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AN ASSESSMENT OF THE CORRELATION BETWEEN THE STRENGTH AND CUTTABILITY OF ROCK

Joel Langham-Williams and Paul Hagan

ABSTRACT: Mechanical rock excavators are widely used in the mining and civil industries. Estimating the performance of these machines can be difficult as well as a costly and time-consuming process. A number of methods exist to assess the cuttability of a rock, ranging from laboratory based cutting tests through to more convenient empirical approaches. Recent research has focussed on developing empirical relationships between rock cutting performance and rock properties involving an indirect assessment of cuttability. This paper outlines the results of a study to determine the level of correlation between the strength and cuttability for rock that is commonly associated with coal-measure formations. A resonable correlation was found between the uniaxial compressive strength and cuttability performance of rock samples, the latter including specific energy, cutting force and normal forces.

INTRODUCTION

Cutting machines such as shearers, roadheaders and continuous miners are used extensively throughout the world in mining and civil operations for the excavation of rock. As theory relating to the mechanical excavation of rock has evolved over time, so too has the utilisation of these machines, often substituting traditional drill and blast methods resulting in an increase in safety and performance and a reduction in operating costs.

The method by which these rock cutting machines work is highly influenced by a number of factors (Neil, *et al.*, 1994). Machine design, machine power, intact rock properties and rock mass properties all play a pivotal role in determining the efficiency of the rock cutting process (Karakas, *et al.*, 2005). As Roxborough (1987) explained, the engineer has a choice over what size and type of machine can be used for a particular excavation, however the engineer, outside of changing the designs of the project cannot influence what rock formation will be encountered in completing a given excavation. As it is the rock mass that governs cuttability and not machine selection, an investigation into the rock mass properties and what affect they have on cuttability should consequently be the focus.

It has been well documented that a number of rock strength characteristics can adversely affect cutting performance (Rostami, 2011). When rock strength increases, there is a near linear response in cutting forces (Hood and Roxborough, 1992). Similarly it has been found that abrasivity of rock tends to increase with rock strength (Jacobs and Hagan, 2009), and laboratory testing has focussed on attempting to find which rock strength properties best describe this relationship. Specific energy is extensively used to evaluate rock cuttability (Tiryaki and Dikmen, 2006). It is a measure of the force required to excavate a unit volume of rock, and hence is a measure of the relative cuttability of a particular rock. McFeat-Smith and Fowell (1977), in their well-known study, correlated rock strength properties with specific energy and found cutting performance of cutting machines diminished with specific energy.

Recent studies have focussed on an array of properties in an effort to estimate rock cuttability, with strong correlations found between the uniaxial compressive strength of rock and specific energy for a number of different rock types (Speight, 1987). Material hardness, sonic velocity, Young's modulus and other rock properties that indirectly relate to rock strength, have been correlated with specific energy, with varying degrees of statistical significance. To date, the most reliable indicator of cuttability however has been based on the uniaxial compressive strength of rock.

From a mining perspective, further investigations to confirm the validity and correlation between rock strength parameters and cuttability would be useful in the estimation of machine performance. The ability to predict cutting performance from direct and indirect rock strength measurements would be of potential benefit to the industry, especially for mining operations interested in assessing the relative cuttability of rock. The purpose of this paper is to outline the results of a study to determine the level of

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correlation between rock-cutting performance and rock strength for 44 rock samples obtained from coal measures in Eastern Australia.

METHODOLOGY

The rock cuttability test procedure was originally developed at the University of Newcastle-upon-Tyne in the UK during the 1960's and 1970's. A rock cutting test facility was established at the University of New South Wales (UNSW) in the early 1980's as part of an industry sponsored project on machine mining of rock. Since then the *UNSW Machine Cuttability Research Facility* has been used in the assessment of the cuttability of wide range of rock types ranging from coal and salt through to haematite and sulphide ores from tunnelling and mining projects around Australia.

The facility is capable of testing blocks of rock samples and diamond-cored rock specimens. The main variables in the core cuttability procedure are indicated in Figure 1.

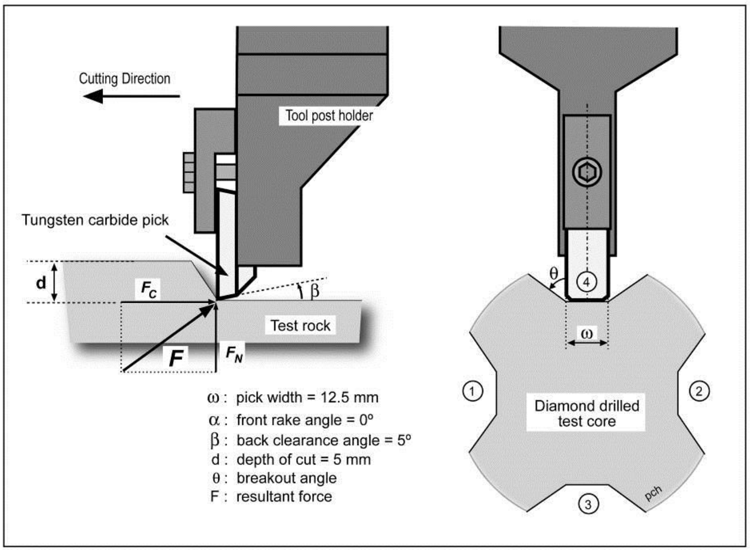

Figure 1 - Schematic of the main variables in the core cuttability test procedure (Hagan, 1990)

During each cutting test, a standard design tungsten carbide cutting tool is made to pass along the longitudinal axis of the core to a depth of 5 mm. Details of the cutting tool geometry are provided in Figure 1.

A tri-axial force dynamometer measures the transient forces acting on a tool during a cutting test. A data acquisition system records the forces at a sampling rate of 1000 readings per channel per second. The dynamometer resolves the resultant force into three orthogonal components of cutting (F_C), normal (F_N) and lateral forces (F_L). At the end of each test cut, measurements are made of the actual length of cut and mass of excavated rock.

After each test cut the core is rotated 90^o and another cut is made with up to four test replications made with a core as indicated by the circled numbers 1 through 4 in Figure 1.

The arrangement of equipment used in the cuttability test procedure is shown in Figure 2. The majority of the cored test specimens in this study had a diameter ranging between 54 and 59 mm and a length of approximately 200 mm.

On completion of each cutting test the following parameters are calculated.

- *Mean cutting force (F_C)* and *mean normal force (F_N)* (reported in units of kN) – the average resultant force acting on the cutting tool resolved into two orthogonal components.
- *Yield (Q)* (reported in units of m^3/km) – based on the mass of rock chippings and density of the rock sample.

- *Specific Energy* (*SE*) (reported in units of MJ/m^3) – the amount of energy expended during cutting per unit volume of rock excavated whereby the value of SE can be calculated using Equation (1).

$$SE\ (MJ/m^3) = \frac{Fc\ (kN)}{Q\ (m^3/km)} \quad (1)$$

Figure 2 - Cutting tool, dynamometer and data acquisition system used in the core cuttability test procedure at UNSW

Rock strength testing methodology

The rock strength tests were based on the ISRM Suggested Methods (Brown, 1981) and conducted using cored test specimens. The tests were conducted in an MTS machine as shown in Figure 3 at a constant displacement rate of 3 μm/s.

Figure 3 - The MTS machine setup for the compressive strength tests

Data analysis methodology

The first step in the process to determine whether there were statistically sound correlations between rock cutting performance parameters and rock strength was to plot a graph of the test result for each parameter, examine the residuals and standard deviation and, remove any significant outliers that might tend to skew the results. In circumstances where there was a question whether it was valid to remove a value from a data set, a conservative approach was followed with the data point included. After the outliers were removed, correlations were determined. Relationships demonstrating a *t*-value higher than that required for a 95% confidence interval, and also possessing a strong R^2 value, were considered statistically significant.

RESULTS

Rock samples

A total of 44 different rock samples were acquired for testing as shown in Table 1. It was found that the test specimens of many of the softer rock types disintegrated in most instances during testing as they were unable to withstand the high internal stresses induced during cutting but more important the relatively small diameter cores provided insufficient confinement to withstand the stresses. There was insufficient volume of sample available to cast it in cement or grout which is the preferred method used to provide confinement for soft rocks. A total of 23 rock samples were available for rock strength testing, with the range of strengths varying between 7 and 167 MPa.

Table 1 - A summary of the samples and material properties included in the analysis

Rock Type	No. of Samples	UCS (MPa)	Density (t/m^3)
Sandstone	30	21-167 (21)*	2.24 – 2.66
Shale	10	-	2.23 – 2.53
Coal	2	18 (1)*	1.26 – 1.41
Grout	1	7 (1)*	1.51
Conglomerate	1	-	2.44

* number in brackets indicates number of test samples

Specific energy and rock strength

One of the primary parameters of interest was changes in rock strength with specific energy. As the majority of the other rock properties are related in some manner to rock strength, and can be used as an indirect method to determine rock strength, it was consequently considered to be the most important relationship to identify.

The variation in specific energy with rock strength is shown in Figure 4. It should be noted that the graph includes all the test data with none of the outliers removed in order to show the extent of the variation. As the graph indicates the majority of results were clustered within the range of 50 to 80 MPa with two rocks tested at strengths of 100 to 125 MPa and a further three rock with strengths of less than 30 MPa. As mentioned many of the the softer rock samples tended to disintegrate during cutting while there was a limited number of higher strength rocks being at the upper end of the capacity of the rock cutting facility. Despite the scatter there is a trend evident with specific energy increasing with rock strength and this is despite the range of rock types tested. In this case a linear trend is shown.

Mean cutting force and rock strength

Figure 5 shows the variation in cutting force with rock strength. As specific energy is a function of both cutting force and yield, it would be expected that the trend in cutting force would mirror that of specific energy. The correlation coefficient (R^2) of 0.64 is on par with that observed for specific energy of 0.63 with the latter including errors in the measurement of the rock chippings. This result is consistent with the results of Roxborough (1987).

A number of cutting tests were also conducted at 2.5 mm, that is at half of the standard depth of cut. These tests results are also included in Figure 5 and show a better correlation coefficient of 0.71. Interestingly the value for the linear regression coefficient at 5 mm depth of cut of 0.022 which is nearly double that found for 2.5 mm. This too is consistent with the theory by Roxborough (1987) where force varies linearly with depth of cut.

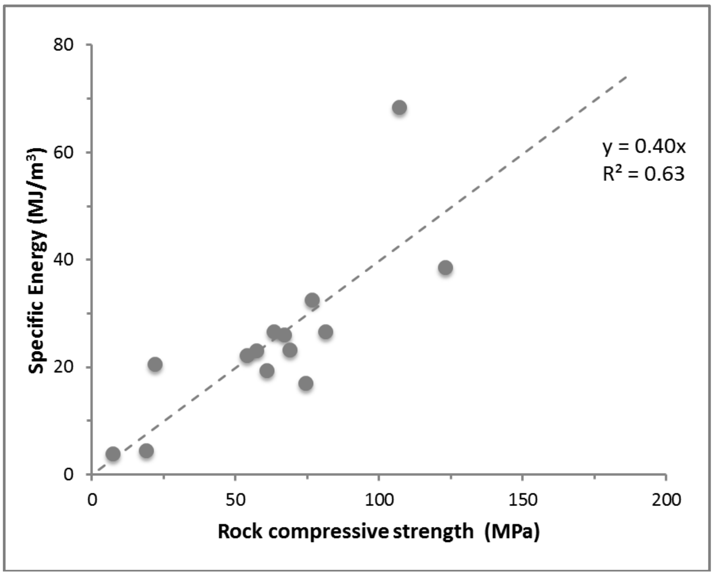

Figure 4 - Variation in specific energy with rock strength

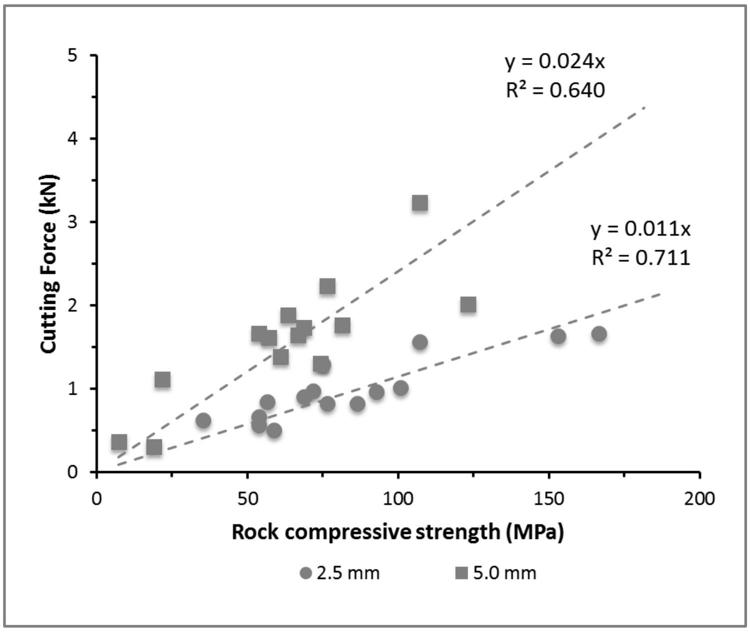

Figure 5 - Variation in cutting force with rock strength at two levels of cutting depth

Mean normal force and rock strength

Similar to the results for cutting force, it was found that normal force increased with rock strength as shown in Figure 6 with similar levels of correlation for both depths of cut. Based on the ratio of the gradients, for any value of rock strength, the normal force is approximately 21% higher than cutting force in this cutting configuration and for this cutting tool. Generally it is found that as the tool wears and back clearance angle reduces, the ratio of forces quickly reduces and then inverses such that the cutting force becomes much greater than normal force Roxborough (1987).

Analysis of correlations and significance

As mentioned, Figures 4, 5 and 6 include the test results for all samples but despite this, reasonable correlations were found. The purpose of this exercise was to demonstrate that baseline relationships were present prior to any statistical analyses and to observe the correlations of the data set as a whole.

After removing the outliers in accordance with the process detailed earlier, the intention was to provide reliable models to describe the observed trends.

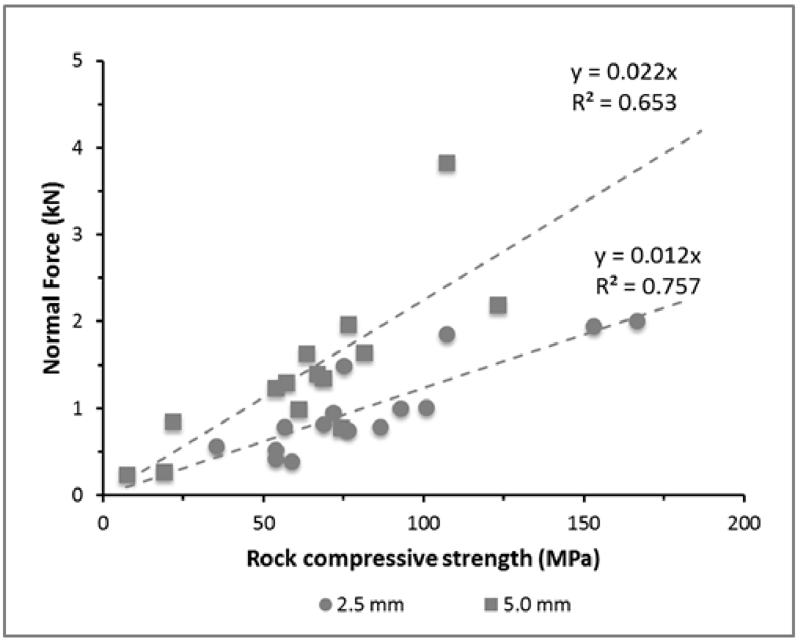

Figure 6 - Variation in normal force with rock strength at two levels of cutting depth

Tables 2 and 3 show the results of a linear regression analysis for the 2.5 mm and 5 mm depth of cut tests respectively. Two outliers were removed from the original 2.5 mm data set with 13 data points remaining for calculation of the regression values between rock strength and cuttability parameters. In the case of the 5 mm tests, there were a total of ten values in the data set. As a result, the correlation coefficients were significantly improved for the 2.5 mm data set and marginally improved for the 5 mm data set.

Table 2 - Results of linear regression analysis against rock strength with outliers removed for the 2.5 mm depth of cut tests

cutting parameter	linear regression model	r^2	pairs	t-value
specific energy	y = 0.40 x	0.93	15	13.5
cutting force	y = 0.011 x	0.85	13	7.86
normal force	y = 0.013 x	0.75	13	5.70

Table 3 - Results of linear regression analysis against rock strength with outliers removed for the 5 mm depth of cut tests

cutting parameter	linear regression model	r^2	pairs	t-value
specific energy	y = 0.36 x	0.85	10	6.85
cutting force	y = 0.027 x	0.78	9	5.01
normal force	y = 0.021 x	0.81	10	5.88

The values from the regression analysis are considered to be in agreement with previous studies. For example Roxborough (1987) found a linear relationship between specific energy and rock strength for Bunter sandstone in the UK, a rock that is said to have highly consistent material properties. It was in the form as shown in Equation (2), where c_1 and c_2 represent values for the gradient and *y*-intercept respectively.

$$SE = c_1 \cdot UCS + c_2 \quad (2)$$

Roxborough stated the value for c_1 in Bunter sandstone was 0.25 which is in good agreement with the values found in this study of 0.36 considering it includes a range of rock types. Hence the resulting correlation coefficients are reasonable and that they indicate statistical significance at the 95% confidence interval level.

CONCLUSIONS

Mechanical rock cutting has become a viable means of excavation and in softer rock types is superior compared to traditional drill and blast methods. This has come about from improvements in machine design as well as better understanding of the underlying rock cutting principles.

The results presented in this paper found there was a reasonable level of correlation between strength and cutting parameters for a range of rock types associated with coal measures in Australia. The cutting parameters were determined using the Newcastle-upon-Tyne rock cuttability index text.

It is recommended further studies be undertaken to assess the effect of other rock properties on cuttability and expand the dataset for different rock types thereby increasing the confidence that can be placed in the collected results.

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