# Strength and Acoustic Emission Behaviour of Coal Containing Weakness Planes at Various Inclinations

**V.S. Vutukuri**
B.S., M.S., Dr. Tech.Sc., FAusIMM
Senior lecturer, Mining Engineering Department, The University of New South Wales, Australia
**M.H. Foroughi**
B.S., M.S.
Ph.D student, Mining Engineering Department, The University of New South Wales, Australia
**M. Seto**
B.E.,M.E.,Dr. Eng., MMIJ, JSCE
Senior Researcher, Research Development Corporation of Japan
Now, Visiting Fellow, The University of New South Wales, Australia

**Summary** The planes of weakness such as bedding, fractures, joints, etc. present in coal often control its strength and deformational behaviour. In this paper, the strength and acoustic emission behaviour of coal specimens containing bedding planes at various inclinations are considered. Compressive strength of coal specimens containing weakness planes at various inclinations to the axial direction were determined. Test results showed that the strength of coal specimen depends upon the angle of bedding planes and W/D (or D/H) ratio. Acoustic emission measurements were conducted during the uniaxial compressive tests of cubic coal specimens. The count rate detected through a low pass window (AE(L)) was compared with high pass window (AE(H)) in each test. The ratio m = AE(L)/[AE(L)+AE(H)] is plotted against the stress for each test. Test results showed that m also depend upon the weakness planes inclination. For specimens with weakness planes inclination parallel to the axial load ($\beta = 0°$) m remained almost constant and failure takes places through extension fracture of the planes of weakness. For other weakness planes inclination m decreased from different levels of stress until the failure. The frequency characteristics of AE measurements in this research work can lead to prediction of coal pillar failures.

## 1. INTRODUCTION

Acoustic Emission (AE) is a term used for describing a phenomenon whereby transient elastic waves are generated by the rapid release of energy from localised sources within a material. Several other terms used to describe this phenomenon have included stress-wave emission, microseismic (MS) activity and microseismic emission. Today, acoustic emission is utilised as a routine tool in a number of geotechnical applications. Through the efforts of an increasing number of researchers in this field, scientists and engineers are now better able to estimate the stresses in rock.

Geotechnical-based AE/MS studies were initiated in the late 1930's when Obert and Duvall (1942) from the U.S. Bureau of Mines, carried out sonic studies in a deep hard rock mine. They discovered that a stressed rock pillar appeared to emit micro-level sounds (Obert, 1977). Later laboratory and field studies by these researchers verified that these sounds, now referred to as AE/MS activity, are measure of the mechanical stability of the rock materials. It is generally known today that many materials besides rock emit acoustic emissions(AE) when they are stressed or deformed or both.

Today by developing AE/MS area, application of AE, particulary in the geotechincal fields, is increasing. During the recent years, AE/MS techniques have been applied to the investigation of a wide range of laboratory and field oriented geotechnical problems. A more detailed review of the historical development of the subject is given by Hardy (1978,1981).

In geological materials, the origin of AE activity is not well understood, but it appears to be related to processes of deformation and failure that are accompanied by a sudden release of strain energy.
The purpose of AE analysis in the present study was to obtain the effect of bedding planes inclination on the acoustic emission of coal and to obtain the fundamental information on the AE regarding the prediction of coal pillar failure.

## 2. ACOUSTIC EMISSION TECHNIQUE

Among a number of acoustic techniques that are currently used to study material behaviour, ultrasonic technique and acoustic emission are mostly popular. The former generally utilise two transducers, one as an emitter generating mechanical signals within the material and the other as a receiver monitoring the variation of the transmitted signals resulting from changes of stress, strain or other mechanical properties in the material.

The acoustic emission tester which was used during testing is a 2-channel AE analysis unit (NF U-PLOT). The system consists of a combination of a sensor, preamplifier, AE analysis unit and x-y plotter.

The AE signal detected by a sensor is amplified by a preamplifier and applied to the input of U-plot and the U-plot has the following functions:

When acoustic emission signals are generated, event data which characterise the emission is extracted and stored in a buffer memory.

Various analyses are performed in real time.

After a measurement is completed (or interrupted), a colour plot can be generated on an X-Y plotter.

## 3. COAL SPECIMENS USED FOR TESTING

The coal specimens were prepared by cutting cubes at various angles relative to the bedding. The dimensions of cubic specimens were 50mm ×50mm × 50mm. The specimens were classified into seven groups depending upon the bedding planes inclination with axial direction, β° (0, 15, 30, 45, 60, 75, 90°) and in each group more than three specimens were tested. Uniaxial compressive strength of specimens were determined in a Servo-controlled testing machine with a capacity of 500 kN. The machine enables us to apply the load at a constant rate of displacement and strain. The principal measurements, axial load and axial deformation of the specimen were conducted by computer which was connected to the testing machine.

## 4. EXPERIMENTAL PROCEDURE

The experimental system used during each test comprises the following major parts: load system; stress-strain measurement system; and AE monitoring system.

The load was applied by the Servo-Controlled Schenck machine.

Acoustic emission generated during the unconfined compression test was counted after band-pass filtering. The count rate detected through low pass window (AE(L)) was compared statistically with that detected through a high pass window (AE(H)) throughout the whole procedure. The elastic wave generated as AE in stressed specimen is converted to electrical signal by the transducer which was attached to one side of each specimen. This electrical signal is then transferred to a preamplifier and then through high pass filter to the AE analyser. Two different frequency bands selected in this study were a low frequency window L which has a frequency range between 50 and 250 kHz (with sensitivity peak around 150 kHz) and a high frequency window H with a range between 200 and 450 kHz.

## 5. TEST RESULTS AND DISCUSSIONS

Test results have shown that both unconfined compressive strength and acoustic emission behaviour of coal specimens with bedding planes depends upon the angle of bedding planes inclination (β°). In the cubic specimens when width-to- height ratio is equal to one (W/H=1), the minimum strength occurs when the bedding planes inclination is 45° . However, it has been shown that the minimum strength of specimens with W/H or D/H = 0.5 occurs when the bedding planes inclination is 30° and with increasing confining pressure, the effect of weakness planes inclination on the compressive strength is reduced (Vutukuri et al., 1995).

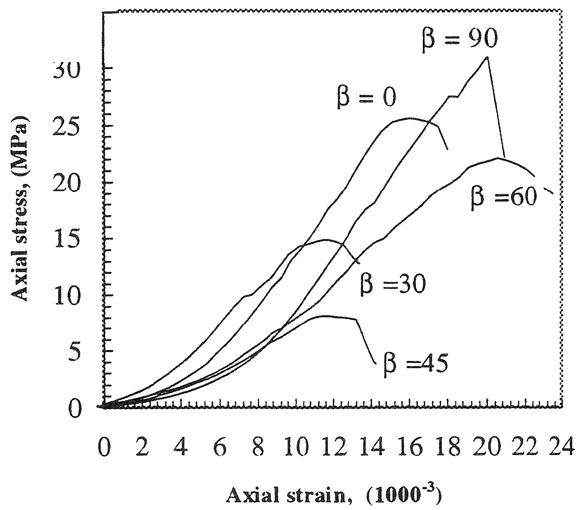


Figure 1 Relationship between stress and strain for coal specimens with various bedding planes inclination, β°.

The relationship between stress and strain for specimens with different bedding planes inclination is given in Figure 1. It can be seen from the curves that when β is between 30° -60° the shape of the curves is similar showing the failure by sliding on the plane of weakness and it is confirmed by AE measurements (Figures 5.b-7.b).

The emission rate detected through a low pass window varied significantly with the bedding planes inclination. Variation of the parameter m which is the ratio between AE(L) and AE(L)+AE(H) is determined for each group of specimens.

The relationship between AE event rate (Low-frequency & High-frequency) and stress for various bedding planes inclination is given in Figures 2.a-8.a.

In the specimens with the bedding planes parallel to the loading axis, the ratio m almost remained constant in the whole process of fracturing and no significant change was recognised before failure (Figure 2.b). However, in the specimens with the bedding planes perpendicular to the loading axis, the ratio m varied significantly during the fracturing process. In the initial stage where stress level was less than 30% of the uniaxial compressive strength ($\sigma_c$ ), m almost remained constant at high values. Also, the ratio m decreased drastically as the stress was increased from $0.3\sigma_c$ to $0.7\ \sigma_c$ , and then increased again until failure (Figure 3.b).

In the specimens with bedding plane inclination between 15° to 30° , m decreased from $0.6\ \sigma_c$ until the failure (Figures 4.b and 5.b).

In the specimens with bedding plane inclination of 45° , the ratio m decreased from $0.4\ \sigma_c$ and the rapid decrease of the ratio was recognised just before the failure (Figure 6.b).

In the specimens with bedding plane inclination of 60° , m remained constant up to $0.75\sigma_c$ , then decreased leading to the failure (Figure 7.b).

In the specimens with bedding plane inclination of 75° , m remained mostly constant up to $0.56\sigma_c$ of stress level, and then increased gradually. However, it decreased rapidly from $0.75\sigma_c$ until the failure (Figure 8.b).

It can be seen that the frequency characteristics of acoustic emission activity was affected by bedding planes inclination.

It is shown that in this series of experiments, the acoustic emission rate monitored through a high-frequency window increased more rapidly than the one monitored through a low-frequency window as the stress increased to the ultimate strength. The value of m starts decreasing at different stress levels depending upon the bedding planes inclination. However, Ohnaka and Mogi (1981) have shown that in the core of rock, the low frequency AE activity increased more rapidly than the high-frequency AE activity as rock approaching failure.

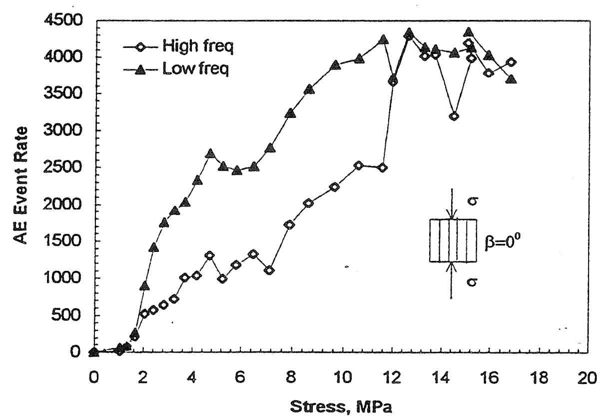


Figure 2.a AE rate history (low frequency and high frequency), bedding planes inclination β=0°.

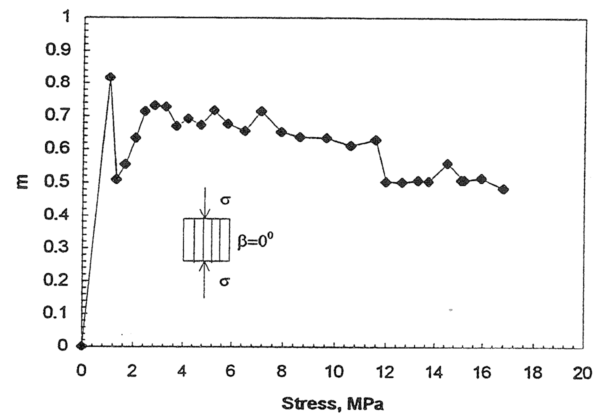


Figure 2.b The change of low frequency contents of AE, bedding plane inclination β=0°.

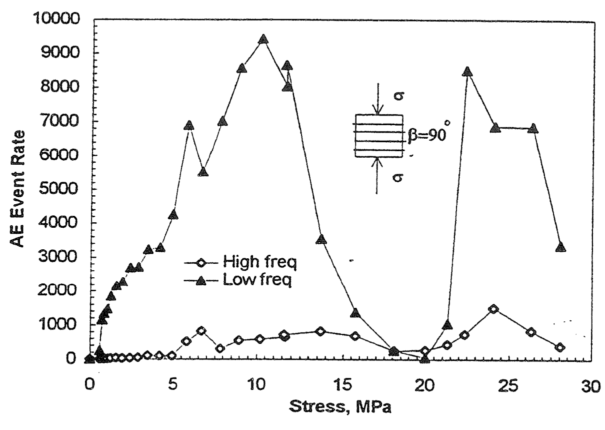


Figure 3.a AE rate history (low frequency and high frequency), bedding planes inclination β=90°.

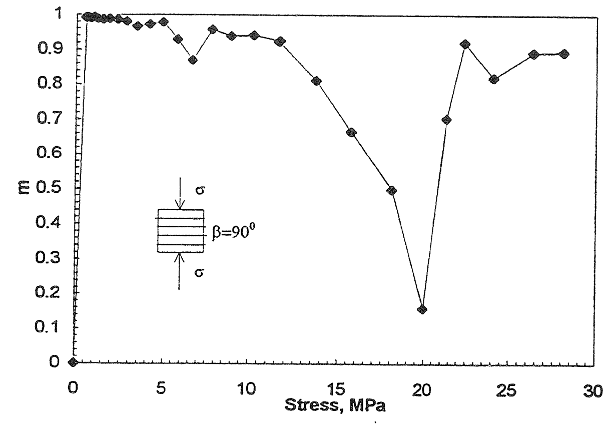


Figure 3.b The change of low frequency contents of AE, bedding plane inclination β=90°.

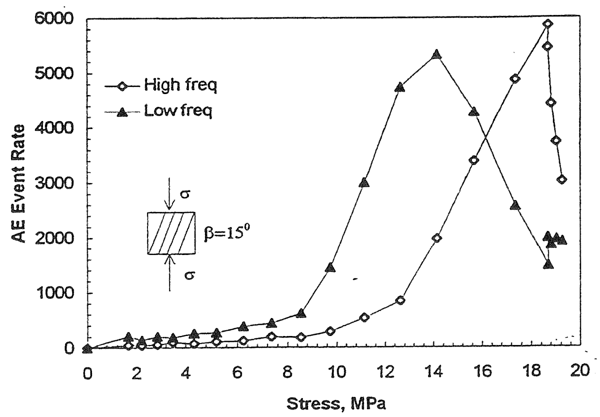


Figure 4.a AE rate history (low frequency and high frequency), bedding planes inclination β=15°.

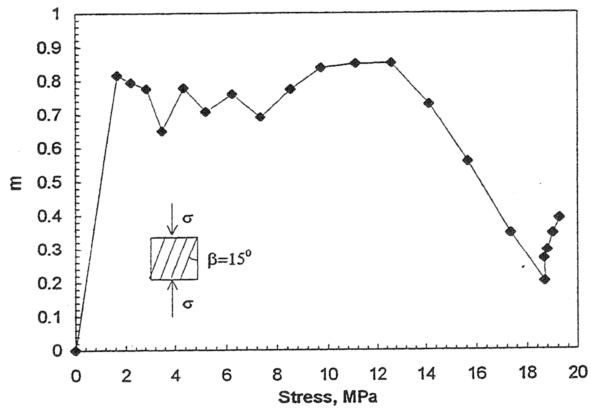


Figure 4.b The change of low frequency contents of AE, bedding plane inclination β=15°.

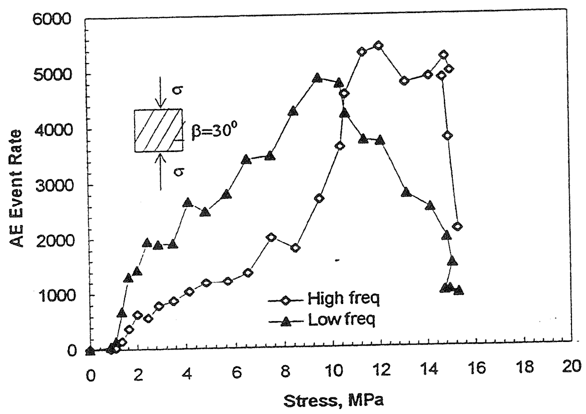


Figure 5.a AE rate history (low frequency and high frequency), bedding planes inclination β=30°.

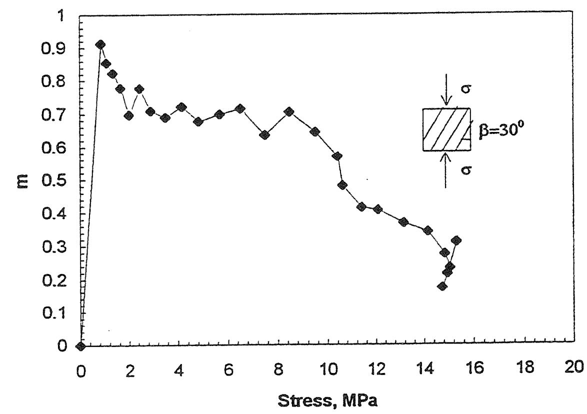


Figure 5.b The change of low frequency contents of AE, bedding plane inclination β=30°.

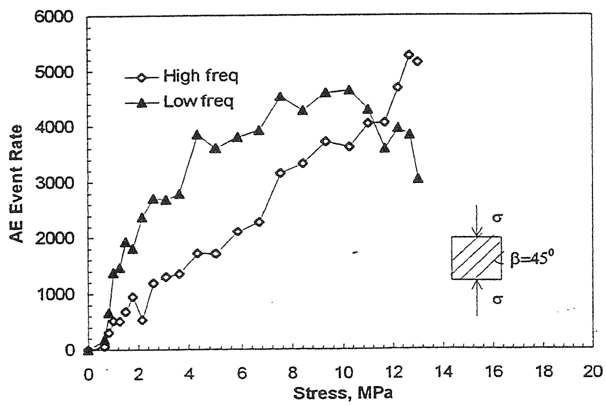


Figure 6.a AE rate history (low frequency and high frequency), bedding planes inclination β=45°.

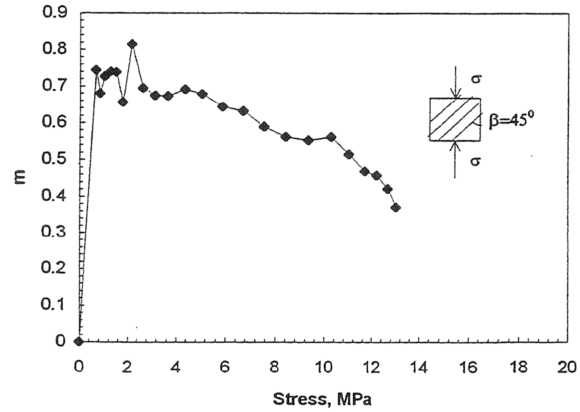


Figure 6.b The change of low frequency contents of AE, bedding plane inclination β=45°.

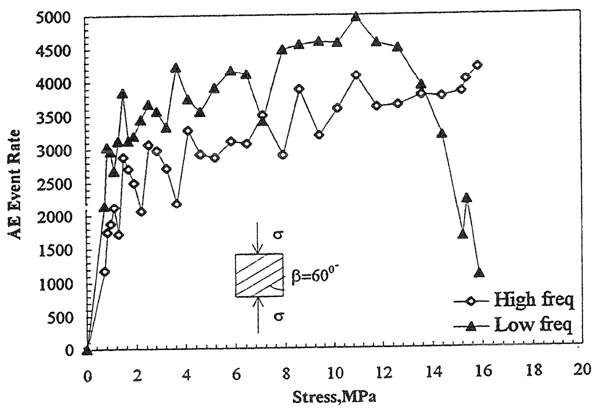


Figure 7.a AE rate history (low frequency and high frequency), bedding planes inclination β=60°.

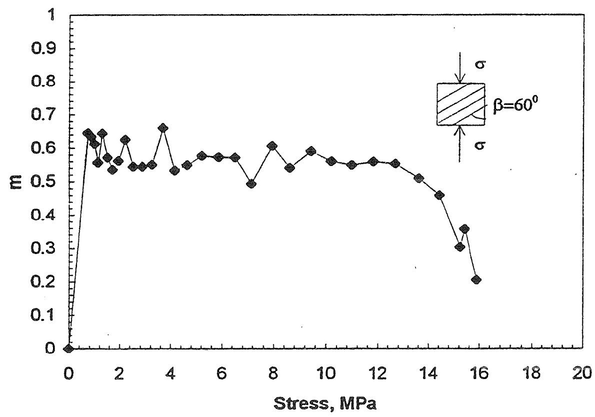


Figure 7.b The change of low frequency contents of AE, bedding plane inclination β=60°.

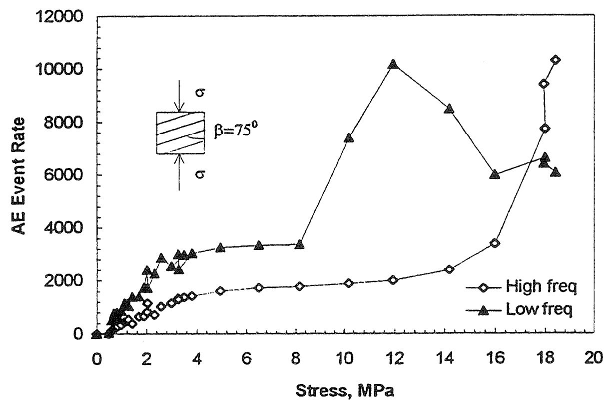


Figure 8.a AE rate history (low frequency and high frequency), bedding planes inclination β=75°.

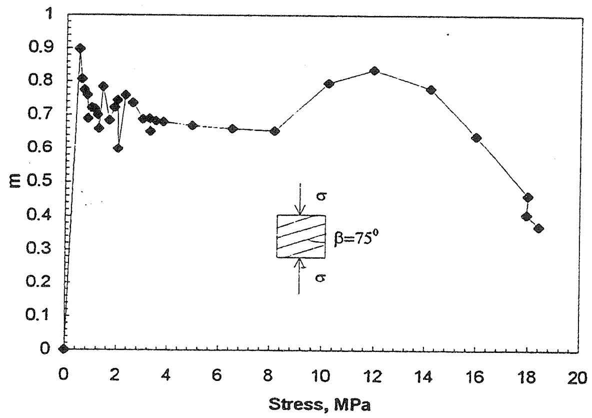


Figure 8.b The change of low frequency contents of AE, bedding plane inclination β=75°.

## 6. CONCLUSIONS

Test results have shown that the strength and acoustic emission behaviour of coal depend upon the weakness plane inclination. The minimum value of failure strength occurred when weakness plane inclination was 45° and the maximum compressive strength occurred in the direction perpendicular to the weakness planes. The acoustic emission rate monitored through a high-frequency window increased more rapidly than the one monitored through a low frequency window with increasing stress until failure. Also the increase of the acoustic emission rate depends upon the bedding plane inclination. For specimens with bedding planes inclination parallel to the axial load, the parameter m remained almost constant and the failure takes places through extension failure of the planes of weakness. For specimens with weakness planes inclination between 15° -30° , m is decreases from 0.6 $\sigma_c$ until failure (slip on the plane of weakness). For the bedding plane inclination of 45° , m decreased from 0.4 $\sigma_c$ (slip on the plane of weakness and minimum strength occurred in this group), and for the bedding planes inclination between 60°-90° , m decreased from 0.75 $\sigma_c$ and failure occurred by fracturing across the bedding planes. As it was mentioned, the frequency characteristics of AE measurements can be used for the prediction of coal pillar failure containing weakness planes at various inclinations.

## REFERENCES

Hardy, H.R. (1978). Some Current Applications of Microseismic Techniques in Geomechanics, *Proceedings of NATO Symposium on Dynamic*

*Methods in Soil and Rock Mechanics*, Balkema, Rotterdom, Vol 3, pp. 173-199.

Hardy, H.R. (1981). Application of Acoustic Emission Techniques to Rock and Rock Structures, *A State-of-the-Art Review. Acoustic Emission in Geothechnical Engineering Practice*. Editors- V.P. Drnevich and R.E. Gray, ASTM STP 750, American Society for Testing and Materials, Philadelphia, Pennsylvania, pp. 4-92.

Obert, L. and Duvall, W.I. (1942). Use of Subandible Noises for the Prediction of Rock Bursts, Part II, RI 3654, *U.S Bureau of Mines*.

Obert, L., (1977). The Microseismic Method-Discovery and Early History, *Proceedings of First Conference on Acoustic Emission/ Microseismic Activity in Geologic Structures and Materials,* Pennsylvania State University, June. Trans Tech Publications, Clausthal, Germany, pp. 11-12.

Ohnaka, M. and Mogi, K. (1981). Frequency Characteristics of Acoustic Emission in Rock under Compression and its Relation to the Fracturing Process to Failure, *J. Geophys. Res*., 87, pp. 3873-3882.

Vutukuri, V.S., Hosseini, S.M.F. and Foroughi, M.H. (1995). A Study of the Effect of Roughness and Inclination of Weakness Planes on the Strength of Rock and Coal, *Mechanics of Jointed and Faulted Rocks*, (Ed: Rossmanith), Balkema, Rotterdam pp. 151-155.