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Assessment of strain energy storage and rock brittleness indices of rockburst potential from microfabric characterizations

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Abstract

Rockburst is one of the most crucial problems for the feasibility studies of underground excavation such as tunnel projects. However, direct standard methods for measuring rock burst potential indices such as Strain energy storage index (W_{ET}) and criterion of rock brittleness (B) are nearly difficult and need high sophisticated equipment. Therefore, in this study, an attempt was made to indirectly calculated as a function of microfabric characteristics such as quartz percentage and grain size by using simple regression statistical model. A dataset established by utilizing the relevant laboratory tests and petrographic image analysis on the rock samples assembled from pen Yin La and Ming Jiong tunnel along the La Ri railway, China. The results exhibit that the statistical W_{ET} and B models revealed responses with moderate to strong correlation coefficient, which proves higher potential of microfabrics analysis for predicting rock burst indices compared to traditional experimental measurements. Both rockburst indices increase with increasing percentage of quarts and grain size. It has been further been noted that in a certain tectonic setup, similar rock types with little different mineralogical composition and texture parameters might have different tendency to rock burst. This indicates that rock bursting potential is a petrographic characteristic dependent.

Keywords

Rockburst, Rock Brittleness, Microfabric, Strain Energy Storage Index, Tunnel

1. Introduction

Usually, underground construction is subject to serious engineering geological hazards, such as rockburst. Rock burst is generally defined as a sudden release of high intensity energy stored in the rock mass accompanying rock failure in form of brittle fracture [1]. This concept has been widely accepted by several scholars [2-5].Localized high-stressed zones are common to most burst occurrences comparable with other factor (high rock strength and good integrity, and unloading and blasting disturbance) which may act independently or together.

Thus, rock burst prediction has been one the biggest challenges in the field of deep underground construction for its nature of unpredictability [6]. Need has stimulated the demand for research in this field. Thus, in the last few years, some potential indices forecasting of rock burst have been proposed, such as: Strain energy storage index W_{ET} [7], potential energy of elastic strain PES [7], criterion of rock brittleness B [8], Criterion of tangential stress [9] and Brittle deformation coefficient (Ku) [4]. Among all these indices, the strain energy storage index (W_{ET}) and Criterion of rock brittleness (B) have a great relationship with tendency of rock burst which is widely used.

To date, there has been full agreement on that petrofabric characteristics of rocks are an efficient technique in initial estimate of rock design. However, this field attracted many researchers where they established specific points as to which role rock fabrics controlling engineering properties of rocks [10-20]. They have been demonstrated that there is a general trend towards higher strength in finer grained rocks of the same sample types. Basically, rock fabric known to affect mechanical properties of rocks include mineral composition, grain size, grain shape, degree of interlocking, arrangement and degree of grain orientation., In general, Changes in mineral consistuent, contents and microsrtructure characterization are of great significance for the failure of rocks, especially when intense deformation is present[21,22].However, microfabric such as micro cracks play a very important role in a fracture process, which may act as fracture nuclei under unfavourable conditions.

Although, intensive studies in the literature for correlating engineering properties of rocks with their petrographic characteristics, there is no study that only focused on the correlating rock burst potential indices with rock microfabric. However, on the basis of understandings mentioned above, a full understanding of the petrographic characteristics of rock mass is very important in predicting the likely tendency of rock bursts at the feasibility and initial design stage. Therefore, an attempt has been made in this paper to examine the relative influence of the certain microfabric such as mineralogy and grain size on the rockburst potential indices such as Strain energy storage index W_{ET} [11] and Criterion of rock brittleness (B)[8].

2. Geology and Type of Samples Collected

Fig. 1. *Location map of the tunnels site*

Keeping in view the purpose of current study, pen yin la and Ming jiong tunnel have been adopted, which located in nian qing tang gu la mountain, western china (Fig 1). These tunnels were excavated for the construction of new La Ri railway linein Xizang province. The tunnels are situated in high tectonic stress region in the southern edge of the Yarlung Zangbo suture zone in the northern margin of Himalayan Mountains. The in situ stress at the tunnel site ranges from 23.1 to 27.4 MPa which measured at depth of 550m. This site-specific condition, a high tectonic stress coupled with the tunnel depth, represents as potential area for development of rock bursts, which constraining the planning and construction of the tunnel. However, the tunnel exhibits moderate to strong tendency to rock burst liability. The rocks consist mostly of granitic to granodioritic rocks with lack of sharp contacts between them. At places, these rock units are highly sheared and cut by felsic dykes and quartz veins, which indicates that they have undergone regional stresses conditions.

3. Material and Experimental Study

3.1. Samples Preparation

Representative rock mass samples were selected along the tunnel based on the degree of fracture intensity and tendency to rock burst. Twenty five cylindrical specimens of length to diameter ration equal to 2 were cored from the rock masses for the mechanical properties according to the ASTM standards [23]. The edge faces of the core specimens were further polished at both ends to avoid end effects. For the petrographic study, thin sections were prepared from each of samples subjected to mechanical test. Furthermore, thin sections were examined under a high power polarized transmitted light microscope (Olympus BX51 model) for microfabric image analysis.

3.2. Mechanical Properties

Rock properties including uniaxial compressive strength (σ_c) and Brazilian tensile strength (σ_t) are usually utilized for rock engineering projects. Consequently, σ_c and σ_t tests were carried out in accordance with the producer suggested by ASTM [24, 25]. At least 5 tests were carried out for the determination of rock strength and then the average values were obtained (Table 1). The attained average results of rock strength were used later in the calculation of rock burst indices.

Table 1. *Mechanical properties of the investigated samples and calculated values of rock burst criterion.*

Sample No	Mechanical properties			Elastic Strain Storage Energy (K_{ET})	Criterion of rock brittleness (B)
	σ_C*(MPa)*	σ_t*(MPa)*	*E MPa)*		
2#-3	87.33	11.68	17371.7	4.56	7.48
020-5	72.4	13.96	11199.3	3.65	5.19
020-11	86.25	9.84	17564.7		8.77
300-1	98.87	10.41	16139.2	5.18	9.50
810-1	122.43	11.88	25760	6.53	10.31

3.3. Loading and Unloading Uniaxial Compressive Strength

This property was determined using displacement controlled uniaxial compressive testing equipment. The axial strain (ε_{axial}) and lateral strain ($\varepsilon_{lateral}$) under uniaxial compression were measured by either electrical resistance strain gages or extensometers and they were arranged in the middle height of the cylindrical specimen as four pairs. Firstly, core specimen was loaded into the uniaxial compressive strength of 70 to 90%, and then prior to the peak strength point, sample is unloaded into compressive strength of 5%. The unloading continued until the lower stress was reached (Fig.2).At least three core samples were tests for each sample and the average values were calculated. In this study, during the Loading and unloading uniaxial compressive strength, special emphasis was given to the careful unload of the tested core sample by displacement normally in value of 0.05m/s.

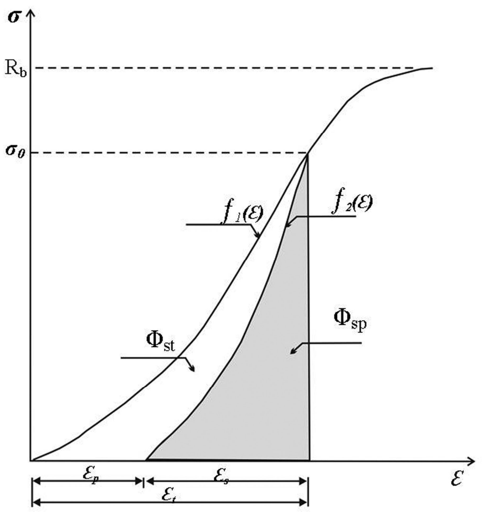

Fig. 2. Analytical schematic diagram for elastic strain energy calculation in cyclic loading of rock samples [11]

4. Measurement of Rock Burst Indices

4.1. Strain Energy Storage Index (K_{ET})

During the linear deformation-failure process, the mechanical energy of the external loading system will be converted into the internal energy of the rock samples. This energy conversion mainly represents the accumulation of elastic energy stored in the rock through loading up to (Φ_{sp}), and dissipated energy (Φ_{st}) lost during the closure of existing micro cracks under low stress. So, the quantity of strain energy stored in the rock depends on elastic energy (E_e) and dissipated plastic energy (E_p) during the pre-peak loading process. Figure (3) shows uniaxial cyclic loading and unloading curve of tested samples. According to the cyclic loading-unloading curve the elastic strain energy retained (Φsp) in the rock and dissipated strain energy (Φst) were measured, and the strain energy storage index W_{ET}(Table.1) was calculated according to:

$$W_{ET} = \frac{\Phi_{sp}}{\Phi_{st}} \quad [1]$$

$$\Phi_{sp} = \int_{\varepsilon_p}^{\varepsilon_t} f_1(\varepsilon)d\varepsilon \quad [2]$$

$$\Phi_{st} = \int_{0}^{\varepsilon_t} f(\varepsilon)d\varepsilon - \int_{\varepsilon_p}^{\varepsilon_t} f_1(\varepsilon)d\varepsilon \quad [3]$$

whereΦ_{sp} is elastic strain energy retained, Φ_{st} is dissipated strain energy.

According to the study of carried out by previous researchers [2, 7] the higher W_{ET} value is, the higher the bursting potential of rock is. However, the intensity of rock burst is scaled as: $W_{ET} \geq 5.0$ high rock burst reliability, $3.5 \leq W_{ET} < 5.0$ medium rock burst reliability,$2.0 \leq W_{ET} < 3.5$ weak rock burst reliability and $W_{ET} < 2.0$ no rock burst.

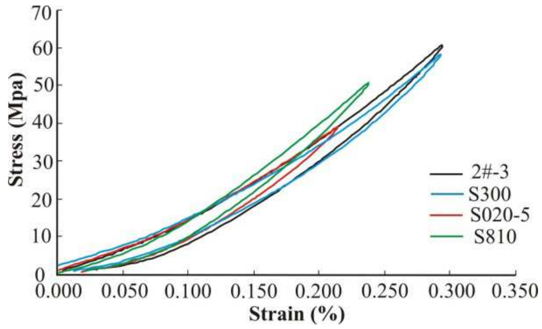

Fig. 3. Uniaxial cyclic loading and unloading stress-strain diagram for rock samples.

4.2. Criterion of Rock Brittleness (B)

The criterion of rock brittleness is defined as the ratio of uniaxial compressive strength to tensile strength of rock, that is:

$$B = \frac{\sigma_c}{\sigma_t} \quad [4]$$

Where σ_c is uniaxial compressive strength (MPa), σ_t is uniaxial tensile strength (MPa)

Qiao and Tian [8]experimental study have shown that the rock brittleness index $B \geq 40$ have no rock burst, $26.7 \leq B < 40$ weak rock burst, $14.5 \leq B < 26.7$ strong rock burst, $B < 14.5$ violent rock burst. Consequently, the values have obtained from the formula and experimental results are shown in Table 1, which indicates very strong tendency of rock burst.

5. Petrographic Descriptions

The mineralogical and texture characteristics of samples were studied by optical microscopy. Detail observations of the samples in the thin section coupled by model composition by X-ray diffraction (Table.2) lead to divide the rocks into: medium- to coarse-grained hornblende granite (Sample 2#), fined-grained foliated granite (Samples 020-5 and 020-10), medium-grained slightly foliated granite(Sample 020-11), porphyritic granite (Sample 810-1)andQuartz-rich granodiorite (sample 300-1) (Fig 4).The rocks are essentially sub-equigranular, fine- to medium-grained (*Samples S020-5, S020-10, 300-1) and medium-to* coarse-grained*(S#-3).* The primary mineralogy of these rocks composed of sub-hedral to anhederal quartz,K-feldspar and plagioclase, in addition to chlorite, muscovite and rare biotite (sample S020-5 and S020-10), biotite and hornblende(Sample S020-11 and 300-1). Euhedral to subhedral garnet porphyroblasts is present, as is calcite occurs locally (sample 810). Sample 810 characterized with phenocrysts-rich plagioclase and quartz containing up to 10% of rock volume. Plagioclase phenocrysts are partially altered to sericite, epidote, and kaolinite. Perthite texture (sample S300) and fine myrmekitic texture (sampleS#-3) are common. Sphene, apatite, zircon, allanite and opaques occur as accessory amounts (<1% of rock volume). The turbitity appearance of feldspar and plagioclase grains due to partially to completely alteration to sericite and epidote. Hornblende and Biotite flakes are partially altered to chlorite and titanite along cleavage planes (samples S300 & S#-3).Thin-sections show gneissose structure defined by the preferred orientation of hornblende, biotite and chlorite fibrous. Evidence of plastic deformation is indicated by vast range of quartz grains in fine to medium-grained matrix (Samples S#3, S0205 and S020-11),stretched quartz and feldspar grains, sutured margin of quartz grains (Fig 4a,b,d,e), strained lamellae in plagioclase(Fig.4c) and bending and kink-bands of platy and fibrous minerals. In places, oriented transgranular micro cracks were observed as a result of brittle deformation (Fig 4a, b). All of these features indicate that these rocks subjected to high brittle deformation event.

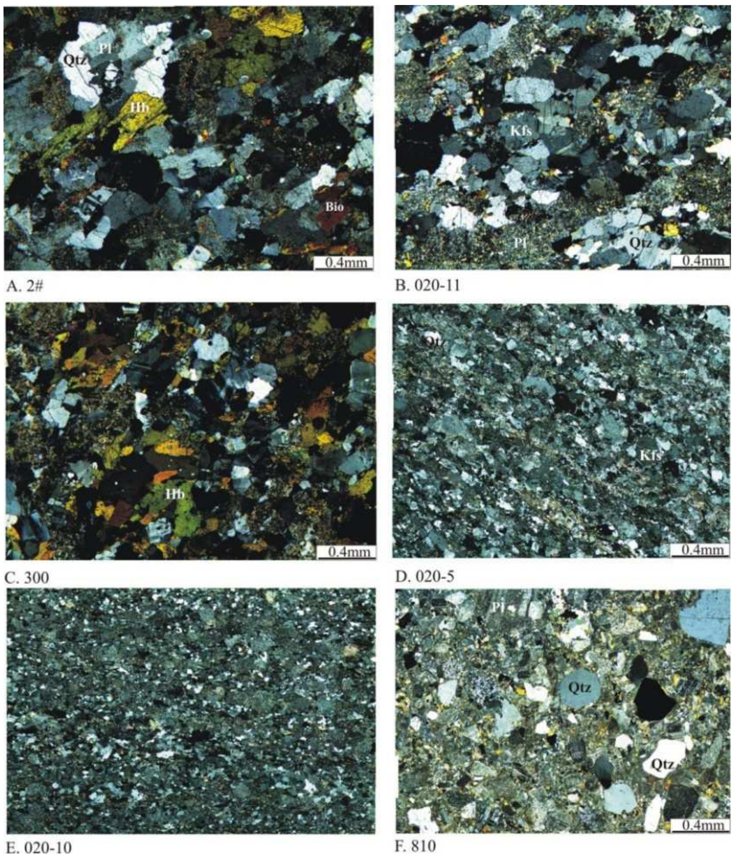

Fig. 4. *Photomicrographs of studied rock samples A) medium- to coarse-grained hornblende granite, B) medium-grained slightly foliated granite, C) Quartz-rich granodiorite, D) and E) fined-grained foliated granite, F) porphyritic granite*

Table 2. *Model compositions (XRD data) and microfabric parameters of the investigated rock samples*

Sample No	Model composition %								Microfabrics parameters				
	Qtz	Kfs	Pl	Mc	Hb	Cc	Cl	Op	Grain Size (mm)			AR	SF
									Min	Max	Mean		
2#-3	23	24.3	28.8	12.2	6	1.1	3.1	0.9	0.17	0.39	0.24	0.63	0.50
020-5	29.3	16.2	25.1	3.5	-	6.6	17.6	0.3	0.05	0.18	0.09	0.67	0.60
020-10	46.5		26.3	7.8	-	3.7	15.0	0.7	0.04	0.10	0.06	0.68	0.62
020-11	35				-				0.18	0.40	0.25	0.64	0.53
300-1	32	33.5	26.3	1.5	21.8	2.7	3.7	1.3	0.15	0.39	0.22	0.70	0.52
810-1	37.7		52.3	1.4	-	1.8	5.6	0.7					

Qtz= Quartz, Kfs = K.feldspar, Pl = Plagioclase, Mc = Mica, Hb = Hornblende, Cc = Calcite, Cl = Clay, Op = Opage, AR =Aspect Ratio, SF = Shape Factor.

6. Microfabrics Assessment by the Image Analysis

A semi-quantitative analysis of microfabric was carried out using image measurement of thin sections employing TIGER 3000P polarized software. The detailed procedure of quantitative image analysis is described in detailed by Prikryl[11]. The method consists of the following stages: image acquisition, digitizing, measurement and data analysis.

Quantitative petrographic analysis is started with image acquisition where the rock microfabricis photographed from the each thin section. The dimension of each image is 1.15mm height and 1.4mm length with special resolution 1024 x 768 pixels. A total of 25 images were captured from each thin section and then mosaiced to represent the whole thin section.

Digitizing stage, which focused on the drawing outlines of grain boundaries using specific software. In this stage it is necessary to apply scale to get real value compared with original thin section that examined in the microscope. The correct interpretation of rock strength variation is mainly influenced by precise determination of microstructures present which represent one of the most crucial factors. The polarized software offers specific-feature for measuring and analyzing the fabric parameters such as grain size, aspect ratio and shape factor. The grain size value is expressed as the diameter of the circle of the equivalent area, which is easy to obtain from the image analysis system. The grain-size values of all analyzed grains were then averaged for each rock type. The average grain sizes were then compared with experimental results of rockburst potential indices. The results of the quantitative image analysis measurement are given in Table2.

7. Correlation Analysis

Regression analysis was applied to the petrographic data in order to recognize potential of predicting the reliability of rock burst indices by each single textural parameter (such as mineral content, average grain size and shape factor). Linear regression was used based on the coefficients of determination (R^2) and the equations of the fitted lines were calculated by the "least squares" method. R^2 is the square of the correlation between the response values and the predicted response values. A value closer to 1 indicates a better fit. The best fit line and its regression analysis for each data set is illustrated in Figures 5 and 6.

According to the previous studies, concerning the mineral composition, the variation in the quartz content is one of the main properties controlling the rock strength. In this paper, the plot of the quartz content as a function of ruck burst Indexes is shown in Figure 5. As can be seen in this figure, there is a positive correlation between quartz percent and elastic strain storage energy index and Strength brittleness coefficient (K), as the quartz content increase the value of rock burst indexes increase. The correlation coefficient was found (R^2=0.8083) to KET and moderate (R^2 = 0.614) to K and the linear correlations can be expressed by the following equations [5, 6]:

$$K_{ET}= 0.2458(Qtz\ \%) - 2.9456 \qquad [5]$$

$$B = 0.4058(Qtz\ \%) - 4.9387 \qquad [6]$$

Similar trend has been found by Meng and Pan [25] while working in clastic rocks. The results of the their experiment studies show that with increasing composition percentage of quartz, the rock strength and brittleness are gradually increased and failure duration of rocks decrease, which indicate higher bursting potential. The result of this correlation indicate that little different in quartz percentage in granitic rocks in same tectonic condition has a great influence in rock burst tendency. However, the studied rock samples from the tunnels site are nearly having similar composition, which consist of granite to granodiorite rocks.

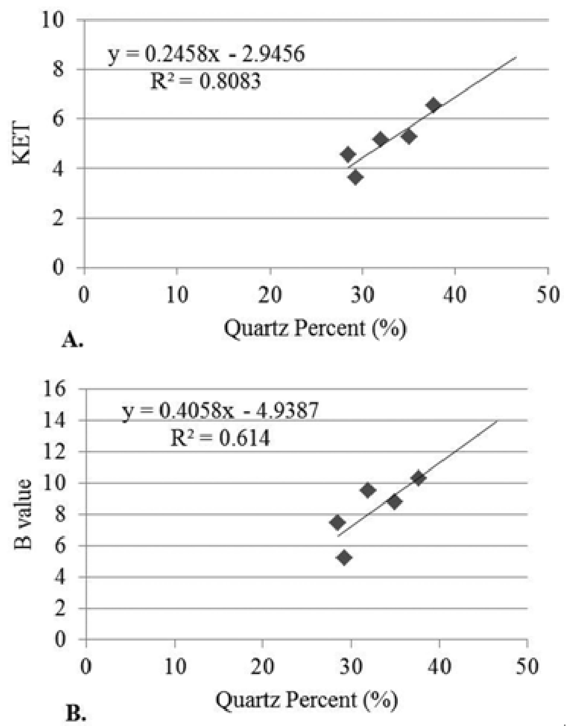

Fig. 5. *Relationship between quartz content of the studies samples and A) elastic strain energy storage index (K_{ET}), B) strength brittleness coefficient (B)*

Generally, it has long been defined that the higher strength related to finer grained rocks of the same rock type [26,27]. Not only the grain size but also the grain size distribution, that with increasing the range of grain size distribution, the rock strength increases. These results coincide with the results obtained from experimental tests of studied rock samples as illustrated in Table 2. Moreover, in this study the average values of grain sizes were correlated with rock burst indices of the studied rock samples. The result shows positive correlation with moderately strong correlation coefficient

(Fig 6). The values of rock burst indexes tend to increase when the grain size increases. However, the statistical linkage model can be depicted by the following equations:

$$K_{ET} = 12.356(G.S) + 2.375 \qquad R^2 = 0.7419 \quad [7]$$

$$B = 24.015(G.S) + 3.0628 \qquad R^2 = 0.7813 \quad [8]$$

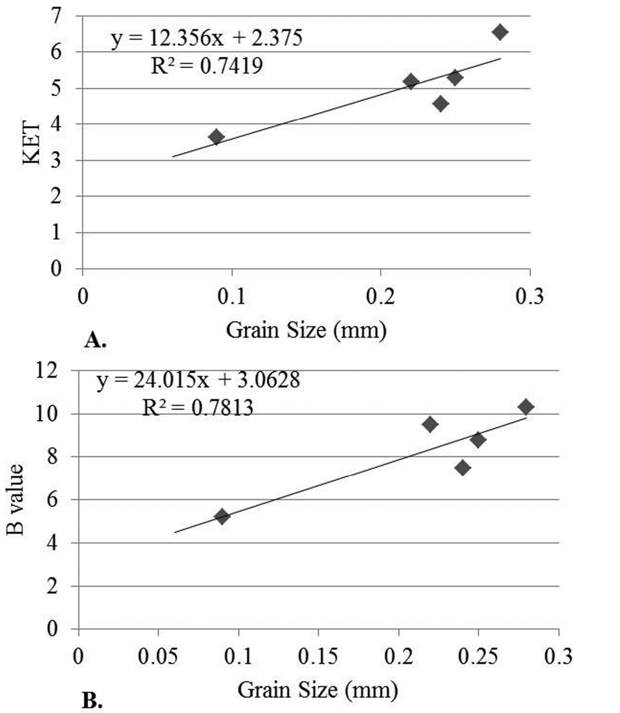

Fig. 6. Relationship between average grain size of the studies samples and A) elastic strain energy storage index (K_{ET}), B) strength brittleness coefficient (B)

8. Conclusions

The interrelationships between rock burst indices, elastic strain storage energy (K_{ET}) and strength brittleness coefficient (B), and microfabric characteristics are correlated within the scope of this research by simple regression analysis. These indexes (K_{ET} and B) were determined in the laboratory from studied rocks obtained from pen yin la and Ming jiong tunnels along La Ri railway. Microfabrics analysis was obtained by using semi-automatic petrographic technique. Consequently, the conclusions of the study are as follow:

1 The variation of quartz content within almost similar rocks is one of the main factors controlling the liability of rock burst. The elastic strain storage energy (K_{ET}) and strength brittleness coefficient (K) increase with increase in quartz percentage.
2 The mean grain size has a good linear correlation with to rock burst indices. The elastic strain storage energy (K_{ET}) and strength brittleness coefficient (K) increase with increase in grain size.
3 According to the current study, before tunneling excavation, the petrographic information could be ideal sources for the estimation of rockburst potential in the initial investigation. However, this study is pointed out that the elastic strain storage energy (K_{ET}) and strength brittleness coefficient (K) can be estimated by determining microfabrics with the given empirical equations under the specified limits without extrapolation.

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