A NOVEL APPARATUS TO DETERMINE THE ROCK STRENGTH PARAMETERS

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ABSTRACT : This paper presents a portable apparatus, the Rock Strength Device (RSD), and the methodology to assess the strength of rock from "partially-destructive" scratching tests. The RSD measures the normal and tangential components of force applied to a cutter while making a groove at a constant depth on the surface of a rock specimen with sharp or blunt tool. Experiments indicate that rock cutting is associated with a “ductile” or a “brittle” mode of failure depending on the depth of cut. The ductile mode takes place at shallow depth of cut and is associated with plastic flow, while the brittle mode occurs above a threshold depth of cut and is characterized by the propagation of tensile crack. In ductile mode, experiments with sharp cutter show that the energy required to remove a unit volume of rock, referred to as the intrinsic specific energy ε, is well correlated to the uniaxial compressive strength q. Furthermore, the friction coefficient μ mobilized along the wear flat of blunt cutter is found to be well correlated to the internal friction angle φ of the rock. It is also possible to capture a thin layer of weak material or heterogeneity along the rock core.

KEYWORDS : ROCK CUTTING EXPERIMENT, SHARP AND BLUNT CUTTERS, UNIAXIAL COMPRESSIVE STRENGTH, FRICTION ANGLE

1. Introduction

A simple cutting (scratching) apparatus to determine the strength of rock cores had been developed at the University of Minnesota for several years during the late 1990’s [1-6]. The apparatus is referred to as the Rock Strength Device (RSD). The scratching test consists of tracing a groove of prescribed geometry on the surface of a rock specimen with a cutting tool. The test is conducted under kinematic control: the depth of the cut d (or depth of the groove) and the cutter velocity v are imposed and maintained constant along the entire cut, see Fig. 1.

Two types of cutters are used in the test: the sharp and blunt cutter. The sharp cutter ($\ell = 0$) presents one contact surface with the rock, the cutting face. The force exerted on the cutting face is defined as the cutting force F^c. The cutting face is normally inclined forward by an angle θ, referred to as back rake angle. In addition to the cutting face, blunt cutters ($\ell > 0$) possess a machined "wear flat", moving parallel to the cutting direction against the bottom of the groove. The frictional force F^f is mobilized at the wear flat/rock interface. For rectangular shaped cutters, chosen for the tests, the description of cutter geometry reduces to the width w and the wear flat length ℓ. The cutting face of the cutters commonly used are made of a thin layer of polycrystalline diamond compact (PDC) laid down on a tungsten carbide base. The diamond offers a high resistance to abrasion.

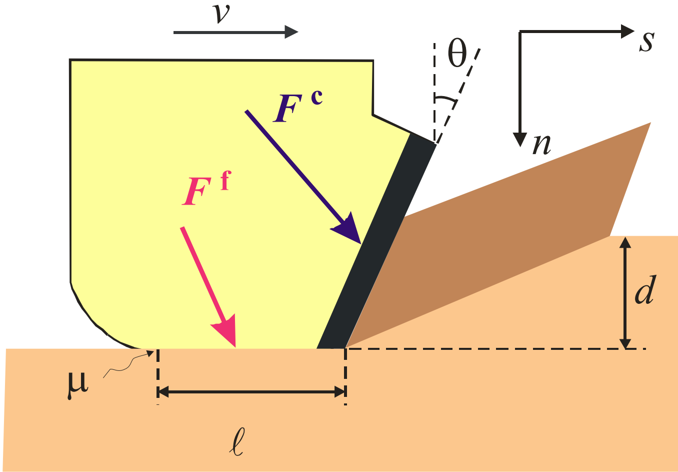


Figure 1 Cutting configuration. Forces acting on a blunt cutter.

The scratching apparatus consists of frame with moving parts, a load sensor, a stepper motor, a data acquisition and control system hooked to a computer. The tests are usually performed at a depth of cut d varying in the range 0.1 mm to 4 mm. A stepper motor imposes a linear relative motion between the rock sample and the cutter, with a speed ranging from 0.1 to 12 mm/s. The load cell attached to a vertically traveling mechanism measures independently the horizontal and vertical forces (F_s and F_n) applied on the cutter. The output voltage of the load cell is converted, after amplification, into a digital signal, which can then be further manipulated by software. Through the stepper motor indexer, the position of the cutter can accurately be determined at any instant. Continuous recording of the forces during a scratch test, together with the knowledge of the position of the cutter, allows therefore to create continuous logs of the cutting force as well as logs of any derived quantity (such as specific energy which will be discussed later on). With the high resolution and sensitivity of the load cell, textural variation and heterogeneity of the material can easily be detected. The apparatus is semi-automated and is controlled by computer through a software program written in Labview.

2. Characteristics of rock cutting test

2.1 Failure modes

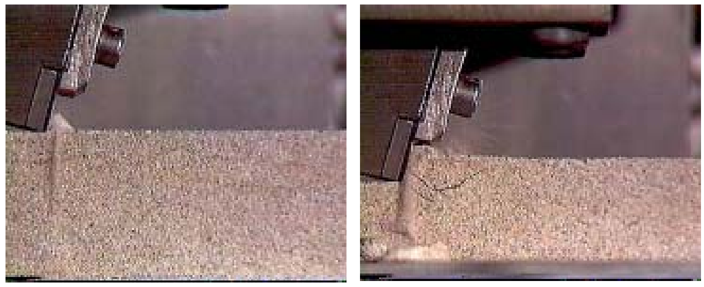
Many cutting experiments performed at Imperial College [7,8] and at the University of Minnesota [1-6] show the existence of two different cutting processes which are related to the depth of cut.

At shallow depth of cut (typically less than 1 mm for a medium strength sandstone), the rock is intensively sheared ahead of the cutter and crushed at the tip. The material is reduced to powder or isolated grains. The cutting proceeds in a continuous manner, in a sense that no particular events can be isolated while cutting, see Fig. 2a. This cutting mode is mainly characterized by a decohesion of the constitutive matrix and grains of the rock with grains and powder accumulating progressively in front of the cutter. From this point of view, this cutting mode can be defined as ductile.

At large depth of cut (typically more than 1 mm for a medium strength sandstone), brittle failure occurs, as shown in Fig. 2b. Isolated events can easily be recognized. Macroscopic cracks are initiated from the tool tip and propagate unstably ahead of the cutter. Chips, fragments of rock are created and removed by the cutter. The process is characterized by unstable failure, which is accompanied by significant sounds. After the chip is removed, the effective depth of cut is almost zero, and progressively increases until a new chip is formed. The successive increase and abrupt release of stress ahead of the cutter can, in the case of very hard rock, generate vibrations in the whole frame of the testing machine.

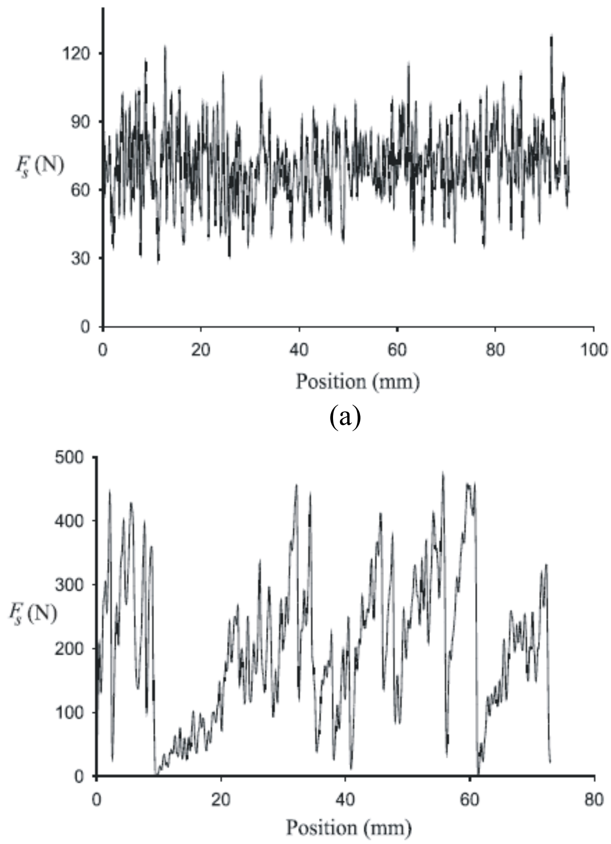
2.2 Force signal

The difference between the two mechanisms is noticeable in the shape of the force signal. With a homogeneous rock sample (i.e. with no major change of strength along the cutting direction), the signal in the ductile mode may be viewed as a white noise (see Fig. 3a), whereas the signal in the chipping mode presents a marked sawtooth pattern (see Fig. 3b). The signal characterizing the brittle cutting mode (chipping) presents more spread between peaks. In the horizontal direction, we can clearly identify an increase of the force over several millimeters up to a peak, when a crack is initiated. The abrupt drop of the force, after the peak, is associated with unstable propagation of the crack leading ultimately to the formation of a chip.



(a) (b)

Figure 2 Two cutting failure modes in slab specimen of Vosges sandstone: (a) ductile mode at shallow depth of cut d = 0.3 mm and (b) brittle mode at larger depth of cut d = 3 mm.



(b)

Figure 3 Horizontal force signal force signal along the cut of a Vosges sandstone: (a) ductile regime and (b) brittle regime.

2.3 Transition between the two failure modes

Experimental evidences show that the average cutting force varies linearly with d in the ductile mode, but non-linearly with d in the brittle mode.

In the ductile mode, the energy dissipation is expected to be proportional to the volume of failed material. It is then reasonable to introduce the uniaxial compressive strength q as the characteristic property for such a mechanism. In the brittle mode, the energy necessary to create a crack is essentially linked to the surface of the crack, not to the volume of rock removed as in the ductile mode. Thus it is reasonable to expect the average cutting force to be proportional to the square root of the depth of cut. The material property associated with crack propagation mechanism is the fracture toughness, K_{Ic}.

This interpretation conceptually explains the transition between the two modes of cutting and the existence of a critical depth d^* at which chips first appear. This threshold depth of cut is given by

$$d^* \sim \left(\frac{K_{Ic}}{q}\right)^2 \tag{1}$$

Obviously, determination of the uniaxial compressive strength q from the cutting test is restricted to the ductile mode. These tests should therefore be performed at depths of cut less than d^*.

3. A phenomenological model for ductile response

The basic equations used to describe the cutting response model in the ductile regime are proposed by Detournay & Defourny [9] as follows:

3.1 Sharp cutter

Consider first a perfectly sharp cutter (Fig. 1 with $\ell = 0$) of width w moving along the horizontal rock surface with a constant velocity and a depth of cut d. For such a cutter, the only force acting on the rock is transmitted by the cutting face of the tool. Let this cutting force be denoted as F^c, with F_n^c and F_s^c being the force components in the direction normal and parallel to the rock surface, respectively. Averaged over a distance larger than the depth of cut, these force components are assumed to be proportional to the cross-sectional area of the cut wd

$$F_s^c = \varepsilon wd \tag{2}$$

$$F_n^c = \zeta\varepsilon wd \tag{3}$$

where ε denotes the *intrinsic specific energy* and ζ is the ratio of the vertical to horizontal force acting on the cutting face. Note that the dimension of ε is the same as stress and the unit MPa is chosen as it will be related to the material strength. The *specific energy* means the amount of energy required to cut a unit volume of rock. The word *intrinsic* emphasizes that this energy is strictly used for the pure cutting action.

The constant parameter ζ is given by

$$\zeta = \tan(\theta + \psi) \tag{4}$$

where θ is the back rake angle of the cutter and ψ is the interfacial angle between the failed rock and the cutting face. It is found that for a given back rake angle, ψ is independent of the depth of cut and almost insensitive to the types of rock (see experimental result in the next section).

3.2 Blunt cutter

In case of a blunt cutter (Fig. 1), in addition to the force F^c acting on the cutting face, there is a frictional force F^f mobilized under the wear flat. The normal and tangential components of the latter force, denoted as F_n^f and F_s^f, are related according to the friction law

$$F_s^f = \mu F_n^f \tag{5}$$

where μ is the coefficient of friction on the wear flat/rock interface. Combining the two processes (pure cutting and frictional contact), the relationship between the tangential and normal components, F_s and F_n, of the total force acting on the blunt cutter is given by

$$F_s = (1 - \mu\zeta)\varepsilon wd + \mu F_n \tag{6}$$

Defining the specific energy E, and the drilling strength S, respectively as

$$E = \frac{F_s}{wd}, \quad S = \frac{F_n}{wd} \tag{7}$$

and dividing (6) by wd, a constraint on the cutter response is obtained

$$E = E_o + \mu S \tag{8}$$

where

$$E_o = (1 - \mu\zeta)\varepsilon \tag{9}$$

A schematic plot of E-S relationship (known as E-S diagram) is shown in Fig. 4. This plot graphically shows a constraint on the cutting response that accounts for cutting and frictional process simultaneously. The cutting point is defined for a perfectly sharp cutter where $E = \varepsilon$ and $S = \zeta\varepsilon$. All the points associated with tests performed by blunt cutters lay down along the friction line in the E-S diagram. The position along the friction line is controlled by the state of wear of the cutter (i.e. the wear flat length, ℓ).

4. Test results with RSD

4.1 Sharp cutter experiments

A series of cutting experiments were performed on different types of rock using a rectangular sharp cutter. Each test is conducted along the entire specimen length under a constant depth of cut d and a fixed cutting velocity v = 4 mm/s and a back rake angle $\theta = 15^o$. The test results in Fig. 5 show the linear dependency of the cutting force F_s and the cross-sectional area of the cut wd, provided that the force is averaged over a distance at least one order of magnitude larger than the depth of cut.

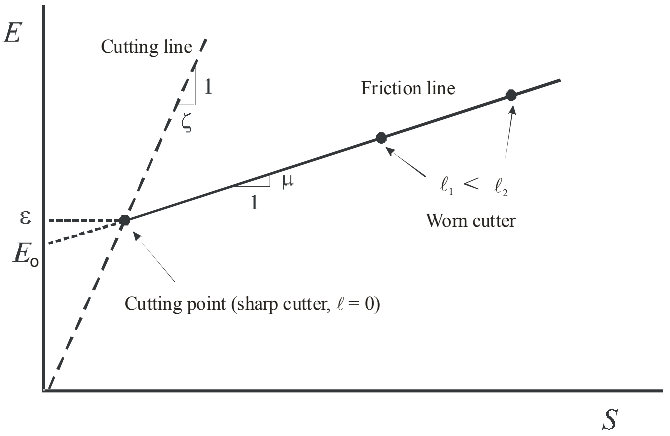


Figure 4 *E-S* diagram.

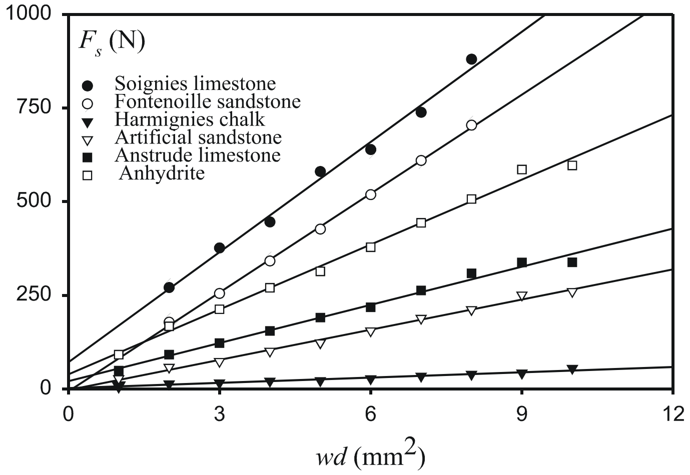


Figure 5 Variation of the tangential force component with the cross-sectional area of the cut. Tests performed with a sharp cutter.

The test results indicate that the cutting line (i.e. the ratio ζ) is relatively independent of the rock being cut, as shown in Fig. 6. This implies that the cutting face/rock interfacial friction angle ψ is practically insensitive to the tested rocks. Typically the ratio ζ is approximately taken to be 0.67, corresponding to $\psi = 19^o$ [2]. Note also that this inclination angle is almost constant during the test.

While the experiments show that the ratio ζ is unique and independent of the rock being cut, the intrinsic specific energy ε is indeed a rock property. Even more, this parameter can be considered as directly related with another strength indices like the uniaxial compressive strength or the cohesion of a rock. The value of the intrinsic specific energy can be obtained from the slope of the force-cross-sectional area in the ductile response. Fig. 7 reveals a good correlation between the uniaxial compressive strength q and the intrinsic specific energy ε for various rocks. It should be noted that ε is not an absolute quantity. It depends upon the cutting geometry (i.e. cutter width, rake angle, and cutter shape).

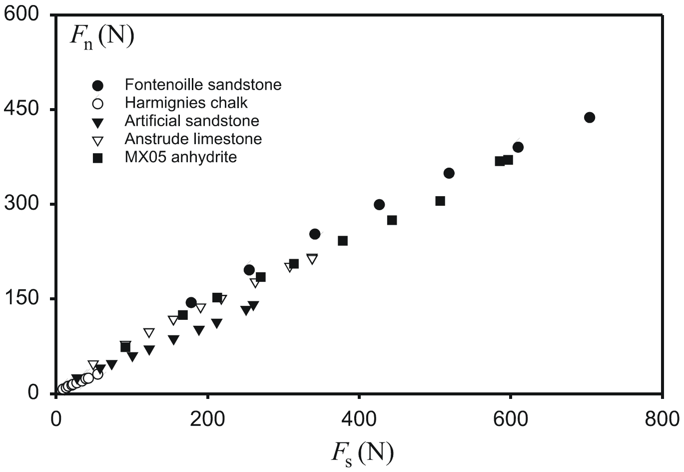


Figure 6 Relationship between the normal and tangential force components for different rocks.

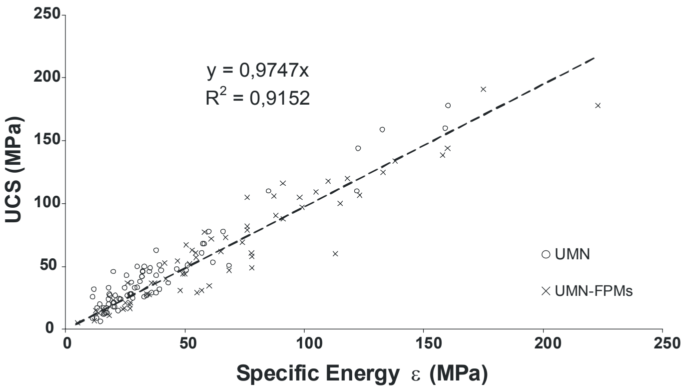


Figure 7 Correlation between the intrinsic specific energy and the uniaxial compressive strength. Tests performed at the University of Minnesota and at the Faculté Polytechnique de Mons.

4.2 Blunt cutter experiments

Cutting experiments on Red Wildmoor sandstone were performed at the University of Minnesota [2,6] using three PDC cutters: one sharp, and two blunt with different wear flat length. The rock specimen is characterized by its homogeneity in composition, grain size and mechanical property (q = 15 MPa). Fig. 8 shows the *E-S* diagram with the experimental data points. Results from the tests with the sharp cutter are clustered around the cutting point. Data points associated with the blunt cutters are scattered along the friction line, depending upon the depth of cut.

Using standard linear regression analysis, the slope of the friction line is given by μ = 0.60, and the intercept E_o = 9.6 MPa. The intrinsic specific energy is ε = 15.9 MPa, which shows a very good agreement with the uniaxial compressive strength q.

The estimated coefficient of friction μ = 0.60 is corresponding the friction angle $\varphi = 30.9^o$. Based on the experimental observations [4,5], the contact friction angle beneath the cutter wear flat is well correlated to the internal friction angle of the rock. This result could be explained by the presence of a boundary layer of loose grains and pulverized rock particles between the wear flat and the rock. An illustration of this phenomena is presented in Fig. 9.

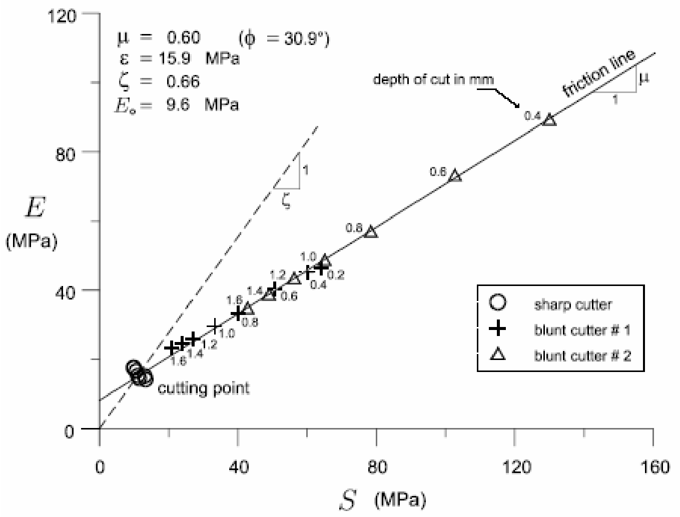


Figure 8 E-S diagram for the test results on Red Wildmoor sandstone performed at the University of Minnesota [2].

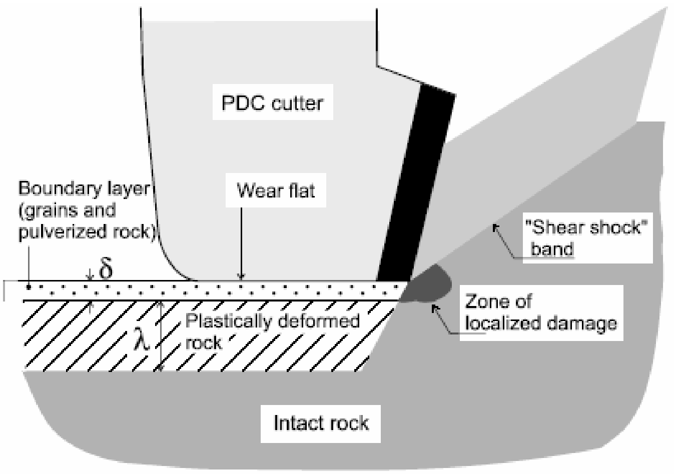


Figure 9 Conceptual model of boundary layer underneath a blunt cutter [2].

4.3 Repeatability of the test

The level of repeatability can be estimated by performing several tests on a rock specimen, keeping all the parameters constant, i.e., rake angle, depth of cut, velocity, and test length. The selected material to be tested should not be too abrasive so that there is no further wear flat area accompanying during the testing campaign. A series of 30 successive tests at a 0.2 mm depth of cut, was completed in a specimen of Indiana limestone (see Fig. 10). The mean recorded force components were remarkably close from one tests to another. The results indicate the high level of repeatability obtained from cutting tests performed with the Rock Strength Device.

4.4 Log of horizontal force

With the high precision in the force measurement and the high spatial resolution, it is possible to obtain the log of forces along the rock specimen from a cutting test with a sharp cutter (see Fig. 11). This force log can be translated into log of specific energy by a moving average procedure, using a window of 1.0 cm length scale resolution (see Fig. 12). This feature of the test allows the detection of precise location of heterogeneities or weak zones along the core specimen. Such measurement is very important as it reflects the actual material strength for each region rather than averaged strength property of the whole specimen..

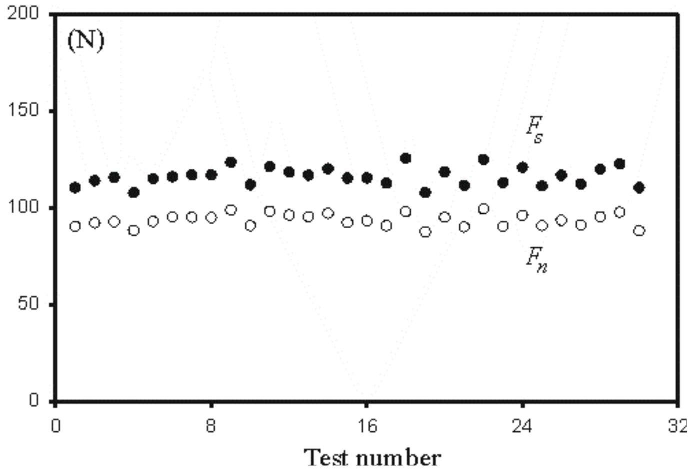


Figure 10 Repeatability of the averaged tangential and normal force components over a series of tests performed in Indiana Limestone.

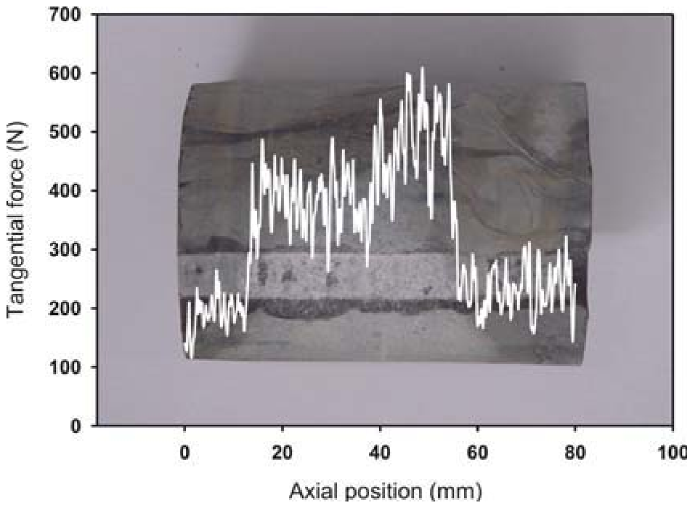


Figure 11 An example of the log of horizontal force recorded along the rock surface characterized by three distinct regions.

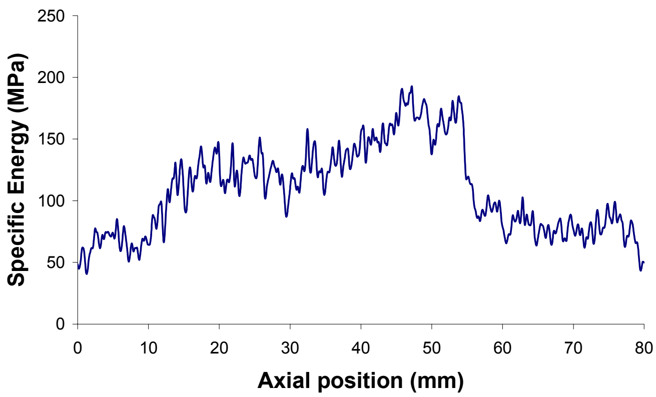


Figure 12 Log of intrinsic specific energy ε.

5. Conclusions

The rock cutting experiments with the Rock Strength Device have shown the possibility to extract the two strength parameters: the intrinsic specific energy (which can be related to the uniaxial compressive strength) and the friction coefficient (which is related to the internal friction angle). Values of both parameters can typically be obtained in a few minutes since the testing procedure only involves scratching the surface of a rock core. The test offers several advantages over the conventional rock strength test: it requires minimal sample preparation; the sample is only semi-destructive so the core remains relatively intact and can be used for other tests (such as permeability or porosity); and the test is reproducible. Finally, a very interesting outcome of the scratch test is its ability to create the log of specific energy along the core sample, which can be interpreted as log of strength. This aspect of the test results is indeed significant as there are currently no other methods available that provide a log of strength at such level of spatial resolution.

6. Acknowledgement

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