Szczepanik, Z., Milne, D., Kostakis, K., Eberhardt, E. Long Term Laboratory Strength Tests in Hard Rock.
ISRM 2003–Technology roadmap for rock mechanics, South African Institute of Mining and Metallurgy, 2003.

Long Term Laboratory Strength Tests in Hard Rock

Z. Szczepanik[*], D. Milne[*], K. Kostakis[**], E. Eberhardt[***]

[*] Department of Civil and Geological Engineering, University of Saskatchewan, Saskatoon, Canada
[**] Technological Educational Institute of Pireaus, Athens, Greece
[***] Engineering Geology, Swiss Federal Institute of Technology (ETH Zurich), Zurich, Switzerland

Abstract

This paper presents the results of a series of creep tests performed on a total of nine samples of Lac du Bonnet granite from the Underground Research Laboratory near Pinawa, Canada. Each of the nine samples were subjected to stresses in excess of 80% of the average uniaxial compressive strength of the granite and were maintained at that level of constant loading for periods of time ranging between a few minutes and several months. Acoustic emission was recorded in order to monitor the development and accumulation of brittle microfracture damage in the samples throughout the long-term loading.

According to previously published theoretical predictions and field results, as well as similar experimental results of creep tests in granite, samples should fail when loaded to 70% of their UCS for an extended period of time. Six of the samples did not fail when subjected to stresses in excess of 80% of their UCS over periods of several months and were subsequently subjected to uniaxial compression to failure. The average strength of the samples that had previously been subjected to long-term loading were comparable to the average published strength of this rock. Three of the nine samples had increased end confinement and these three samples failed under long term loading.

Résumé

Cet article présente les résultats d'une série d'essais de fluage de roche exécutés sur neuf échantillons de granite de Lac du Bonnet, du laboratoire souterrain de recherches près de Pinawa, Canada. Chacun des neuf échantillons a été alors soumis aux charges au-dessus de 80% de la résistance à la UCS moyenne du granit et a été maintenu à ce niveau du chargement constant pendant des périodes s'étendant entre quelques minutes et plusieurs mois. L'émission acoustique a été enregistrée pendant les essais afin d'obtenir des indications des dommages pendant le chargement à long terme.

Selon des résultats théoriques précédemment édités et les résultats expérimentaux semblables des essais à long terme en granite, échantillons devrait échouer si chargé à 70% de leur UCS pendant une période prolongée. Six des échantillons n'ont pas cassé quant ils ont été soumis aux charges au-dessus de 80% de leur UCS et ont été plus tard soumis à la compression uniaxiale à la rupture. La force moyenne des échantillons qui avaient été précédemment soumis au chargement à long terme étaient comparable à la force éditée moyenne de cette roche. Trois des neuf échantillons avaient augmenté le confinement de fin et ces trois échantillons ont cassé sous le chargement à long terme.

Zusammenfassung

Dieser Artikel beschreibt die Resultate von Kriechversuchen, die an neun Proben aus dem Lac du Bonnet Granit des "Underground Research Laboratory" bei Pinawa in Kanada durchgeführt wurden. Jede der neun Proben wurde Drücken unterworfen, die mehr als 80% der einaxialen Druckfestigkeit des Granites entsprechen. Diese Drücke wurden für verschiedene Zeitspannen von wenigen Minuten bis zu einigen Monaten auf einem konstanten Niveau gehalten. Während der gesamten Langzeitbelastung wurden akustische Emissionen aufgezeichnet, um die Entwicklung und gesamthafte Beschädigung der Proben durch Sprödbruch aufzuzeichnen.

Entsprechend bisher veröffentlichter theoretischer Vorhersagen, Feldversuchen und auch experimentellen Resultaten von Kriechversuchen an Granitproben wäre ein Versagen der Proben zu erwarten gewesen, wenn sie über längere Zeit einer Last von 70% ihrer einaxialen Druckfestigkeit unterworfen werden. Wider Erwarten trat bei sechs der Proben kein Versagen ein, als sie mit über 80% ihrer einaxialen Druckfestigkeit über mehrere Monate belastet wurden; daher wurden sie im Anschluss bei einaxialer Kompression zum Versagen gebracht. Die mittleren Festigkeiten der im Langzeittest verwendeten Proben sind vergleichbar mit den normalerweise für diesen Gesteinstyp angegebenen Festigkeiten. Drei der neun Proben versagten unter der Langzeitbelastung; diese drei Proben hatten eine erhöhte Endflächenreibung.

1. Introduction

Some of the key concerns regarding the design of underground nuclear waste repositories, include the implications of potential ground disturbance by the excavation method and the redistribution of *in situ* stresses around the excavation. Both of these factors relate to the initiation and propagation of brittle fractures and the extent of the excavation disturbed zone (EDZ), which could adversely affect the stability of the excavation boundary and could increase the permeability of the near-field host rock.

Establishing the initiation and development of stress-induced microfractures in the EDZ is thus of key interest. In general, the propagation of a brittle fracture can be equated with the irreversible destruction of molecular cohesion along the generated fracture path. In this sense, the microfracturing process acts to 'damage' the rock material. As the number of propagating fractures multiplies, damage can be viewed as accumulative and can be correlated to observed decreases in the elastic stiffness[5] and cohesive strength of the material[10].

Considerable effort has been extended towards the understanding of brittle fracture processes and mechanisms. Much of this focus has been extended to laboratory testing and the measurement/quantification of brittle fracture thresholds[1, 12, 7, 10, 4]. Of these, the crack damage threshold (marked by the onset of dilatancy and taken as the point of reversal in the volumetric strain curve; Figure 1) is of specific interest as several studies have associated the threshold with unstable crack propagation in brittle rocks[1,10]. Unstable crack propagation corresponds to the point where the relationship between the applied stress and the crack length ceases to exist and other parameters, such as the crack growth velocity, take control of the propagation process. Under such conditions crack propagation will continue until failure even if the applied loading is stopped and held constant. As such, Martin & Chandler[10] and Read *et al.*[11] have equated the crack damage threshold to the long-term *in situ* strength of brittle rock, a practice they note that has been similarly adopted in the concrete industry.

Thus, the identification of these processes and their associated mechanisms are of key interest in predicting both the short and long-term strength of rock. This paper focuses on these processes by presenting the results from several short and long-term laboratory creep tests performed on Lac du Bonnet granite samples. Preliminary assessment of these test results considers the validity of the crack damage threshold with respect to its coincidence with volumetric strain reversal.

2. Sample Description and Loading Procedure

Testing was conducted at the University of Saskatchewan's Rock Mechanics Laboratory on cylindrical samples of pink Lac du Bonnet granite obtained from the 130 m level (i.e. 130 m below ground surface) of the Underground Research Laboratory (URL).

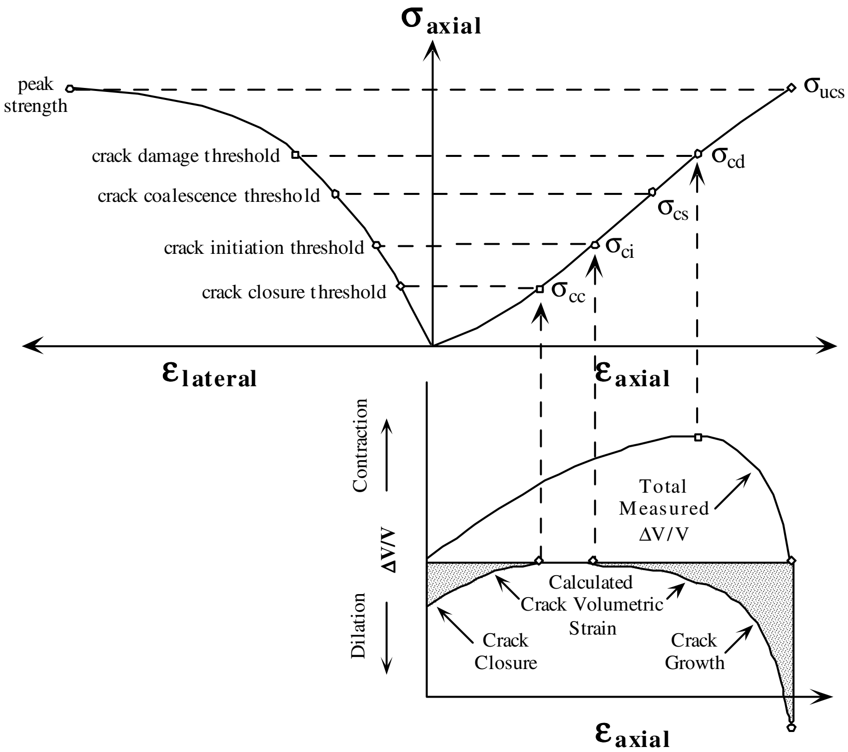

Figure 1. Stress-strain diagram showing the stages of crack development (modified after Martin[9]). Note that the axial and lateral strains are measured, and the volumetric and crack volumetric strains are calculated.

Threshold Parameter	Avg. Value
Number of Tests	20
Young's Modulus	66.5 GPa
Poisson's Ratio	0.31
Crack Closure, σ_{cc}	47.3 MPa
Crack Initiation, σ_{ci}	81.5 MPa
Crack Coalescence, σ_{cs}	132.8 MPa
Crack Damage, σ_{cd}	156.0 MPa
Peak Strength, σ_{UCS}	206.9 MPa

Table I. Average crack threshold values for Lac du Bonnet granite (after Eberhardt et al.[4]).

The pink granite is medium to coarse-grained with an average grain size between 3 and 4 mm. Table I provides the material properties and crack thresholds for this rock type as established by Eberhardt *et al.*[4].
Samples were prepared for testing according to ASTM standards with length to diameter ratios of approximately 2.25, and were instrumented with both electric resistance strain gauges and piezoelectric acoustic emission (AE) transducers. Six of the samples had highly polished end surfaces to minimize end effects and three were tested with confined ends (using clamps) or were tested using roughened loading platens to increase sample end frictional confinement. Applied loads and the resulting strains were recorded using an automatic data acquisition system, sampling at a rate between 1-3 readings per second, thereby overcoming any deficiencies in data resolution. The AE monitoring system consisted of a bandpass filter with a frequency range of 125 KHz to 1 MHz and a pre-amplifier with 40 dB total gain and a dynamic range of 85 dB. The AE data was recorded with an AET 5500 monitoring system using a threshold value of 0.1 V.

The testing procedure adopted involved loading the samples at a constant rate of approximately 0.25 MPa/s up to 180 MPa. This is well above the previously measured average crack damage threshold of 156 MPa. At this point, the load was held constant and sample strains and AE monitored. Samples that did not fail under long term loading at 180 MPa were unloaded, and then tested to failure using the standard testing procedure outlined.

3. Test Results

Nine long-term loading tests were conducted for test durations between 15 minutes and 7 months. Sample results are given in Table II. None of the tests conducted on samples without additional end confinement resulted in failure during the long-term loading at 180 MPa. These samples were unloaded and retested to failure. However, accurate failure estimates are only available for 5 of these 6 tests. The average unconfined compressive strength of these 5 samples was 212 MPa. This is close to the average UCS previously estimated from 20 samples (Table I). The results do not indicate significant weakening of the samples due to the long-term loading.
The sample ends for test 130-2-8 were confined with hose clamps to investigate the possible influence of sample end effects. This was the first sample to fail at a load of 180 MPa, after 35 hours of loading. Subsequent tests were conducted with roughened loading platens and with circumferential strain gauges installed at the centre of the sample as well as 2 cm from each sample end. Sample 130-2-15 failed after 15 minutes of loading. The ratio between the minimum circumferential strain at the sample end and the circumferential strain at the centre of the sample was 0.08. Sample 130-2-11 failed after over 16 days under a load of 180 MPa. The ratio between the minimum circumferential strain at the sample end and the circumferential strain at the centre of the sample was 0.43.

Axial stress-strain results were assessed and Figure 2 shows an example stress-strain plot for an 18-day duration test (130-2-1). The volumetric strain reversal corresponding to the crack damage threshold occurred during initial sample loading at a stress of approximately 141 MPa. This is compared to the average crack damage threshold stress of 156 MPa (± 13 MPa), previously estimated from 20 samples (Eberhardt et al., 1998).

Figures 3 and 4 show the volumetric strain and acoustic emission data collected during constant creep loads for two tests. Only the data collected after strain reversal is shown. Figure 3 shows data from the same 18-day test shown in Figure 2 (130-2-1). This sample did not fail and the acoustic emission data shows only a few sporadic events after initial application of the 180 MPa load. Figure 4 shows the volumetric strain and acoustic emission data from sample 130-2-15. This sample was tested with roughened loading platens to provide additional end confinement. This sample failed after 16 days of loading.

Sample No.	Length (mm)	Diameter (mm)	P-Wave Velocity (m/s)	S-Wave Velocity (m/s)	Strength (MPa)	Test Duration (min.)	Volumetric Strain Reversal (MPa)
130-2-10	133.4	60.9	4860	2905	209.6	300933	120
130-2-6	135.0	60.9	5030	3065	239	2842	155
130-2-13	134.2	60.8	4905	3065	>220	24810	154
130-2-9	135.1	60.8	4790	3130	216.2	59096	148
130-1-20	132.2	60.7	4420	2935	206	48853	173
130-2-1	137.0	60.6	4645	2940	188.4	27122	141
Sample ends clamped							
130-2-8	131.6	60.9	4650	3005	(f)	2123	130
Sample ends loaded with roughened platens							
130-2-11	137.2	60.9	4610	3125	(f)	15	135
130-2-15	135.7	60.8	4935	3000	(f)	23420	158

Table II. Summary test results for the nine Lac du Bonnet granite samples

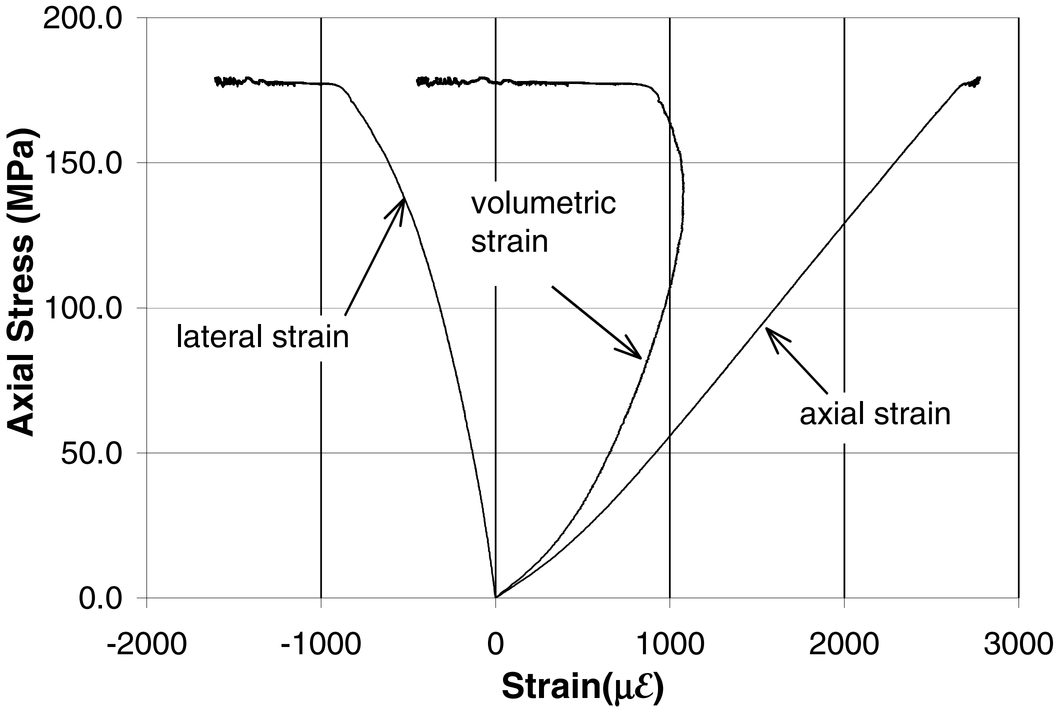

Figure 2. Axial stress versus strain values for 18-day creep load test (sample 130-2-1).

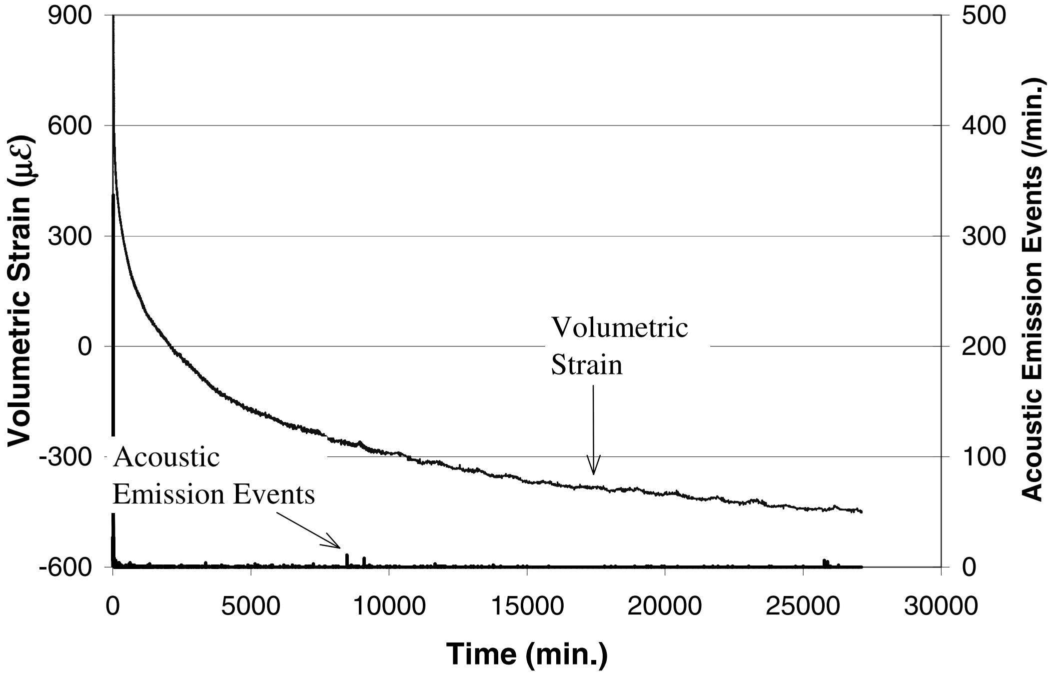

Figure 3. Volumetric strain and acoustic emission versus time (sample 130-2-1). Note that peak values during initial sample loading have not been shown.

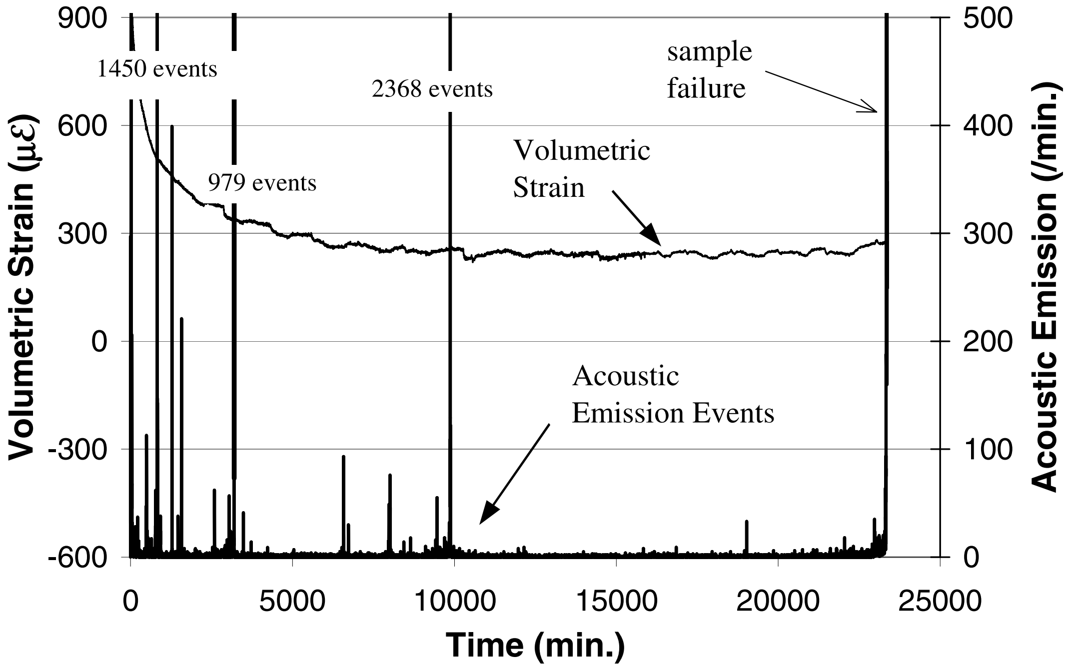

Figure 4: Volumetric strain and acoustic emission versus time (sample 130-2-15). Note that peak values during initial sample loading and failure have not been shown.

Figure 4 shows that the acoustic emission response in this case is significant, indicating damage is occurring, the accumulation of which drives the sample to failure. It is of interest to note that the sample that failed with the roughened loading platens (Figure 4) experienced less volumetric strain reversal than the sample that did not fail after being loaded for 18 days (Figure 3). It should be further noted that the test period of 18 days shown in Figure 3 (i.e. no failure) was chosen for comparative reasons, and that several other tests under the same creep loading conditions likewise showed little AE activity nor signs of imminent failure after several months of testing.

4. Discussion - Conclusions

The initiation, accumulation and growth of stress-induced cracks in rock is generally referred to as rock damage. Martin & Chandler[10] refer to the crack damage stress as the load at which a sample will eventually fail, under prolonged loading, which they suggest corresponds to approximately 70% to 80% of the peak sample strength. This crack damage stress or crack damage threshold point is also believed to corresponds to the point at which strain reversal or sample dilation starts. Based on the current tests, the average axial stress corresponding to the volumetric strain reversal point approximately equals 70% of the estimated unconfined compressive strength of the rock.

The stress at volumetric strain reversal corresponds to expected levels, however, in six of the nine samples tested, failure did not occur under long-term loads in excess of the proposed crack damage threshold. This is in agreement with results by Lajtai[8] who showed that through tests on quarried granite samples near Lac du Bonnet and the URL, the stress-level at which dry samples enter into steady-state creep and eventually fail by static fatigue is 200 MPa. At this stress level, the overall effect of time on strength reduction was approximately 20% of the uniaxial compressive strength.

These stresses are well-above those of the crack damage stress threshold. It has been suggested that the sample configuration for unconfined compressive strength tests acts to limit crack propagation. Diederichs[2, 3] suggests that hoop strain is generated between a dilating crack and the outer surface of a cylindrical sample. This hoop strain may generate a confinement that limits continued crack growth.

Preliminary test results suggest an alternate mechanism may be influencing unstable crack propagation. Under purely uniaxial loading conditions, splitting parallel to the direction of maximum compression can be expected. Fairhurst and Cook[6] suggest eventual failure at a macroscopic level may be due to buckling of the slabs of rock created by the tensile fractures oriented in the direction of the maximum compressive stress. The three samples that did fail had additional confinement at the sample ends, either with a clamp or by roughening of the surface of the loading platen. The increased end confinement produces differential lateral strain along the sample that may promote buckling and eventual sample failure.

Additional laboratory testing is planned. Continued lateral strain monitoring near the sample ends and at the centre will be conducted to further investigate the influence of end effects on sample behaviour under long term loading conditions.

References

1. Bieniawski, Z.T. (1967). Mechanism of brittle rock fracture: Part I - Theory of the fracture process. *International Journal of Rock Mechanics and Mining Sciences & Geomechanical Abstracts*: **4**(4), 395-406.
2. Diederichs, M.S. (1999). *Instability of Hard Rockmasses: The Role of Tensile Damage and Relaxation.* Ph.D. thesis, Department of Civil Engineering, University of Waterloo, Canada, 566pp.
3. Diederichs, M. (2002). Stress induced damage accumulation and implications for hard rock engineering, Proceedings of the 5th North American Rock Mechanics Symposium and the 17th Tunnelling Association of Canada Conference: NARMS-TAC 2002. Toronto, Canada, 3-12.
4. Eberhardt, E., Stead, D. Stimpson, B. & Read, R.S. (1998). Identifying crack initiation and propagation thresholds in brittle rock. *Canadian Geotechnical Journal*: **35**(2), 222-233.
5. Eberhardt, E., Stead, D. & Stimpson, B. (1999). Quantifying pre-peak progressive fracture damage in rock during uniaxial loading. *International Journal of Rock Mechanics and Mining Sciences*: **36**(3), 361-380.
6. Fairhurst,C. and Cook, N.G.W. (1966). The phenomenon of rock splitting parallel to the direction of maximum compression in the neighbourhood of a surface. *Proc. of the 1st Congress of the International Society of Rock Mechanics,* p. 687-692.
7. 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. *International Journal of Rock Mechanics and Mining Sciences & Geomechanical Abstracts*: **10**(6), 713-726.
8. Lajtai, E.Z. (1981). Creep and crack growth in Lac du Bonnet granite due to compressive stress. *Proc. of the 5th Canadian Fracture Conference: Fracture Problems and Solutions for the Energy Industry,* p. 229-238.
9. Martin, C. D. (1993). *Strength of Massive Lac du Bonnet Granite around Underground Openings.* Ph.D. thesis, Department of Civil and Geological Engineering, University of Manitoba, Canada, 278pp.
10. Martin, C.D. & Chandler, N.A. (1994). The progressive fracture of Lac du Bonnet granite. *International Journal of Rock Mechanics and Mining Sciences & Geomechanical Abstracts*: **31**(6), 643-659.
11. Read, R.S., Chandler, N.A. and Dzik, E.J. (1998). The In situ strength criteria for tunnel design in highly stressed rock masses. *International Journal of Rock Mechanics and Mining Sciences & Geomechanical Abstracts*: **35**(3), 319-368.
12. Wawersik, W.R. & Fairhurst, C. (1970). A study of brittle rock fracture in laboratory compression experiments. *International Journal of Rock Mechanics and Mining Sciences & Geomechanical Abstracts*: **7**(5), 561-575.