Indian Society for
Non-Destructive Testing
Hyderabad Chapter

Proc. National Seminar on
Non-Destructive Evaluation
Dec. 7 - 9, 2006, Hyderabad

A Laboratory Investigation of Acoustic Emissions Associated with the Brittle Fracture of Rock Under Dry and Wet Conditions

G.M. Nagaraja Rao[1], K.B. Chary[2], K.J. Prasanna Lakshmi[2], N.A. Vijaya Kumar[2], S. Udaykumar[1], M.V.M.S. Rao[2] and R.K. Chadha[2]

[1]National Institute of Rock Mechanics, KGF 563 117
[2]National Geophysical Research Institute, Hyderabad -500 007
e-mail: kbchary@rediffmail.com, mvmsraodr@yahoo.com

Abstract

We have carried out a series of laboratory experiments on AE monitoring to investigate the fracture behaviour of some dry and water-saturated rock samples of south-east Gujarat and Maharashtra which have been experiencing prolific seismicity in recent years in India. The results obtained from the study of Pavgadh rhyolites and Godhra granites tested to failure under triaxial compression are presented and discussed in this paper. The AE monitoring was carried out using a 2-channel Spartan AE system during the deformation and failure of rock at confining pressures ranging between 15 MPa and 60 MPa. The tests were carried out using a Hoek cell and a 150-Ton MTS Servo-controlled Testing Machine. The stress-strain data and statistical parameters of Acoustic Emissions (AE) were monitored and recorded concurrently during each test using PC-based systems. The time-histories, load-based plots and distribution functions of AE have been analyzed using Mistras software. The results show that at 60 MPa confining pressure, the triaxial compressive strength of these rocks reach values of nearly 3 to 3.5 times the UCS. The water–saturated rhyolite showed a lower compressive strength at 60 MPa confining pressure than the dry rock by nearly 50-60 MPa. Correspondingly, the AE statistics (occurrence rate, energy counts etc) of water-saturated sample were found to be less than those of the dry sample. Whereas the water-saturated fine-grained Godhra granite showed a marginal increase in triaxial compressive strength at 60 MPa confining pressure with reduced AE statistics. The AE signatures in general, and *b*-value in particular, have indicated that the rate at which the crack damage accumulates is functionally dependent on the fluid-rock interaction and the linkage of cracks during the inelastic deformation and failure of the rock.

Keywords: *AE statistics, Rock fracture, Confining pressure*

1. Introduction

Crustal rocks of the earth contain many interstitial fluids which are mostly composed of water, salts and gases. The major sources for these fluids have been due to metamorphic reactions in the lower curst and mantle. All such fluids, especially water, has a very strong influence on crustal seismicity and the properties of rocks. Several field and laboratory observations commonly indicate that relatively small changes in effective stress (≈ 0.1 MPa) due to pore pressure changes either during hydrocarbon extraction or dam impoundment etc are sufficient to induce earthquakes in the upper crust on time scales of 5 to 10 years [1-4]. In addition to the pore pressure effects, the interstitial fluids can play an active role to weaken the rock through chemical and other processes [5–8]. Hence laboratory experiments which are specially aimed at investigating the physical and chemical influence of fluids such as water and salt solutions on the local processes of rock fracture and friction are very useful. The fluids may either accelerate the fracture by stress corrosion reaction or retard the fracture by time-dependent stress relaxation [8]. These aspects have some vital applications to understand and model the nucleation processes and development of both natural and induced earthquakes at shallow depths in the earth's upper crust. To address this problem and also in order to make an in depth study of the inelastic processes such as cracking and slip on crack surfaces during the deformation of rock, the application of acoustic emission monitoring technique and the analysis of AE signatures of the above mentioned processes have been found to be useful [7-13]. As a part of the ongoing activity in the study of 'Physics of rock fracturing and seismic energy release' at the NGRI, we have carried out a series of experiments on AE monitoring to investigate the fracture behaviour of some dry and water-saturated rock samples of south-east Gujarat and Maharashtra which have been experiencing prolific seismicity. The results obtained from the study of Pavgadh rhyolites and Godhra granites tested to failure under triaxial compression are presented and discussed in this paper.

2. Experimental Procedure

We have carried out triaxial compression tests on AX-size rock cores (dia: 30 mm) at confining pressures ranging between 15 MPa and 60 MPa using a ELE Hoek Cell and a 150-Ton MTS 815 Rock Mechanics System [14]. Several test samples were core-drilled from one rhyolite block (F-3) and one Godhra granite (K-2) for the present study. We selected one core from each block and saturated it with water for 24 hours using a high vacuum pump. The remaining core samples were oven-dried and the triaxial compressional failure tests were carried out on them at confining pressures of 15, 30, 45 and 60 MPa. The water-saturated sample was tested to failure at 60 MPa confining pressure. The confining pressure during each test was maintained constant at the preset level. We used a 'Spartan AE Monitoring System' of the Physical Acoustics Corporation for the detection and data storage of AE. The AE were detected on a single channel using a 150 KHz resonant sensor which was fixed to the top platen during the test. The AE data files were processed using 'Mistras software' as described in detail in our earlier papers [15-17]. The time-histories, load-based plots and distribution function graphs of AE have been obtained from the data. The Mohr's circles, Mohr-Coulomb envelope and the values of 'C' and 'ϕ' have been obtained by using standard software [18]

3. Results and Discussion

3.1 Physico-Mechanical Properties

The rhyolites have been collected from the top of the Pavgadh hill near Vadodara and the granites were from the outcrops near Sureli village, Gujarat (Lat. N 22^{o} 47$^{/}$ and Long. E 73^{o} 40$^{/}$). The rhyolite is a volcanic representative of granite. It is a rapidly crystallized rock and contains glass in large quantities in which the quartz and alkali feldspar are hidden. The microscopic examination of the rock revealed that it has many micro-cavities and most of them have been filled with low modulus material (spherulites) on account of which the stresses concentrate in it more easily [15]. The granites are post-Delhi Godhra granites which have intruded into the Precambrian Champaner sedimentary rocks and they relatively young (955 $\pm$ 20 Ma). Some physico-mechanical property tests have been carried out at the room conditions on a large number of oven-dried core samples of rhyolites and granites.

Table 1: AE Statistics and triaxial compression test data of dry and water-saturated rhyolites and granites

Sl. No.	Sample Number	Density (gm/cc)	Confining Pressure (MPa)	AE Statistics					Triaxial compressive Strength (MPa)
				Hits	Counts	Energy	Average peak amp. (dB)	*b*-value	
PAVGADH RHYOLITE									
1.	F-3.15	2.426	30	3451	79944	204850	53.21	1.06	391.97
2.	F-3.16	2.427	45	8181	277465	515523	53.77	0.99	426.79
3.	F-3.17	2.379	60	12508	339784	537232	54.33	0.93	500.63
							Shear strength, **C = 72.72, MPa**		
							Angle of internal friction, **$\phi = 34.56^0$**		
4.	**F-3.18 (water-saturated)**	**2.404**	**60**	**8867**	**233123**	**275551**	**52.91**	**1.10**	**462.28**
GODHRA GRANITE									
5.	K-2.15	2.626	15	28698	540188	860415	53.66	1.00	475.81
6.	K-2.16	2.626	30	19083	450307	615065	53.92	0.97	558.38
7.	K-2.17	2.625	45	21390	361110	651464	53.80	0.99	721.47
8.	K-2.18	2.619	60	24111	525462	1173339	55.90	0.80	786.12
							Shear strength, **C = 67.01, MPa**		
							Angle of internal friction, **$\phi = 49.36^0$**		
9.	K-2.19 **(water-saturated)**	**2.624**	**60**	**24716**	**473706**	**744489**	**53.99**	**0.97**	**795.19**

The rhyoloites have low density (2.386 g/cc) and high porosity (8.44 %). The average values of P- and S-wave velocity of rhyolites have been found to be 4451 m/ sec and 2705 m/ sec respectively. The AE signatures of dilatant microcracking and failure behaviour of these rhyolite samples under uniaxial compression have shown distinct precursory changes, particularly in AE *b*-value, before the final failure occurred [15]. The granite samples have a low porosity (0.36 %) and density (2.585 gm/cc). The average P-wave velocity and UCS of K-2 have been found to be 4321 m/sec and 229.27 MPa respectively [15,19].

3.2 Triaxial Compressive Strength, C and ϕ

The triaxial compressive strength increased with the increase of confining pressure in both the rocks (Table 1). The individual cores tested have shown some small differences in density and wave velocities at the ambient conditions. But with the increase of confining pressure those differences have been suppressed to a large extent. The Mohr's circles have been constructed from the experimental data and the values of 'C' and 'ϕ' have been obtained from the Mohr-coulomb failure envelope (Fig. 1). The rhyolite showed a higher 'C' value and lower 'ϕ' than granite as expected in accordance with their physical properties and modal data. The strength values and AE statistics data of dry samples at different confining pressures and those of water saturated cores tested to failure at 60 MPa confining pressure are shown in Table 1. The values of 'C' and 'ϕ' are in general agreement with the results reported on granites in general. The water-saturated rhyolite sample showed a lower compressive strength than the dry sample (Table 1, Fig. 2). It implies that the stress-induced cracks have formed a net-work and led to the increase in pore pressure since it was an ‘undrained test’. Consequently, the water-saturated sample failed at a lower stress than the dry sample (Table 1, Fig. 2). Whereas the water-saturated sample of Godhra granite (K-2.19) showed a marginal increase in strength at 60 MPa confining pressure than the dry sample (Table 1, Fig. 2). It may be inferred that the stress induced microcracks may not have been favourably connected for the water to exert its mechanical influence to lower the pore pressure in granite. The AE statistics also support these inferences in both the rocks (Table 1, Figs. 3-5).

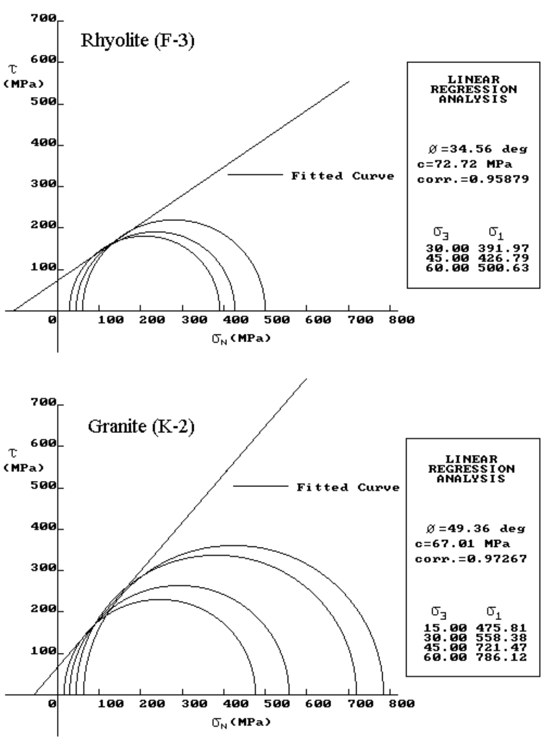

Fig. 1: Mohr’s circles, Mohr-Coulomb envelope and the results of ‘C’ and ‘φ’ of dry rhyolite (F-3) and granite (K-2).

3.3 Acoustic Emission (AE) Signatures

3.3.1 AE Hits

The recorded data has yielded many useful time-histories and load-based plots of AE hits. The load-based plots at different confining pressures have shown more or less the same trend. The results obtained from the replay of AE data of dry and water-saturated rhyolite and granite samples which have been tested to failure at 60 MPa confining pressure are shown in Fig. 3. Unlike the results obtained under uniaxial compression, the occurrence rate of AE was found to be quite low in dry samples until the applied stress reached nearly 90% – 95% failure stress in both the rocks of the present study. It was then followed by steep increase to peak at 400 hits in rhyolite (Figs. 3a and 3b) and 2000 hits in granite (Figs. 3c and 3d). Furthermore, both the dry and water-saturated samples have shown the same trends in occurrence rate of AE hits at stresses close to failure. But, during the preparatory fracture processes at lower stress levels, the influence of water saturation and the interaction of water with the growing cracks have been found to be quite appreciable in rhyolite (Fig. 3b) while they were of a very low order of magnitude in granite (Fig. 3d). The differences in occurrence rate and other signatures of AE among the dry and water-saturated samples have been quite significant in rhyolite, whereas the granite rock did not display such a feature (Table 1, Figs. 3-5). This can be attributed to the fact that the formation of new cracks in rhyolite has been more extensive due to its relatively high porosity (8.44 %) and also due to the presence of large number of spherulites (cavities filled with low modulus material) compared to Godhra granite (K-2). The presence of water and its influence to increase the pore pressure have decreased the strength of the water saturated rhyolite and also the statistics of the accompanying AE during the fault nucleation and its growth in the test sample (Table 1, Figs. 3-5).

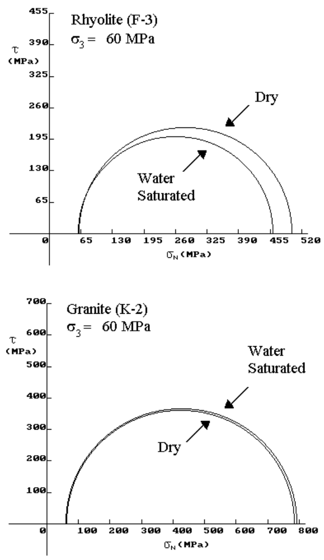

Fig. 2: Mohr's circles drawn from the triaxial compression stress data of dry and water-saturated rhyolite (F-3) and granite (K-2)

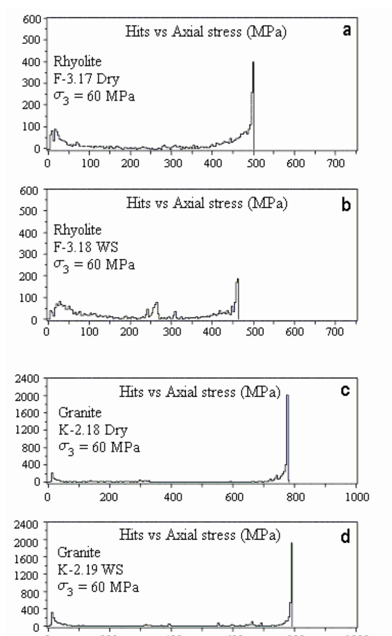

Fig. 3: Hard copies of the graphs showing the occurrence rate of AE hits plotted against the axial stress in dry and water-saturated samples of rhyolite and granite. The tests were carried out at 60 MPa confining pressure. The experimental conditions and detection level of AE were kept identical during all these tests.

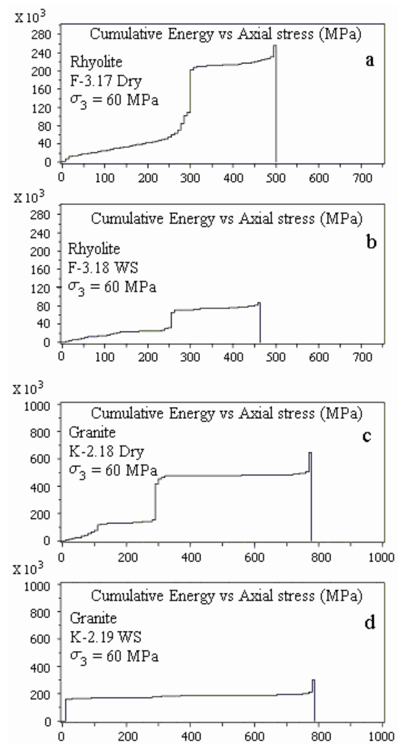

Fig. 4: Hard copies of the graphs showing the cumulative energy of AE counts plotted against the axial stress in dry and water-saturated samples of rhyolite and granite. The tests were carried out at 60 Mpa onfining pressure. The experimental conditions and detection level of AE were kept identical during all these tests

3.3.2 AE Cumulative Energy Counts

Hard copies of the cumulative energy counts versus stress graphs that have been obtained from the replay of the recorded AE data of dry and water-saturated samples of rhyolite and granite are shown in Figs. 4a&4b and 4c & 4d respectively. The dry rhyolite showed a steady increase in AE energy with the increase of axial stress up to nearly 300 MPa (i.e., 60% failure stress). At that stress level, the energy count increased sharply (Fig. 4a) to reach a value of ~ 220,000 which indicates the sudden formation of large number of new cracks in a localized volume of the test rock. With further increase in stress, the newly formed cracks have grown stably following which the energy count data had stabilized until the final failure approached. The sharp rise in energy count again at stresses close to failure indicates the onset of crack coalescence and faster growth of the fault. A similar trend but of lesser magnitude has been found in the energy count data of the water-saturated rhyolite (Fig. 4b). Furthermore, the formation of new cracks commenced at 250 MPa (~ 55 % failure stress) itself in the water- saturated sample (Fig. 4b) which indicates the influence of water through the development of pore pressure. With further increase of stress, the fluid-crack interaction might have contributed to the decrease of stress intensity at the crack tips and reduced the AE activity in rhyolite (Fig. 4b). Whereas in Godhra granite the AE energy count data steadily increased during the early stages of loading due to the closure of pre-existing microcracks up to 100 MPa and then stabilized before it showed a sharp rise at 300 MPa (i.e., 38 % failure stress) axial stress to reach a value of nearly 500, 000 (Fig. 4c). It is perhaps at that stage some few cracks might have formed in weak zones which are randomly distributed in the whole volume of the test sample. With further increase of stress, the energy counts did not increase until the applied stress became close to the failure stress (Fig. 4c). It is at that stage, the crack density must have increased sharply to facilitate the crack-to-crack interaction and crack-fluid interaction. The energy count data of the water-saturated sample is in complete accordance with the inferences drawn as above (Fig. 4d). Furthermore, the water-saturated sample showed a marginally higher strength than the dry sample which indicates that the network of newly formed cracks was not as dense as in rhyolite. Both the dry and water-saturated samples of granite have shown similar trends but of different magnitude with regard to the energy count peaks at stresses close to failure (Figs. 4c and 4d).

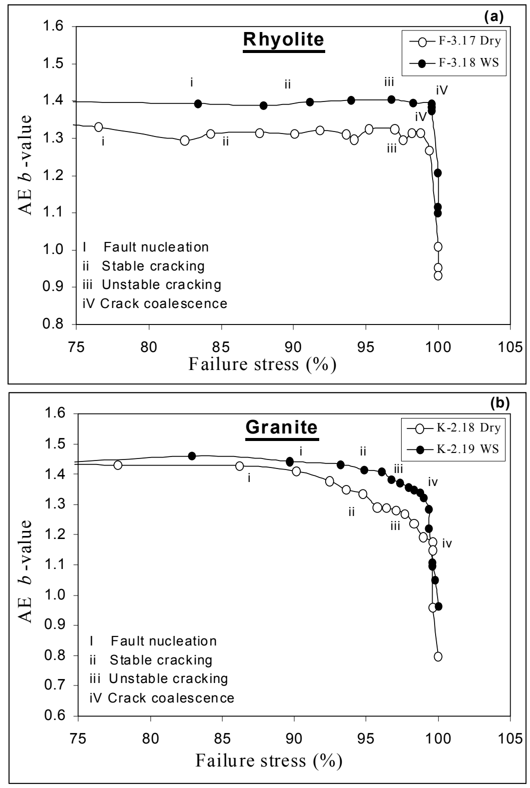

Fig. 5: AE b value is plotted as a function of normalized failure stress (75 % - 100 % failure stress). The results have been obtained from the replay of AE amplitude data (discrete frequency distribution) which was recorded during the deformation and failure of dry and water-saturated test samples of (a) Pavgadh rhyolite (F-3) and (b) Godhra granite (K-2) under triaxial compression at 60 MPa confining pressure. The various stages such as onset of fault nucleation and its growth as inferred from the *b*-value data are shown marked in the plots

3.3.3 AE b-value

In the present study, a large number of subsets of the peak amplitude distribution graphs of AE hits have been obtained as log-linear graphs during the replay of AE data. The *b*-value of each sub-set has been computed using the 'Maximum likelihood' method introduced by Aki [17] and the equation $[b = 20\log_{10} e / (\langle a \rangle - a_c)]$ where $\langle a \rangle$ is the average amplitude of the sub-set and a_c is the threshold amplitude level for the detection of AE. The a_c was set at 45 dB for acquiring the AE data while testing the rock to failure [15,16]. The method takes into account only the 'discrete frequency distribution' of AE. The *b*-value of each AE subset when plotted against the applied stress particularly after the commencement of the inelastic deformation due to the formation of new cracks would help in identifying, tracking and characterizing the growth of crack population. Examples of such plots from the results of the preset study are shown in Figs. 5a and 5b. The results of both the rocks show that the water-saturated samples yield a higher *b*-value than the dry samples in view of the reduced AE activity in wet samples. Further, the transitions from stable-to-unstable cracking and unstable cracking-to-crack coalescence (as inferred from this data) are fairly sharp in dry samples compared to those in water-saturated samples. The *b*-value in dry rhyolite sample began to drop at ≈ 76% failure stress marking the beginning of fault nucleation due to the formation of new cracks (Fig. 5a). It continued up to ≈ 82% failure stress. With further increase of stress, the *b*-value has slightly increased and stabilized at that level indicating that the newly formed cracks grow stably until the applied stress reached a value of ≈ 92% failure stress. The *b*-value decreased again at 92 % and 97% failure stresses to facilitate increased interaction between the growing cracks in dry sample, and growing cracks and water and water-saturated rhyolites (Fig. 5a). These are the stress levels at which the transition from stable-to-unstable cracking and unstable cracking-to-crack coalescence might have occurred respectively in both dry and water-saturated rhyolites (Fig. 5a). As the impending failure was approaching, the crack density increased for the cracks to coalesce and complete the formation of fault at the peak stress in both the dry and water-saturated samples. There was a sharp fall in the *b*-value to reach a minimum of 0.9 in dry rhyolites and 1.07 in water-saturated sample due to the release of a large number of high amplitude hits (Fig. 5a). Whereas in Godhra granite the first indication of the formation of appreciable number of new cracks and interaction of water were noticed at ≈ 90% failure stress (Fig. 5b). With further increase in stress, the *b*-value began to decrease steadily in both the dry and water-saturated samples. In fact, the dry sample showed sharp changes in *b*-value at ≈ 95% and 99% failure stress indicating the increase in crack density and linkage / coalescence of cracks respectively. Accordingly, the *b*-value changed sharply in water-saturated sample also at those two stress levels (Fig. 5b). Among all these AE signatures, the *b*-value has more clearly shown the stress levels at which the fluid-rock and fluid-crack interactions were quite active in the samples studied.

4. Conclusions

1. This experimental study has provided the first laboratory data on triaxial compressive strength and AE signatures of micro-cracking and progressive failure of some dry and water-saturated rocks of one of the most seismically active areas of the Indian peninsular shield.

2. The triaxial compressive strength increased linearly with the increase of confining pressure in both rhyolite and granite. At 60 MPa confining pressure, the water-saturated rhyolite showed a lower compressive strength (≈460 MPa) than the dry sample (≈ 500 MPa). Whereas the water-saturated granite has shown a marginal increase in strength (≈ 795 MPa) than the dry sample (≈ 785 MPa).

3. The Godhra granite (porosity: 0.36%) is more homogeneous and the formation and growth of cracks began only after

the axial stress reached a value of ~ 90 % failure stress. The crack-to-crack interaction became evident only at stresses ≥ 98 – 99 % failure stress as inferred from the stress-induced changes in AE *b*-value and occurrence rate of hits.

4. Among AE signatures, the hit rate and *b*-value gave more useful information about the various stages of the development of stress-induced cracks, fault nucleation and shear fracture of the samples tested.

5. Acknowledgements

The financial support for carrying out this work was provided by the Department of Science & Technology (Grant No. DST / 23 / (171) / ESS / 97), Government of India. We thank Dr. D.S.N. Murthy for his help in field work and petrology. This paper is released for publication with the kind permission of the Director, NGRI, Hyderabad, and the Director, NIRM, Kolar Gold Fields. .

6. References

1. Segall P., “Earthquakes triggered by fluid extraction”, Geology, 17, 942-946, 1989.
2. Scholz C.H., “The Mechanics of Earthquakes and Faulting”, Cambridge University Press, Cambridge, 1990.
3. Gupta H.K., *Reservoir Induced Earthquakes*, Elsevier Publ., Amsterdam, 1992.
4. Keller E.A. and Loaciga H.A., “Fluid-pressure induced seismicity at regional scales”, Geophys. Res. Lett., 20, 1683-1686, 1993.
5. Anderson, O.L. and Grew P.C., “Stress corrosion theory of crack propagation with application to geophysics”, Rev. Geophys. & Space Phys., 15, 77-104, 1977.
6. Atkinson B.K., “Subcritical crack propagation in rocks: theory, experimental results and application”, J. Struct. Geol., 4, 41-56, 1982.
7. Masuda K., Nishizawa O., Kusunose K., Satoh T. and Takahashi M., “Positive feed-back fracture process induced by non-uniform high-pressure water flow in dilatant granite”, J. Geophys. Res., 95, 21583-21592, 1990.
8. Sammonds P.R., Meredith P.G. and Main I.G., “Role of pore-fluids in the generation of seismic precursors to shear fracture”, Nature, 359, 228-230, 1992.
9. Main I.G., Sammonds P.R. and Meredith P.G., “Application of modified Griffith criterion to the evolution of fractal damage during compressional rock fracture”, Geophys. J. Int., 115, 67-80, 1993.
10. Lockner D., “The role of acoustic emission in the study of rock fracture”, Int. J. Rock Mech. Min. Sci.,, & Geomech. Abstr., 30, 883-899, 1993.
11. Rao M.V.M.S. and Kusunose K., “Failure zone development in andesite as observed from acoustic emission locations and velocity changes”, Phys. Earth Planet. Interiors, 88, 31-143, 1995.
12. Rao M.V.M.S., “Significance of AE-based *b*-value in the study of progressive failure of brittle rock: Some examples from recent experiments”, *In* Trends *in NDE Science and Technology*. (Eds. Krishnadas Nair, C.G. et al.), Vol.4, Oxford & IBH Publ., New Delhi, 2463-2467, 1996.
13. Lei X., Kusunose K., Rao M.V.M.S., Nishizawa, O. and Satoh, T., “Quasi-static fault growth and cracking in homogeneous brittle rock under tri-axial compression using acoustic emission monitoring”, J. Geophys. Res., 105, 6127-6139, 2000.
14. Rao M.V.M.S., “A laboratory study of acoustic emission signatures of microcracking and brittle failure of some of the magmatic rocks under dry and water-saturated conditions”, Tech. Rep. No. NGRI-2003-LITHOS-395. Report submitted to the DST, Govt. of India, May 2003, 1-21, 2003.
15. Rao M.V.M.S., Adesh Kumar, Murthy D.S.N., Nagaraja Rao G.M., Udayakumar S. and Mohanty S.K., “Deformation and failure behaviour of deccan rhyolites under unconfined stress : An experimental study”, J. Ind. Geophys. Union, 5, 83-91, 2001.

16. Rao M.V.M.S., “Stress-induced micro-crack damage and progressive failure of granites of Gujarat: A laboratory investigation using AE statistics”, J. Non-Dest. Test. Eval., 1(3), 22-27, 2002.
17. Aki K., “Maximum likelihood estimates of b in the formula log N = a – bm and its confidence limits”, Bull. Earthquake Res. Inst., Tokyo Univ., 43, 237-239, 1965.
18. Mohanty S.K., Udayakumar S. and Nagaraja Rao G.M., “Physico-mechanical properties of rock.”, Tech. Report submitted to the Singareni Collieries Co. Ltd., March 1998, 1-24, 1998.
19. Rao M.V.M.S., Murthy D.S.N., Nagaraja Rao G.M., Mohanty S.K. And Udayakumar S., “Stress-induced microcracking and brittle failure of Godra granite: A laboratory investigation using acoustic emission”, J. Geol. Soc. Ind., 64, 775-783, 2004.