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Evaluation of Anisotropy of Fracture Toughness in Brittle Rock, Migmatized Gneiss

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Abstract

Most rocks in nature are affected by a certain degree of anisotropy. They contain cracks mostly with certain distributions. Therefore their mechanical behaviour is dependent on the direction of the strength distribution, which is different in each direction. We can distinguish the directions in which the rock is relatively firm and conversely the directions in which it is weak. The strength anisotropy and the direction of weakening is useful information for engineering applications. Metamorphic foliation with the specific orientation of rock grains also influences the mechanical behaviour, and the mechanical properties, i.e. strength, are changed in different directions of loading. This change of strength is called the strength anisotropy. The main purpose of this research is to analyze the effect of the orientation of metamorphic foliation distinguished within the rock specimens on their strength anisotropy. In the article, the anisotropy of a mechanical property, i.e. the fracture toughness, of migmatized gneiss is discussed. For this purpose, series of semi-circular bend tests were carried out on specimens of migmatized gneiss with a metamorphic foliation. The methodology used in this research is effective for evaluating the strength anisotropy of a brittle rock.

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*Keywords:*strength anisotropy; metamorphic foliation; semi-circular bend test; fracture toughness

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1. Introduction

It is well known that a directional variation of rock properties is one of the key aspects of rock mechanics. It is relatively uncommon to find a rock mass with completely isotropic properties. The regular distribution of the internal fabric of rocks is mostly disturbed by the presence of planes of weakness, such as discontinuities, microstructures or any mechanical fractures. Besides, the internal fabric of the rock in many cases presents a predisposition to mechanical anisotropy [1]. Metamorphic rocks were subject to extreme loading and high temperature in the course of their development. These processes led to their particular properties, where the orientation of grains in one direction forms the specific features of the rock [2]. When mechanical properties change in different directions of loading, this is defined as strength anisotropy.

The strength behaviour of rocks can be characterized with an evaluation of mechanical parameters. The uniaxial compressive strength, shear strength, and tensile strength determine the macroscopic strength behaviour. Fracture toughness is one of the most important material properties of rocks in their microscopic strength behaviour. It expresses the resistance of a rock material to the initiation and propagation of cracks. It supposes a linear strength–deformation relationship with no plastic flow in the rock mass [3]. It describes the fracture behaviour of rocks in loading conditions and it is closely related to the macroscopic strength. The mechanical properties that express the deformation behaviour of rocks are very important for rock mass classification in mines or underground constructions.

The stability of mine workings, tunnels and underground constructions in general is a basic question for the protection of personnel and equipment. Moreover, the reinterpretation of strength anisotropy can contribute to an understanding of rock structures and rock fabric development. That is why we consider the strength anisotropy (i.e. the strength in different directions in rocks) to be very important data for planning the stability of underground constructions.

For other reasons, too, we have chosen to test strength anisotropy on metamorphic rock. The main one was the presence of foliation planes. We assume that foliation planes are planes of weakness, which result in a higher degree of strength anisotropy.

The research is focused on the strength anisotropy of brittle rock. In the article, the influence of the orientation of foliation planes within the rock samples on the anisotropy of fracture toughness is evaluated and discussed. The values of fracture toughness were obtained by using a semi-circular bend (SCB) test [4, 5, 6]. After the test, the fractured planes were examined and analyzed by optical microscopy in order to recognize the fracture mechanism of the rock.

2. Rock material and method

2.1. Migmatized gneiss

Samples were taken in a deep mine of the uranium deposit at Rožná in the Czech Republic. The selected block of migmatized gneiss with distinguishable anisotropy was broken out at level 22 at a depth of about 1100 m. Rocks from this mine were chosen due to their minimal damage by weathering processes.

The uranium deposit at Rožná is situated in the eastern part of the Strážek Moldanubicum, which is a crystalline unit situated in the north-eastern border of the Moldanubian Zone in the eastern margin of the Bohemian Massif. The Strážek Moldanubicum is composed of high-grade metamorphic rocks such as biotite and amphibole-biotite gneisses that were affected by different degrees of migmatization and strain under ductile conditions [7]. These rocks are medium- to coarse-grained and significantly foliated and banded. The bands are created by melanosome and leucosome material.

Physical and mechanical properties of the studied gneiss are varied due to different orientations of the foliated planes distinguishable within the rock samples [8]. Parameters of the physical and mechanical properties are shown in Table 1. Gneiss-P represents the drilled rock samples parallel to the metamorphic foliation and gneiss-K represents the drilled rock samples perpendicularly to the metamorphic foliation.

Table 1. Bulk density – ρ_0, ultrasonic velocity of P-waves – Vp, uniaxial compressive strength – σ_{UCS}, Young´s modulus – E, Poisson´s ratio – υ of the tested migmatized gneiss in two different orientations of foliation [8].

	ρ_0 (kg/m^3)		Vp (km/s)		σ_{UCS} (MPa)		E (MPa)		υ (-)	
gneiss-P	aver (kg/m^3)	2700	aver (km/s)	5.4	aver (MPa)	98	aver (MPa)	26377	aver (-)	0.20
	S.D. (kg/m^3)	11	S.D. (km/s)	0.26	S.D. (MPa)	20	S.D. (MPa)	4202	S.D. (-)	0.05
	CV (%)	0.4	CV (%)	5	CV (%)	20	CV (%)	16	CV (%)	27
gneiss-K	aver (kg/m^3)	2700	aver (km/s)	4.0	aver (MPa)	133	aver (MPa)	30757	aver (-)	0.18
	S.D. (kg/m^3)	11	S.D. (km/s)	0.32	S.D. (MPa)	11	S.D. (MPa)	4308	S.D. (-)	0.04
	CV (%)	0.4	CV (%)	8	CV (%)	8	CV (%)	14	CV (%)	21

*Note: aver – average measured value, S.D. – standard deviation, CV – coefficient of variation

2.1.1. Petrography analysis of the migmatized gneiss

In order to describe petrographic features of the gneiss a thin section was prepared across the foliation of the tested rock. Optical microphotograph was observed under a high power polarized microscope (Fig. 1). The thin section petrography shows that the leucosome contains varying proportions of quartz, potassium feldspar and plagioclase. The melanosome is mainly characterized by the presence of a dark mineral — biotite. The biotite is oriented parallel to the foliation and its flakes create the weakness planes, from the point of view of our research. Accessory minerals include sillimanite, garnet, sulfide minerals and zircone.

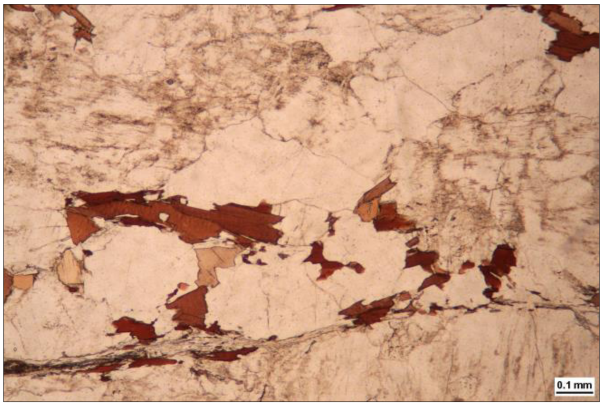

Fig. 1. Optical microphotograph of thin section illustrated the microstructure of migmatized gneiss.

2.2. Semi-circular bend (SCB) test

The SCB test was performed according to the ISRM’s suggested method for determining the mode I static fracture toughness using a semi-circular bend specimen [4]. The rock cores with diameter d = 48 mm and thickness t = 20 mm were drilled out of a larger rock block. The specimens were cut into halves to form two semi-circular specimens. Finally, straight edge notches were carved out throughout the specimen using a diamond blade with a thickness of 0.4 mm. The experimental arrangement of the SCB specimens is illustrated in Fig. 2(a). Two groups of SCB specimens were prepared. GROUP 0 represents the specimens with metamorphic foliation parallel to the artificial straight notch. Specimens with the artificial straight notch produced perpendicularly to the foliated planes were called GROUP 90. Examples of the specimens in both groups are shown in Fig. 2(b).

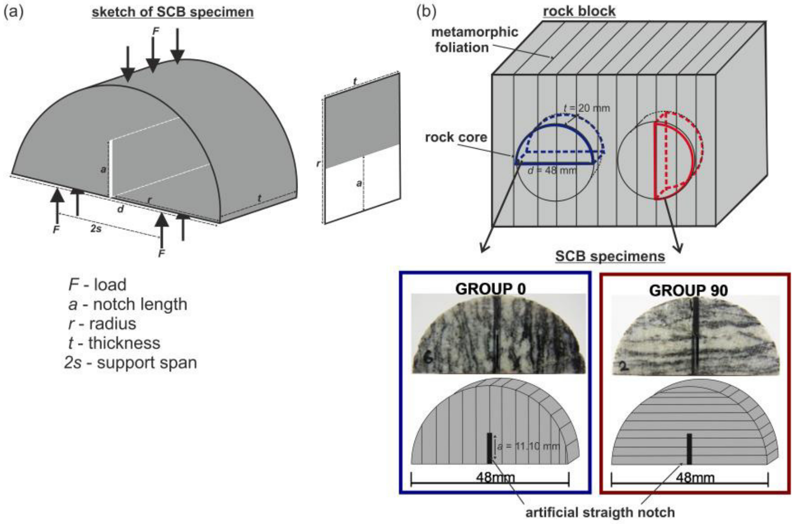

Fig. 2. (a) Experimental arrangement of SCB specimens pursuant to ISRM recommendation [4]; (b) Two different groups of SCB specimens in respect to straight notch and metamorphic foliation.

In the test, the SCB specimen was placed on two bottom-loading cylindrical rollers with a distance $2s = 24.7$ mm. The load F was applied through three-point bending, i.e. one upper and two support rollers, to the specimen with the straight edge notch. The tests were carried out under three different loading rates $v = 0.01$, $v = 1$ and $v = 100$ mm/min. Values of fracture toughness (K_{Ic}) were calculated using the following equation [4]:

$$K_{IC} = \frac{\sqrt{\pi \alpha} F\mathrm{max}}{2rt} Y_i \tag{1}$$

where $F_{\max}$ is the maximum load, a is the artificial notch length, t is the specimen thickness, r is the specimen radius and Y_{i} is normalized stress intensity factor depended on the specimen geometry.

2.3. Optical microscope analysis

The analytical method was used for evaluation and discussion of the fracture mechanism of the migmatized gneiss. Firstly, the geometry of the created fracture surfaces was analyzed under an optical microscope (Keyence VHX-5000) and the minerals distribution could be recognized, as shown in Fig. 3(a).

Secondly, in order to analyze the fracture initiation behaviour of the rock, three lines from an area near the notch tip were set and height profiles along the lines were generated. The dimensions of the area are length 10 mm and width 1 mm. The region is considered to represent a part of the supposed area where a fracture was initiated, as shown in Fig. 3(b).The first line represents the notch tip. These two lines were measured at distances of around 200 μm and 800 μm from the notch tip in each analyzed fracture surface.

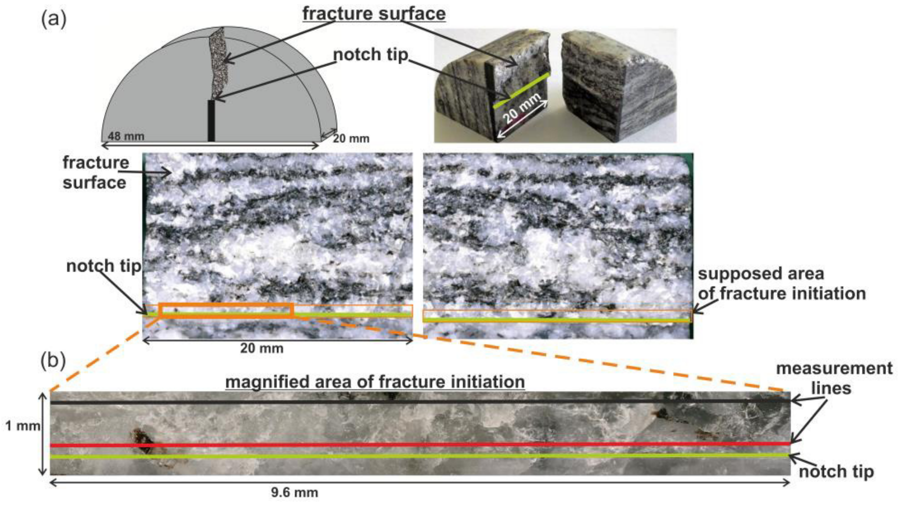

Fig. 3.(a) Pictures of fractured specimen using the optical microscope; (b) Picture of magnified area where fracture initiation was supposed.

3. Results and discussion

3.1. SCB results

After the SCB tests, load–displacement relationships were estimated. The two graphs are illustrated in Fig. 4. The curves in the graphs are evaluated in respect to three different loading rates in both groups. All curves reveal a similar increasing trend. The curves are downward convex at a low load and linear until the specimens fracture and reach the maximum load $F_{\max}$. The values were used in equation (1) in order to calculate the fracture toughness.

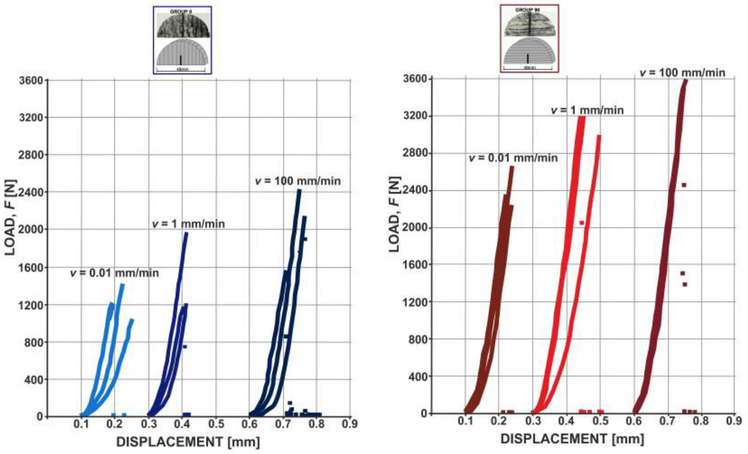

Fig. 4. Load-displacement relationships in both groups.

The relationship between the values of fracture toughness and the loading rates in both groups is plotted in Fig. 5. The migmatized gneiss confirmed the anisotropy of the fracture toughness. The specimens reached values of fracture toughness from 0.718 to 2.532 MN/m$^{3/2}$. The values of fracture toughness increased with increasing loading. The values of GROUP 90 were significantly greater than those of GROUP 0.

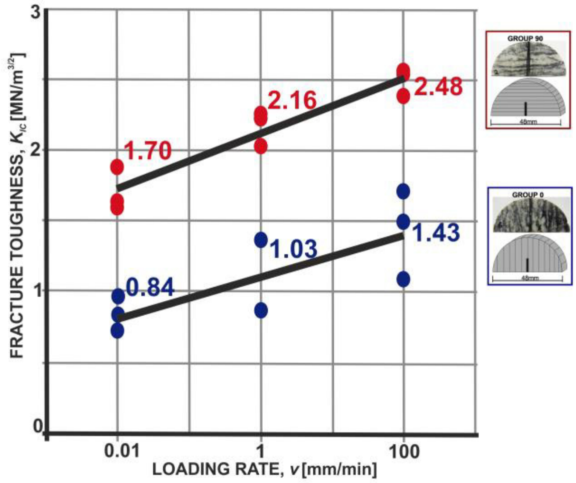

Fig. 5. Relation between fracture toughness and loading rates in both groups.

It can be considered that the strength of the specimens decreases in the case of loading on the specimens in which a notch is produced parallel to metamorphic foliation. Obviously, it is more difficult to fracture perpendicular to the metamorphic foliation than parallel to the metamorphic foliation. It can be considered that the parallel position of metamorphic foliation with loading reduces the strength of the specimens and the values of fractures toughness are lower too. Accordingly, it is possible to say that the orientation of metamorphic foliation influences the strength in loading and also the fracture toughness of the rock.

3.2. Results from optical microscope analysis

Examples of images and height profiles from the optical microscope analysis are presented in Fig. 6. The green lines represent the notch tip and the black and red lines are locations in the area of the supposed fracture initiations on the fracture surfaces. It is clear that the fracture surfaces abound in a light material that represents the quartz-feldspar aggregates. The dark part, biotite, is rarely found on the fractured surfaces. This can explain why the shape of the smooth lines is changed and became curved in the profiles. The presence of biotite caused a significant deviation of the black and the red lines. This means that the fractures occurred within the light grains or along the boundaries of light and dark grains. Based on the results, it can be considered that fracture initiation originates mainly within grains of the quartz-feldspar material or at the boundaries with the biotite.

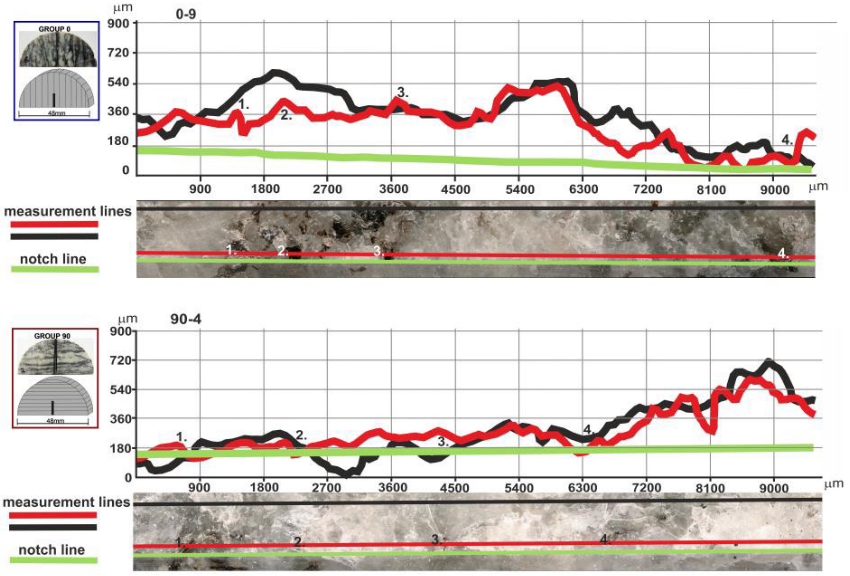

Fig. 6. Two examples of profiles of the measurement lines on fracture surfaces of SCB specimens.

4. Conclusion

Mechanical properties express the strength and deformation behaviour of rocks. They are very important for rock mass classification in mines or underground constructions. The research is focused on strength anisotropy. The article deals with the influence of the orientation of foliation planes within the rock samples of migmatized gneiss on the anisotropy of fracture toughness.

Eighteen SCB tests were performed in order to evaluate the fracture toughness. SCB specimens were divided into two groups with artificial straight notches produced parallel and perpendicular to the foliated planes. The tests were performed under three different loading rates, $v = 0.01$, $v = 1$ and $v = 100$ mm/min. An optical microscope was used for visualization and analysis of the fractured planes in order to evaluate the fracture mechanism of the rock.

According to the preliminary results of the research, we can deduce that:

- the migmatized gneiss with metamorphic foliation confirms the strength anisotropy,
- the position of the notch tip parallel to the foliated planes significantly reduces the values of fracture toughness,
- the values of fracture toughness increase with increasing loading rate,
- fracture initiation was observed mainly within the grains of quartz-feldspar material, to a lesser extent, between grain boundaries with biotite.

In summary, the foliation planes have a fundamental influence on the strength anisotropy. It can be considered that the anisotropy of the fracture toughness is dependent mainly on the distribution and orientation of the grains of quartz and feldspar in the tested rock.

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