Determination of an empirical relations between mode I fracture toughness using CB and SCB specimens and Brazilian tensile strength of rocks

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ABSTRACT: Fracture toughness (FT) expresses material resistance to crack propagation leading to its final macroscopic failure. Approximately 20 different laboratory methods are currently used for a mode I and mixed mode I/II FT rock testing. However, it is a well-known fact that, for the same rock, the mode I FT value varies when different specimen types are utilized. Moreover, the preparation of specimens for FT testing may be associated with difficulties in obtaining required notch dimensions. From this point of view, Brazilian tensile strength (BTS) represents an easily and quickly detectable parameter that can be applied for prediction of the mode I FT. In this contribution, the results of investigations of mutual empirical relationships between FT determined using CB and SCB tests, as well as among FT values obtained via these testing methods and BTS are presented. A total of 14 different rock types, mostly sandstones, were used for this research.

Keywords: rock, mode I fracture toughness, CB specimen, SCB specimen, Brazilian tensile strength.

1 INTRODUCTION

The failure process of rocks and similar quasi-brittle materials is the result of complex mechanisms, including microcrack initiation, propagation, and interactions with each other, resulting in crack coalescence. Crack initiation occurs when the stress intensity factor at a microcrack tip reaches its critical value, known as fracture toughness (FT). FT thus expresses the resistance of the material to crack propagation. To date, no uniform, generally valid method for determining the rock FT has been defined. Since the beginning of 1980s, more than 20 different laboratory methods with various experimental arrangements and specimen geometries have been developed especially for a mode I and mixed mode I/II FT rock testing. Four of them, including chevron bend (CB) test and semi-circular bend (SCB) test, were approved as an ISRM suggested methods for FT measurements.

However, it is a well-known fact that, for the same rock sample, the mode I FT varies when different specimen types are used for measurement. This is most likely due to the fact that the measured values of the rock FT are influenced by material heterogeneity, sample dimensions, boundary conditions and asymmetric mechanical behavior of rocks (Vavrik et al. 2021). The discrepancies between the results of FT measurements performed using different methods attracted the interest of many researchers (see, e.g., Funatsu et al. 2015). As for the comparison between SCB and CB methods, it was mostly shown (Chang et al. 2002, Funatsu et al. 2015, Wong et al. 2017) that the FT obtained from this test is much lower than the FT achieved using the CB specimen. On the other hand, some other published results suggest that the FT values from SCB specimens can be comparable with the results from the CB tests (Aliha et al. 2017, Kataoka et al. 2015).

Regarding the determination of FT, it should be also emphasized that the preparation of some type of specimens is often somewhat lengthy and may be associated with difficulties in obtaining consistent notch dimensions within required tolerances. Therefore, a simple method for estimation of the rock FT would be helpful. In this regard, the mode I FT, i.e., the opening mode, should be empirically correlated to the BTS as was presented, e.g., by Feng et al. (2019), Gunsallus & Kulhawy (1984), Souček & Vavro (2013), Wang et al. (2007), Wei et al. (2017) or Zhang (2002).

The presented article is a short contribution to this issue. Specifically, it deals with the intercomparison of the FT results determined using the CB and SCB tests and the relationship between these FT values and the BTS performed on a relatively wide range of rock types.

2 ROCK MATERIALS

A total of 14 different types of rocks were used for laboratory experiments, of which 9 were sandstone and then two types of granite, one basalt, marble and amphibolite. Within the sandstones, quartz sandstones predominated, namely Javorka sandstone, Kocbeře sandstone, Hořice sandstone, Krákorka sandstone and Paskov sandstone. Most of them represent long-term utilized Czech building and sculpture stone materials, whose mineralogical composition and physico-mechanical properties are described, e.g., in Koudelka et al. (2020), Vavrik et al. (2021), Vavro & Souček (2013), Vavro et al. (2019, 2022). Glauconitic sandstones were represented by green and brown varieties of Záměl sandstone (Martinec et al. 2010) and by Godula sandstone (Vavro et al. 2016, 2017). The last tested sandstone was tuffaceous Kimachi sandstone mined in Japan (Kataoka et al. 2015).

The group of plutonic rocks included biotitic granite from the Černá Voda quarry in the Czech Republic (Malíková et al. 2019, Vyhlídal et al. 2022) and two-mica Korean Gyeonggi granite. Olivine basalt as a representative of effusives came from Bílčice quarry (Slivka & Vavro 1996).

Tested metamorphites consisted of dark marble from Horní Lipová quarry (Vavro & Souček 2013) and coarse-grained amphibolite from former Rožná I uranium mine (Vyhlídal et al. 2022).

3 DESCRIPTION OF THE EXPERIMENT

3.1 Test specimens

Cylindrical chevron-notched specimens of 50 mm in diameter (d) and a length (l) of ca 200 mm were drilled from rock blocks in the laboratory. For most of the tested rocks, core drilling was carried out parallel to the planes of anisotropy, for example bedding planes. In the case of rocks with developed stratification, metamorphic foliation or rock-forming minerals preferred orientation, drilling was carried out in two directions. The first one was parallel to the anisotropy planes (designated as “P” direction), the samples with the designation letter “K” were prepared perpendicular to the planes of anisotropy. In the center of the test specimen, a chevron edge notch with an internal angle of 90° was carved using a circular diamond blade (Figure 1). The width of the chevron notch was ~1.5 mm. The specimen geometry followed the relevant ISRM recommendation (ISRM 1988).

After FT measurements using CB test method, SCB specimens were prepared from the parts of cores unaffected by the formation of a macrocrack. This means that both the CB and SCB tests was performed on the same core specimen. For the SCB specimens, the end parts of cores were cut into disks with thickness (t) of 20 mm and each disk was subsequently cut into halves to form two semi-circular specimens. Finally, the straight edge notch with the thickness of 0.5 mm was produced using a diamond blade in the centre of the specimen (Figure 1). As in the case of CB specimens, the SCB specimens satisfied the ISRM-suggested dimensions (Kuruppu et al. 2014).

Test specimens for splitting tensile strength measurements using Brazilian test were prepared from separate cores, the ends of which were cut perpendicularly to the length, so that the slenderness ratio was about 0.7 and thus complied with the ISRM suggestion (ISRM 1978). Specifically, prepared disc-like specimens had a diameter of ca 50 mm and a thickness of about 35 mm.

It should be emphasized that the CB and BTS tests were performed for all 14 rock types, while the SCB test was carried out only on selected rocks (see Table 1).

3.2 *Instrumentation and experimental conditions*

Before mechanical and fracture testing, all the specimens were dried in an electric drying oven at 105° C for 24 hours to remove the water from within the rock material.

FT in the both CB and SCB tests was measured using three-point bending loading scenario. The FT measurements on CB specimen were performed using FPZ 100 mechanical power press (VEB Thüringer Industriewerk, Germany). The bottom support span (*s*) was 166 mm (Figure 1). CB tests were carried out in the laboratories of the Institute of Geonics, ASCR, Czech Republic.

In the SCB tests, the MTS 810 servo-hydraulic testing machine (MTS Systems Corporation, USA) with a loading capacity 100 kN was used. The bottom support span (*s*) was 40 mm (Figure 1). SCB test were done in the laboratories of the Kumamoto University, Japan. Both the CB and SCB tests were performed in a displacement control mode at a constant loading rate of 0.01 mm/min.

Brazilian tests were also performed using mechanical FPZ 100 press, the loading rate was 0.1 mm/min. All the tests specified above were performed at room temperature.

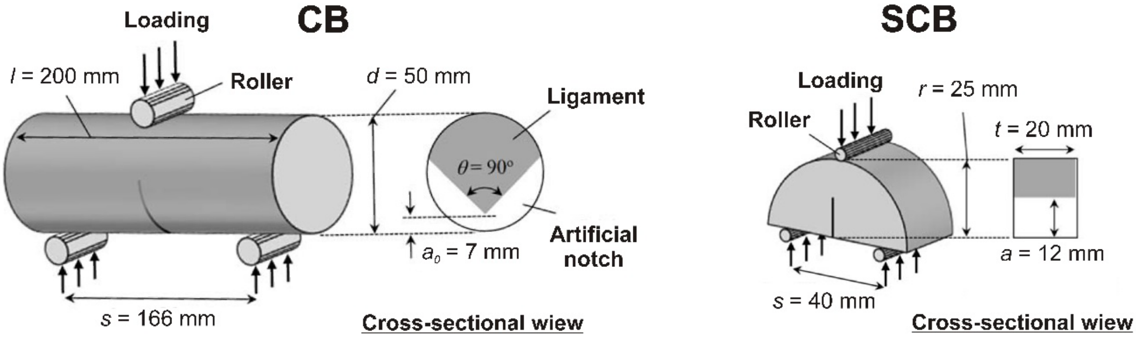

Figure 1. Geometry and loading scheme of the CB and SCB specimens. According to Kataoka et al. (2015).

4 RESULTS

The results of determination of FT using CB and SCB specimens as well as relationships between FT and BTS values are presented in Table 1 and Figures 2 and 3.

In the case of BTS, nine test samples were tested for each rock type. For CB and SCB tests, six test samples were used for each rock. The values shown in Table 1 and Figures 2 and 3 represent arithmetic means of individual measurements.

Table 1. Summary of FT tests using CB and SCB specimens.

Locality	Rock	Direction	FT_{CB} [MPa·m$^{0.5}$]	FT_{SCB} [MPa·m$^{0.5}$]	FT_{SCB}/ FT_{CB}
Godula	sandstone	P	1.462	0.881	0.603
Godula	sandstone	K	1.124	0.862	0.767
Javorka	sandstone	P	0.384	0.158	0.411
Kimachi	sandstone	P	0.693	0.689	0.994
Kimachi	sandstone	K	0.632	0.739	1.169
Kocbeře	sandstone	P	0.834	0.458	0.549
Záměl - brown	sandstone	P	0.645	0.338	0.524
Záměl - brown	sandstone	K	0.559	0.395	0.707

Table 1. Summary of FT tests using CB and SCB specimens - continuation.

Locality	Rock	Direction	FT_{CB} [MPa·m$^{0.5}$]	FT_{SCB} [MPa·m$^{0.5}$]	FT_{SCB}/ FT_{CB}
Gyeonggi	granite	P	3.137	1.304	0.416
Gyeonggi	granite	K	3.712	1.113	0.300
Rožná	amphibolite	P	3.715	1.994	0.537
Rožná	amphibolite	K	3.134	1.691	0.540

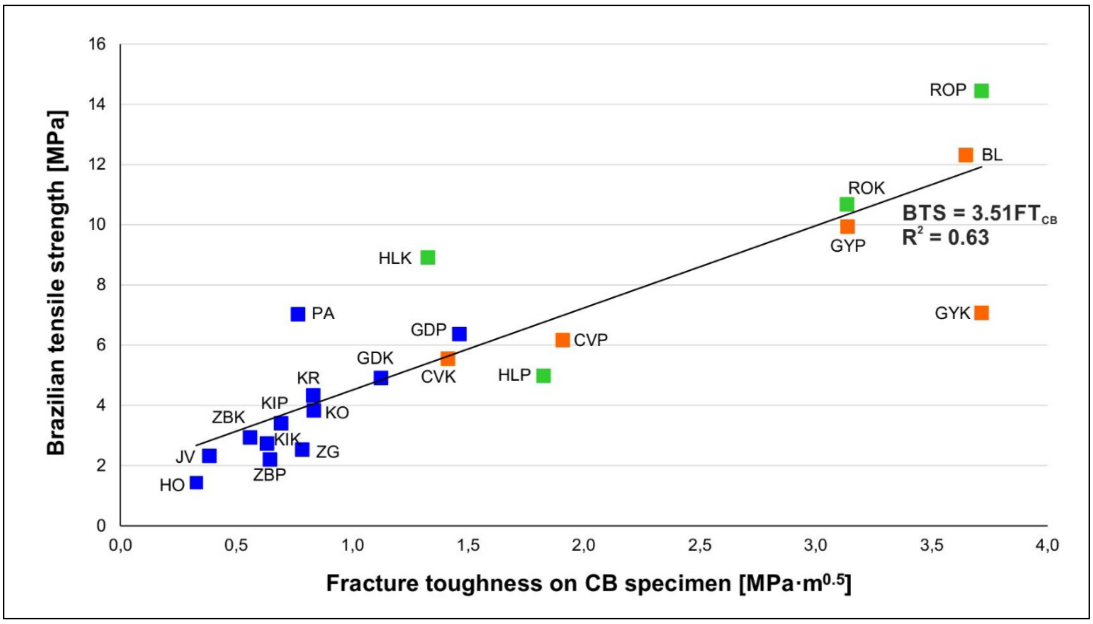

Figure 2. Relation between FT on CB samples and BTS of the studied rocks. Explanations to Figures 2 and 3: BL – Bílčice; CVP, CVK – Černá Voda (P, K directions); GDP, GDK – Godula (P, K directions); GYP, GYK – Gyeonggi (P, K directions); HC – Hořice; HLP, HLK – Horní Lipová (P, K directions); JV – Javorka; KIP, KIK – Kimachi (P, K directions); KO – Kocbeře; KR – Krákorka; PA – Paskov; ROP, ROK (P, K directions) – Rožná; ZBP, ZBK – Záměl brown (P, K directions), ZG – Záměl green; blue squares – sandstones; orange squares – igneous rocks; green squares – metamorphic rocks.

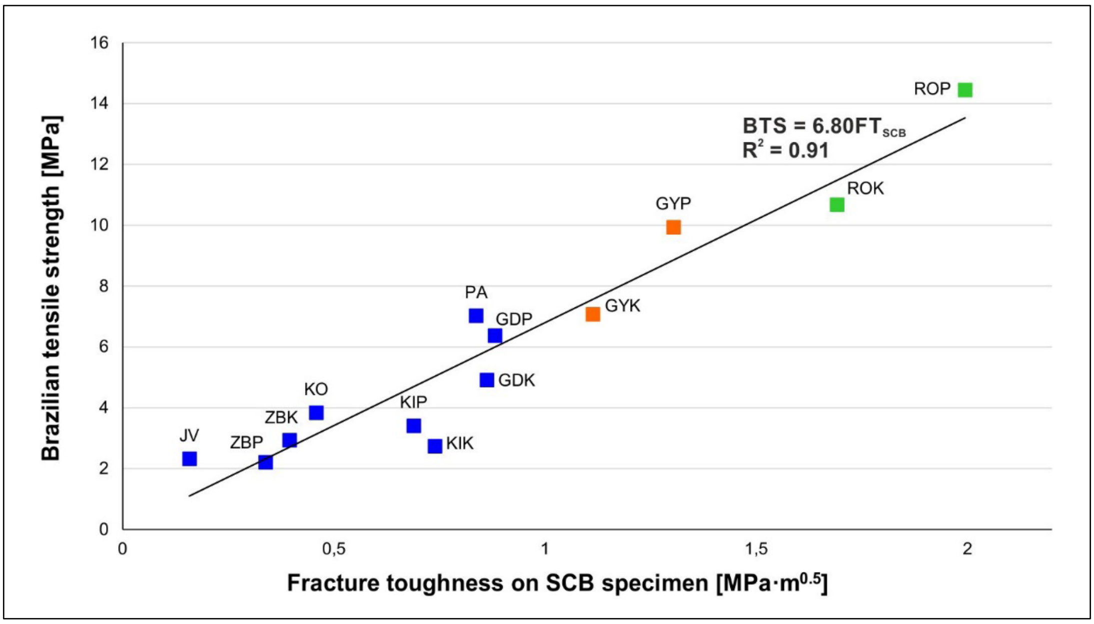

Figure 3. Relation between FT on SCB samples and BTS of the studied rocks.

5 CONCLUSIONS

From the results of the research, which are described above, the following summary can be drawn.

For practically all the rocks studied, the mean FT value obtained by the SCB test was lower, and often quite significantly, than those using the CB test. More specifically, the FT_{SCB}/FT_{CB} ratio most often ranged between 0.3 and ca 0.7. This finding is consistent with previous results published, e.g., by Chang et al. (2002) or Wong et al. (2019). The only rock which fall outside this trend was Kimachi sandstone, whose FT evaluated by the SCB test was almost the same or even higher as that determined by the CB test. These differences in the measured FT values determined by the CB and SCB test performed on the same rock are most likely the consequence of different notch geometries (V-shaped versus straight-edge notched samples) and related differences in the fracture process zone sizes and geometries, as stated by, e.g., Funatsu et al. (2015).

As can be seen from Table 1 and Figures 2 and 3, the rock structural anisotropy also has an influence on the measured FT value. In the vast majority of tested rocks, the FT is higher for rock samples that were drilled parallel to the anisotropy planes, i.e. in which the crack propagates perpendicular to these planes. In the case of the CB test, the highest difference between the FT values in P and K directions was found in Horní Lipová marble (37%) and Godula sandstone (30%). For SCB samples, these differences were the highest for Rožná amphibolite (18%) and Gyeonggi granite (17%). The anisotropy of the values was also determined for BTS, which was generally lower in K direction compared to the strength in P direction. Significant BTS values differences were identified, e.g., for Rožná amphibolite (35%), Godula sandstone (30%) or Kimachi sandstone (24%). Thus, anisotropy of properties must always be taken into account in evaluating FT and BTS.

The relation between FT measured on CB specimens and BTS of various types of studied rock can be expressed by the equation $BTS = 3.51FT_{CB}$, with a coefficient of determination $R^2 = 0.63$. In the case of FT measured via SCB specimens and BTS is then this mutual relationship different, namely $BTS = 6.80FT_{SCB}$, with $R^2 = 0.91$. Finding about the different proportionality coefficients between BTS and different FT test methods is in accordance with results of, e.g., Zhang (2002).

Therefore, when assessing the empirical relationship between FT and BTS, it is necessary to use the results of determining FT on one specific and always the same type of test samples, prepared in a uniform spatial relationship to the rock structural features.

ACKNOWLEDGEMENTS

Presented work was financially supported by Czech projects GA23-05128S and RVO: 68145535.

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