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Strength, toughness, damage and fatigue of rock

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ABSTRACT: Assessment of rock mechanical properties depends on sample size and testing methodologies. Even for samples cored from the same rock outcrop the difference in properties appears to be sensitive to the local thermal and stress histories of the rock structure. Variations in the fracture toughness, unconfined compressive strength and tensile strength of a suite of granite samples, when tested using different procedures, are discussed in terms of experimental errors of the loading system as well as the thermal history.

1 INTRODUCTION

Intact rock samples generally exhibit a size effect in that the strength decreases with increasing sample size [Goodman, 1989]. The effects of sample size on the measurement of rock properties can generally be attributed to the microcrack density and distribution [Walsh, 1965; Wong, 1985] both of which will depend on the thermal and stress histories of the rock [Engelder 1987]. Further it has also been observed that rock strength is dependent on the type of test or test methodology. Examples showing this latter effect are: (1) tensile strengths as measured using the Brazilian (BTS) and direct tensile (DTS) strength tests and (2) the fracture toughness using the three point bend (TPBFT) and the short rod (SRFT) methodologies [Ouchterlony, 1988; Bazant et al, 1993]. This paper presents the results of a study of testing methods and thermal history on the mechanical properties of an Australian granite.

2 ROCK AS A COMPLEX MATERIAL

Rocks have deformation-stress memory. Unlike metals, the fatigue life cycle of a rock is comparatively very short, particularly at loads near peak strength [Costin, 1987, Alehossein & Boland, 1995]. This is because of the high stress concentration at the tips of micro fractures and flaws that are generated by processes such as thermal fluctuations or external loading conditions [Korinets & Alehossein, 2002] during the geological development of the rock. Such stress concentration effects contribute to crack growth from randomly oriented microcracks inducing further damage and reducing the rock strength.

Substantial discrepancies are observed in the load-displacement curves of apparently identical rock samples taken from a specific geological location. Even though the source material may be characterised as intact rock having uniform geology, geochemistry and mineralogy, various parts of rock outcrop experience different thermal and stress histories and hence different crack size distributions.

Brittleness factor, K_p, is defined as the ratio of the uniaxial compressive strength and the uniaxial tensile strength [Iyengar & Raviraj, 2001] for a strain-based definition of a brittleness factor. We observe that unlike metals where $K_p \approx 1$ the brittleness factor for rocks is much greater than unity. In compressive loading, this difference is partially due to the large frictional shear stress needed to propagate the lateral wing cracks as well as the complex nature of crack interaction and coalescence [Horii & Nasser, 1985; Wong & Chau, 1998]. In tensile loading, only a limited number of critical cracks are required to induce failure – refer Figure 1.

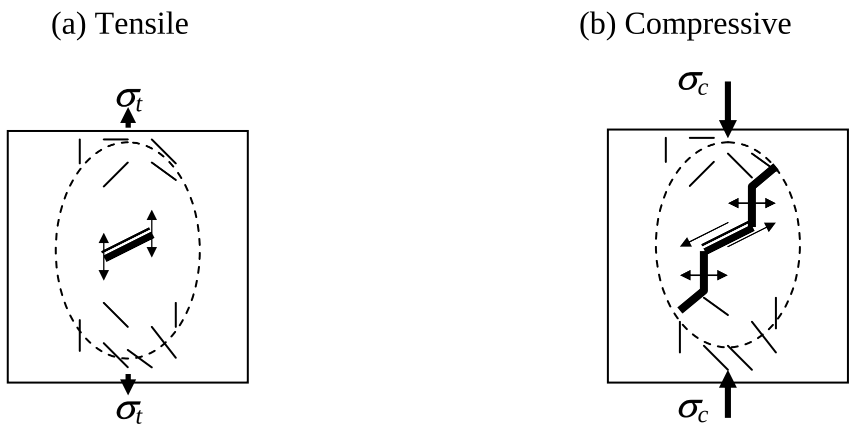

Figure 1. Crack growth under (a) tensile and (b) compressive loading.

Crack extension processes that are reflected in a non-unity brittleness factor account for the increasing strength of rock with confining pressure. For a rock sample with UCS/BTS = 20, the rock shear strength can increase by several times the original unconfined shear strength at a confining stress of half of the rock UCS depending on whether the material behaves according to the Mohr-Coulomb (MC) or Hoek and Brown (HB) failure models [Brady & Brown, 1993] .

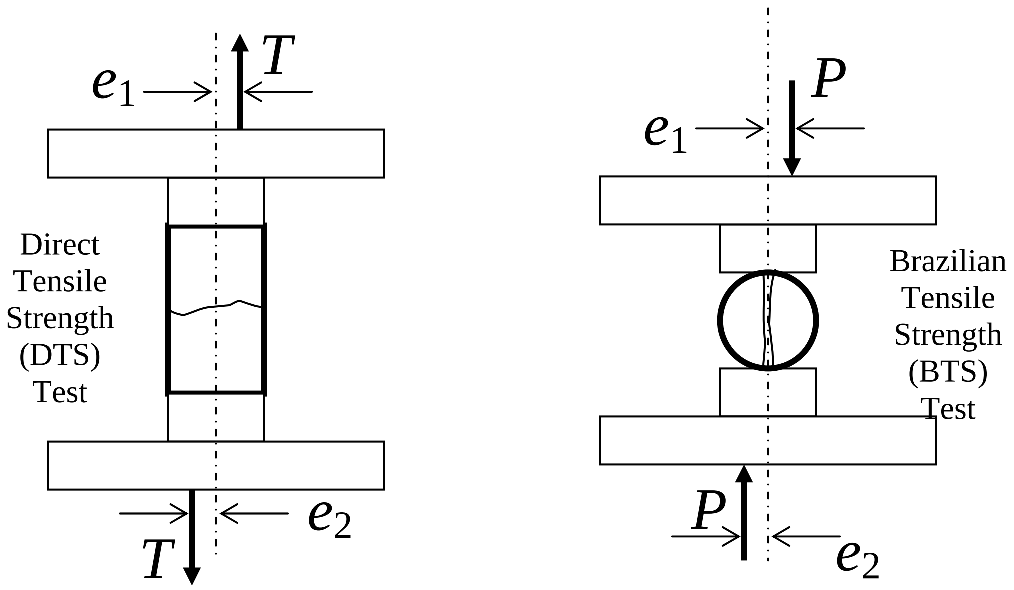

Figure 2. Direct tensile (left) and indirect Brazilian tensile (right) strength tests.

There are errors associated with the testing of rock samples. Tensile strength of a given rock sample (σ_t) should be independent of the method of testing. Theoretically it might be expected that the tensile strengths from a direct test (σ_{DTS}) and from a Brazilian test (σ_{BTS}) are both equal. In fact this is not generally the case because of the several uncontrolled experimental factors that are involved. Consider one factor for example the eccentricity error ($e = e_1 + e_2$) that can arise in these two tests - Figure 2. It is easy to show that the measured strength is different from the authenticated strength (σ_t). In other words:

$$\sigma_{DTS} = \frac{\sigma_t}{A + B\dfrac{e_{DTS}}{D_{DTS}}} \tag{1}$$

$$\sigma_{BTS} = a\sigma_t\sqrt{1 - b\left(\frac{e_{BTS}}{D_{BTS}}\right)^2} \tag{2}$$

By elimination of σ_t from Equations (1) and (2) we have

$$\sigma_{BTS} = a\,\sigma_{DTS}\left(A + B\frac{e_{DTS}}{D_{DTS}}\right)\sqrt{1 - b\left(\frac{e_{BTS}}{D_{BTS}}\right)^2} \tag{3}$$

A, *B*, *a* and *b* are constants best obtained experimentally, although their theoretical values in ideal experiments are given by $a = A = 1$, $b = 4$ and $B = 8$; D is the sample diameter. A Brazilian disc may not fail in pure tensile mode causing $\sigma_{BTS} > \sigma_t$, even in the absence of any eccentricity effects, i.e. $e = 0$. In this case *a* is greater than 1 because of the partial contribution of the shear strength of the rock, which is normally greater than rock tensile strength.

3 EXPERIMENTS

3.1 Compressive Strength (UCS)

Five samples with a length to diameter ratio of 2.5:1 were prepared according to the suggested ISRM method [Brown, 1981]. The results of these mechanical UCS tests (Figure 3) are shown in Table 1.

Table 1. UCS tests results

Parameter	*D* (mm)	*H* (mm)	*Moisture %*	ρ (gr/cc)	ν Poisson's ratio	*E* GPa	σ_{UCS} MPa
Minimum	57.86	144.21	0.003	2.64	0.19	77.5	212.5
Maximum	57.96	145.40	0.003	2.65	0.26	80.8	254.4
Average	57.94	144.76	0.003	2.65	0.22	79.6	238.6
Standard Deviation	0.04	0.47	0.0001	0.00	0.03	1.3	15.8

Figure 3. A UCS sample before (left) and after (right) the test

3.2 Tensile Strength

Direct Tensile Strength

A tension test machine, in which loading is controlled by a stress-feedback method [Okubo & Fukui, 1996; Alehossein et al, 2003] was used to conduct the tests for direct tensile strength on cored and heat treated samples (DTS and DTST respectively). Figures 4a and 4b display the stress-strain curves obtained from these two sets of tests.

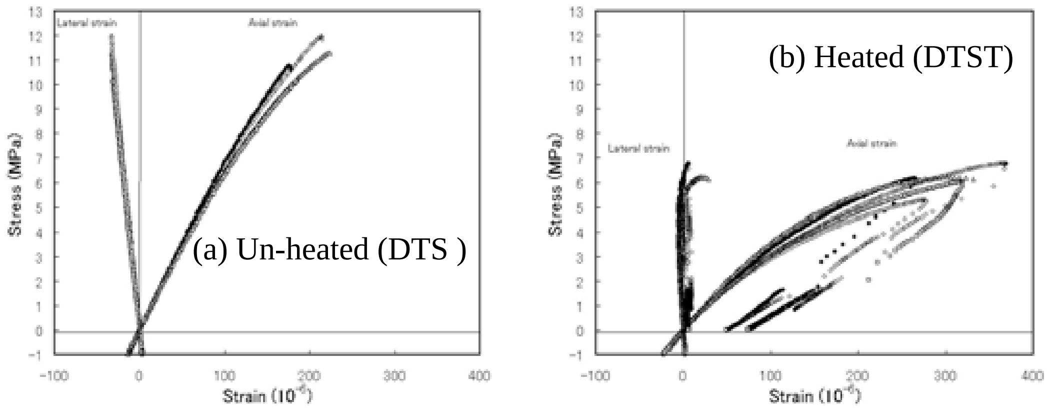

Figure 4. Stress-strain behaviour of unheated and heated samples in tensile tests.

The results of the ten samples tested for the direct tensile strength tests (Figure 5) are summarised in Tables 2 and 3.

Table 2. Direct tensile strength tests results under non thermal condition (DTS)

Parameter	Minimum	Maximum	**Average**	Standard Deviation
σ_t = Tensile strength (MPa)	10.77	11.97	**11.11**	0.62
E = Secant ($0 \Rightarrow 0.5\sigma_t$) Young's modulus (GPa)	64.8	70.1	**67**	2.34
ν = Poisson's ratio	0.187	0.208	**0.199**	0.01

Table 3. Direct tensile strength tests results under thermal condition (DTST)

Parameter	Minimum	Maximum	**Average**	Standard Deviation
σ_t = Tensile strength (MPa)	5.28	6.79	**6.10**	0.54
E = Secant ($0 \Rightarrow 0.5\sigma_t$) Young's modulus (GPa)	29.4	37	**32**	3.26
ν = Poisson's ratio	0.031	0.053	**0.042**	0.008

A comparison of these two tables reveals the effects of the thermal cycle 25°C⇒300°C⇒25°C. The percentage strength loss is about 45%. Stiffness loss is 52% and the Poisson's ratio reduction 79%.

Figure 5. DTS samples

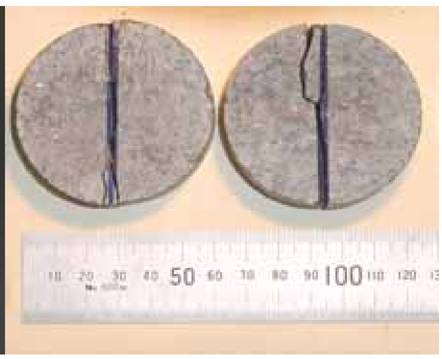

Figure 6. Two BTS samples

Brazilian Tensile Strength (BTS)

Discs of 1:2 length to diameter ratios were cut from the cores for the Brazilian tensile tests (Figure 6). There was only slight deviation of the cracks from their symmetrical crack planes for any of the five samples tested. Results of these tests are summarized in Table 4 and compared with the DTS results in Table 2.

Table 4. BTS tests results

Parameter	D (mm)	H (mm)	σ_{BTS} MPa	σ_{DTS} MPa
Minimum	57.95	28.57	10.75	10.77
Maximum	57.98	29.36	14.83	11.97
Average	57.97	28.96	13.46	11.11
Standard Deviation	0.01	0.30	1.57	0.62

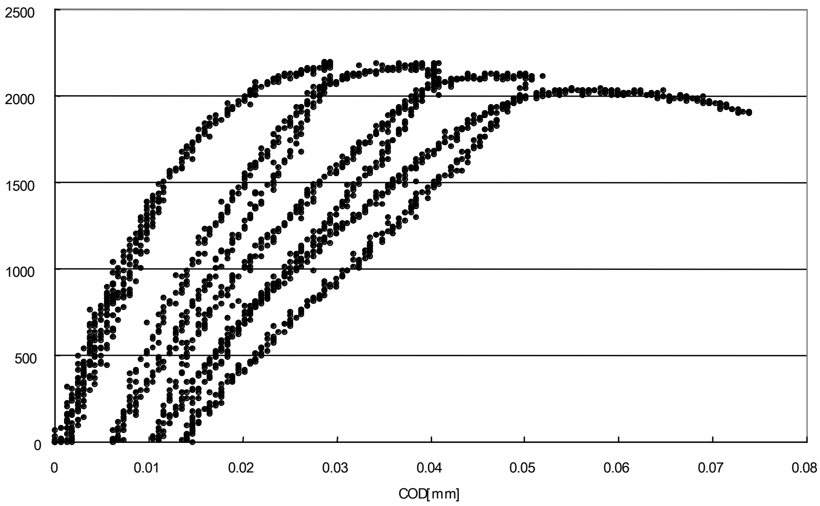

Figure 7. Load-COD behaviour for TPBFTT (heated) samples

3.3 Fracture Toughness

Three Point Bending Fracture Toughness (TPBFT)

Granite cores were prepared for three point bending tests according to the ISRM suggested methods. Two thermal conditions were used: (i) thermally unconditioned (25°C) and (ii) thermally conditioned (25°C⇒300°C⇒25°C) (TPBFT & TPBFTT respectively). Only four out of the ten samples were appropriate for testing. In these limited number of samples, the average specimen diameter, D = 58mm, length, H = 200mm and the average chevron tip distance from the specimen, a_0 = 8.7mm. Loading was controlled by COD velocity constant and for each test load (P), COD and LVDT were monitored and measured during the test. Results of the fracture toughness calculations are summarised in Table 5 and shown in Figure 7. A major finding of these tests is that even a single heat cycle can reduce fracture toughness by about 15%.

Table 5. Three point bending fracture toughness tests

Three-Point-Bending Fracture Toughness	Minimum (MPam^{½})	Maximum (MPam^{½})	**Average** (MPam^{½})
TPBFT	2.2	2.4	**2.3**
TPBFTT	1.9	2.1	**2.0**

Short Rod Fracture Toughness (SRFT)

Nine SRFT test samples were prepared ($D \approx$ 58mm, length 1.45D). Each sample had a notch of width $t \approx$ 2.2mm cut parallel to the core axis with subtended chevron angle, $\theta = 56^0$. Two semi-circle steel slices were bonded to the top of each sample using a two-part epoxy adhesive. A V-shaped notch with an angle of 42^0 was formed in the middle of the slices. The tensile load was applied by a steel wedge (angle 46°) inducing catastrophic crack growth in the ligament of the notched section during the test [Zhang et al., 1999] – see Figure 8. Four specimens were tested using a standard direct tensile or "pull apart" method. The tests were performed under displacement control with a loading rate of 0.01 mm s^{-1}. The results are summarised in Table 6.

Table 6. SRFT tests results

Sample No	Loading type	D (mm)	H (mm)	R_L (mm)	R_R (mm)	a_1 (mm)	K_{IC} (MPam^{½})
1	Wedge	57.95	85.51	27.16	28.3	54	2.75
2	Wedge	57.91	85.07	28.28	27.24	54.72	2.25
3	Pull-Out	57.96	84.31	27.3	28.42	54.66	**2.31**
4	Pull-Out	57.95	84.45	28	27.98	54.94	**2.67**
5	Wedge	57.96	85.24	28	27.98	55.54	2.71
6	Wedge	57.93	85.22	28.34	27.26	55.24	2.14
7	Wedge	57.92	84.87	28.1	27.68	54.78	2.10
8	Pull-Out	57.96	84.56	27.42	28.54	54.42	**2.49**
9	Pull-Out	57.94	84.73	28.08	27.66	54.64	**2.60**
Minimum		57.91	84.31	27.16	27.24	54.00	2.10
Maximum		57.96	85.51	28.34	28.54	55.54	2.75
Average		57.94	84.88	27.85	27.90	54.77	2.45
Standard Dev.		0.02	0.41	0.44	0.47	0.45	0.25

Figure 8. SRFT two test samples after the test; left (wedge), right (pull-apart)

4 DISCUSSION

Results of the direct tensile strength tests indicate that there was a 45% reduction in the strength of the rock resulting from one thermal cycle. The stiffness was reduced by 52% and Poisson's ratio by 79%. In contrast, the effect of the thermal cycling on the fracture toughness was significantly less – only 15%. The most likely explanation of such differences in the deformation of the granite samples is the marked differences in the microcrack lengths and densities (and their distributions) between the heated and unheated samples. Furthermore, tensile loading would activate the whole spectrum of microcracks throughout the sample while in 3-point bend testing for fracture toughness only those defects located in the vicinity of the notch would influence the response of the material.

For unheated samples, Young's modulus and Poisson's ratio in tensile loading are both slightly less than those obtained during compressive loading. The average compressive strength of this rock was 238.6 MPa. Assuming a UCS/BTS of 20, the tensile strength is estimated at 12MPa. This value is between that measured by the Brazilian and the direct tensile methods – i.e. 13.46 and 11.11 MPa respectively.

Two different values of mode I fracture toughness have been obtained. The three point bending method gave a fracture toughness of 2.30 MPa $m^{½}$, while the short rod method 2.45 MPa $m^{½}$. The standard deviation from the two different testing methods was in the same range as the standard deviation from samples tested by one single method. Hence, on the basis of the limited sample numbers, it has not been possible to assess any intrinsic differences between these two testing methods.

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