SAMIR KUMAR PAL
NIKHIL PANDEY
and
ANUP KUMAR TRIPATHI

Characteristics of vibration at failure and its relation to rock properties during tensile failure

The paper describes the study carried out to determine the relationships between the amount of vibrations that happen inside the rock at the time of failure under tensile loading and different rock properties such as uniaxial compressive strength, uniaxial tensile strength, Young's modulus, cohesion, angle of internal friction and density. It is then tried to interpret what are the factors that affect the vibrations and the time to failure. To capture the vibrations piezoelectric sensors are used which capture the acoustic signals and convert them into electric signals. With the help of Picoscope, it was then possible to recover the acoustic signals.

At the time of failure, the peak voltage (h) was recorded along with the span of time the rock took to fail (w). The h/w ratio was then obtained and used to relate it with different rock properties. h/w ratio is the measure of how much vibrations happen inside the rock and for what amount of time. It was observed to be highly related to uniaxial tensile strength, angle of internal friction and rock density.

Keywords: *Rock properties, tensile loading, rock vibrations, piezoelectric sensors, PicoScope.*

1. Introduction

In recent years, the process of rock failure has become especially useful with reference to predicting earthquakes and to various dynamic rock pressure manifestations in rock masses. In rock mechanics, fracturing of rock has long been studied to help understand the behaviour of a particular rock mass when under stress. In general, loading of rock samples will cause some changes in the mechanical and physical behaviour that can be measured in the laboratory. In most cases, before a rock mass failure, some measurable changes in the rock parameters have been reported, including acoustic emissions, elastic wave velocity, temperature and infrared radiation, as well as low frequency electromagnetic emissions. These parameters could be used for long-term evaluation of the stability of underground excavations or fault rupture and, as a result, could be used for earthquake prediction. In particular, this might help to understand how micro cracks in a rock sample, under an applied stress, combine to ultimately produce macroscopic failure. Such understanding is also of an engineering interest, particularly how cracks are formed under in situ stress around an underground excavation such as a tunnel or borehole [1, 2].

In this work, acoustic emissions monitoring using piezoelectric sensors during loading of rock have been used to study the amount of vibrations that happen at the time of failure. The aim of this research is to show the relationship between different rock properties and the intensity of vibrations and failure time when the rock fails.

Piezoelectric sensors are low cost with long-term durability, fast dynamic response and negligible aging, and are characterized by large range of linearity. In addition to high sensitivity, they are immune to ambient noise. Piezoelectric sensors transducers are relatively new sensors, barely fifteen years old. They do not measure direct physical parameters like stress, strain or temperature. Rather, they are capable of extracting a signature of the host structure to detect the occurrence of structural damages at the incipient stage [3, 4].

2. Literature review

2.1 Acoustic waves in rock

Acoustic waves are a type of longitudinal waves that propagate by adiabatic compression and decompression. Longitudinal waves are waves that have the same direction of vibration as their direction of travel. The acoustic properties of most crustal rocks are dominated by micro cracks, pores, and the fluids contained within them [5, 6]. Dry rocks have much lower elastic moduli than do any of the constituent minerals. The different stages of acoustic emission are:

- Emission caused by load application,
- Elastic region,
- Initiation of micro cracking,
- Onset of stable micro cracking,

Prof. Samir Kumar Pal, Professor and Head, Department of Mining Engineering, Indian Institute of Technology (IIT), Kharagpur, Mr. Nikhil Pandey, Ex-Undergraduate Student, Department of Mining Engineering, Indian Institute of Technology (IIT), Kharagpur, and Dr. Anup Kumar Tripathi, Assistant Professor, Department of Mining Engineering, National Institute of Technology (NIT), Surathkal.

- Beginning of unstable micro cracking.

2.2 Tensile loading

When a specimen of material is loaded in such a way that it extends it is said to be in tension. Tensile load is the ability of a material to withstand a pulling force. It is customarily measured in units of force per cross-sectional area. This is an important concept in engineering, especially in the fields of material science, mechanical engineering and structural engineering. The ability to resist breaking under tensile stress is one of the most important and widely measured properties of materials used in structural applications [7, 8]. Tensile load is important in the use of brittle materials more than ductile materials.

In the Brazilian test, a disc shape specimen of the rock is loaded by two opposing normal strip loads at the disc periphery. The specimen diameter shall preferably be not less than core size (54 mm), or at least 10 times the average grain size. The thickness/diameter ratio should be 0.5 to 0.6. The load is continuously increased at a constant rate until failure of the sample occurs within few minutes [9, 10]. The tensile strength of the rock specimen can then be calculated using the following equation:

$$\sigma_t = \frac{2P}{DL} \quad \text{... (1)}$$

where,

σ_t = Tensile strength,

P = Applied pressure,

D = Diameter of the sample ($D = 2 \times \text{radius} = 2R$),

L = Thickness of the sample.

2.3 Piezoelectric sensor

A piezoelectric sensor is a device that uses the piezoelectric effect, to measure changes in pressure, acceleration, temperature, strain or force by converting them into an electrical charge. The prefix piezo is Greek word for ‘press’ or ‘squeeze’. When a force is exerted on certain crystalline materials, electric charges are formed on the crystal surface in proportion to the change of applied force. To make use of the device, a charge amplifier is required to give a signal that is proportional to the applied force and big enough to measure. The first transducers to generate piezoelectric effect for measurement used naturally grown quartz but today mostly artificial quartz is used. Because of this, these devices are often known as quartz force transducers, though here the more general term piezoelectric crystal will be used [11].

3. Apparatus used in experimentation

PicoScope shown in Fig.1 is computer software for real-time signal acquisition from Pico technology oscilloscopes. PicoScope is primarily used to view real-time signals from PicoScope oscilloscopes and data loggers. The software has

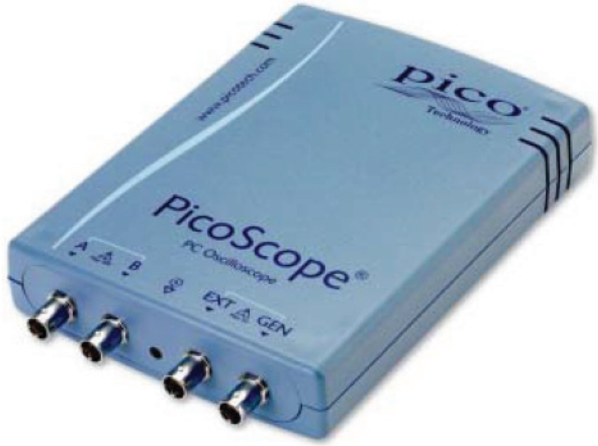

Fig.1: PicoScope

been described as very good for laptops and can be used with desktop or laptop PCs. The Linux version has been described as a lot more advanced than the Q PicoScope and capable of replacing a professional bench top scope. Beta versions of the software also work on the ARM-based Beagle Bone Black and Raspberry Pi development hardware. A piezoelectric sensor is shown in Fig.2, which is a device that uses the piezoelectric effect to measure changes in pressure, acceleration, temperature, strain, or force by converting them into an electrical charge. Piezoelectric sensors capture the acoustic signals and convert them into electric signals. With the help of PicoScope, it is then possible to recover the acoustic signals [12].

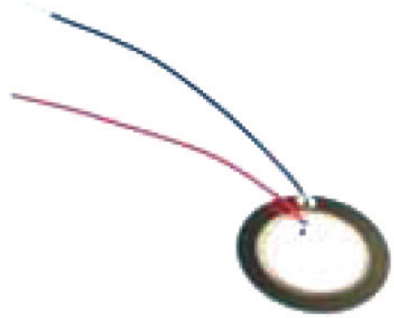

Fig.2: Piezoelectric sensor

4. Experimental observations

Four types of rock samples which were used in the research include shale, fine grained shaly sandstone, coarse grained shaly sandstone, and intercalation between shale and sandstone. Table 1 summarizes the samples used for our experimentation along with their physical properties obtained in the laboratory.

Table 2 summarizes the values obtained from the PicoScope during tensile failure of the rock samples.

The voltage versus time graphs obtained from the PicoScope for the four types of samples are shown in Figs.3 to 6.

Table 1: Properties of rock samples used in the research

.	Rock type	UCS(MPa)	UTS(MPa)	Young's Modulus, *E*(GPa)	Cohesion (MPa)	Angle of internal friction, ϕ (Degrees)	Density (Kg/m^3)
1	Shale	46.53	4.85	8.49	13.10	31.6	2429
2	Shaly sandstone (Fine grained)	62.70	10.21	11.20	12.80	41.4	2494
3	Shaly sandstone(Coarse grained)	41.82	4.38	10.40	16.99	25.9	2371
4	Intercalation between shale and sandstone	72.80	3.26	13.83	24.70	18.7	2396

Table 2: Results obtained from the PicoScope during tensile failure of the rock samples.

Rock type	Diameter (mm)	Width (mm)	Fracture duration (ms)	Height of Peak (mV)	Height span of time (h/w)
Shale	47.60	24.06	1.04	3206.01	3083.46
Shaly sandstone (fine grained)	47.50	24.02	0.75	6473.90	8620.37
Shaly sandstone (coarse grained)	47.60	20.51	1.23	1021.46	849.09
Intercalation between shale and sandstone	47.54	22.03	8.53	891.99	104.58

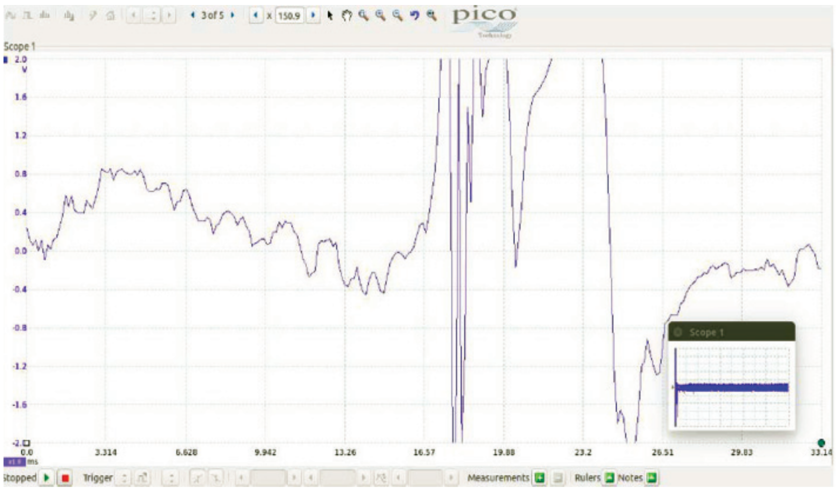

Fig.3: Shale voltage vs time graph

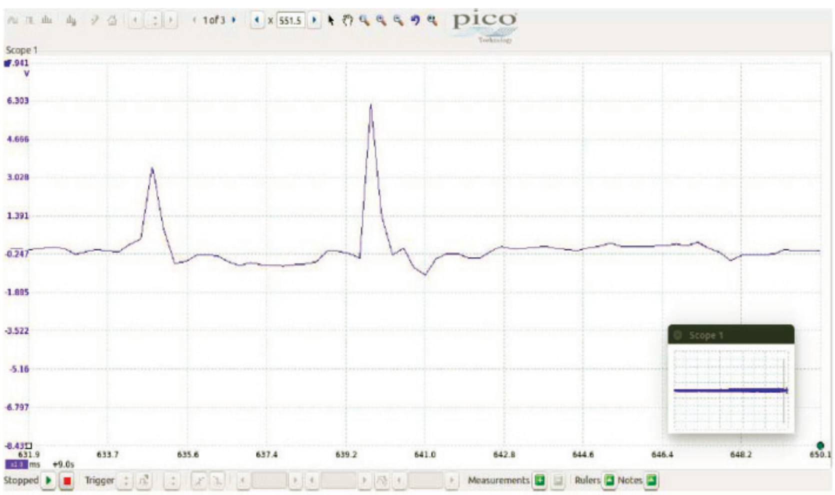

Fig.4: Fine-grained shaly sandstone voltage vs time graph

5. Comparison of h/w ratio with different physical properties

Scatter plots were then drawn between h/w ratios obtained against various rock properties of different rock samples. Best fit linear trend lines were also fitted between h/w ratios and different rock property values and corresponding R^2 values observed to determine the quality of relationship.

5.1 h/w vs UCS

Fig.7 shows the scatter plot between h/w ratios versus uniaxial compressive strengths of different rock samples. The best fit trend line equation obtained between h/w and UCS is also shown in the plot. It can be observed that there is little correlation between h/w and UCS, since the R^2 value (0.012) is extremely low.

5.2 h/w vs UTS

Fig.8 shows the scatter plot between h/w ratios versus uniaxial tensile strengths of different rock samples. The best fit trend line equation obtained between h/w and UCS is also shown in the plot. It can be observed that there is extremely high correlation between h/w and UTS, since the R^2 value (0.968) is extremely high.

5.3 h/w vs Young's Modulus (E)

Fig.9 shows the scatter plot between h/w ratios versus Young's modulus (E) values of different rock samples. The best fit trend line equation obtained between h/w and E is also shown in the plot. It can be observed that

Fig.5: Coarse-grained shaly sandstone voltage vs time graph

Fig.6: Intercalation between shale and sandstone voltage vs time graph

there is little correlation between h/w and Young's modulus, since the R^2 value (0.054) is extremely low.

5.4 h/w VS COHESION

Fig.10 shows the scatter plot between h/w ratios versus cohesion values of different rock samples. The best fit trend line equation obtained between h/w and cohesion is also shown in the plot. It can be observed that there is low level correlation between h/w and cohesion, since the R^2 value (0.519) is not high.

5.5 h/w VS ANGLE OF INTERNAL FRICTION

Fig.11 shows the scatter plot between h/w ratios versus angles of internal friction (ϕ) of different rock samples. The best fit trend line equation obtained between h/w and ϕ is also shown in the plot. It can be observed that there is high correlation between h/w and ϕ, since the R^2 value (0.918) is high.

5.6 h/w VS DENSITY

Fig.12 shows the scatter plot between h/w ratios versus densities of different rock samples. The best fit trend line equation obtained between h/w and density is also shown in the plot. It can be observed that there is high correlation between h/w and UTS, since the R^2 value (0.919) is high.

To summarize, by seeing the pattern of h/w under tensile loading with respect to various physical

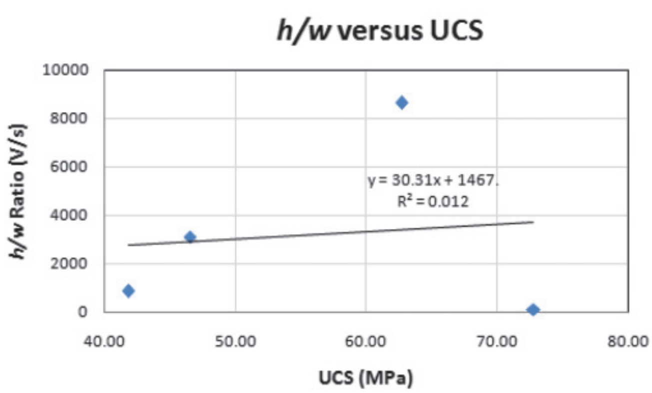

Fig.7 Plot of h/w vs UCS

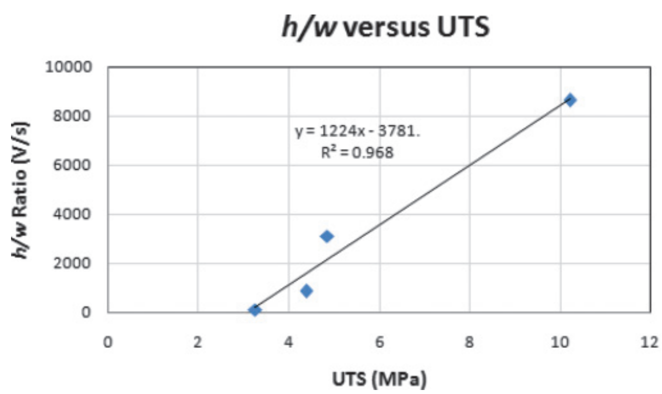

Fig.8: Plot of h/w vs UTS

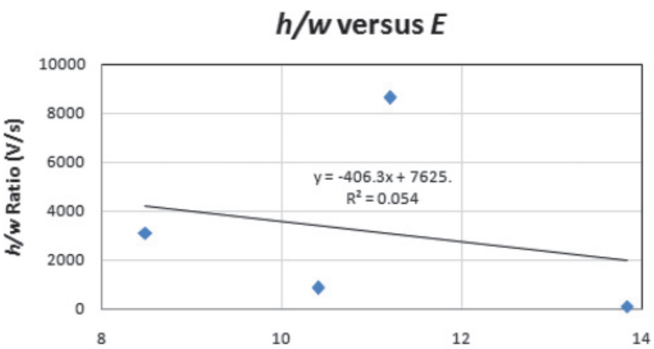

Fig.9 Plot of h/w vs Young's modulus.

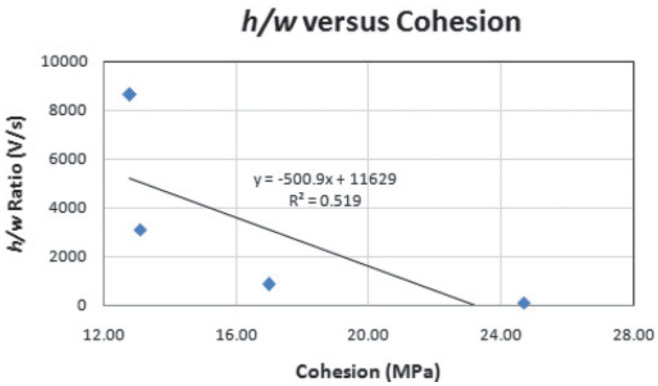

Fig.10: Plot of h/w vs cohesion.

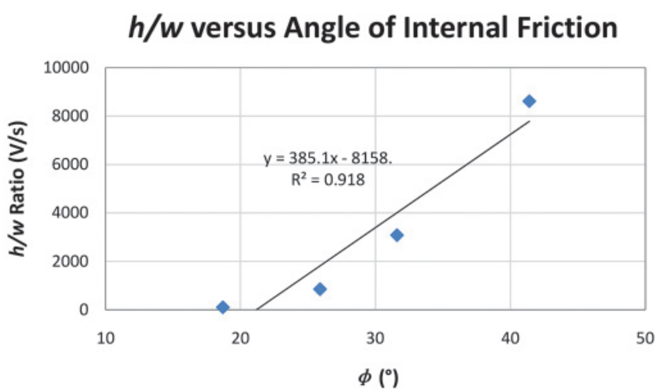

Fig.11: Plot of h/w vs angle of internal friction.

properties of rock, we can say that h/w is highly correlated to UTS, angle of internal friction and density as their R^2 values are 0.968, 0.918, 0.919 respectively. It also depends to some extent on cohesion as its R^2 value is 0.519 . UCS and Young's modulus have very low R^2 value.

6. Conclusions and discussions

Piezoelectric sensors are versatile tools for the measurement of various processes. They are used for quality assurance, process control, and for research and development in many industries. The piezoelectric effect was discovered in 1880, but only in the 1950s did companies begin to use the piezoelectric effect in industrial sensing applications. Since

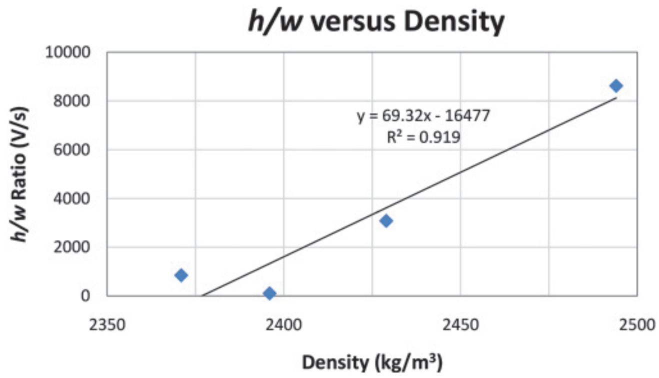

Fig.12: Plot of h/w vs density.

then, this measuring principle has been increasingly used, and has become a mature technology with excellent inherent reliability. They have been successfully used in various applications, such as in medical science, aerospace engineering, nuclear instrumentation, and as a pressure sensor in the touch pads of mobile phones.

This research includes a detailed experimental programme for evaluating the behaviour of different rock type at the time of failure. The higher the h/w ratio is, the higher are the vibrations inside the rock. It is tried to determine the relationship of the the h/w ratio with different rock properties and it turns out that it depends mostly on uniaxial tensile strength, angle of internal friction and density.

References

1. Stein S. and Wysession M. (2013): "An Introduction to Seismology, Earthquakes, and Earth Structure", Wiley India Private Limited, 512 pp.
2. Hucka, V., (1965): "A Rapid Method for Determining the Strength of Rocks In Situ", *International Journal of Rock Mechanics and Mining Sciences*, Vol. 2, No. 2, pp. 127 – 134.
3. Yang Y. W., Bhalla S., Wang C., Soh C. K., Zhao J. (2007): "Monitoring of Rocks Using Smart Sensors", Tunnelling and Underground Space Technology, Vol. 22, Issue 2, March 2007, pp. 206 221.
4. Trolier-McKinstry S. (2008): "Crystal Chemistry of Piezoelectric Materials", Piezoelectric and Acoustic Materials for Transducer Applications, Edited by A. Safari, E. K. Akdogan, Springer Publishers, New York, pp. 39 56.
5. Denecke, E. J., (2007): "Let's Review: Earth Science, The Physical Setting", 2nd Edition, Barron's Educational Series, Inc., New York, 348 – 350.
6. Jumikis, A. R., (1988): "Rock Mechanics", CRC Press, 2nd Edition, 614 pp.

(Continued on page 130)