Some Aspects of Rock Mechanics Applicable to Underground Coal Mining

V S Vutukuri[1], M Seto[2], K Katsuyama[2] and D K Nag[3]

ABSTRACT

Three aspects of rock mechanics, namely, in-situ stress estimation by acoustic emission (AE) method, strength of rock mass and role of chemicals to reduce the strength are covered. It is possible to detect the previously applied maximum stress by stressing a rock specimen to the point where there is a substantial increase in AE activity. This is known as Kaiser effect. From the AE signatures in the second and subsequent loadings, AE take-off point was identified more easily than in the first loading. In determining the compressive strength of rock mass, two factors have to be considered, namely, the size effect on the compressive strength of intact rock and the effect of discontinuities on the compressive strength of rock mass. Although a modified Bieniawski criterion gives best agreement with the triaxial test data, modifications have been suggested to Hoek-Brown criterion due to its popularity. It is possible to reduce the tensile strength of sandstone by saturating it with weak chemical solutions made with dodecyltrimethyl ammonium bromide, polyethylene oxide and aluminium chloride by up to 30%. In the case of compressive strength, there is no appreciable effect. The possible explanation is that the chemical solutions produce an effect on the strength of sandstone only when the failure mechanism is dominated by tensile mode.

INTRODUCTION

The design for underground excavations begins with investigations to determine characteristics of rock and rock mass. Chief among these is Structural Geology because, in underground excavations, instability is usually caused by discontinuities (faults, joints and bedding planes). Next is the estimation of in-situ stress. The third is testing of the rock and rock mass to determine Mechanical Properties such as compressive and shear strengths. The fourth activity concerns Groundwater which is significant to underground operations and to excavation stability in particular.

This paper concentrates on acoustic emission technique for estimation of in-situ stress, strength of rock mass and the effect of chemical solutions on the strength of sandstone.

ESTIMATION OF IN-SITU STRESS

Although various techniques have been proposed and developed to determine in-situ stress, the determination of in-situ stress is not an easy task and all suffer from deficiencies and limitations. The main deficiency of established techniques such as over coring method or hydraulic fracturing method is that they are usually expensive and time-consuming. Other shortcomings of the techniques are that they are deficient for measuring in-situ stress at depth in remote regions which are hard to access from boreholes or mine workings. An alternative method for determining the stress state at depth and in remote regions is to take advantage of the acoustic emission (AE) method.

AE method of determining in-situ rock stress

The "Kaiser effect" of AE suggests that previously applied maximum stress might be detected by stressing a rock specimen to the point where there is a substantial increase in AE activity. The AE technique has been developed and tried by various researchers in the past (Kanagawa et al., 1976; Kurita and Fujii, 1979; Houghton and Crawford, 1987; Seto et al., 1989a, b, 1992a, b, 1996; Holocomb, 1993; Utagawa et al., 1995) with the aim of providing a practical technique for retrieving the

[1] The University of New South Wales, School of Mining Engineering
[2] National Institute for Resources and Environment, Tsukuba, Japan
[3] Monash University, Gippsland Campus, Department of Civil Engineering

Kaiser effect. That is a recollection of the maximum previous stress to which a rock had been subjected to its in-situ environment.

Fig. 1 shows a typical example that indicates the existence of Kaiser effect in a sandstone specimen. Data for the specimen tested 5 minutes after the previous cyclic loading up to 10 MPa are shown. An arrow indicates the previous maximum stress. The previous stress level was within elastic range. In all experiments conducted within the short delay time, the existence of Kaiser effect in rock specimens could be clearly observed and the assigned stress from the take-off point of AE signature was within 5 %.

Fig. 2 shows the AE signatures in the repeated loading-unloading of a coal core specimen "A" taken from the depth of 356 m 44 days before the test. The maximum previous stress was recognised by clear indication of AE increase, which is indicated by the arrow in the figure. In both the first and second loadings, AE increase can be recognised clearly at the same stress level. In the second loading the emissions below the stress level were significantly reduced, and an AE take-off point was identified more easily than in the first loading. The estimated stress from the AE signatures was 9.2 MPa, which was very close to the overburden pressure (8.5 MPa) estimated from the depth of 356 m.

In the same area, CSIRO have conducted a number of in-situ stress measurements using hollow cells and hydraulic fracturing technique (Enever and Doyle, 1996). When compared the result of vertical stress at the same depth with that from AE method, 8.9 MPa was from hydraulic fracturing technique and 9.2 MPa from AE method, which are also well consistent.

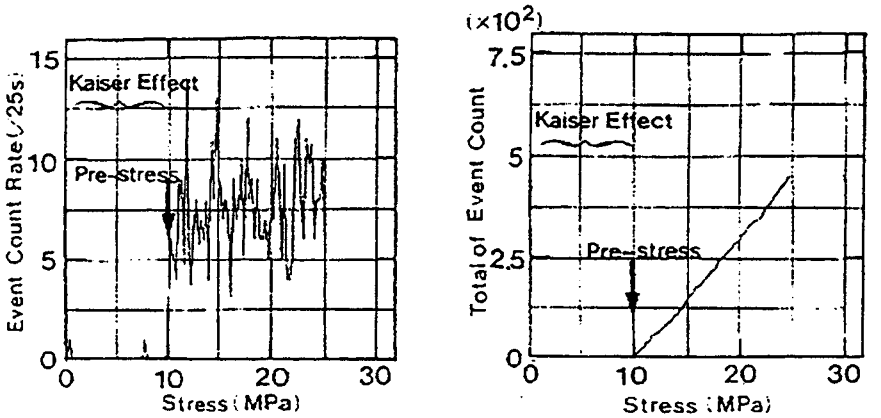

Fig. 1 - A typical example of Kaiser effect in sandstone

Fig. 3 shows the AE signatures of a rock core specimen "B" taken from the depth of 310 m nearly two years ago. Although the take-off point of AE event rate was not clear in the first loading, the previous stress could be estimated from AE signature in the second loading. The estimated stress (7.1 MPa) was also well consistent with the overburden pressure (6.4 MPa). The time lag of two years did not deter the evaluation of the critical in-situ stress condition. Rock cores could recollect the in-situ vertical stresses reasonably well within 10 % even in case of two years time lag. The estimated vertical stresses from the AE method suggested in this paper, which utilises the AE signature in cyclic loading, agree well with the overburden pressure.

Strength of rock mass

The discussion is limited to compressive strength. To properly assess the compressive strength of rock mass, two factors have to be taken into account. The first factor is the effect of size on the compressive strength of intact rock (in between the discontinuities) of the size under consideration and the second factor is the effect of discontinuities (number and orientation with respect to stress field) on the compressive strength estimated taking into account the size effect.

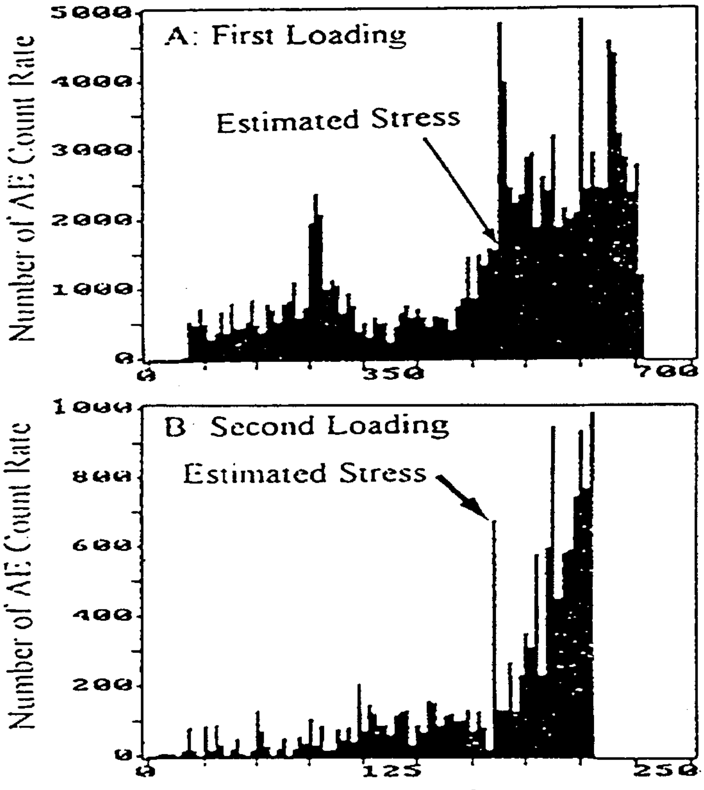

Fig. 2 - AE signatures in the 1st and 2nd loading of a coal core taken from the depth of 365m

The influence of joints on the compressive strength of a rock mass was studied by a number of investigators using models. Lama (1974) studied the effect of horizontal, vertical and orthogonal joints on uniaxial compressive strength in models. The drop in uniaxial compressive strength is small after the number of joints exceeds 6 and is in accordance with the results of Goldstein et al. (1966) and Walker (1971). On a percentage basis, the decrease in the uniaxial compressive strength of the model with horizontal or vertical joints is about 30 %.

According to Goldstein et al. (1966), the results can be represented by the following relationship:-

$$\rho_{cm}/\rho_{ce} = a + b\,(l/L) \qquad (1)$$

where ρ_{cm} = uniaxial compressive strength of the model (composite block);
ρ_{ce} = uniaxial compressive strength of the element constituting the block;
L = length of the model;
l = length of each element;
a, b and c are constants, where c < 1 and b = (1 – a) (Fig. 4).

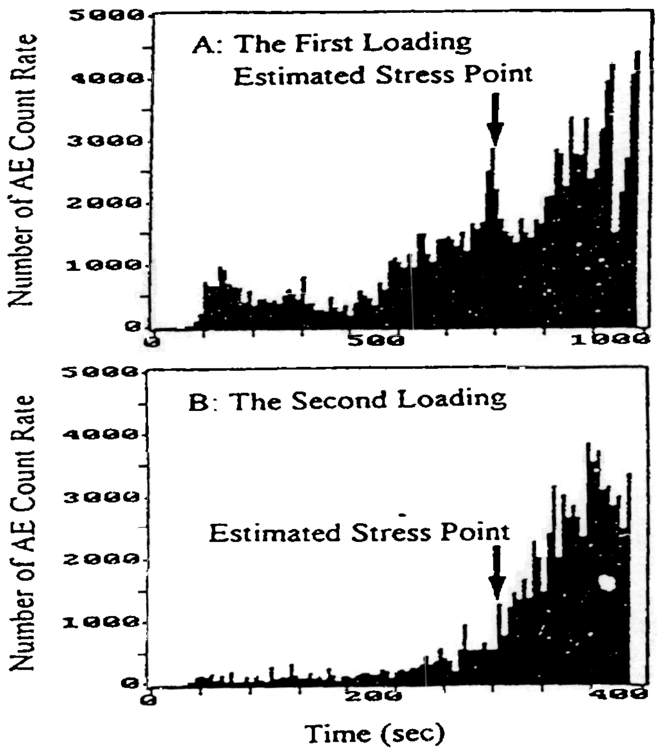

Fig. 3 - AE signatures in the 1[st] and 2[nd] loading of a rock core taken from the depth of 310m nearly2 years ago

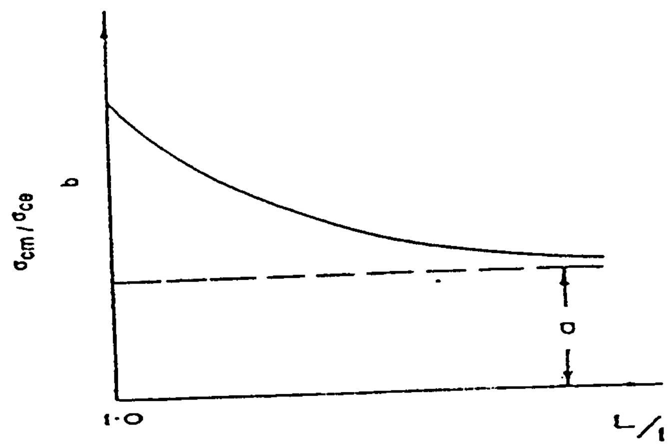

Fig. 4 - Variation of uniaxial comprehensive strength ratio, σcm/σce with joint frequency, L/l, of rock mass[4]

For models with orthogonal joints, the results of Lama (1974) indicate that the uniaxial compressive strength reduces as the number of elements increases. It reduces to more or less constant value when the joint density (number of elements) reaches about 150. The relationship between uniaxial compressive strength and joint density can be represented by the following equation:-

$$\rho_c = k + n^c \qquad (2)$$

[4] After Goldstein et al., 1966

where ρ_c = uniaxial compressive strength of a model with less than 150 elements;
k = uniaxial compressive strength of model containing more than about 150 elements (real strength of the system);
n = number of elements; and
d = constant.

The value of d is higher for models of stronger material and comparatively lower for models of weaker material.

The configuration of the joint system with respect to the stress field also influences the compressive strength. The influence of the inclination of the weakness plane on the compressive strength for various rocks was studied by a number of authors (McLamore and Gray, 1967; Donath, 1972).

Strength criteria for rock and rock mass

The theoretical strength criteria based on the actual mechanism of fracture do not fit the experimental results properly and to overcome this problem, many empirical criteria were formulated for rocks and rock masses. The strength criteria can be written in terms of either (1) principal stresses, ρ_1 and ρ_3 at fracture or normalised principal stresses at fracture obtained by dividing the principal stresses, ρ_1 and ρ_3 at fracture by the relevant uniaxial compressive strength, ρ_c or (2) shear and normal stresses at fracture or normalised shear and normal stresses at fracture with respect to uniaxial compressive strength. A typical relationship between ρ_1 and ρ_3 or ρ_1/ρ_c and ρ_3/ρ_c at fracture for rocks is a nonlinear one.

Four empirical strength criteria for rock and rock mass proposed by Bieniawski (1974a) – Yudhbir et al. (1983), Hoek and Brown (1980a, b), Johnston (1985) – Sheorey et al. (1989) and Ramamurthy (1986) – Arora (1988) were assessed regarding their applicability for coal (Vutukuri and Hossaini, 1992a) and jointed plaster of Paris (Vutukuri and Hossaini, 1992b). The following modified Bieniawski criterion gave the best agreement with the triaxial test data:-

$$\rho_1/\rho_{cm} = 1 + B_m (\rho_3/\rho_{cm})^{am} \qquad (3)$$

where ρ_1 and ρ_3 = principal stresses at fracture;
ρ_{cm} = uniaxial compressive strength of rock mass;
B_m and a_m = rock mass parameters.

The important conclusions are that a_m is more or less constant but B_m is a function of ρ_{cm}.

Due to popularity of Hoek-Brown criterion, the following modification has been suggested:-

$$\rho_1/\rho_{cm} = \rho_3/\rho_{cm} + (1 + m_m \rho_3/\rho_{cm})^{0.5} \qquad (4)$$

where m_m = rock mass constant.

To use the equation, ρ_{cm} and m_m are required. From the original Hoek and Brown criterion for rock mass, the following equations have been derived:-

For undisturbed rock mass:

$$\rho_{cm}/\rho_c = [\exp((RMR - 100)/9)]^{0.5} \qquad (5)$$

$$m_m/m = 1/[(\rho_{cm}/\rho_c)^{0.3588}] \qquad (6)$$

where RMR = Rock Mass Rating (Bieniawski, 1974b);
ρ_c = uniaxial compressive strength of intact rock comprising the rock mass and
m = constant for the intact rock.

Fig. 5 depicts the relationship given in Equation (6).

The critical parameter in the modified criterion is the ratio between ρ_{cm} and ρ_c. According to Hoek and Brown (1988), the ratio depends upon Rock Mass Rating (RMR) as well as condition of the rock mass i.e. undisturbed or disturbed. The relationship for undisturbed rock mass is given in Equation (5). Aydan et al. (1997) reviewed the topic of rock mass strength in some detail.

From the results obtained in laboratory experiments on discontinuous models of plaster and sandstone, the following relationships have been determined:-

For plaster:-

$$m_m/m = 1/\left[(\rho_{cm}/\rho_c)^{0.8942}\right] \qquad (7)$$

For sandstone:-

$$m_m/m = 1/\left[(\rho_{cm}/\rho_c)^{0.4949}\right] \qquad (8)$$

Fig. (6) depicts the relationship given in Equation (8).

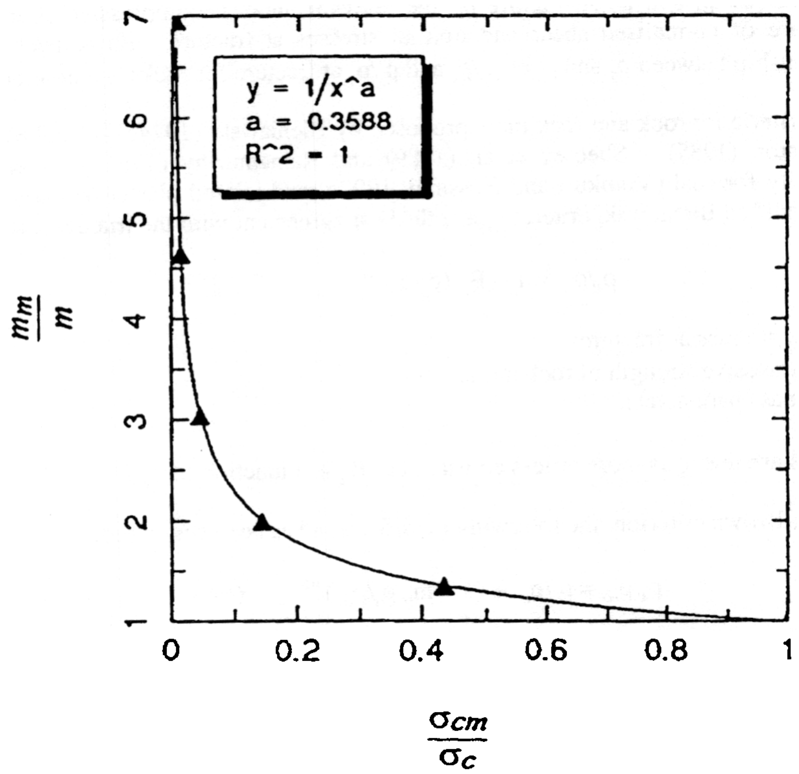

Fig. 5 - σcm/σc versus mm/m for the undistributed rock mass for the modified Hoek and brown criterion (after Vutukuri and Hossaini, 1995)

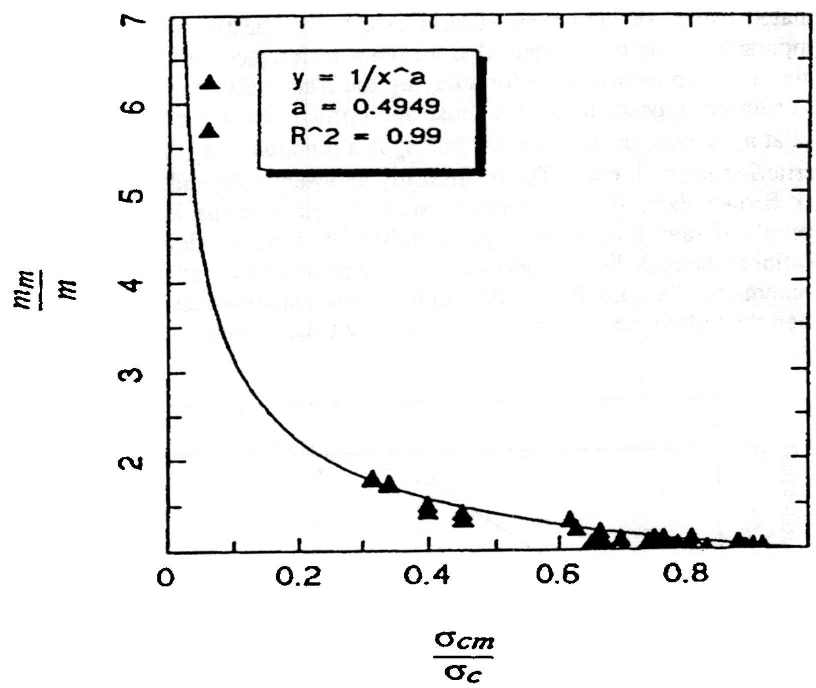

Fig. 6 - σcm/σc versus mm/m for sandstone models tested in the laboratory for the modified Hoek and brown criterion[5]

Effect of chemical solutions on the strength of sandstone

Chemical alteration of the strength was investigated to establish the fundamental knowledge for chemically assisted fracturing. If the rock strength can be chemically lowered, this technology would be useful to raise the fracturing efficiency. Brazilian tests and multi-stage triaxial compression tests were performed on Gosford sandstone saturated with solutions of dodecyltrimethyl ammonium bromide (DTAB), polyethylene oxide (PEO) and aluminium chloride ($AlCl_3$). The tensile strength varied with the concentration of chemical additives, became the lowest at certain concentrations which are consistent with the zero zeta-potential concentrations (Fig. 7). AE activity was the most active in dry specimen, and the least AE activity was found in the specimen saturated with chemical solution (Fig. 8). The uniaxial and triaxial compressive strengths did not vary significantly with concentration of the chemical solutions. In these tests, the failure mode was dominated by shear failure.

In some coal mines, hard massive sandstone formations are encountered in the immediate vicinity of the coal seam in the roof. In such situations, delayed caving of the roof creates a number of problems including air blast. Four alternatives can be thought of to deal with such roof formations difficult to cave.

1. Packing of goaf with filling material
2. Using very high capacity supports
3. Using supports with high flow relief valves
4. Reducing the strength properties of roof formations by water injection under high pressure or blasting

The results of this part can be applied to reduce the strength properties of roof formations by injecting water mixed with appropriate chemicals.

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5 After Vutukuri and Hossaini, 1995

CONCLUSIONS

In-situ stresses were estimated using AE signatures (Kaiser effect) in repeated loadings on rock core specimens. The estimated values were comparable to the ones obtained from other techniques such as overcoring method and hydraulic fracturing method. The time lag of up to two years for studying the Kaiser effect on cores has not influenced the results. The modified Bieniawski criterion appears to be the most appropriate one for coal and jointed plaster of Paris. The important conclusions are that a_m is more or less constant but B_m is a function of ρ_{cm}. A modification has been suggested to the original Hoek-Brown criterion for rock mass. The relationship between m_m/m and ρ_{cm}/ρ_c has been given for undisturbed rock as per original Hoek-Brown data. From laboratory studies, relationships have been suggested for plaster and sandstone. The tensile strength of sandstone varies significantly with concentration of chemicals and can be markedly influenced by the zeta potential at the rock-liquid interface. The compressive strength did not vary to any significant extent with the concentration of chemical. The possible explanation for the experimental results is that the chemical solution affects the strength only when the failure mechanism is dominated by tensile mode.

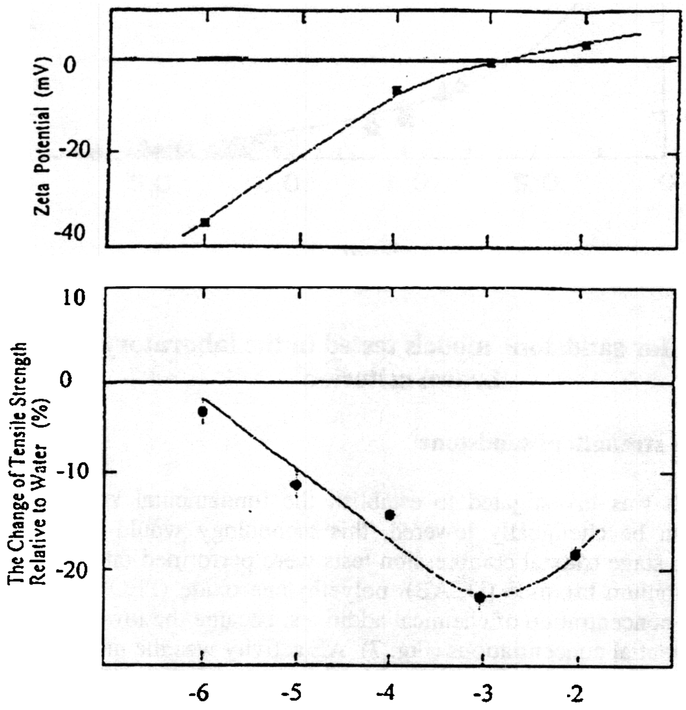
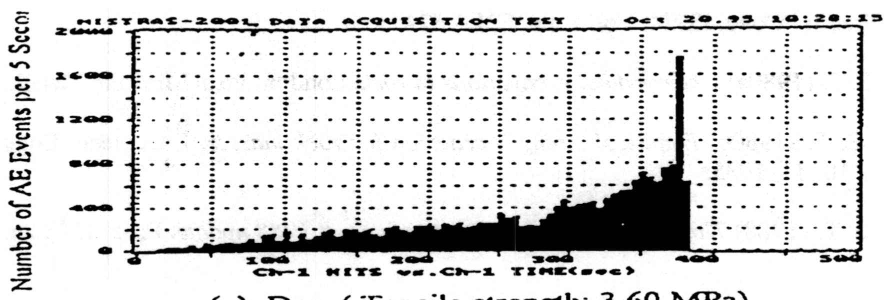
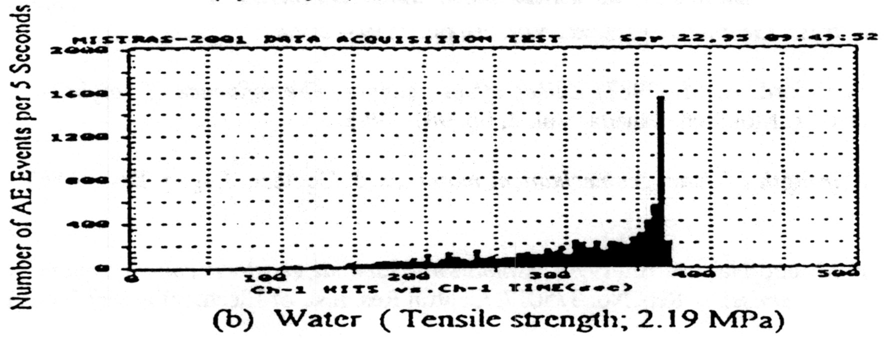


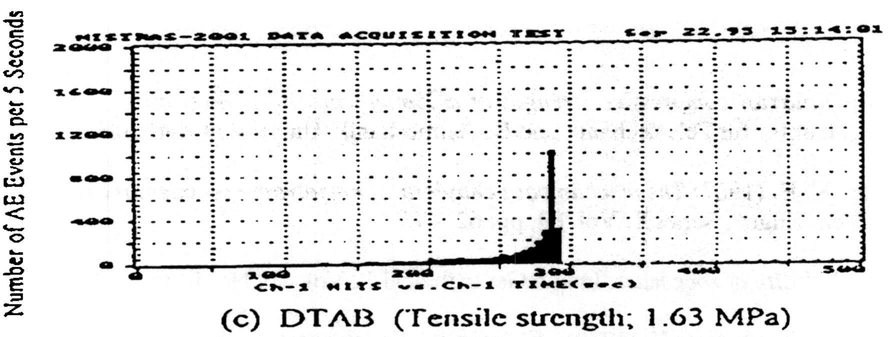
Fig. 7 - Tensile strength variation and zeta potential versus DTAB concentration in water for Gosford sandstone



(a) Dry (Tensile strength; 3.60 MPa)



(b) Water (Tensile strength; 2.19 MPa)



(c) DTAB (Tensile strength; 1.63 MPa)

Fig. 8 - AE behaviors of dry sandstone, water-saturated sandstone and sandstone saturated with DTAB solution (10-3 mol/l) during Brazilian test

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