Experimental Study of Mode I Fracture Toughness Anisotropy in Granitic Rocks

Jéssica Santana Pereira Nunes*, Raquel Quadros Velloso, Eurípedes Vargas Jr, Bruno Pires

Department of Civil Engineering, Catholic University of Rio de Janeiro, Rio de Janeiro, Brazil.

jessicaspn@hotmail.com, raquelvelloso@puc-rio.br

Abstract. Granitic rocks can in general be easily split through three mutually orthogonal surfaces, empirically identified in the field. In this regard, the present study intends to evaluate the mode I fracture toughness of a syenogranite, obtained from a quarry in the city of Cachoeiro de Itapemirim in the state of Espirito Santo. Fracture toughness consists of an intrinsic mechanical property of rocks and indicates the resistance to the initiation or propagation of a fracture as well as the amount of energy the rock absorbs until its fracture. In order to evaluate mode I fracture toughness anisotropy, the Cracked Chevron Notched Brazilian Disc (CCNBD) test was conducted, following ISRM. Twenty-five (25) samples were tested considering four (4) different orientations: short transverse, arrester, divider and a random direction (inclined). In addition, the indirect tensile strength test (Brazilian test) was also conducted, in order to characterize the samples. The test was performed on fifteen (15) samples and in three (3) different orientations: short transverse, arrester and divider. The tests and sample preparation were carried out at the Structural and Materials Laboratory (LEM-DEC), and the physical properties were obtained at the Geotechnical and Environmental Laboratory (LGMA), both located at PUC-Rio. It is possible to observed that the physical properties results obtained in the present study were very similar to the results obtained by Almeida et al. and by Jaques. In the Brazilian test it was possible to observe that all the mean tensile strength values are similar to each other, which indicates that there is little anisotropy in this rock. In the CCNBD test it was possible to verify that the mean fracture toughness values are similar in every direction, which indicates that there is little anisotropy in this rock as well as in the Brazilian test.

1. Introduction

The field of Fracture Mechanics aims to study the formation and propagation of fractures, specifically the behavior of materials containing cracks or fissures. The importance of this field can be noted in its wide-ranging applications within Civil Engineering, such as in blasting operations, hydraulic fracturing, mechanical fragmentation, slope stability analysis, geophysics, earthquake mechanics and geothermal energy extraction, amongst other examples.

One of the most important characteristics and basic parameters evaluated in Rock Mechanics and Fracture Mechanics is Fracture Toughness, an intrinsic mechanical rock property. Fracture Toughness can be defined as the resistance to crack propagation and is used in several fields of engineering. The property indicates the magnitude of fracture resistance or the rock’s ability to resist crack propagation.
The purpose of this study is to evaluate the Mode I Fracture Toughness anisotropy of a syenogranite. Experimental tests were carried out in Mode I given that it is the easiest way to experimentally prepare the specimens, conduct the experiment in the laboratory and analyze the results. Furthermore, crack propagation in most brittle materials preferentially occurs in Mode I.

Several methodologies have been recommended to determine the Fracture Toughness of rocks. In 1988, the International Society of Rock Mechanics (ISRM) proposed two methods for Mode I propagation: Chevron Bend (CB) and Short Rod (SR). Later, in 1995, the same organization published the Cracked Chevron Notched Brazilian Disc (CCNBD) method.

In order to evaluate the anisotropy of Fracture Toughness in Mode I, the present research followed the CCNBD method recommended by the ISRM.

2. Materials and Methods

2.1. Materials

To conduct this research, five (5) blocks of unweathered rock were retrieved from quarries located in the region of the Cachoeiro de Itapemirim Municipality in southern Espirito Santo State, as shown in Figure 1. The blocks were removed from five (5) different outcrops (Profiles 1 to 5) which exhibited at least five degrees of weathering. The blocks were transported and stored in the Structures and Materials Laboratory at PUC-Rio. Subsequently, the cutting orientations (short-transverse, arrester, divider or inclined direction) were determined.

![Figure 1. General view of Profile 1, separating the degrees of weathering (white boundaries) and indicating discontinuities (red lines) (Jaques).](image)

2.1.1. Geological-geotechnical Characterization

The Cachoeiro de Itapemirim Municipality, in southern Espirito Santo State, is inserted in the geotectonic setting of the Araçuai Orogen, which is primarily comprised of granitic and metamorphic rocks that border the southeaster margin of the São Francisco Craton. According to Jaques, most of the rocks in this area belong to the Santa Angélica Suite and the Paraíba do Sul Complex.

The five existing outcrops in Cachoeiro de Itapemirim are distributed in the following manner: Profiles 1, 2 and 3 are in the domain of the Santa Angélica Intrusive Suite, and Profiles 4 and 5 are at the boundary between the Santa Angélica Suite and the Paraíba do Sul Complex.

A hand sample was collected and sent to the National Museum (UFRJ), where a thin section was prepared for petrographic analysis. The thin section was analyzed with a polarized light optical microscope at the PUC-Rio Geotechnical and Environmental Laboratory.
2.2. Methods

2.2.1. CCNBD Fracture Toughness Method

The present research followed the methodology described in the “Suggested Method for Determining Mode I Fracture Toughness Using Cracked Chevron Notched Brazilian Disc (CCNBD) Specimens” (ISRM3). The method requires a cylindrical specimen with a V-shaped notch (or chevron), as detailed in Figure 2.

The first step to perform this method is to create the notch in the specimen. The purpose of the notch is to stably induce the propagation of cracks, radially outwards, from the tip of the notch until the point in which the Fracture Toughness is evaluated, equivalent to the point of maximum load. For a pure Mode I test, the notch orientation must be exactly along the loading diameter.

According to ISRM3, the average stress intensity loading rate during the test must not be less than $0.25 \text{ MPa} \sqrt{\text{m sec}}$, or such that failure occurs within 20 sec of initial load application. In this study, the applied loading rate was $0.0025 \text{ mm/min}$.

The CCNBD tests were performed with the use of clip-gauge extensometers in order to control the displacement at the opening of the notch and to obtain more precise data. This allows for the displacement curve behavior of the material to be analyzed after failure has occurred.

The Fracture Toughness of a specimen should be calculated according to the following equation:

$$K_{IC} = \frac{P_{max}}{B\sqrt{D}} y'_{min}$$

Equation 1: Fracture Toughness formula

Where:

- $P_{max}$: maximum applied force;
- $B$: specimen thickness;
- $D$: specimen diameter;
- $y'_{min}$: critical (minimum) dimensionless stress intensity value for the specimen;
- $y'_{min}$: determined by the geometrical dimensions of the specimen ($\alpha_0$, $\alpha_1 e \alpha B$), calculated according to the equation below:
  $$y'_{min} = u \ e^{v \alpha_1}$$

where:

- $u$ and $v$ are constants determined by $\alpha_0$ e $\alpha_0$.

The values for the constants $u$ and $v$ can be determined by a table presented in the ISRM3 method, and can be interpolated in case the alpha values are not present in the table.
The Fracture Toughness ($K_{IC}$) calculation was based on the ISRM\textsuperscript{3} recommended specimen dimensions presented in Table 1, which also provides the dimensionless factors for a 75 mm diameter specimen.

**Table 1.** Standard geometric dimensions for CCNDB specimens suggested by ISRM\textsuperscript{3}.

| Descriptions                        | Values | Dimensionless expression |
|-------------------------------------|--------|--------------------------|
| Diameter D (mm)                     | 75.0   |                          |
| Tickness B (mm)                     | 30.0   | $\alpha_B = \frac{B}{R} = 0.80$ |
| Initial chevron notched crack length $\alpha_0$ (mm) | 9.89   | $\alpha_0 = \frac{a_0}{R} = 0.2637$ |
| Final chevron notched crack length $\alpha_1$ (mm) | 24.37  | $\alpha_1 = \frac{a_1}{R} = 0.65$ |
| Saw diameter $D_s$ (mm)             | 52.0   | $\alpha_s = \frac{D_s}{D} = 0.6933$ |
| Cutting depth $h_c$ (mm)            | 16.95  |                          |
| $\gamma_{\min}$ (dimensionless)    | 0.84   |                          |
| $\alpha_m$ (mm)                    | 19.31  | $\alpha_m = \frac{a_m}{R} = 0.5149$ |

According to ISRM\textsuperscript{3}, two LVDT transducers should be placed perpendicularly to the upper and lower bases of the equipment, together with two magnetic supports. The LVDT transducers should be located as close as possible to the loading point, as illustrated in Figure 3. In this study, it was not possible to place the magnetic supports and thus, two rods and an acrylic support were used to position the LVDT transducers.
Figure 3. Experimental CCNDNDB Fracture Toughness test.

3. Results

3.1. Physical properties

The physical properties obtained were porosity, bulk density and specific weight, whereas these define the basic relations of the rock. All tested specimens were previously characterized. Table 2 presents the results for the physical properties in four granites.

| Physical properties | Pereira Nunes (2020) Syenogranite | Almeida et al. (2006) Favela granite | Almeida et al. (2006) Utinga granite | Jaques (2019) Syenogranite |
|---------------------|----------------------------------|-------------------------------------|-------------------------------------|--------------------------|
| Porosity (%)        | 1,16                             | 0,76                                | 0,79                                | 0,80                     |
| Bulk density (g/cm³) | 2,61                             | 2,66                                | 2,60                                | 2,67                     |
| Specific weight (kN/m³) | 25,57                            | 26,07                               | 25,53                               | 26,19                    |

In Table 2, it is possible to observed that the physical properties results obtained in the present study were very similar to the results obtained by Almeida et al.⁴ in the Favela granite and Utinga granite and by Jaques⁵ in syenogranite.

3.2. Brazilian Disk

Fifteen (15) Brazilian Disk tests were performed, of which four (4) specimens were cut in a short-transverse orientation, five (5) in an arrester orientation and six (6) in a divider orientation. Figure 4 depicts four specimens in different cutting orientations.
Figure 4. Specimens for the CCNBD test in three orientations (a) short-transverse, (b) arrester, (c) divider and (d) random direction.

Table 3 presents the results for the mean tensile strength value for each specimen orientation.

| Cutting orientations | $\sigma_t$ (MPa) |
|----------------------|------------------|
| Short transverse     | 8.28             |
| Arrester             | 8.79             |
| Divider              | 7.87             |

The information presented in Table 3 shows that the values of the mean tensile strength obtained in the short transverse, arrester and divider directions are very similar, which indicates that there is little anisotropy in this rock.

Table 4. Mean Tensile Strength results by cutting orientation in four granites.

| Cutting orientations | Pereira Nunes (2020) Syenogranite $\sigma_t$ (MPa) | Almeida et al. (2006) Favela granite $\sigma_t$ (MPa) | Almeida et al. (2006) Utinga granite $\sigma_t$ (MPa) | Jaques (2019) Syenogranite $\sigma_t$ (MPa) |
|----------------------|---------------------------------------------------|-----------------------------------------------|-----------------------------------------------|------------------------------------------|
| Short transverse     | 8.30                                              | 8.00                                          | 6.30                                          | 9.70                                     |
| Arrester             | 8.80                                              | 8.40                                          | 5.70                                          |                                          |
| Divider              | 7.90                                              | 7.40                                          | 7.30                                          |                                          |

In Table 4, it is possible to observed that the tensile strength results obtained in the present study were very similar to the results obtained by Almeida et al.\(^4\) in the Favela granite and by Jaques\(^5\) in syenogranite.

3.3. CCNBD Test

A total of twenty-five (25) CCNBD tests were conducted, of which six (6) specimens were cut in a short-transverse orientation, five (5) in an arrester orientation, six (6) in a divider orientation and eight (8) in a random direction orientation. Figure 5 depicts three specimens in different cutting orientations.
**Figure 5.** Specimens for the CCNBD test in three orientations (a) short-transverse, (b) arrester, (c) random direction.

Table 5 presents the results for the mean Fracture Toughness value ($K_{IC}$) for each specimen orientation and its normalized ratio with respect to the divider orientation result, $\frac{K_{IC,mean}}{K_{IC,divider}}$.

| Cutting orientations  | $K_{IC,mean}$ ($MPa x m^{0.5}$) | $\frac{K_{IC,mean}}{K_{IC,divider}}$ |
|-----------------------|---------------------------------|-------------------------------------|
| Short transverse       | 0,97                            | 0,92                                |
| Arrester               | 1,13                            | 1,07                                |
| Divider                | 1,06                            | 1,00                                |
| Inclined               | 0,93                            | 0,88                                |

Based on the $\frac{K_{IC,mean}}{K_{IC,divider}}$ ratio, it was possible to analyze the anisotropy of the rock more precisely. The resulting ratio for the short-transverse, arrester, and inclined orientations were all close to 1.00, indicating that the studied rock possesses little anisotropy.

The mean Fracture Toughness values from the present research as well as from other studies are presented in Table 6. Almeida et al.\textsuperscript{4} performed CCNBD tests on granites collected in the City of Rio de Janeiro in order to determine the Fracture Toughness in the three cutting directions. The results of these studies can be compared due to the similarities between the sampled rocks.

**Table 6.** Mean Fracture Toughness results by cutting orientation in three granites.

| Cutting orientations  | Pereira Nunes (2020) | Almeida et al. (2006) | Almeida et al. (2006) |
|-----------------------|----------------------|----------------------|----------------------|
| Syenogranite          |                      | Favela granite       | Utinga granite       |
| Short transverse       | 0,97                 | 0,97                 | 0,60                 |
| Arrester               | 1,13                 | 0,90                 | 0,73                 |
| Divider                | 1,06                 | 1,16                 | 0,82                 |
| Inclined               | 0,93                 | ***                  | ***                  |
It can be observed that the Fracture Toughness results from this study are of similar value to the Fracture Toughness results obtained by Almeida et al.\(^4\) for the Favela granite. It should be noted that the Utinga granite (Almeida et al.\(^4\)) presents lower fracture toughness values compared to both the Favela granite (Almeida et al.\(^4\)) and the syenogranite.

In the experiments conducted on the Favela granite specimens (Almeida et al.\(^4\)), the lowest resistance occurred in the arrester orientation (2), followed by the short transverse orientation (1) and lastly by the divider orientation (3). These results did not coincide with what is identified in the field\(^1\)\(^2\) (Almeida et al.\(^4\)). On the other hand, the results from the tests conducted on the Utinga granite (Almeida et al.\(^4\)) followed the expected behavior, in which the lowest resistance occurred in the short transverse orientation (1), followed by the arrester orientation (2) and lastly by the divider orientation (3).

Similarly to the behavior observed in the Favela granite (Almeida et al.\(^4\)), the results in this study did not follow the expected order. Figure 6 presents the Fracture Toughness results obtained as a function of the cutting orientation (short-transverse, arrester, divider and inclined).

![Figure 6: CCNBD Fracture Toughness results as a function of the cutting orientation.](image)

The experimental results indicated an outlier in the short transverse orientation, below the expected standard \(KIC (0.73 \text{ MPa m}^{0.5})\). The results in the short-transverse and inclined orientations presented the largest dispersion, while the divider results presented the smallest variation. The Fracture Toughness results obtained in the short transverse and inclined orientations demonstrated a similar range of values. Despite the observed differences, the Fracture Toughness results were close in value for all orientations, indicating little anisotropy.

4. Conclusion

The main purpose of this study was to better understand the existence of anisotropy in the Fracture Toughness of granitic rocks. In addition, the study also sought to assess the relationship between Fracture Toughness and the physical and mechanical property of rocks. The Brazilian Tests presented values within the expected order of magnitude. The tensile strength results of the studied granitic rocks were similar to the values obtained by Almeida et al.\(^4\) for Favela granite and by Jaques\(^5\) for syenogranite. Since the experimental results were similar in all orientations, isotropic tensile strength was confirmed in the studied granite.

The Fracture Toughness results in the different cutting orientations were also similar to those obtained by Almeida et al.\(^4\) for Favela granite. The experimental results were similar in all orientations and thus did not indicate an anisotropic behavior related to fracture propagation in the studied granite.

The ISRM\(^3\) CCNBD method demonstrated adequate applicability, presenting no major difficulties in terms of preparation, execution and data interpretation.
References

[1] Caruso LG, Braga TO 1991 Granites and marbles in the state of S. Paulo. In: Principal mineral deposits in Brazil. Brasilia, Brazil: DNPM (National Department of Mineral Production), CPRM; p. 399–409

[2] Almeida LCR, Marques EAG, Vargas Jr E do A, Barros WT 1998 Characterisation and utilisation of tensile strength and toughness of granitic and gneissic rocks from Rio de Janeiro — A proposal for optimisation of rock blasting processes. Eighth congress of the international association of engineering geology, IAEG, Vancouver, Canada. p. 351–7.

[3] ISRM 1995 Determining mode I fracture toughness: suggested method for determining mode I fracture toughness using cracked chevron notched Brazilian disc (CCNBD) specimens. Int J Rock Mech Min Sci Geomech Abstr;32:57–64.

[4] Almeida, LCR; Vargas Jr E do A; De Figueiredo, R P 2006 Mechanical characterization of rock splitting planes in granitic rocks. International Journal of Rock Mechanics and Mining Sciences, v. 43, n. 7, p. 1139–1145.

[5] Jaques, D 2019 Morphological, mineralogical and geomechanical characterization of weathering profiles of granitic rocks in tropical climate. Doctoral thesis, Federal University of Viçosa, Minas Gerais.

[6] Prikryl R 2001 Some microstructural aspects of strength variation in rocks. Int J Rock Mech Min Sci; 38:671–82.

[7] Nasseri, MHB & Mohanty, B 2007 Fracture toughness anisotropy in granitic rocks. International Journal of Rock Mechanics and Mining Sciences.

[8] Ouchterlony, F 1980 Compliance measurements on notched rock cores in bending. Stockholm: Swedish Detonic Research Foundation. Report DS.

[9] Schmidt, RA 1976 Fracture toughness testing of limestone. Experimental Mechanics, Esaton, v. 16, p. 161-167.

[10] Alvarez, HIP 2004 Non-conventional tests for determining the fracture toughness in rocks: analysis and comparison. Master's thesis. São Carlos School of Engineering, University of São Paulo, São Carlos, p. 13-15.

[11] Almeida, FFO 1977 Cráton San Francisco. Brazilian Journal of Geosciences, v. 7, n. 4.

Acknowledgments

The authors wish to thank Geol. Wilmar T. de Barros from the Geotechnical Control Office of the municipality of Rio de Janeiro (Geo-Rio) for helping find the three mutually orthogonal surfaces. They wish to thank the Coordination for the Improvement of Higher Education Personnel (CAPES) for the financial support of the first author for his graduate program at the Civil and Environmental Engineering Department of Catholic University of Rio de Janeiro, Brazil.