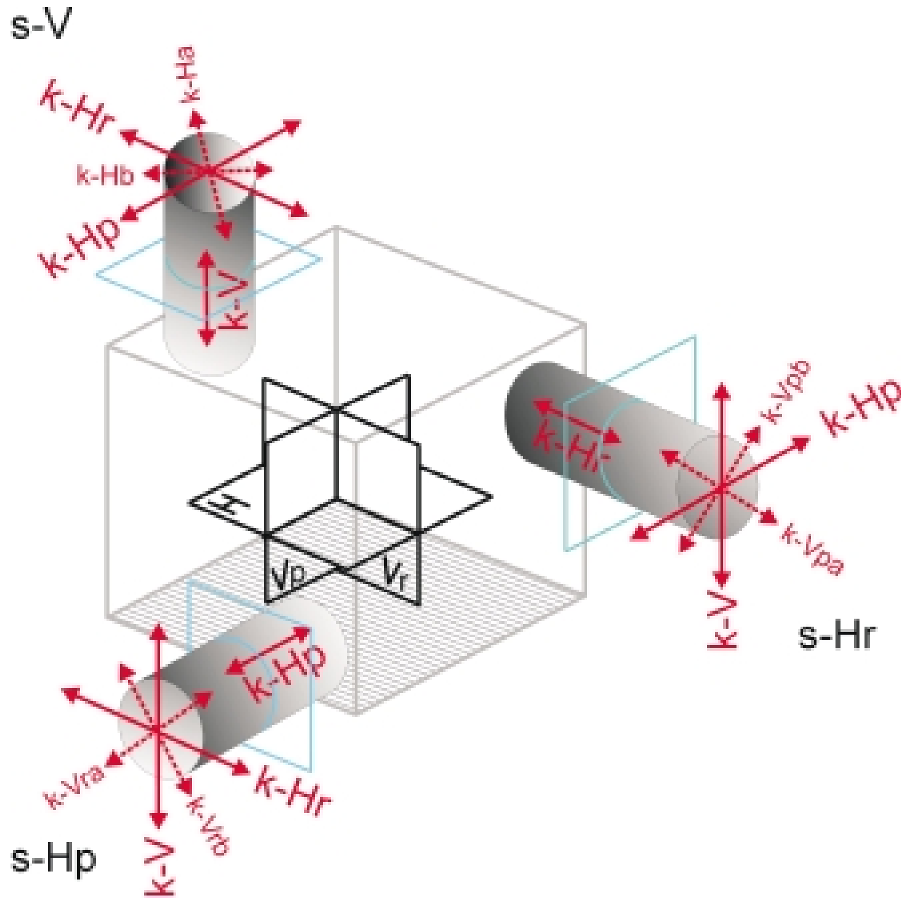

Fig. 5. The symbols used for fracture planes: Vr — perpendicular to lamination and parallel to the longer mineral axes, Vp — perpendicular to lamination and perpendicular to the longer mineral axes, H — parallel to lamination; specimens: s-Hr — cut out perpendicular to Vp plane, s-Hp — cut out perpendicular to Vr plane, s-V — cut out perpendicular to H plane; directions of ultrasound wave measurement (main: k-Hr — parallel to lamination and parallel to the longer mineral axes, k-Hp — parallel to lamination and perpendicular to the longer mineral axes, k-V — perpendicular to lamination; auxiliary: k-Ha, k-Hb — measurements in H plane, k-Vra, k-Vrb — measurements in Vr plane, k-Vpa, k-Vpb — measurements in Vp plane)

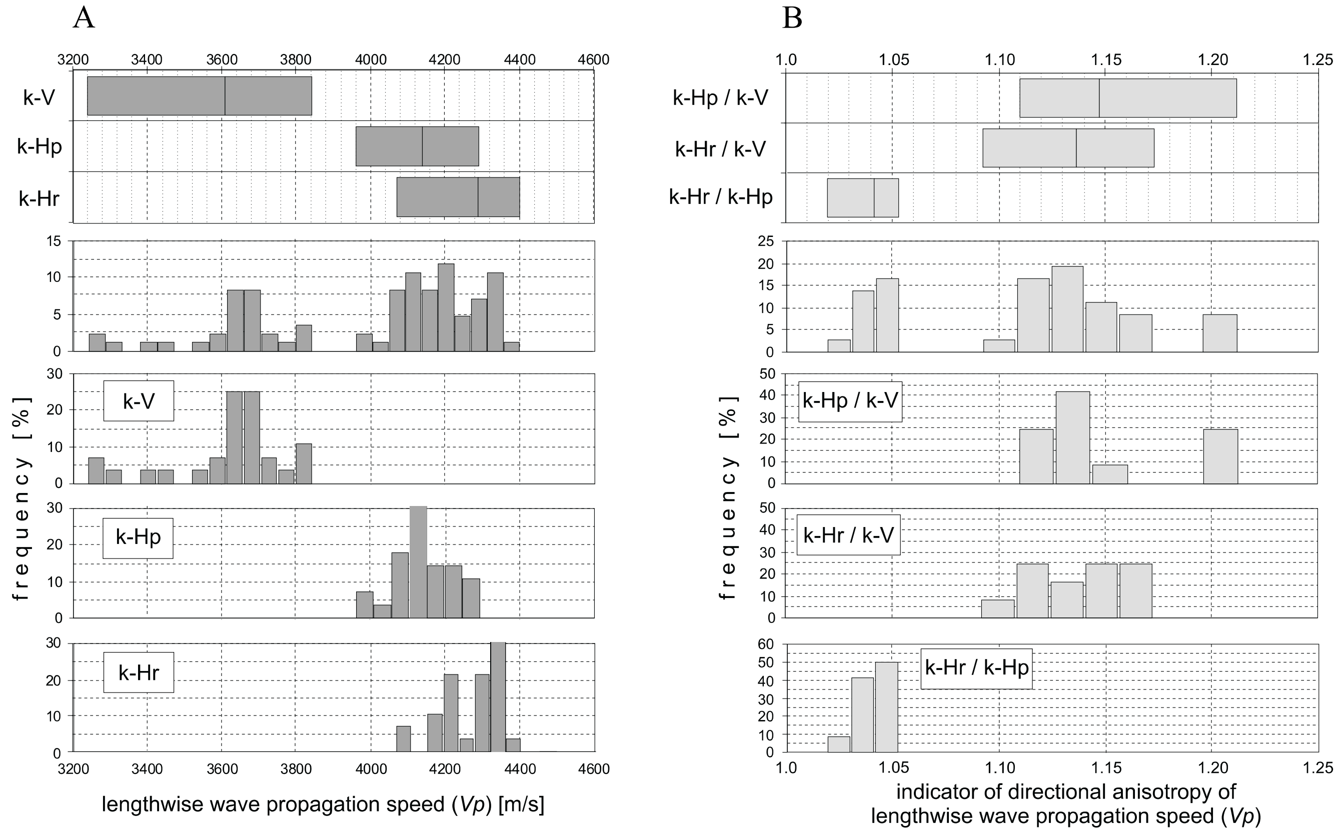

Fig. 6. Diagrams of variability and histograms of distribution of lengthwise wave propagation speed — A and its indicators of directional anisotropy — B; directions of ultrasound wave measurement: k-V — perpendicular to lamination, k-Hp — parallel to lamination and perpendicular to the longer mineral axes, k-Hr — parallel to lamination and parallel to the longer mineral axes

RESULTS

Analysis of the dynamic features of the Krosno Sandstones from Mucharz were based upon measurements of propagation speeds of lengthwise and crosswise waves in accordance with the previously assumed directions. In total, 12 measurements were taken for each specimen: in 4 directions at three different heights. In addition, on the basis of the results, dynamic material constants were determined, namely Young's modulus and Poisson's ratio. The results are presented as diagrams of variability and histograms of distribution of lengthwise wave propagation speed (Fig. 6A). These results show the variability of the dynamic features of the sandstones. The smallest values of wave propagation speed are in the direction k-V, that is, in the plane perpendicular to lamination. The two other directions: k-Hr and k-Hp, show slight differences. The direction k-Hr, along longer mineral axes, is preferred rather than the direction perpendicular to it — k-Hp. The variability of dynamic features, using directional anisotropy indicators is shown in Figure 6B. Clearly visible anisotropy between the direction perpendicular to lamination and directions parallel to lamination average 15%. The differences between the two directions parallel to lamination average 5%.

The ultrasound tests results show that, in directions parallel to lamination, the examined sandstone shows more elasticity than in the perpendicular direction. The greater number of contact planes between mineral grains and areas filled with lithic and clay cement/matrix make propagation of ultrasound waves in the k-V direction more difficult. This is also influenced by intergranular microcracks inside the rock, which can be exploited during deformation. This relation between the static and dynamic characteristics of the rocks suggests that their toughness is also variable.

Toughness tests, using the chevron bend method, were performed in a rigid MTS press, controlled by a computer, using special software. Specimens with the initial notch were bent in such a way as to ensure that the crack propagated in accordance with the direction of the load applied. In accordance with the recommendation of ISRM, changes in the stress intensity factor K_I during testing cannot exceed 0.25 $\mathrm{Mpa} \times \mathrm{m}^{1/2}$ per second, therefore the load increase speed was equal to 15 kN/min. The test itself took several seconds, less than 10, which is also consistent with ISRM instruction. During the test, the load (*F*) and the crack mouth opening displacement (*CMOD*) were measured.

The results obtained were as anticipated. In planes perpendicular to lamination surfaces, greater strength was observed than in the plane parallel with lamination. Values of maximum fracturing force obtained in planes Vr and Vp are similar, slightly greater than 2 kN. Slightly greater values were obtained in the plane parallel to longer mineral axes, with only one exception. Strength in the plane H was smaller (no greater

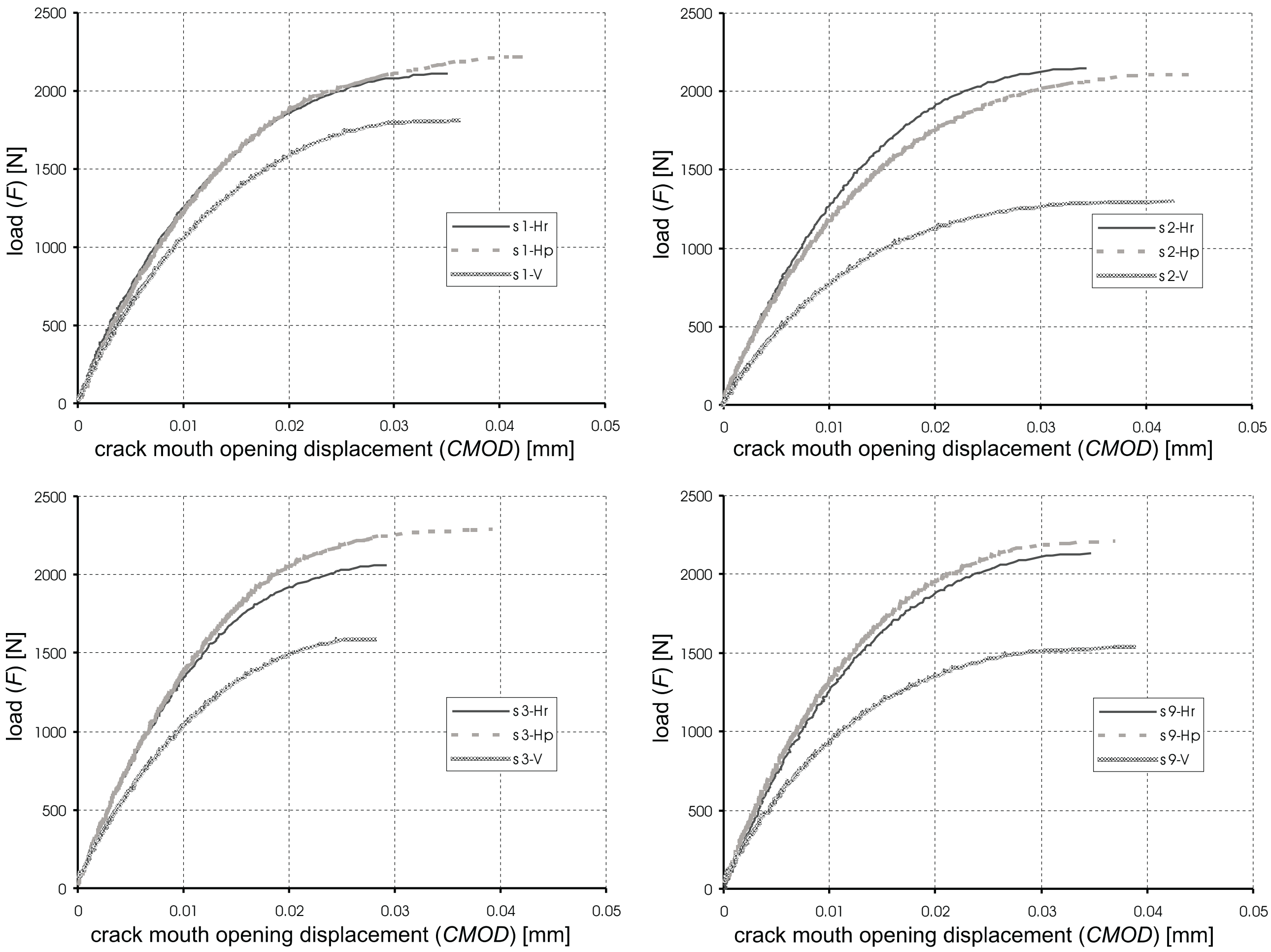

Fig. 7. Charts of dependence of crack mouth opening displacement (*CMOD*) upon the load (*F*) applied during the stage up to specimen failure. Symbols of specimens: s(number)-Hr — cut out perpendicular to Vp plane, s(number)-Hp — cut out perpendicular to Vr plane, s(number)-V — cut out perpendicular to H plane

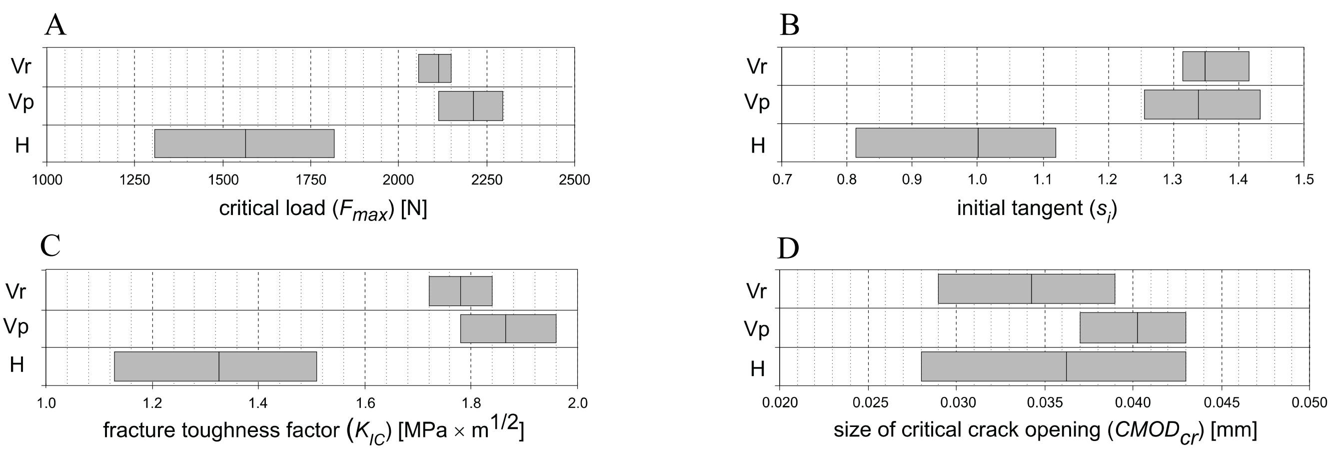

Fig. 8. Diagrams of variability of mechanical parameters for various failure surfaces: A — critical load, B — initial tangent, C — brittle fracture toughness indicator, D — critical mouth crack opening

symbols for fracture planes: Vr — perpendicular to lamination and parallel to the longer mineral axes, Vp — perpendicular to lamination and perpendicular to the longer mineral axes, H — parallel to lamination

Table 2

Statistical comparison of dynamic parameters and indicators of directional anisotropy

	Directions of ultrasound wave measurement											
	k-Hr				**k-Hp**				**k-V**			
	V_p [m/s]	V_s [m/s]	E_d [MPa×10^4]	ν_d	V_p [m/s]	V_s [m/s]	E_d [MPa×10^4]	ν_d	V_p [m/s]	V_s [m/s]	E_d [MPa×10^4]	ν_d
minimum	4072	2638	4.37	0.02	3962	2550	3.81	0.11	3238	2541	2.34	0.16
average	4273	2764	4.70	0.10	4125	2769	4.25	0.15	3607	2603	3.08	0.21
maximum	4401	2842	5.01	0.19	4257	2887	4.59	0.24	3842	2690	3.64	0.25
standard deviation	93	61	0.20	0.05	75	76	0.19	0.03	167	40	0.34	0.03
	Indicators of directional anisotropy [-]											
	k-Hr / k-V				**k-Hp / k-V**				**k-Hr / k-Hp**			
	V_p	V_s	E_d	ν_d	V_p	V_s	E_d	ν_d	V_p	V_s	E_d	ν_d
minimum	1.11	0.99	–	–	1.09	1.01	–	–	1.02	0.94	–	–
average	1.15	1.07	–	–	1.14	1.06	–	–	1.04	1.00	–	–
maximum	1.21	1.10	–	–	1.17	1.09	–	–	1.05	1.04	–	–
standard deviation	0.03	0.03	–	–	0.03	0.03	–		0.01	0.02	–	–

Directions of ultrasound wave measurement: k-Hr — parallel to lamination and parallel to the longer mineral axes, k-Hp — parallel to lamination and perpendicular to the longer mineral axes, k-V — perpendicular to lamination; dynamic parameters: V_p — propagation speed of lengthwise waves, V_s — propagation speed of crosswise waves, E_d — dynamic Young's modulus, ν_d — dynamic Poisson's ratio

than 2 kN) and more varied, as in the case of the dynamic features (Fig. 7). Similar variability occurs in the value of K_{IC} stress intensity factor, which is directly related to the value of the fracturing force:

$$K_{IC} = \frac{A_{\min} \cdot F_{\max}}{D^{1.5}}$$

where: $A_{\min}$ — variable depending upon the size of the initial notch and the specimen, D — diameter.

The initial tangent s_i, specified for the curve segment between its starting point up to 50% $F_{\max}$, can be used as a determinant of rock material elasticity. Values of s_i for the H plane are significantly lower, which indicates a more "plastic" character of failure. The propagating crack runs along the mineral sides, cutting through the lithic-clay matrix. In the case of the two other planes, the fracture process takes place in a slightly different manner. Mineral grains lie in the way of the propagating crack and so provide greater resistance. The material thus fractures in a more "brittle" way, causing the increase of tension resistance. Indicators of directional anisotropy for these parameters are very similar and reach approximately 40% on the average, along planes perpendicular to lamination (Fig. 8A–C). This value is greater than in the case of the dynamic features, but the tendency is the same.

The size of maximum crack opening is variable, though, maximum values are most often observed in s-Hp specimens, that is, in planes perpendicular to lamination and parallel to longer mineral axes. Nevertheless, no conclusions can be drawn on the basis of this parameter (Fig. 8D).

CONCLUSIONS

The results of this study show that the Krosno Sandstones show anisotropy of dynamic features and strength characteristics. Lamination, emphasised by iron compounds, causes significant diversity in the parameters obtained. The speed of ultrasound wave propagation is about 15% greater on the average in planes parallel to lamination, and brittle fracture toughness changes on average by up to 40% (Tables 2 and 3). This phenomenon likely relations to the directionality of arrangement of minerals and numerous intergranular microcracks, observed microscopically. These elements, on one hand, are a barrier to the propagating wave, and on the other hand, they cause a change in the character of crack propagation during toughness tests. In places where the developing discontinuity surface encounters an increase in the quantity of lithic-clay matrix, the material fractures in a more "plastic" way, which results in a decrease of its tension strength and in a decrease of the fracture toughness factor K_{IC}. Where the propagating crack has to overcome barriers in the form of materials arranged perpendicular to its front, an increase of toughness occurs, which is caused by the necessity to break the strong interatomic bonds inside mineral grains.

As has been shown, the variability of features related to toughness and strain is largely dependent upon the structure of the rock material. However, the results obtained should not be directly applied to rocks of a different origin, since their mineral composition and structure can be very different. Nevertheless, it is important during toughness tests to al-

Table 3

Comparison of strength test results and directional anisotropy indicators

	Failure planes											
	Vr				**Vp**				**H**			
	F_{max} [N]	K_{IC} [MPa×m$^{1/2}$]	s_i	$CMOD_{cr}$ [mm]	F_{max} [N]	K_{IC} [MPa×m$^{1/2}$]	s_i	$CMOD_{cr}$ [mm]	F_{max} [N]	K_{IC} [MPa×m$^{1/2}$]	s_i	$CMOD_{cr}$ [mm]
s1-Hr	2113	1.79	1.31	0.035								
s1-Hp					2222	1.89	1.26	0.042				
s1-V									1817	1.51	1.12	0.036
s2-Hr	2149	1.84	1.33	0.039								
s2-Hp					2114	1.78	1.33	0.043				
s2-V									1307	1.13	0.81	0.043
s3-Hr	2056	1.72	1.42	0.029								
s3-Hp					2297	1.96	1.43	0.039				
s3-V									1592	1.36	1.09	0.028
s9-Hr	2136	1.77	1.33	0.034								
s9-Hp					2216	1.83	1.34	0.037				
s9-V									1541	1.30	0.98	0.038
minimum	2056	1.72	1.31	0.029	2114	1.78	1.26	0.037	1307	1.13	0.81	0.028
average	2114	1.78	1.35	0.034	2212	1.87	1.39	0.040	1564	1.33	1.00	0.036
maximum	2149	1.84	1.42	0.039	2297	1.96	1.43	0.043	1817	1.51	1.12	0.043
standard deviation	41	0.05	0.05	0.004	75	0.08	0.07	0.003	209	0.16	0.13	0.006

	Indicators of directional anisotropy											
	Vr / H				**Vp / H**				**Vr / Vp**			
	F_{max}	K_{IC}	s_i	$CMOD_{cr}$	F_{max}	K_{IC}	s_i	$CMOD_{cr}$	F_{max}	K_{IC}	s_i	$CMOD_{cr}$
minimum	1.16	1.19	1.17	0.89	1.22	1.25	1.12	0.97	0.90	0.88	0.99	0.74
average	1.37	1.36	1.37	0.95	1.43	1.42	1.36	1.13	0.96	0.96	1.01	0.85
maximum	1.64	1.63	1.64	1.04	1.62	1.58	1.64	1.39	1.02	1.03	1.05	0.92
standard deviation	0.20	0.19	0.20	0.07	0.16	0.13	0.21	0.19	0.05	0.06	0.03	0.08

Failure planes: Vr — perpendicular to lamination and parallel to the longer mineral axes, Vp — perpendicular to lamination and perpendicular to the longer mineral axes, H – parallel to lamination; parameters: F_{max} — critical load, K_{IC} — fracture toughness factor, *si* — initial tangent, $CMOD_{cr}$ — size of critical crack opening; symbols of specimens: s(number)-Hr — cut out perpendicularly to Vp plane, s(number)-Hp — cut out perpendicularly to Vr plane, s(number)-V — cut out perpendicularly to H plane

ways pay attention to the structure of the material tested. Rocks are often described as heterogeneous, but this feature is not always taken into consideration while doing research in geodynamic laboratories. Anisotropy of strength features can turn out to be so great that, depending upon the direction of the load applied, they may behave like completely different rock materials.

REFERENCES

DZIEDZIC A. (1999) — A new method of study of fracture toughness of rocks (in Polish with English summary). Prz. Geol., **47** (10): 927–932.

GRIFFITH A. A. (1920) — Phenomenon of rupture and flow of solids. Trans. Roy. Soc. London., **A 221**: 163–168.

GUSTKIEWICZ J. (1997) — Co to jest kruche pękanie?. Konferencja „XX Zimowa Szkoła Mechaniki Górotworu”: 1–11, Szklarska Poręba.

INTERNATIONAL SOCIETY FOR ROCK MECHANIC (1988) — Suggested methods for determining the fracture toughness of rock. Int. J. Rock Mechs. Min. Sc. Geomech. Abstr., **25**: 71–96.

KSIĄŻKIEWICZ M. (1951) — Objaśnienia do arkusza Wadowice, 1:50000. Warszawa.

KSIĄŻKIEWICZ M. (1972) — Budowa geologiczna Polski. Tektonika — Karpaty. 4, 3. Warszawa.

MOROZ-KOPCZYŃSKA M. (1976) — Piaskowce krośnieńskie (eocen górny–oligocen). In: Piaskowce karpackie, ich znaczenie surowcowe i perspektywy wykorzystania (ed. C. Peszat). Zesz. Nauk. AGH, Geologia, **2** (2): 53–62.

OUCHTERLONY F. (1989) — Fracture toughness testing of rock with core based specimens, the development of an ISRM standard. Fracture Toughness and Fracture Energy. Test methods for concrete and rock: 231–251. Balkema. Rotterdam.

PETTIJOHN F. J., POTTER P. E. and SIEVER R. (1972) — Sand and sandstone. Berlin, Heildeberg, New York.

PINIŃSKA J. (1980) — The effects of low temperatures on the physico-mechanical properties of the Krosno Sandstones (in Polish with English summary). Biul. Inst. Geol., **324.**

PINIŃSKA J. (1995) — Procesy kruchego pękania w skałach osadowych przy jednoosiowym ściskaniu ze stałą prędkością odkształcenia. Prz. Geol., **43** (7): 546–553.

POPRAWA D. and NEMČOK J. (1988–1989) — Map of tectonic elements of the western outer Carpathians and their foreland. Scale 1:500 000. In: Geological Atlas of the Western Outer Carpathians and their Foreland. PIG, Warszawa.