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A Method for Estimating Crack-initiation Stress of Rock Materials by Porosity

A. Basu and D. A. Mishra
Department of Geology & Geophysics, Indian Institute of Technology Kharagpur - 721 302
Email: abasu@gg.iitkgp.ernet.in

Abstract: Crack-initiation stress of a rock under compression is the stress level that marks the initiation of the rock microfracturing process or in other words, the onset of new damage to the rock. This paper proposed a simple methodology with justifications to explore the feasibility of using total and effective porosities as estimators of crack-initiation stress of brittle crystalline rock materials under uniaxial compression. The validity/applicability of the proposed method was examined by an experimental study of granitic materials from Malanjkhand, Madhya Pradesh. It was found that effective porosity depicts better correlation with crack-initiation stress than with uniaxial compressive strength of the granitic materials. On the other hand, total porosity does not show any perceptible correlation with uniaxial compressive strength and crack-initiation stress. Plausible reasons for the nature of the obtained results were also explained in view of rock failure process under compression. It is concluded that following the proposed method, effective porosity can be used as a physical index to obtain a quick estimate of crack-initiation stress of the investigated rocks empirically.

Keywords: Granite, Crack-initiation stress, Uniaxial compressive strength, Rock failure process, Porosity.

INTRODUCTION

An excavation in rocks causes redistribution of *in-situ* stresses and this could lead to brittle fracturing at or near the excavation boundary and permeability increase of the host rock in close proximity of the excavation (Lau and Chandler, 2004; Verma et al., 2011). Ascertaining the initiation and development of stress-induced microcracks in brittle rock is, therefore, potentially important. Crack-initiation stress (ci) of a rock under compression is the stress level that marks the initiation of the rock microfracturing process or in other words, the onset of new damage to the rock.

In-situ, a rock mass is generally under triaxial stress conditions. As compressive strength of a rock material increases with the increase in confining pressure, uniaxial compressive strength (UCS) provides a measure of minimum strength a rock material can have under compression and therefore, UCS is considered as the parameter to gauge strength of rock materials in Rock Mass Rating (RMR) proposed by Bieniawski (1989). Although UCS of a rock material corresponds to maximum uniaxial compressive stress the material can sustain prior to failure, formation and propagation and/or coalescence of microcracks begin long before this stage. In order to understand this, laboratory tests involving various rock types, loading conditions, specimen shapes, and observation methods have been performed by many researchers (e.g. Brace et al., 1966; Bieniawski, 1967; Wawersik and Brace, 1971; Lajtai and Lajtai, 1974; Hallbauer et al., 1973; Swan, 1975; Henry et al., 1977; Chen et al., 1979; Nolen-Hoeksema and Gordon, 1987; Huang et al., 1993; Martin and Chandler, 1994; Eberhardt et al., 1998; Li et al., 2003; Zhang and Wong, 2013; Nicksiar and Martin, 2012 and 2013; Palchik, 2013). According to these investigations, determination of crack-initiation stress under uniaxial/triaxial compression not only requires quality machined specimens (ASTM D4543, 2001) but also demands sophisticated and expensive laboratory test setup (elaborated in the next section). In spite of such pricey methods adopted by previous researchers, accuracy of the obtained crack-initiation stress value was not guaranteed. Predicting crack-initiation stress empirically from another meaningful/relevant rock index property that is easy to determine and inexpensive is, therefore, useful at site investigation stage for obvious reasons. Porosity is one of the most often used physical indices to predict rock mechanical properties (e.g. Dunn et al., 1973; Dearman et al., 1978; Lumb, 1983; Palchik and Hatzor, 2000; Kahraman et al., 2005; Basu, 2006). It is also well-known that role of

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microcracks is of great importance in controlling the mechanical behavior of rocks (e.g. Kranz, 1983; Goodman, 1989; Akesson et al., 2001; Nasseri et al., 2005; Basu et al., 2009). However, till date, no attempt has been made to predict crack-initiation stress by porosity or by any other rock index property. This paper proposes a simple methodology to explore the feasibility of using total porosity (ratio of total volume of voids to total rock volume) and effective porosity (a measure of interconnectedness of pores with reference to water permeability) as estimators of crack-initiation stress of rock materials under uniaxial compression. The validity of the proposed method is examined by an experimental study of granitic materials from Malanjkhand, Madhya Pradesh.

JUSTIFICATION FOR THE PROPOSED METHODOLOGY

When a brittle crystalline rock material is subjected to uniaxial compression (Fig. 1a), the failure process of the material could be divided into a number of stages. Based on the stress-strain behavioral response of the material, Brace (1964) and Bieniawski (1967) described these stages as (i) crack closure, (ii) linear elastic deformation, (iii) crack initiation and stable crack growth and (iv) crack-damage and unstable crack growth leading to failure. The generalized axial stress (σ_{axial}) vs. axial (ε_{axial}) and lateral ($\varepsilon_{lateral}$) strain curves expected from a uniaxial test of a brittle crystalline rock material is presented in Fig. 1b. The elements of crack development within the rock specimen under uniaxial compression are explained in Fig. 1c in relation to the different stress thresholds indicated in Fig 1b. Under uniaxial state of stress, pre-existing microflaws/microcracks/Griffith flaws (assumed to be elliptical in shape) with suitable dimensions and orientations with respect to the maximum principal stress get closed as the applied compressive stress reaches a particular level known as crack-closure stress (cc) (Figs. 1b and c). During the process of crack closure, a non-linear stress-strain response is exhibited (Fig. 1b). The rock material which has become virtually flawless/intact starts portraying linear elastic behavior (Fig. 1b). When the tensile stresses induced by compression exceed the local tensile

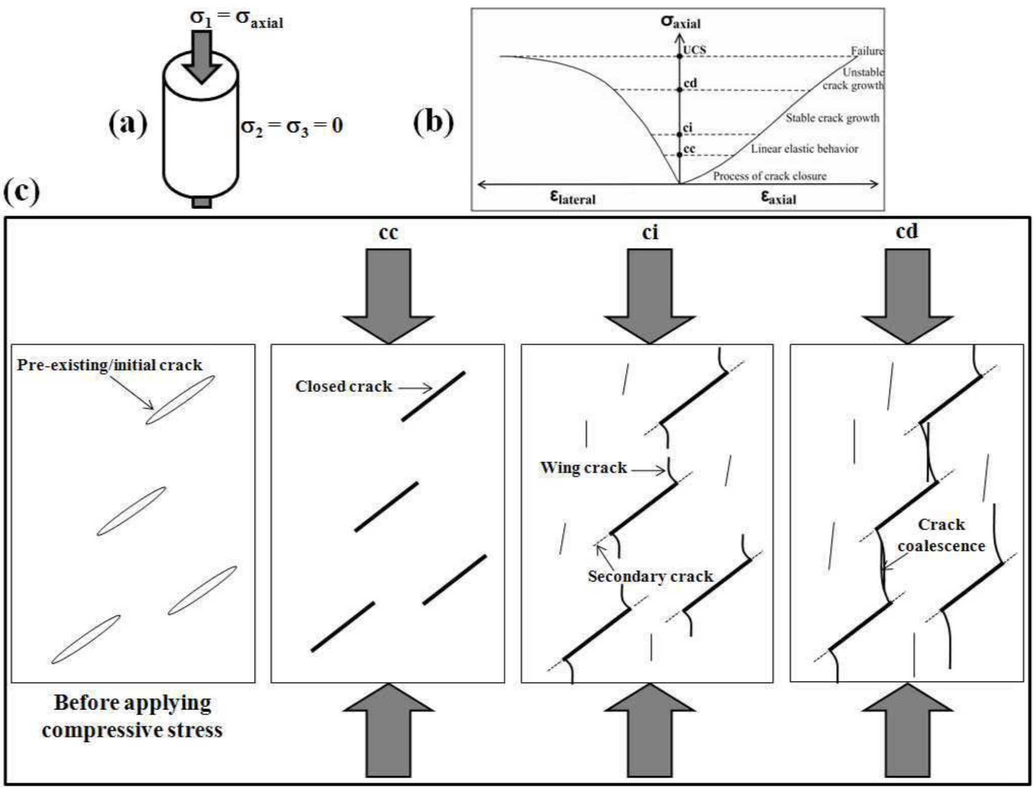

Fig.1. (a) Schematic representation of uniaxial compression of a brittle crystalline cylindrical rock specimen. **(b)** Generalized axial stress (σ_{axial}) vs. axial (ε_{axial}) and lateral ($\varepsilon_{lateral}$) strain curves expected from a uniaxial compression test of a brittle crystalline rock material and corresponding stages of rock failure process (abbreviations used: cc = crack-closure stress, ci = crack-initiation stress, cd = crack-damage stress, and UCS = uniaxial compressive strength) [modified after Martin (1993)]. **(c)** Elements of crack development (initiation, propagation and coalescence) within the rock specimen under uniaxial compression in relation to the different stress thresholds (i.e. cc, ci and cd) (modified after Cai et al. 2004).

strength at the tips of the pre-existing flaws, crack propagates from those tips and propagating cracks, known as wing cracks, make themselves parallel to the maximum principal stress (Einstein and Dershowitz, 1990; Bobet and Einstein, 1998) (Fig. 1c). Secondary cracks also form simultaneously with wing cracks, but in the crack planes of the flaws (Bobet and Einstein, 1996) (Fig. 1c). These new cracks are generated at crack-initiation stress (ci) where the stress-strain curves depart from linearity indicating development and growth of stable cracks (Figs. 1b and c). As at this stage, crack growth can be stopped by controlling the applied stress, it is known as stable crack growth. The stress level beyond which crack propagation and coalescence become unstable/time-dependent is known as crack-damage stress (cd) (Figs. 1b and c). In other words, from crack-damage stress level (cd), with little or no increase in applied stress, crack coalescence can continue and subsequently, unstable crack growth leads to specimen failure. The crack-initiation stress, as determined through laboratory testing, has been defined as the point where the lateral strain curve departs from linearity (Brace et al., 1966; Bieniawski, 1967; Lajtai and Lajtai, 1974). However, examination of the lateral strain curve reveals that the identification of this point can be very subjective as at no time is the lateral stress-strain curve truly linear. Noting this difficulty, Martin (1993) suggested the use of the calculated crack-volumetric strain to identify crack initiation and defined crack initiation stress as the stress level at which dilation (crack-volume increase) begins in the crack-volume plot (readers are referred to Martin and Chandler, 1994). It should be noted that approximation of volumetric strain requires simultaneous measurement and recording of both axial and lateral strains ($\varepsilon_{volumetric} \approx \varepsilon_{axial} + 2\varepsilon_{lateral}$). Nicksiar and Martin (2012) have recently introduced a technique that relies on the lateral strain response. In this method, the change in recorded lateral strain relative to a reference line is used to calculate lateral strain difference value. The crack initiation stress is determined by fitting a best-fitted parabola and selecting the stress associated with maximum strain difference. This technique, however, is also not free from approximation error.

Acoustic emission is another tool to identify initiation and propagation of cracks in rocks under compression (Scholz, 1968; Hardy, 1977; Eberhardt et al., 1998). The elastic strain energy stored within a rock material under compression is suddenly released in the form of elastic waves and the related acoustic emission patterns correlate well with the stress-strain behavior of the material under compression as described in the previous paragraph. In either of these techniques (i.e. techniques of determining crack-initiation stress from crack-volume plot and from acoustic emission patterns), complex and expensive experimental setups are needed, whereas, finding out error-free value of crack initiation stress is not guaranteed.

In this study, analysis of the axial stress vs. axial strain curve obtained from uniaxial tests of rock materials is proposed to find out crack-initiation stresses. As axial strain is easier to determine and record than lateral strain in practice and as in terms of magnitude it is greater than lateral strain because of the Poisson's effect, axial stress *vs.* axial strain curve is expected to depict different stages of failure processes more conspicuously than axial stress *vs.* lateral strain curve. By doing this, both approximation of volumetric strain and measurement of lateral strain could be avoided. The proposed method is also significantly cheaper than acoustic emission technique.

Feasibility of using total and effective porosities (nt and ne respectively) in estimating crack-initiation stress of granitic materials determined by adopting the method described above is also proposed to be explored in this study. It is well-known that existing pores (or flaws) in a rock material under compression are significant stress concentrators and therefore, strongly influence the rock strength (Dunn et al., 1973; Logan, 1987; Scott and Nielson, 1991). Relations between UCS of rock materials and porosity have been reported by a number of researchers (e.g. Dunn et al., 1973; Dearman et al., 1978; Lumb, 1983; Vernik, et al., 1993; Schultz and Li, 1995; Al-Harthi et al., 1999; Tugrul and Zarif, 1999; Palchik and Hatzor, 2000; Kahraman et al., 2005; Basu, 2006; Yilmaz and Yuksek, 2009). In Indian context, however, there exist a few studies that have presented relations between compressive strength and porosity. Gupta and Rao (1998) found that negative curvilinear relationships exist between UCS and nt of fresh to weathered Malanjkhand granites, Nagpur basalts and Delhi quartzites. Chatterjee and Mukhopadhyay (2002) demonstrated a negative linear relationship between UCS and ne for rocks like sandstones, siltstones, limestones, shale and augen gneiss from Krishna-Godavari and Cauvery basins. Chatterjee et al. (2005) provided relations of UCS and ne for Indian black decorative stones from ten active quarries in Andhra Pradesh. An unusual positive linear relationship was found by them. This unacceptable relation seems to have been resulted from the flawed approach of mixing data from different rock types with different geology adopted in this investigation. Mishra and Basu (2013) demonstrated why data from different rock types should not be clubbed together while correlating porosity and UCS. Although determination of ci of rocks under uniaxial compression has been a part of several research works, to the best of the authors' knowledge, no attempt has been made to check the efficiency of nt and ne in predicting ci. As crack-initiation takes place from the tips of the pre-existing flaws, performance of nt and ne in estimating ci is proposed to be evaluated in this study. Granite is a virtually isotropic crystalline igneous rock and the porosity of this rock is mainly attributed to microcracks present in it. Moreover, several earlier studies explored the issue of crack-initiation stress determination following other methods for granitic materials. Therefore, granite is consciously chosen to examine the validity of the proposed method in this study.

SAMPLES

Core samples (diameter ≈ 58mm) of granitic rocks were collected from Malanjkhand Copper Project, Malanjkhand, Madhya Pradesh for the investigation. Malanjkhand granitiod is exposed in Balaghat district of Madhya Pradesh, which intrudes the Amgaon and Nandgaon Groups, and is overlain by younger Chilpi metasediments (Kumar et al., 2004). Granites collected for testing are from gray and pink granitoid of Palaeoproterozoic (~2400 Ma) age. These granitoids are essentially mica-bearing, and have been subjected to deuteric alterations (Panigrahi et al., 2004).

Only fresh or slightly discolored intact and uniform cores (devoid of densely spaced fractures, any shear signature or mixed lithology) were selected for the investigation. Preliminary visual inspection of the cleaned core surfaces ascertained comparable mineralogy and texture of the samples. All samples are grayish or pinkish in colour, medium grained and display equigranular phaneritic texture (Fig. 2). Uniaxial compression test specimens (length-diameter ratio ≈ 2:1) were prepared according to ASTM D4543 (2001) stipulations. Two/three specimens from the same core sample were also obtained for determining effective porosity (ne). Powdered equivalents of the samples were prepared for total porosity (nt) measurement.

LABORATORY INVESTIGATIONS AND DATA ANALYSIS

An Automatic Compression Test Machine (AIM-314-FA©) of 1000kN loading capacity was used for uniaxial compression tests (Fig 3a). The compressive strength of rocks usually increases with the increase in loading rate (Vutukuri et al., 1974). Martin (1993) noted that UCS of granite is not a unique material property but is dependent on loading conditions such as the loading rate. Therefore, the standards (e.g. ASTM D2938, 2001) stipulate the loading rate in case of UCS determination. The crack-initiation stress was found to be more characteristic of the material, essentially independent of loading rate (Martin, 1993; Eberhardt, 1998). In this study, a loading rate of 0.5kN/s was employed in compliance with ASTM D2938 (2001). An LVDT attached to a compressometer gripping the core specimen was meant for measuring axial deformation (Fig. 3a). The data acquisition system (Fig. 3a) was operational to record both applied load and axial deformation simultaneously. A total of 39 uniaxial tests were carried out along with continuous and simultaneous recording of load and axial deformation. From the failure load, UCS was calculated (Fig. 3b). It should be noted that according to the stipulations by ASTM D4543 (2001), a uniaxial compression test specimen should be cylindrical in shape and the specimen shall have a length-to-diameter ratio of 2.0 to 2.5 and a diameter of not less than 47 mm. As in this study, the specimen shape and size were in compliance with ASTM D4543 (2001), no size correction to re-calculate the UCS values was needed. From the axial stress *vs.* axial strain curve obtained by processing load-deformation data in Microsoft Excel©, crack-initiation stress (ci) was determined as the stress level where the stress-strain curve departed from linearity (Fig. 3b). For example, in Fig 3b, the point corresponding to crack-initiation stress was determined where the slope of the straight line dropped which is

Fig.2. Examples of collected granite cores and a generalized photomicrograph of the granite.

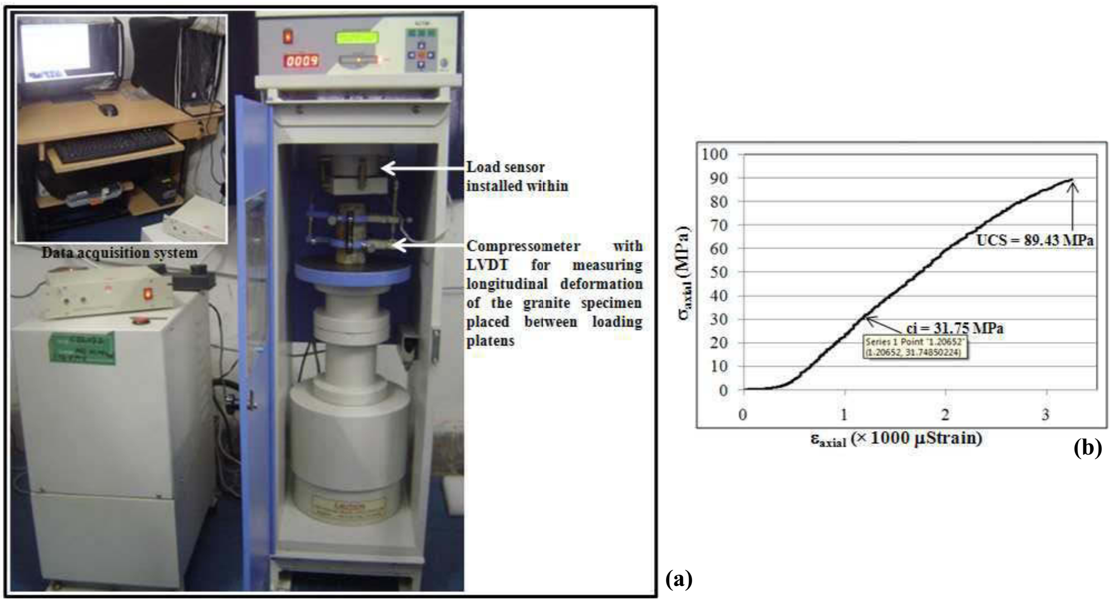

Fig.3. (a) Laboratory setup for uniaxial compression test. **(b)** An example of determining crack-initiation stress (ci) and uniaxial compressive strength (UCS) of a tested granite specimen from the axial stress (σ_{axial}) vs. axial strain (ε_{axial}) curve obtained by processing axial load and axial deformation data.

calculated from the Excel data sheet of axial stress and axial strain values.

In this study, both nt and ne were measured for all samples under investigation. For determination of ne, a representative rock piece (> 50gm) was saturated by immersing it into water in a vacuum of around 90kPa for at least 2 hrs. The vacuum pressure applied in this study was more than that (800Pa) specified in ISRM (1979) in order to saturate rocks like fresh granites. Dry mass (M_{dry}) and saturated mass (M_{sat}) of the specimen, and mass of the saturated specimen while suspended inside water (M_{sus}) were measured. ne was calculated from the following equation:

$$ne = ((M_{sat} - M_{dry})/(M_{sat} - M_{sus}))\times 100\% \quad (1)$$

For determining nt, the rock specimen was powdered (Basu, 2006). Mass (M_p) and volume (V_p) of any portion of the powder were measured and volume ($V_{eq.}$) of the equivalent mass of an intact rock specimen (i.e. before powdering) was calculated by dividing M_p by the dry density of the intact rock specimen [i.e. $\rho_{dry} = (M_{dry}/(M_{sat} - M_{sus}))$, ρ_{water} = 1gm/cc]. nt was calculated from the following equation:

$$nt = ((Veq. - Vp)/Veq.) \times 100\% \quad (2)$$

The values of ne and nt representative for a sample were obtained by averaging two to three vigilant test results.

The complete test results including ne, nt, ci and UCS for all samples are summarized in Table 1. It should be noted that no ci value is given against Sample no. 20 in Table 1, as the distance sensor (LVDT) attached to the compressometer did not function properly during the uniaxial test of the corresponding specimen. When UCS and ci were plotted against nt separately, widely scattered data points showed crude negative distributions (Fig. 4). On the other hand, when UCS and ci were plotted against ne, conspicuous negative linear relations emerged (Fig. 5). The equations for the trend lines (best-fit lines) and corresponding absolute values of Pearson's correlation coefficients (|R| values) are given in the Fig. 5. For the plots UCS vs. ne and ci vs. ne, the degrees of freedom are 37 and 36 respectively (Table 1). Hence, minimum theoretical |R| values of 0.408 and 0.413 are necessary to consider the correlations as statistically significant at 99% confidence level respectively (calculated using the url: *http://secamlocal.ex.ac.uk/people/staff/dbs202/cat/stats/corr.html)*. Figure 5 depicts that |R| values for both UCS vs. ne and ci vs. ne plots are greater than the calculated |R| values at 99% confidence level. Therefore, it can be concluded that both correlations in Fig. 5 are statistically significant. Based on the |R| value, however, the correlation between ci and ne appears to be much better than the correlation between UCS and ne.

Porosity of a rock is a measure of the void space with respect to the bulk volume of the rock. The void space within the rock is attributed to the presence of pores and cracks/fissures which may function as stress concentrators when the rock is subjected to compression. Palchik (1999) showed

Table 1. Laboratory test results

Sample no.	ne (%)	nt (%)	ci (MPa)	UCS (MPa)
1	0.22	0.83	23.26	127.74
2	0.14	0.88	63.88	142.05
3	0.12	0.59	75.99	179.45
4	0.16	0.62	67.33	146.05
5	0.17	0.46	69.34	139.93
6	0.19	0.63	48.39	83.57
7	0.17	0.74	59.26	118.90
8	0.19	1.03	60.00	137.77
9	0.16	0.82	60.00	179.25
10	0.15	0.91	76.35	165.81
11	0.21	1.78	56.92	158.93
12	0.24	1.25	30.20	98.49
13	0.18	1.10	64.99	112.48
14	0.16	0.69	58.78	152.26
15	0.18	0.72	48.28	179.13
16	0.17	1.07	48.22	144.03
17	0.22	1.36	41.44	144.60
18	0.21	2.13	50.92	166.50
19	0.11	1.04	70.69	180.35
20	0.16	0.58	–	184.08
21	0.11	0.71	85.48	154.43
22	0.21	2.47	59.88	130.34
23	0.20	1.31	52.14	159.17
24	0.17	0.87	53.53	153.77
25	0.19	0.68	40.66	154.99
26	0.22	1.14	35.62	80.73
27	0.23	2.02	31.68	86.44
28	0.19	1.74	43.17	182.71
29	0.19	0.80	41.09	171.28
30	0.24	0.98	33.09	93.48
31	0.18	0.77	56.19	162.18
32	0.18	0.91	50.27	170.90
33	0.15	1.11	78.37	154.37
34	0.18	0.96	58.68	153.30
35	0.23	1.45	31.75	89.43
36	0.17	0.60	72.47	152.80
37	0.21	1.37	50.14	152.06
38	0.20	0.88	54.46	138.43
39	0.23	2.22	40.00	98.81

ne = effective porosity, nt = total porosity, ci = crack-initiation stress, UCS = uniaxial compressive strength
Note: ne and nt for each sample were obtained by averaging two/three vigilant test results from individual specimen

that in porous heterogeneous sandstones, porosity has an effect on UCS, whereas the role of grain boundaries is negligible. Although unlike sedimentary rocks, a brittle crystalline rock such as granite is devoid of primary pores, it inevitably contains numerous microscopic/submicroscopic flaws/cracks (e.g. grain boundary, intra- and trans-granular cracks) which are distributed with random orientation throughout the volume of the material. Crack initiation is caused by the stress concentrations at the ends of these cracks. It should be noted that microcracks only with suitable orientations and dimensions give rise to new cracks from their tips. Moreover, the process of crack coalescence is a

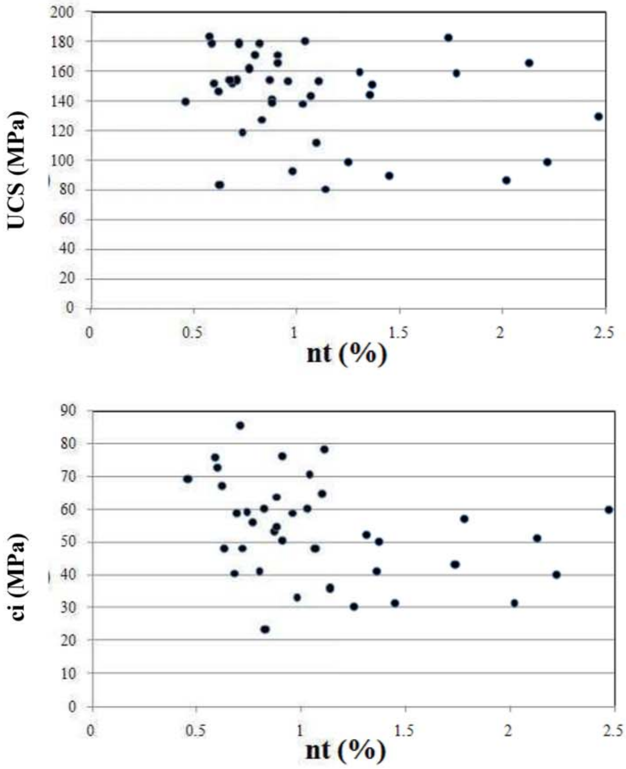

Fig.4. Uniaxial compressive strength (UCS) and crack-initiation stress (ci) plotted separately against total porosity (nt).

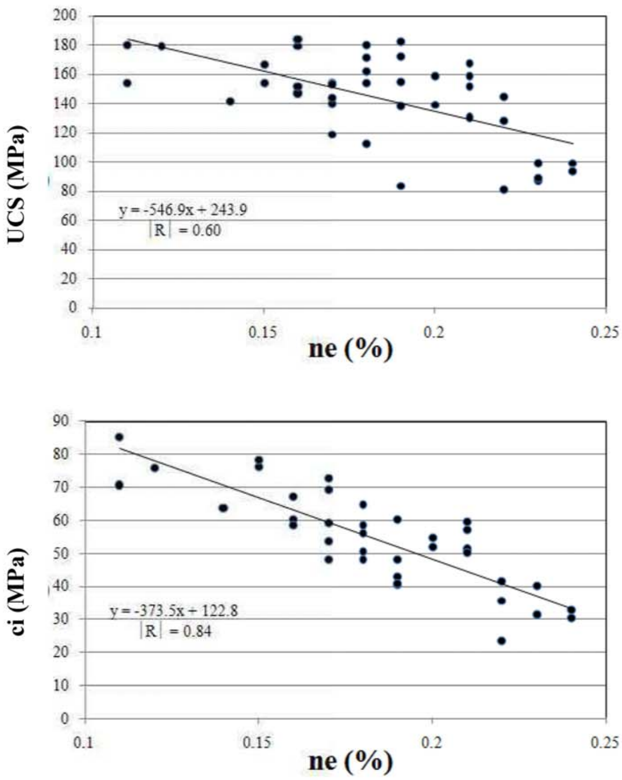

Fig.5. Uniaxial compressive strength (UCS) and crack-initiation stress (ci) plotted separately against effective porosity (ne).

Splitting along single plane | Splitting along multiple planes | Partial shearing | Shear failure along single plane | Shear failure with conjugates

Fig.6. Examples of common failure modes of granite specimens under uniaxial compression.

function of distribution and interconnectedness of the pre-existing microcracks. This is also supported or supplemented by various failure modes of the granite specimens under uniaxial compression (Fig. 6). All these points explain significantly stronger relations of UCS and ci with ne than with nt (Figs. 4 and 5). Basu (2006) also found ne to be more efficient than nt in predicting UCS of granitic rock materials of different weathering grades from Hong Kong.

Another point to be noted is that the correlation between ci and ne is better than that between UCS and ne (Fig. 5). After the crack initiation from the tips of the pre-existing cracks of the rock specimen under uniaxial compression, a stage of stable crack growth is attained which is followed by unstable crack growth that initiates at crack-damage stress (cd) (Fig. 1). This unstable crack growth eventually leads to failure of the rock specimen (Fig. 1). It is, therefore, evident that the pattern, density and distribution of microcracks during the stages of stable and unstable crack growth are significantly different from the nature of the pre-existing cracks (i.e. microcracks before applying compressive stress) (Fig. 1). At crack initiation stress, however, this difference is understandably less (Fig. 1). This explains a better performance of ne in estimating ci than in predicting UCS of the granitic materials. Palchik and Hatzor (2002) showed that there exists a negative curvilinear relation between cd and nt of limestones and dolomites. However, the data point distribution was too scattered to be presented in the form of any correlation equation which could be attributed to the reasons explained.

CONCLUSIONS

Establishing the initiation and development of stress-induced microcracks in brittle rock under compression is important. For understanding the onset of rock damage, expensive laboratory tests involving various rock types, loading conditions, specimen shapes, and observation methods were performed by many researchers in the past. Nevertheless, finding out an error-free value of crack initiation stress was not possible. This study proposed a method to estimate crack-initiation stress of rock materials empirically by rock physical indices like total and effective porosities, which is a much simpler and less expensive technique than the methods employed before. The validity of the proposed method was examined by an experimental investigation of granitic materials from Malanjkhand (in the state of Madhya Pradesh, India). The following conclusions are drawn based on the study.

- Effective porosity is significantly more efficient than total porosity in predicting uniaxial compressive strength and crack-initiation stress of the granitic materials.
- Effective porosity is more efficient in estimating crack initiation stress than in predicting uniaxial compressive strength of the granitic materials.
- Plausible reasons for the nature of the obtained results can also be explained in view of rock failure process under compression.

It should, however, be noted that for the first time, a method of estimating crack-initiation stress of rock materials by porosity has been proposed and the validity of this simple and low-cost method has been examined experimentally by investigating granitic materials (from Malanjkhand) in this study. Further research with the said objective needs to be carried out considering other brittle crystalline rocks from other areas with specific geology in order to be ascertained about the efficiency of effective porosity as a physical index to obtain a quick estimate of crack-initiation stress of such rocks.

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References

Akesson, U., Lindqvist, J.E., Goransson, M. and Stigh, J. (2001) Relationship between texture and mechanical properties of granites, central Sweden, by use of image-analysing techniques. Bull. Eng. Geol. Env., v.60, pp.277-284.

Al-Harthi, A.A., Al-Amri and Shehata, W.M. (1999) The porosity and engineering properties of vesicular basalt in Saudi Arabia. Eng. Geol., v.54, pp.313-320.

ASTM (2001) Standard practice for preparing rock core specimens and determining dimensional and shape tolerances. Designation D4543.

ASTM (2001) Standard test method for unconfined compressive strength of intact rock core specimens. Designation D2938.

Basu, A. (2006) Mechanical characterization of granitic rocks of Hong Kong by improved index testing procedures with reference to weathering induced microstructural changes. PhD thesis, The University of Hong Kong.

Basu, A., Cellestino, T.B. and Bortolucci, A.A. (2009) Evaluation of rock mechanical behaviors under uniaxial compression with reference to assessed weathering grades. Rock Mech. Rock Eng., v.42, pp.73-93.

Bieniawski, Z.T. (1967) Mechanism of brittle rock fracture. Part I. Theory of the fracture process. Int. J. Rock Mech. Min. Sci. & Geomech. Abstr., v.4, pp.395-406.

Bieniawski, Z.T. (1989) Engineering Rock Mass Classifications. John Wiley & Sons, New York, pp.251.

Bobet, A. and Einstein, H.H. (1996) Fracture coalescence in rock material under uniaxial and biaxial loading. Proceeding of the 2nd North American Rock Mechanics Sympossium: NARMS'96, Montreal, pp.1603-1609.

Bobet, A. and Einstein, H.H. (1998) Fracture coalescence in rock-type materials under uniaxial and biaxial compression. Int. Jour. Rock Mech. Min. Sci., v.35, pp.863-888.

Brace W.F. (1964) Brittle fracture of rocks. In State of Stress in the Earth's Crust. In: W.R. Judd (Ed.), Proceedings of the International Conference, Santa Monica, America. Elsevier, New York, pp.110-178.

Brace, W.F., Paulding, B.W. and Scholz, C. (1966) Dilatancy in the fracture of crystalline rocks. Jour. Geophys. Res., v.71, pp.3939-3953.

Cai, M., Kaiser, P.K., Tasaka, Y., Maejima, T., Morioka, H. and Minami, M. (2004) Generalized crack initiation and crack damage stress thresholds of brittle rock masses near underground excavations. Int. Jour. Rock Mech. Min. Sci., v.41, pp.677-680.

Chatterjee, R. and Mukhopadhyay, M. (2002) Petrophysical and geomechanical properties of rocks from the oilfields of the Krishna-Godavari and Cauvery Basins, India. Bull. Eng. Geol. Env., v.61, pp.169-178.

Chatterjee, T.K., Chatterjee, R. and Singh, S.K. (2005) Classification of black decorative stones from Warangal District, Andhra Pradesh, India. Bull. Eng. Geol. Env., v.64, pp.167-173.

Chen, R., Yao, X. X. and Xie, H.S. (1979) Studies of the fracture of gabbro. Int. Jour. Rock Mech. Min. Sci. & Geomech. Abstr., v.16, pp.187-193.

Dearman, W.R., Baynes, E.J. and Irfan, T. Y. (1978) Engineering grading of weathered granite. Engg. Geol., v.12, pp.345-374.

Dunn, D.E., Lafountain, L.J. and Jackson, R.E., (1973) Porosity dependence and mechanism of brittle fracture in sandstones. Jour. Geophys. Res., v.78, pp.2403-2417.

Eberhardt, E., Stead, D., Stimpson, B. and Read, R.S. (1998) Identifying crack initiation and propagation thresholds in brittle rock. Can. Geotech. Jour., v.35, pp.222-233.

Einstein, H.H. and Dershowitz, W.S. (1990) Tensile and shear fracturing in predominantly compressive stress fields- a review. Engg. Geol., v.29, pp.149-172.

Goodman, R.E. (1989) Introduction to Rock Mechanics, 2nd ed. John Wiley & Sons, New York, pp.562.

Gupta, A.S. and Rao, K.S. (1998) Index properties of weathered rocks: inter-relationships and applicability. Bull. Eng. Geol. Env., v.57, pp.161-172.

Hallbauer, D.K., Wagner, H. and Cook, N.G.W. (1973) Some observations concerning the microscopic and mechanical behaviour of quartzite specimens in stiff, triaxial compression tests. Int. Jour. Rock Mech. Min. Sci. & Geomech. Abstr., v.10, pp.713-726.

Hardy, H.R., Jr. (1977) Emergence of acoustic emission/ microseismic activity as a tool in geomechanics: Proceedings of the 1st Conference on Acoustic Emission/Microseismic Activity in Geologic Structures and Materials, 1975, University Park, Pa., H.R. Hardy and L.W. Leighton, (Eds.). Trans Tech Publications, Clausthal, Germany, pp. 3-31.

Henry, J.P., Paquet, J. and Tancrez, J.P. (1977) Experimental study of crack propagation in calcite rocks. Int. Jour. Rock Mech. Min. Sci. & Geomech. Abstr., v.30, pp.925-928.

Huang, J.F., Wang, Z.Y. and Zhao, Y.H. (1993) The development of rock fracture from microfracturing to main fracture formation. Int. J. Rock Mech. Min. Sci. & Geomech. Abstr., v.30, pp.925-928.

ISRM (1979) Suggested methods for determining water content, porosity, density, absorption and related properties and swelling and slake-durability index properties. Int. J. Rock Mech. Mining Sci. & Geomech. Abstr., v.16, pp.141-156.

Kahraman, S., Gunaydin, O. and Fener, M. (2005) The effect of porosity on the relation between uniaxial compressive strength and point load index. Int. Jour. Rock Mech. Mining Sci., v.42, pp.584-589.

Kranz, R.L. (1983) Microcracks in rocks: a review. Tectonophysics, v.100, pp.449-480.

Kumar, S., Rinol, V. and Pal, A.B. (2004) Field Evidence of Magma Mixing from Microgranular Enclaves Hosted in Palaeoproterozoic Malanjkhand Granitoids, Central India. Gondwana Res., v.7, pp. 539-548.

Lajtai, E.Z. and Lajtai, V.N. (1974) The evolution of brittle fracture in rocks. Jour. Geol. Soc. London, v.130, pp.1-18.

Lau, J.S.O. and Chandler, N.A. (2004) Innovative laboratory testing. Int. J. Rock Mech. Mining Sci., v.41, pp.1427-1445.

Li, L., Lee, P.K.K., Tsui, Y., Tham, L.G. and Tang, C.A. (2003) Failure process of granite. Int. Jour. Geomeh., v.3, pp.84-98.

Logan, J.M. (1987) Porosity and brittle-ductile transition in sedimentary rocks. In Banavar JR, Koplik J,Winkler KW (eds) physics and chemistry of porous media II, AIP conference proceedings, Amer. Inst. Phys., New York, pp. 229-242.

Lumb, P. (1983) Engineering properties of fresh and decomposed igneous rocks from Hong Kong. Eng. Geol., v.19, pp.81-94.

Martin, C.D. (1993) The strength of massive Lac du granite around underground openings. PhD thesis, University of Manitoba.

Martin, C.D. and Chandler, N.A. (1994) The progressive fracture of Lac du Bonnet granite. Int. J. Rock Mech. Min. Sci. & Geomech. Abstr., v.31, pp.643-659.

Mishra, D.A. and Basu, A. (2013) Estimation of uniaxial compressive strength of rock materials by index tests using regression analysis and fuzzy inference system. Engg. Geol., v.160, pp.54-68.

Nasseri, M.H.B., Mohanty, B. and Robin, P.Y.F. (2005) Characterization of microstructures and fracture toughness in five granitic rocks. Int. Jour. Rock Mech. Min. Sci., v.42, pp.450-460.

Nicksiar, M. and Martin, C.D. (2012) Evaluation of methods for determining crack initiation in compression tests on low-porosity rocks. Rock Mech. and Rock Engg., v.45, pp.607-617.

Nicksiar, M. and Martin, C.D. (2013) Crack initiation stress in low porosity crystalline and sedimentary rocks. Engg. Geol., v.154, pp.64-76.

Nolen-Hoeksema, R.C. and Gordon, R.B. (1987) Optical detection of crack patterns in the opening-mode fracture of marble. Int. Jour. Rock Mech. Min. Sci. & Geomech. Abstr., v.24, pp.135-144.

Palchik, V. (1999) Influence of porosity and elastic modulus on uniaxial compressive strength in soft brittle porous sandstones. Rock Mech. and Rock Engg., v.32, pp.303-309.

Palchik, V. (2013) Is there link between the type of the volumetric strain curve and elastic constants, porosity, stress and strain characteristics? Rock Mech. and Rock Engg., v.46, pp.315-326.

Palchik, V. and Hatzor, Y.H. (2000) Correlation between mechanical strength and microstructural parameters of dolomites and limestones in the Judea group. Israel. Israel Jour. Earth Sci., v.49, pp.65-79.

Palchik, V. and Hatzor, Y.H. (2002) Crack damage stress as a composite function of porosity and elastic matrix stiffness in dolomites and limestones. Engg. Geol., v.63, pp.233-245.

Panigrahi, M.K., Bream, B.R., Misra, K.C. and Naik, R.K. (2004) Age of granitic activity associated with copper–molybdenum mineralization at Malanjkhand, Central India. Mineralium Deposita, v.39, pp.670-677.

Scholz, C. (1968) Experimental study of the fracturing process in brittle rock. Jour. Geophys. Res., v.73, pp.1447-1454.

Schultz, R.A. and Li, Q. (1995) Uniaxial strength testing of non-welded Calico Hills tuff, Yucca Mountain, Nevada. Engg. Geol., v.40, pp.287-299.

Scott, T.E. and Nielsen, K.C. (1991) The Effect of Porosity on the Brittle-Ductile Transition in Sandstones. Jour. Geophys. Res., v.96, pp. 405-414.

Swan, G. (1975) The observation of cracks propagating in rock plates. Int. Jour. Rock Mech. Min. Sci. & Geomech. Abstr., v.12, pp.329-334.

Tugrul, A. and Zarif, I.H. (1999) Correlation of mineralogical and textural characteristics with engineering properties of selected granitic rocks from Turkey. Engg. Geol., v.51, pp.303-317.

Verma, A.K., Saini, M.S., Singh, T.N. and Dutt, A. (2011) Effect of excavation stages on stress and pore pressure changes for an underground nuclear repository. Arab. Jour. Geosci., DOI 10.1007/s12517-011-0382-8.

Vernik, L., Bruno, M. and Bovberg, C. (1993) Empirical relations between compressive strength and porosity of siliclastic rocks. Int. Jour. Rock Mech. Min. Sci. & Geomech. Abstr., v.30, pp.677-680.

Vutukuri, V.S., Lama, R.D. and Saluja, S.S. (1974) Handbook on mechanical properties of rocks. Trans. Tech. Publ., Clausthal, pp.280.

Wawersik, W.R. and Brace, W.F. (1971) Post-failure behavior of a granite and diabase. Rock Mech. Rock Eng., v.3, pp.61-85.

Yilmaz, I. and Yuksek, G. (2009) Prediction of the strength and elasticity modulus of gypsum using multiple regression, ANN, and ANFIS models. Int. J. Rock Mech. Mining Sci., v.46, pp.803-810.

Zhang, X-P. and Wong, L.N.Y. (2013) Crack initiation, propagation and coalescence in rock-like material containing two flaws: a numerical study based on bonded-particle model approach. Rock Mech. Rock Eng., v.46, pp.1001-1021.

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