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Mechanical behaviour of granite with naturally occurring open joints under compression

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Abstract

Understanding the mechanical behaviour of jointed rock masses is crucial in a rock engineering environment. In order to comprehend this, laboratory investigations on rock materials with pre-existing flaws are useful. Natural rock joints with distinct surface characteristics are likely to behave differently in comparison with laboratory-fabricated fractures. Despite numerous investigations conducted by previous researchers on natural rocks or rock-like materials with artificial or fabricated fractures, a comprehensive experimental investigation of rocks with naturally occurring joints requires further exploration. This article aims to understand the mechanical behaviour of brittle rock materials containing persistent and open naturally existing joints, having varying surface orientation and characteristics, under different stress conditions. In this regard, core specimens of Malanjkhand granite (from the state of Madhya Pradesh, India) with pre-existing natural joints having inclination ranging from 15° to 55° with respect to the core axis were tested under uniaxial compression as well as under triaxial compression (with displacement-controlled mode of loading) at confining pressures of 5 MPa and 10 MPa. Test data were analysed, and it was found that the strength and deformational behaviour of the jointed samples primarily depended on the joint orientation rather than on the surface characteristics. Although failure through the intact material was not uncommon, sliding and/or shearing were found to be the primary failure mechanism. Specimen failure patterns were also scrutinized with reference to the specimen strength and joint orientation.

Keywords

Rock Joints, Uniaxial and Triaxial compression test, Granite, Strength, Failure pattern

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1 Introduction

The existence of discontinuities (joints, faults, weak planes, etc.) in rock materials is of primary concern for the stability and safety of designs in rock engineering environments. Research on persistent and non-persistent joints indicates that the mechanical behaviour of rock masses in natural conditions is also influenced by the properties of joint surfaces, their orientation, and the infilling materials (Rosso 1976; Barton 1976; Ramamurthy 2001; Yang and Huang 2017). Since several engineering activities occur within the in-situ rock masses, the study of the behaviour of naturally occurring joints is essential. For this, numerous research studies were carried out on the prepared jointed specimens with varying inclination angles and surface characteristics on rock-like materials or artificially created joints on the natural rock materials to examine the influence and behaviours of the joint on rock masses (Ramamurthy and Arora 1994; Fahimifar and Soroush 2005; Cao et al. 2017; Tang et al. 2022). However, it was found that naturally existing joints exhibit different strength and mechanical properties compared to artificially produced joints, even when the rock type and surface features are similar.

Singh and Basu (2016) performed direct shear tests on naturally jointed granite specimens and compared the results with those of produced replica specimens. Their analysis revealed the disparity in shear mechanical and deformational behaviour, even after the joint surface is reproduced. Vogler et al. (2017) artificially induced tensile fractures in granodiorite specimens to examine the variations in surface roughness characteristics from natural tensile and shear fractures and a computational technique was also employed for their investigation. Despite the numerical fractal model revealing no significant differences between natural and artificial fracture surfaces, a notable difference exists between laboratory-scale and natural-scale fracture surfaces, which cannot be ignored as the joint strength is one of the key parameters for the rock mass strength calculation.

Previous research shows that most tests on natural joints were performed using direct shear apparatus. However, at in-situ field conditions, the strength and behaviour of rock masses depend on the surrounding stresses as well as on the controlling effect of joint interlocking and orientation. The study of Gao et al. (2020) on the effect of closed joints on the natural jointed marble specimens under true triaxial compression reveals that the compressive strength of the rock exhibits varying trends with increasing joint inclination angle at different confining pressures but, at a specific confining pressure, strength diminishes as the inclination angle increases. Liu et al. (2024) studied the influence of the presence of closed natural joints and joint networks on hard rock on the strength and failure characteristics of rock masses under uniaxial compression. From the previous literature, it becomes apparent that more detailed investigations need to be carried out to examine the mechanical behaviours of naturally occurring persistent joints under triaxial compressive loading conditions. The present study aims to provide additional insights into this issue by examining naturally occurring open and matched granitic joints having different inclination angles under uniaxial and triaxial compression. “A comprehensive study on rock failure modes is, therefore, potentially important to stabilize engineering rock masses. It helps recognize the adequacy of the support designed on the basis of the nature of the engineering work” (Basu et al. 2013). Thus, the failure patterns of the jointed specimens were also analysed.

2 Methodology

2.1 Sample geology

The granitic samples used in this study are provided by Hindustan Copper Ltd. from the Malanjkhand area of Balaghat district, Madhya Pradesh, India. The fresh pink and grey-coloured granitic core samples, drilled from the Malanjkhand Granitoids complex of Paleoproterozoic age (~2,400 Ma), primarily consist of quartz, plagioclase, and alkali feldspar (Fig. 1). These rocks are mainly characterized by the presence of mica that have undergone deuteric alterations in the form of saussuritization of plagioclase, breakdown of hornblende and chloritization of biotite (Fig. 1) (Panigrahi et al. 2004).

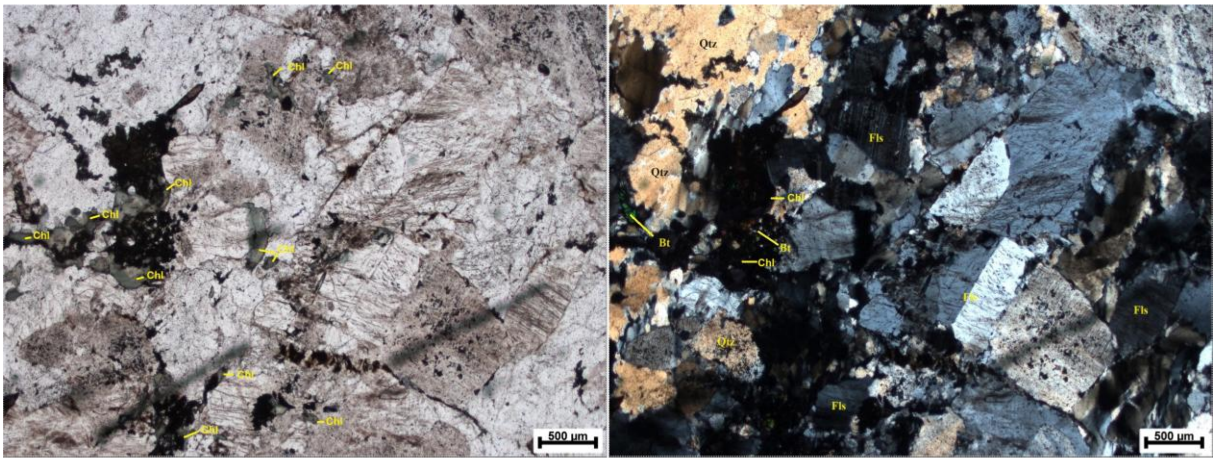

Fig. 1 A representative photomicrograph of Malanjkhand granite under plane-polarised and cross-polarised light. (Qtz-Quartz, Fls-Feldspar, Bt-Biotite, Chl-Chlorite).

2.2 Specimen Preparation

The cylindrical granitic core of diameter approx. 47.5 mm having natural, single, open and matched joints were selected from the provided core samples. The samples were cut carefully to prepare the specimens of size having length-diameter ratio ≈ 2 - 2.5 for uniaxial and triaxial compression test, according to ASTM D4543 (2001) stipulations (Fig. 2). The single, matched joints are then wrapped together using cling film and then polished to meet the parallelism tolerance. The specimens were air-dried to constant mass and again wrapped using cling film before the test. The wrapper used is strong enough to hold the joints together without affecting the mechanical behaviour of the jointed specimens.

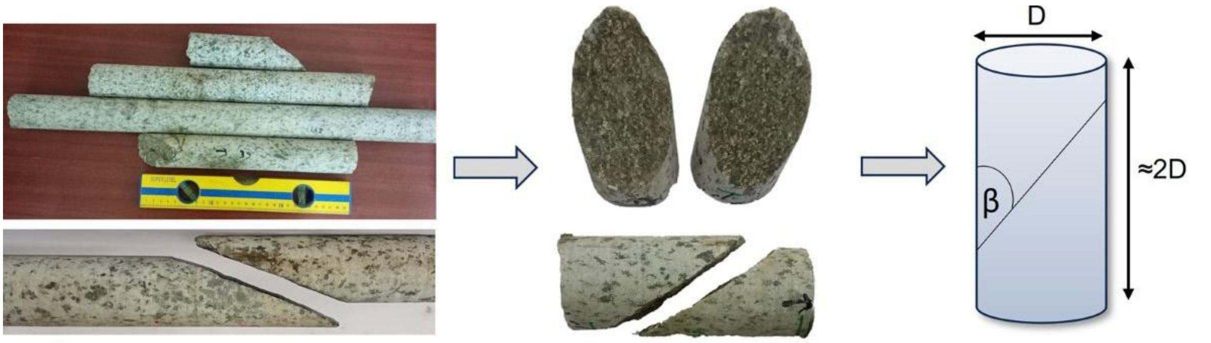

Fig. 2 Representative jointed samples used in this investigation.

2.3 Test set-up and procedure

Before wrapping the specimens for the triaxial compression test, the dip of the joint surface (β) was determined with respect to the loading axis using a goniometer. Then, the joint surface roughness profile was measured using Barton's comb and profilometer to compare with the standard JRC chart by Barton and Choubey (1977). The JRC value of most of the specimens used was found to be within the range between 2 – 4, otherwise 4 – 6. However, in this study, the JRC value was not considered for joint strength measurement, but the surface roughness was kept similar within the specimens for joint behaviour analysis.

All the experiments performed on the jointed granitic specimens under uniaxial and triaxial compression, following the ASTM D2938 and D2664 (2001) stipulations, were done using a servo-controlled conventional triaxial compression test machine with a loading capacity of 2000 kN (HEICO©) (Fig. 3). The LVDT sensor attached to the apparatus can measure the axial displacement with an accuracy of 0.001 mm. The predetermined confining pressure was sustained using the triaxial system software.

All the tests were performed at room temperature and under a constant displacement-controlled mode of loading. The confining pressures of 0 MPa, 5 MPa and 10 MPa were considered for triaxial compression tests. The confining pressure applied rises gradually to the desired level before the load is provided to the specimen. Then, the axial load was applied at the displacement rate of 0.6 mm/min, and the load-displacement raw data was recorded.

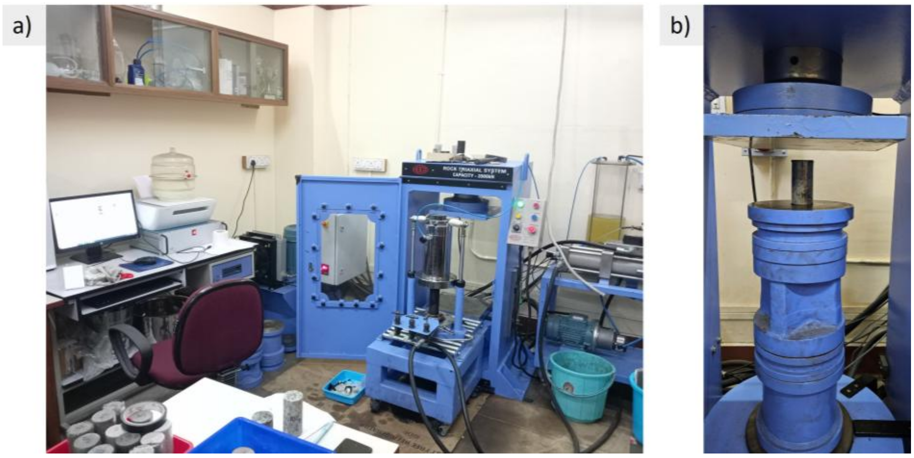

Fig. 3 Servo-controlled rock triaxial testing machine for a) triaxial compression and b) uniaxial compression tests.

3 Results and Interpretation

3.1 Characteristics of stress-strain curve

Figure 4 illustrates the axial stress-strain curve for jointed granite specimens subjected to uniaxial compression at various inclination degrees. As observed from the plots in Fig. 4, the jointed specimens either acquire a maximum stress value early in the curve and are subsequently stable at a residual state or, after attaining a peak value, experience complete failure. The existence of a peak in the plots of Fig. 4 indicates the brittle nature of jointed granite specimens. The interlocking of the joint surfaces results in an increase in the stress value. The failure of the interlocks yields a consistent residual value, leading to displacement on the joint surface even under minimal applied stress. In some cases, where interlocking is robust and the likelihood of joint surface shearing is negligible, specimen failure is characterised by a sudden drop in stress value.

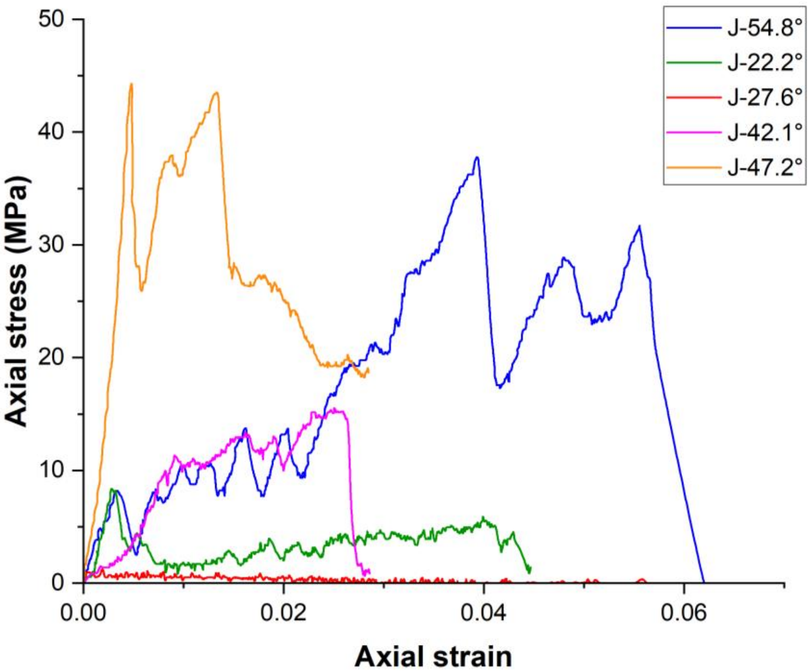

Fig. 4 Axial stress-strain plot at different joint inclination angles under uniaxial compression.

Ramamurthy and Arora (1994) noted a U-shaped pattern for soft rock, like sandstone, and a shoulder-shaped pattern for hard rock, such as granite, when the uniaxial compressive strength is plotted against the orientation of the joint plane. Similarly, Gao et al. (2020) indicated that a U-shaped pattern was observed in the graph illustrating the strength in relation to the dip angle of the joint surface under uniaxial compression for close-jointed marble. However, when the peak strength is plotted against β, in this study, under uniaxial compression, an S-shaped pattern is observed for natural, open-jointed granite specimens, is shown in Fig. 5.

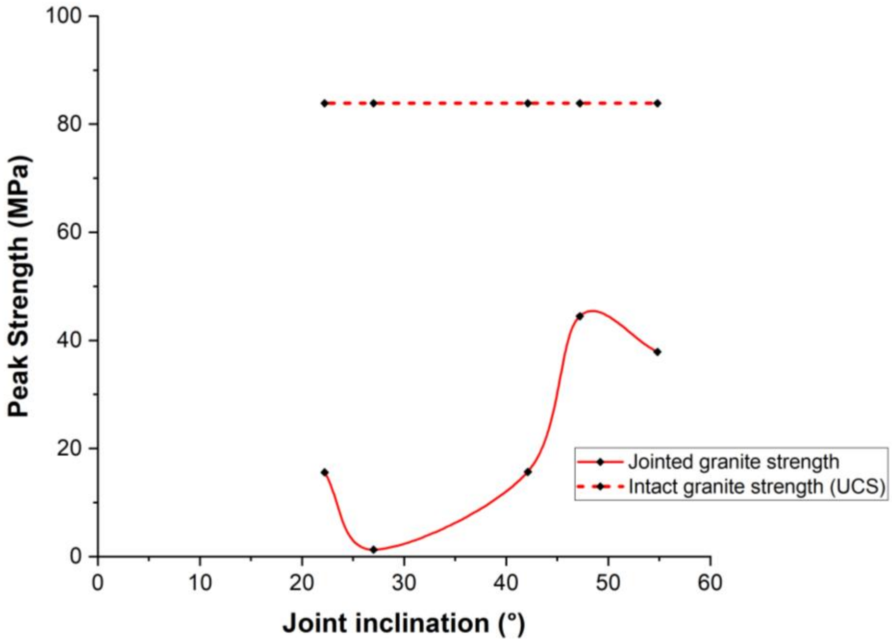

Fig. 5 Peak strength of jointed granite against joint inclination.

Figure 5 illustrates that the uniaxial compressive strength is lowest at β values of 25°–30° and maximum at 50°–55°. The minimum strength value is observed at critical joint inclination closer to $\beta = (45° + \phi / 2)$ as demonstrated in the existing literature. An increasing strength is noted before and subsequent to the critical β value. From the microscopic studies, it was found that the used granitic rock samples, which are compositionally inhomogeneous, have experienced hydrothermal alteration (Fig. 1). The pre-existing open joints have provided the conduit for the circulation of hydrothermal fluid along the joint under deep-seated conditions. Consequently, the joint surfaces have undergone varying degrees of alteration due to immediate interaction with hot, mineral-rich fluids, leading to different mineralogical compositions, including minerals such as chlorite and fibrous minerals like asbestos, as evidenced by the macroscopic inspection of the rock masses (Fig. 7). The formation of soft and silky minerals on the surfaces reduces the frictional resistance and shear strength along the joints may account for the less increase in strength at low β angles and decrease in strength at $\beta > 55°$. The above discussion might explain the different trends of the peak strength vs. joint angle curve from previous literature.

To characterise the behaviours of naturally jointed granite specimens (having inclinations within 35°–45° range) under triaxial compression, a stress-strain curve is plotted for the test conducted at confining pressures of 0 MPa, 5 MPa and 10 MPa (Fig. 6). The previous research literature (Hoek 1983; Tiwari and Rao 2007; Arzúa et al. 2014; Alejano et al. 2017) reported that the strength of jointed specimens rises as the confining pressure is increased. However, from the graphs in Fig. 6, a decreasing trend is observed for jointed rock triaxial strength with increasing confining pressure. The possible reasons may be due to the difference in joint surface material and roughness characteristics of the specimens that can be seen from the figures in Fig. 7. The joint surface is showing different degrees of hydrothermal alteration, like chloritization and fibrous mineral formation, which also influence the roughness characteristics of the joint surface. This is restraining the confining pressure from exerting its usual effect on the strength of jointed rock.

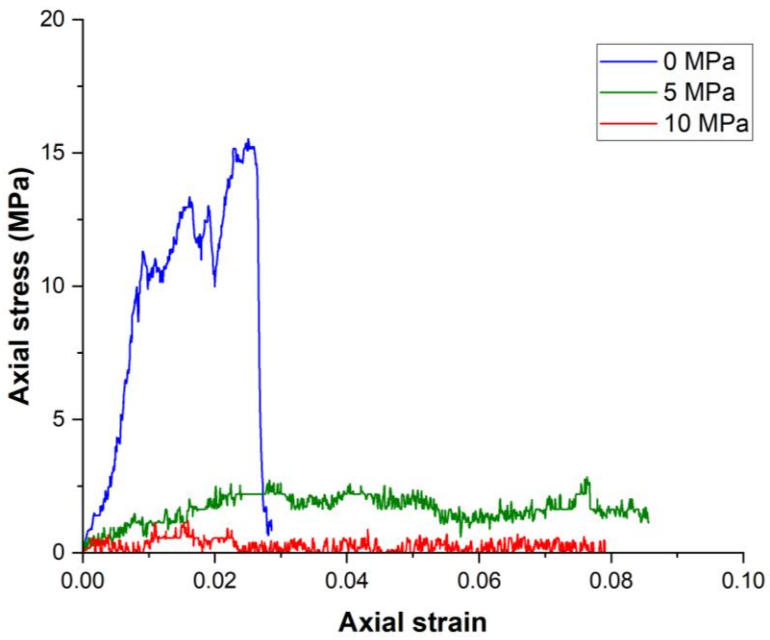

Fig. 6 Axial stress-strain plot under different confining pressures. *Note: investigated joint surfaces are considerably different in terms of roughness and surface materials because of different degrees of hydrothermal alteration (refer Fig. 7). The confining pressure does not portray its typical influence on the jointed rock strength.*

3.2 Failure patterns

Numerous researchers, including Fahimifar and Soroush (2005), Yang and Huang (2017), Song et al. (2022), and Wang et al. (2023), have investigated the failure mode exhibited in inclined jointed specimens. Multiple failure modes were seen in the specimens, including splitting of the intact part, shearing along the joint, splitting through the jointed surface, shearing through the jointed surface, sliding along the joint, and combinations of various failure modes. The failure mode of the jointed specimens is dependent upon the degree of asperity and the interlocking of asperities along the joint surface.

In this study, three types of failure modes were identified: splitting of the intact section (Fig. 7a), shearing along the joint (Fig. 7b), and sliding along the joint (Fig. 7c). Under the uniaxial compression test, joint failure occurs in sliding or shearing along the joint at low β (20°–35°), and as the inclination angle increases, failure mode evolves from shearing along the joint to splitting of the intact part (for β > 50°) of the jointed rock, along with shearing of roughness on the joint surface due to enhanced stability from interlocking of asperities. These three failure modes are also observed with the application of confining pressure. At the confining pressures of 5 MPa and 10 MPa, the shearing of high-degree asperities on the joint surface leads to sliding along the joint, as depicted in Fig. 7b and 7c, respectively. Under low confining pressure, once the initial degree of asperity is sheared off, and if the succeeding degree of asperity interlocking becomes stable, the intact portion undergoes splitting, with the fracture appearing to originate from the joint surface. The mechanism of joint failure can also be interpreted from the stress-strain curve. Shearing along the joint type is evident in the stress-strain graph, where the curve displays residual values after reaching the peak while sliding along the joint is indicated if the curve lacks peak values (Fig. 4). The significant, abrupt decline in the peak value (Fig. 4) reflects the failure mode marked by splitting of the intact section of the jointed granite specimens. The presence of multiple peak values in the stress-strain curve indicates varying degrees of shearing among the interlocking asperities.

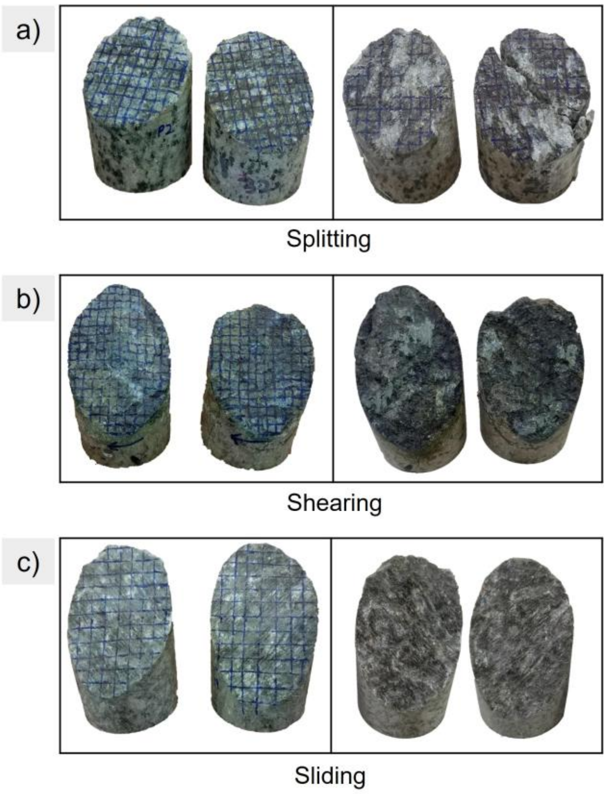

Fig. 7 Failure pattern at different confining pressure and joint inclination angle.

4 Conclusions

The uniaxial compression test and the triaxial compression test at confining pressures of 5 MPa and 10 MPa were conducted under a constant displacement rate on single inclined open-jointed granite specimens to investigate the mechanical behaviours of naturally occurring joints having different inclination angles varying in the range from 25°-55°. It is observed that the uniaxial compressive strength increases with an increase in joint inclination angle, illustrating an S-shaped trend. However, the triaxial compressive strength of the joint decreases with the increase in confining pressure from 0 MPa to 10 MPa, deviating from its usual behaviour due to different joint surface material properties and roughness parameters. Three types of failure modes were identified in the jointed granite specimens both under uniaxial and triaxial compression, i.e., splitting of the intact part of the jointed rock, shearing along the joint, and sliding along the joint. As the inclination angle increases under uniaxial compression or the confining pressure increases under triaxial compression, the failure mode changes from splitting of the intact part to shearing along the joint to sliding along the joint. Since the specimens utilised here are naturally existent joints, this study tends to more precisely simulate the impact of joints on the mechanical characteristics of rock masses under its field conditions.

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References

ASTM D4543, Standard practice for preparing rock core specimens and determining dimensional and shape tolerances, ASTM Standards on Disc, 04.08 (2001)

ASTM D2938, Standard test method for unconfined compressive strength of intact rock core specimens, ASTM Standards on Disc, 04.08 (2001)

ASTM D2664, Standard Test Method for Triaxial Compressive Strength of Undrained Rock Core Specimens Without Pore Pressure Measurement, ASTM Standards on Disc, 04.08 (2001)

Alejano LR, Arzúa J, Bozorgzadeh N, Harrison JP (2017) Triaxial strength and deformability of intact and increasingly jointed granite samples. Int J Rock Mech Min Sci 95:87–103. https://doi.org/10.1016/j.ijrmms.2017.03.009

Arzúa J, Alejano LR, Walton G (2014) Strength and dilation of jointed granite specimens in servo-controlled triaxial tests. Int J Rock Mech Min Sci 69:93–104. https://doi.org/10.1016/j.ijrmms.2014.04.001

Barton N (1976) The shear strength of rock and rock joints. Int J Rock Mech Min Sci Geomech Abstr 13:255–279. https://doi.org/10.1016/0148-9062(76)90003-6

Barton N, Choubey V (1977) The shear strength of rock joints in theory and practice. Rock Mech 10:1–54. https://doi.org/10.1007/BF01261801

Basu A, Mishra DA, Roychowdhury K (2013) Rock failure modes under uniaxial compression, Brazilian, and point load tests. Bull Eng Geol Environ 72:457–475. https://doi.org/10.1007/s10064-013-0505-4

Cao R, Cao P, Lin H, Fan X (2017) Experimental and numerical study of the failure process and energy mechanisms of rock-like materials containing cross un-persistent joints under uniaxial compression. PLOS ONE 12: e0188646. https://doi.org/10.1371/journal.pone.0188646

Fahimifar A, Soroush H (2005) Effect of time on the stress–strain behaviour of a single rock joint. Bull Eng Geol Environ 64:383–396. https://doi.org/10.1007/s10064-005-0003-4

Gao Y, Feng X-T, Wang Z, Zhang X (2020) Strength and failure characteristics of jointed marble under true triaxial compression. Bull Eng Geol Environ 79:891–905. https://doi.org/10.1007/s10064-019-01610-2

Hoek E (1983) Strength of jointed rock masses. Géotechnique 33:187–223. https://doi.org/10.1680/geot.1983.33.3.187

Liu M, Bi R, Luo X, Du K (2024) Natural joint effect on mechanical characteristics and fracture evolution of In-Site rocks under uniaxial compression. Eng Fail Anal 157:107880. https://doi.org/10.1016/j.engfailanal.2023.107880

Panigrahi MK, Bream BR, Misra KC, Naik RK (2004) Age of granitic activity associated with copper–molybdenum mineralization at Malanjkhand, Central India. Miner Deposita 39:670–677. https://doi.org/10.1007/s00126-004-0441-0

Ramamurthy T (2001) Shear strength response of some geological materials in triaxial compression. Int J Rock Mech Min Sci 38:683–697. https://doi.org/10.1016/S1365-1609(01)00035-1

Ramamurthy T, Arora VK (1994) Strength predictions for jointed rocks in confined and unconfined states. Int J Rock Mech Min Sci Geomech Abstr 31:9–22. https://doi.org/10.1016/0148-9062(94)92311-6

Rosso RS (1976) A comparison of joint stiffness measurements in direct shear, triaxial compression, and In Situ. Int J Rock Mech Min Sci Geomech Abstr 13:167–172. https://doi.org/10.1016/0148-9062(76)91282-1

Singh HK, Basu A (2018) A Comparison Between the Shear Behavior of 'Real' Natural Rock Discontinuities and Their Replicas. Rock Mech Rock Eng 51:329–340. https://doi.org/10.1007/s00603-017-1334-8

Song L, Wang G, Wang X, et al (2022) The Influence of Joint Inclination and Opening Width on Fracture Characteristics of Granite under Triaxial Compression. Int J Geomech 22:04022031. https://doi.org/10.1061/(ASCE)GM.1943-5622.0002372

Tang J-Z, Yang S-Q, Tian W-L, Tao Y (2022) Effect of confining pressure on mechanics and deformation behavior of sandstone containing a single inclined joint. Eur J Environ Civ Eng 26:1022–1045. https://doi.org/10.1080/19648189.2019.1694076

Tiwari RP, Rao KS (2007) Response of an Anisotropic Rock Mass under Polyaxial Stress State. J Mater Civ Eng 19:393–403. https://doi.org/10.1061/(ASCE)0899-1561(2007)19:5(393)

Vogler D, Walsh SDC, Bayer P, Amann F (2017) Comparison of Surface Properties in Natural and Artificially Generated Fractures in a Crystalline Rock. Rock Mech Rock Eng 50:2891–2909. https://doi.org/10.1007/s00603-017-1281-4

Wang T, Elsworth D, He Y, et al (2023) Impact of loading rate on the mechanical behavior of jointed rock. Geomech Geophys Geo-Energy Geo-Resour 9:127. https://doi.org/10.1007/s40948-023-00669-2

Yang S-Q, Huang Y-H (2017) An experimental study on deformation and failure mechanical behavior of granite containing a single fissure under different confining pressures. Environ Earth Sci 76:364. https://doi.org/10.1007/s12665-017-6696-4