An experimental approach to evaluate the role of rock failure modes in mechanical characterization of metabasalts

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Research Article

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Abstract

A detailed understanding on rock failure modes testifies the competence of support designs for engineering work. Studying such failure modes using physical models of rock samples under laboratory conditions can be time efficient, informative and economically viable. In this study, the mechanical behavior of massive metabasalts were characterized with reference to rock failure modes through index tests such as point load and Brazilian testing conditions. Rock failure modes under point load test are categorized as i) single plane failure mode, ii) triple junction failure mode, iii) twisted failure mode and iv) single plane (inclined). It is observed that twisted and triple junction failure modes are observed for the samples with higher point load strength values (> 6 MPa). A total of five types of rock failure modes were observed in metabasalts under Brazilian testing conditions such as i) central multiple, ii) central, iii) non-central, iv) central multiple + layer activation and v) conjugate failure modes. Central multiple failure mode is found to be the most common failure mode in metabasalts due to its massive nature. It is also observed that all failure modes under Brazilian test are transpired in the range of 8 to 12 MPa. Among all other perceived rock failure modes, single plane (inclined) and conjugate failure modes under point load and Brazilian tests respectively are introduced in this study. It is evident that rock failure modes, which lead to control the strength of the rocks, should be considered as an important aspect for mechanical characterization of rock materials.

1. Introduction

Mechanical characterization of rock materials is considered to be the most important component in any engineering geology project (Diamantis et al. 2009). It is well evident from the existing literature that mineral composition, crystal size, rock fabric, alteration degree, weathering and anisotropy are the most important factors which influence the strength and deformation behaviour of intact rocks (Tsidzi 1990; Saroglou 2004; Khanlari et al. 2014). Moreover, we ask do the failure modes provide information on mechanical behaviour of virtually isotropic rocks such as metabasalts, within an external stress field? The study of failure modes in rock mechanics provides an insight regarding the material strength, vis-à-vis inherent fabric of the material (Szwedzicki 2007; Vishnu et al. 2010, 2018). The crystalline rocks preserve a range of micro-flaws leading to the crack initiation, propagation and subsequent failure (Scholz 1968; Martin and Chandler 1994; Eberhardt et al. 1998; Li et al. 2003; Jaeger et al. 2007). The deformation of micro-flaws has significant effect on the strength and failure behaviour of rock masses (Yang et al. 2008; Janeiro and Einstein 2010; Lee and Jeon 2011; Bahaaddini et al. 2013; Zhou et al. 2014; Du et al. 2020). Therefore, a comprehensive study on such aspect is important to analyse the geometric arrangements of particles and micro-flaws (Akesson et al. 2004; Hudyma et al. 2004; Basu 2006; Szwedzicki 2007; Basu et al. 2009). However, there are many challenges, in quantifying or predicting the nature of fracture propagation as well as the mode of failure under compression (Santarelli and Brown 1989; Peng and Johnson 1972). Although, there are no such numerical model that can predict the failure modes, a number of physical models were derived to provide insightful information on the failure modes of crystalline rocks (Hudyma et al. 2004; Santarelli and Brown 1989; Jaeger and Cook

1979; Klein et al. 2001). Failure modes of such physical models when examined carefully under laboratory conditions, it can derive useful information about the presence of inherent micro-flaws (Bieniawski 1984). In line with this, Basu et al., 2013 documented the failure modes in granite, sandstone and schist under uniaxial compression, Brazilian and point load conditions and evaluated the relation between failure mode and mechanical strength of rock materials. Moreover, several researchers (e.g. Tien and Kuo, 2001; Debecker and Vervoort 2009; Tavallali and Vervoort, 2010; Kim et al., 2016) have investigated the failure modes in anisotropic rock materials under different loading conditions. However, the role of failure modes on mechanical behaviour of fine grained brittle massive volcanic rocks such as basalts or metabasalts have not gained significant attention.

Moreover, tensile stress zones frequently occur in the vicinity of rock masses and tensile failure has been recognized as the primary failure mode in several rock excavation projects such as in the construction of tunnels and mines (Xue et al. 2020). Therefore, rock failure modes along the tensional regime are routinely considered as the key factor to characterize the damaging properties of rocks (Li et al. 2013; Liu et al. 2014).

In accordance with the above discussion, we intend to understand the rock failure patterns of metabasalts under different index testing procedures such as point load and Brazilian testing conditions. It should be noted that, under both tensile and point-load testing conditions, the intact rock fails under compression induced tension (Russell and Muir Wood 2009, Masoumi et al. 2018). Moreover, the importance of point load testing in estimating the UCS as well as in geo-mechanical classification of rock masses have been widely discussed by several researchers in the past (Bieniawski 1975; Yin et al. 2017; Xue et al. 2020). In this study, a total of 21 samples were tested under point load testing condition and 16 samples were tested under Brazilian testing condition. The variations in strength index of the metabasalts were discussed subsequently in terms of rock failure modes. Moreover, the P-wave velocity was also used to check the dependence of micro-flaws on the variation of point load strength index of the investigated metabasalts.

2. Sample Collection

Block samples of metabasalt were collected from the exposures in and around Chitradurga, western Dharwar craton (WDC), southern India (Fig. 1a). The metabasalts are dark greyish to blackish, massive to fine grained, altered and devoid of any mesoscopic foliation. The collected blocks were used for core retrieval, and the obtained cores were later investigated for mechanical characterization.

In terms of regional geology, the study area (marked with a rectangular box in Fig. 1b) is a part of the Chitradurga Greenstone Belt (CSB), WDC. Dharwar craton consists of two cratonic blocks; the western (WDC) and the eastern blocks (EDC). Stabilization of this craton is dated back to the accretion of these two tectonic blocks along the Chitradurga Shear Zone (Naqvi and Rogers 1987; Chadwick et al. 2003; Jayananda et al. 2006), at about 2.75-2.51 Ga. The Chitradurga schist belt (CSB) situated in the eastern part of WDC comprises of the gneisses and the younger supracrustals. The latter consists of the

metavolcanics/metabasalts (greenstone belt; greenschist to lower amphibolite facies metamorphism), metamorphosed greywacke-argillite (interbanded with ferruginous chert and banded iron formation), polymict conglomerate, and ferruginous chert. Petrological and geochemical investigation ensures the presence of actinolite, albite, chlorite, epidote, quartz and calcite in the basaltic rocks of the study area (Chakrabarti et al. 2006).

3. Laboratory Investigations

3.1. Sample preparation

Core samples were drilled from the collected blocks in the laboratory. Subsequently, the drilled cores were saw-cut into point load and Brazilian test specimens. The specimen dimensions were maintained as per the specifications of the International Society for Rock Mechanics, ISRM (2007); length-diameter ratio for point load test and Brazilian test were fixed at 1 and 0.5 respectively. All the specimens were air-dried to constant mass before the tests were conducted.

3.2. Experimental setups and testing procedures

A total of 37 intact core samples (21 samples for point load and 16 samples for Brazilian test, Fig. 2a) were prepared. P-wave velocity (V_p) has been determined for each of the point load samples using the Portable Ultrasonic Non-destructive Digital Indicating Tester (PUNDIT) (Fig. 2b) following the ISRM (2007) standards.

For the point load test, a load system of about 100 kN load capacity were used along with a deformation sensor (range = 50 mm; resolution= 0.01 mm) that remains attached with the testing frame. The sample core is placed axially along the line of loading (line joining the two centres on the opposite faces of the sample), in between the two conical platens (see Fig. 2c). The data acquisition system measures the applied load along with the corresponding deformation continuously as a function of time.

The Brazilian testing frame remains fitted within the point load testing system. The sample is placed diametrically inside the testing frame (Fig. 2d). As compression is applied, the sample fails due to induced tensile stress. The corresponding peak load was recorded through the data acquisition system. The failed samples obtained through both the testing procedures are thereby given in (Fig. 2e; point load test) and (Fig. 2f, Brazilian test). The entire testing procedures and determination of the point load strength index, Brazilian tensile strength have been conducted in compliance with ISRM (2007, 2014).

4. Results And Discussion

The calculation of point load strength index ($I_{s(50)}$) and Brazilian tensile strength (BTS) of each specimen was done in accordance to the ISRM (2007). The maximum, minimum and mean values of the mechanical properties of the concerned metabasalt samples are presented in Table 1. The $I_{s(50)}$ values were plotted against V_p in Fig. 3 in order to substantiate the role of inherent microstructure on the

variation of mechanical strength of the rock. It should be noted that the velocity of ultrasonic waves in rocks is commonly used as an index in evaluating microstructure and associated properties of rocks (Basu and Aydin 2006). A positive linear correlation between these two properties with $R^2 = 0.77$ is noticeable (Fig. 3). Moreover, in order to access the role of rock failure modes in strength of the metabasalts, the different failure modes under the point loading condition and indirect tension were subsequently analysed and discussed further.

4.1 Failure modes under Point load test

The rock failure modes in metabasalts conspicuous in this investigation can be classified as Single plane failure mode (i.e. single extensional failure plane containing the line of loading), Triple junction failure mode (i.e. failure along three extensional planes containing the line of loading), Twisted failure mode (i.e. failure along a twisted or curved surface containing the points of loading) and Single plane (inclined) (i.e. single extensional failure plane containing the line of loading, at an angle). It should be noted that the first three rock failure modes were also documented by Basu et al. (2013); however, the last one (i.e. single plane (Inclined)) is introduced in this study which is perceived in a few metabasalt samples. The schematic diagram of rock failure modes in metabasalts are shown in Fig. 4.

The number of samples that failed under different ranges of point load strength with their corresponding failure modes are shown in Fig. 5 and the failed metabasalt samples are shown in Fig. 6. The bar diagram in Fig. 5 depicts that, single plane and single plane (inclined) failure modes occurred at point load strength up to 6 MPa, however, at higher point load strength values i.e. more than 6 MPa, twisted and triple junction failure modes are perceived. It is also evident in this investigation that Twisted failure mode shows a wide range of strength value.

Triple junction failure mode at high point load strength index values implies that it has been generated in order to release the high strain energy. Whereas, twisted failure mode could be attributed due to fracture propagation along selective pathways depending upon the inherent microstructure of those specimens, assisting in rapid release of the stored strain energy. It is also noticed from Fig. 5, that single plane failure mode (i.e. the primary failure mode to be expected under point load conditions) is the most prominent failure mode in metabasalt. Similarly, four of the specimens possess single plane (inclined) failure mode, which could be attributed to the propagation of cracks/micro-flaws at an angle to the line of loading. On a concluding note, it can be said that several rock failure modes may occur under point load testing conditions depending upon the presence of inherent micro flaws which has a significant effect on the strength of the rock materials or rock masses.

4.2 Failure modes under Brazilian test

Several types of failure of disc specimens are possible under Brazilian testing conditions such as 1. Central fracture (failure plane is roughly parallel to the loading direction and located in the central part), 2. Layer activation (failure planes are parallel to the foliation plane), 3. Non-central fracture (Failure planes deviate from the central part and do not correspond to layer activation), 4. Central multiple fractures

(Multiple failure planes parallel to the loading direction and located in the central part) and central or non-central + layer activation (central or non-central failure plane with layer activation). The first three failure modes were proposed based on the investigation of anisotropic rocks whereas the latter ones were included based on a detailed study of both isotropic and anisotropic rock (Basu et al. 2013; and Tavallali and Vervoort, 2010).

Following the above discussed approach, the rock failure modes of metabasalts under indirect testing conditions were classified. Moreover, in this investigation an additional failure mode i.e., conjugate failure mode (with multiple failure planes crossing each other) is also identified in a sample. So, in total five types of rock failure modes i.e., i) central multiple, ii) central, iii) Non central, iv) central multiple + layer activation v) conjugate failure modes were observed in metabasalts under the Brazilian testing conditions. The schematic diagrams of different failure modes perceived in this investigation are shown in Fig. 7. The number of samples which failed under different ranges of tensile strength with their corresponding failure modes are shown in Fig. 8 and the failed metabasalt samples are given in Fig. 9.

From Fig. 8, it is evident that central multiple is the most common failure mode in metabasalts. This could be materialized because of the massive nature of metabasalts, that released high stored strain energy during the loading. However, central multiple + layer activation is perceived in some specimens due to the presence of inherent fracture which got activated during the process of loading. When there are different inherent microfractures present and if they propagate in such a way that fracture planes cross each other, it may result into conjugate fracturing. Although, this is not a common failure mode under the compression induced tension conditions, but this type of failure modes might be a possibility in case of massive rocks, where the inherent micro-flaws are essentially difficult to identify. Under the compression induced tensile stress regime, central failure mode is usually expected which is developed when induced tensional stresses are homogeneously distributed, whereas when such exploitation is not possible, it might develop a non-central failure mode.

This is also evident from Fig. 8 that in between the mean zone of tensile strength of metabasalts (i.e. 8-12 MPa), all the possible failure modes are transpired. This can be conceived that rock materials may fail in any failure mode depending upon the presence and disposition of the inherent micro-flaws. Therefore, investigation of failure modes will prove to be a useful index in the identification of micro flaws or weakness planes in the rock materials. Moreover, from this investigation, it is evident that the rock failure modes can also control the mechanical properties of rock. The mechanical characterization incorporating rock failure modes can therefore, provide a better understanding of the mechanical behaviour of isotropic rocks such as metabasalts and can be insightful for adopting engineering measures.

5. Conclusions

Rock failure modes along the tensional stress regime are characteristically considered as the key factor to characterize the damaging properties of rock masses. It is believed that the variation of rock failure modes significantly affects the strength of the rock materials. Therefore, in this study strength

characterization of metabasalts was demonstrated under the point load and Brazilian tensile strength conditions with reference to their failure modes. It is found that among all other failure modes, single plane is the most prevalent one for point load tests. Moreover, Single plane (Inclined) failure mode is introduced in this study which is materialized in a few metabasalt samples under point load condition. Triple junction and twisted failure modes are also perceived for samples with higher point load strength index, such variation in failure modes are attributed to the internal micro-flaws of the sample. It is also envisaged that central multiple is the most common failure mode among the samples used for Brazilian tests owing to the massive/virtually isotropic nature of the metabasalt samples. Whereas, reactivation of microfractures and propagation of crosscutting fractures yield conjugate fracturing mode, which is also introduced in this study. These results obtained from the point load and Brazilian tensile tests thus ascertain that the fracture propagation paths are governed by the distribution of inherent micro-flaws, that requires further investigation. Under the predominance of such micro-flaws, failure modes tend to deviate from the most expected ones for both the tests, in order to release the high strain energy within a shortest time span. Therefore, we conclude that mechanical characterization and studies made on this aspect can provide a better understanding of the mechanical behaviour of rocks such as metabasalts and can be insightful for adopting engineering measures. The hypothesis on the relationship between the modes of failure and strength of rock samples tested under point load and Brazilian test conditions is presented to incite further investigation on this issue thereby conducting a detailed micro structural analysis through modern techniques such as X-ray micro CT. Such analysis will be insightful in visualizing the internal failure mechanism of micro-flaws that controls the strength and failure modes of rock materials as envisaged from this investigation and can be regarded as the future scope of this work.

Declarations

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Table

Table 1 is available in the Supplementary Files

Figures

Figure 1

Geological map of the study area. (a) Regional map of western Dharwar craton, South Indian Shield (after Chadwick et al., 2003). Inset shows the map of India. EDC = Eastern Dharwar Craton; WDC = Western Dharwar Craton, TTG = Tonalite-Trondhjemitic-Granodiorite; Supracrustals = volcano-sedimentary assemblages. (b) Regional geological map (DEM) of the Chitradurga Schist Belt (modified after Jayananda et al., 2013). Dotted line (in b) marks the eastern boundary of the Chitradurga Schist Belt,

representing the Chitradurga Shear Zone (CSZ). Rectangular box near Chitradurga demarcates the study area from where the metabasalt samples were retrieved. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 2

(a) Representative metabasalt samples for analysis. (b) P-wave velocity determination, (c) and (d) show the set-up for Point load test (PLT) and Brazilian tensile strength test (BTS) respectively. (e) and (f) are the close-up views of failed samples after PLT and BTS respectively.

Figure 3

Linear correlation between the P-wave velocity (V_p) and point load strength index ($I_{s(50)}$) of the metabasalt samples.

Figure 4

Schematic representation of different failure modes observed in the metabasalt under point load test conditions (a) Twisted (b) Single Plane (c) Triple Junction (d) Single Plane Inclined

Figure 5

Bar diagram showing the number of failed samples against each failure mode for a definite range of point load strength index ($I_{s(50)}$) in metabasalts.

Figure 6

Failed samples after PLT with their respective failure modes annotated below each photograph. T = Twisted, SP = Single Plane, TJ = Triple Junction, SP (I) = Single Plane Inclined respectively.

Figure 7

Schematic representation of different failure modes observed in the metabasalt core samples under Brazilian test conditions (a) Central Multiple (b) Non-Central (c) Central Multiple + Layer Activation (d) Conjugate (e) Central

Figure 8

Bar diagram showing the number of failed samples against each failure mode for a definite range of Brazilian Tensile Strength (BTS) in metabasalts.

Figure 9

Failed samples after BTS determination with their respective failure modes annotated below each photograph. CM = Central Multiple, NC = Non-Central, C = Central, CM+LA = Central multiple with layer activation. Yellow dotted line marks the failure surfaces.

Supplementary Files

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