A Study on the Effect of Moisture Content on Rock Cutting Performance

J. Mammen
University of New South Wales

S. Saydam
University of New South Wales

P. Hagan
University of New South Wales

A STUDY ON THE EFFECT OF MOISTURE CONTENT ON ROCK CUTTING PERFORMANCE

Joseph Mammen[1], Serkan Saydam[1] and Paul Hagan[1]

ABSTRACT: Road headers and other cutting machines are often used for excavation in the mining and tunnelling industries. During excavation, changes in the properties of the rock mass can alter which adversely impact machine performance. Also it has also been found that an estimation of machine performance differs from that actually achieved in the field. It has been postulated that one reason for this variation in performance could be due to a rock's moisture content.

This paper outlines the results of a study that examined the impact on rock cutting performance of changes in the moisture content of sandstone. The study found both cutting and normal forces decreased with moisture content by up to 40 and 49% respectively when cutting a saturated sample compared to the dry rock sample. Reductions were also found in specific energy, cutter pick wear and some other rock properties.

INTRODUCTION

Research into machine mining as a means of rock excavation has been on-going particularly since the 1950's when there was intense interest in mechanisation to improve productivity. From that time a number of theories have been developed to estimate the magnitude of cutting force and other cutting parameters in the machine excavation of rock (Nishimatsu, 1993). In addition many empirical studies have quantified the effect of changes in tool and operational variables on cutting performance (Hood and Roxborough, 1992). Roxborough (1987) noted that in many cases the force required to cut rock is primarily governed by its strength. In some instances consideration has also been given to other properties of the rock mass that may influence cutting performance. One aspect that has been given little attention is the moisture content of a rock. It has been postulated that the presence of water can alter a rock's behaviour particularly with respect to the energy necessary to fracture the rock and crack propagation though little has been published on its effect on rock cutting performance.

A study was undertaken to determine what changes if any might occur in rock cutting performance with moisture content. The study involved testing sandstone in the dry and saturated states and at various levels of moisture content in between, measuring changes in cutting forces, energy and material properties.

PREVIOUS STUDIES

Rock properties

Various studies have noted the presence of water in rock can alter the properties and behaviour of a rock mass. For example some rock can be reactive to water especially if clay is present as it will soften the material loosening its structure and increasing its deformability leading to a reduction in the overall strength of the rock mass (Brady and Brown, 2004). The presence of water in a rock mass can also reduce the shear resistance of joint sets dependant on the level of pore water pressure (Budhu, 2000).

In terms of its mechanical strength, Roxborough (1987) stated that "the mechanical strength of a rock commonly reduces as its moisture content increases." Vasarhelyi and Van (2006) found "water content is one of the most important factors influencing rock strength…the strength decrease is remarkable after only 1% water saturation."

[1] *School of Mining Engineering, UNSW,SYDNEY*

Cutting mechanisms

Most pick-type cutting tools fracture rock by inducing a tensile failure. As the tensile strength of rock is approximately one-tenth of its compressive strength, picks are relatively effective in mechanical rock breakage albeit they limited to use in soft rock types such as those normally associated with coal formations including coals, shales and sandstones. Picks and other cutting tools are used as a means of funnelling energy from the cutting machine and focusing it to fracture rock (Fowell, 1993). As the power of cutting machines is limited, any change in the amount of energy necessary to fracture rock will translate to changes in cutting rates.

The objective of this study was to measure changes in cutting performance that might be brought about by changes in the moisture content of rock. In particular, sandstone samples at various levels of moisture content were tested with respect to changes in cutting force, normal force, specific energy, yield, pick wear rate, Cerchar Abrasivity Index (CAI) value, compressive strength and Young's Modulus.

TESTING METHOD

Rock sample preparation

In this study, rock test samples were diamond cored from a single block of Mt White Sandstone, the characteristics of which as contained in Table 1. Sandstone was chosen due to it being highly porous and permeable and hence being able to absorb water more readily than other rock types. It is also a rock frequently excavated using pick-type rock cutting machines.

Test samples with a diameter of 57 mm (large diameter test core sample) were obtained for rock cutting tests and a diameter of 43 mm (small diameter test core sample) for the rock strength tests.

Table 1 - Characteristics of Mt White Sandstone

Geological Name	Argillaceous quartz sandstone
Geological Age	Triassic
Petrologic Description	Medium-grained quartz sandstone with a predominantly argillaceous matrix.
Bulk Density	2.27 tonnes/m^3
Absorption by Weight	4.4%
Modulus of Rupture	8.9 MPa (dry) and 2.5 MPa (wet)
UCS	57 MPa (dry) and 22 MPa (wet)

Moisture content

As the purpose of the study was to measure changes in cutting performance with moisture content, it was important to minimise the impact of changes between different test samples. Hence the moisture content was altered in a single rock type. Two techniques were investigated to achieve a desired level of moisture content in a test sample. Moisture content was determined in accordance with the International Society for Rock Mechanics (ISRM, 1981).

The first technique involved measuring the mass of cores after they had been placed in a drying oven for fourteen days. This established the mass of the "dry" core samples. Ten cores in all were weighted; five each of the small and large test core samples. At one minute intervals a sample was placed in water. After a period of time, a sample was removed and weighted. Soaking times varied between 5 minutes and 30 minutes at 5 minute intervals then at 40, 60, 90, 120, 150, 180, 660, 960 and 1440 minutes.

Results of the soaking testing are summarised in Figure 1. The graph shows measurements for each of the individual test samples and the average of the two sample sizes. The graph indicates different rates of water uptake between the two sample sizes as would be expected due to differences in volume and hence length of the migration path of water. Both sample sizes achieved the equivalent of nearly 50% of the saturated water level within the first minutes of soaking. Thereafter the rate decreased with time with nearly 90% of the saturated water content being achieved within 120 minutes for larger sample and 40 minutes for the smaller sample.

The second technique involved placing fully saturated samples in a drying oven and weighting the mass at predetermined intervals. Results of drying test are shown in Figure 2.

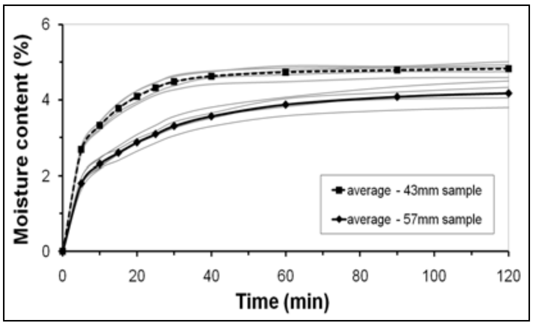

Figure 1 - Variation in moisture content with time in soaking two size core samples

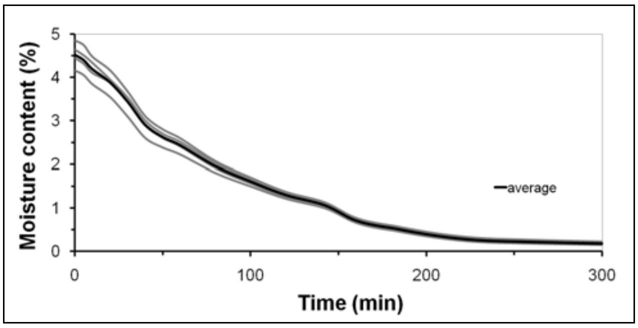

Figure 2 - Variation in moisture content with timeon drying of a 57 mm core sample

The first technique proved the most practical as the soaking times to achieve the different levels of water content were of short duration and hence more controllable. The various levels of moisture content selected for the study are indicated in Figure 3 and are summarised in Table 2.

Table 2 - Targeted and measured moisture content for test samples

moisture content		*soak time*
target	*as measured*	
0.5%	1.15%	1.5
1.5%	1.71%	4 min
2.5%	2.51%	13 min
3.5%	3.28%	35 min

Measurement of the five large samples found after being left for several weeks at room conditions in the laboratory they retained some moisture. The average moisture content of the samples in the "air-dried" condition was 0.22%.

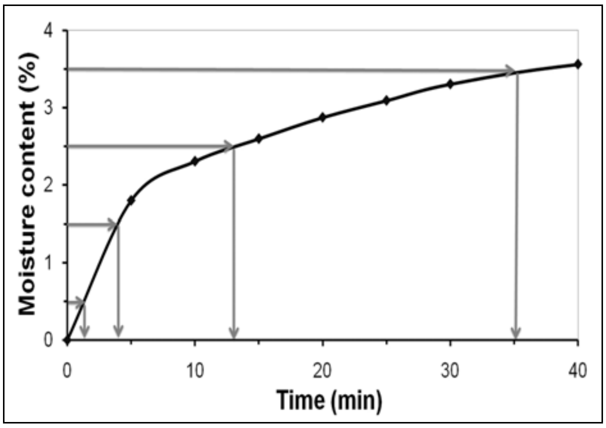

Figure 3 - Selected moisture content for testing and corresponding required soaking time

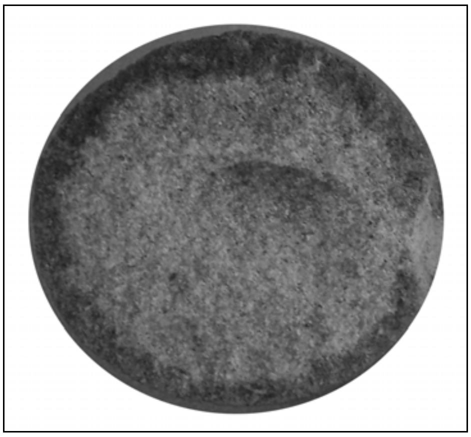

Figure 4 - Extent of water absorption indicated by a discoloured ring around the edge of rock test sample

Uneven diffusion

It was observed during these tests that the samples appeared to be drying unevenly and that they become hard and brittle. This raised the issue about the nature of the moisture distribution within the samples.

A further test was undertaken to ascertain the nature of the moisture profile across the cross-section of the samples. This was done by submerging samples in water containing a coloured dye. After being submerged for several minutes the sample was removed. On breaking the sample, the cross-section revealed water had migrated inwards from the outer surface with the dye forming a ring pattern as illustrated in Figure 4. This indicated that while the outer part of the core was fully saturated, the inner core remained dry. Hence the moisture content in the rock sample was uneven.

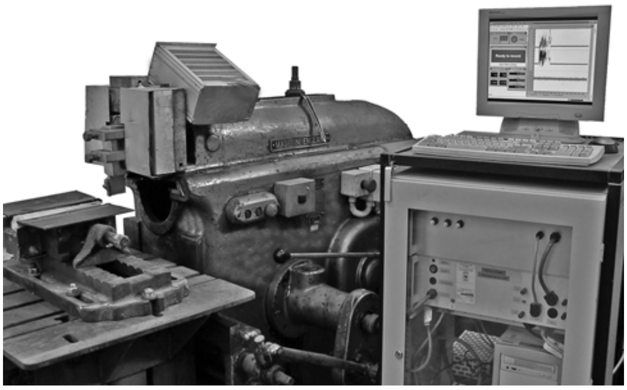

Figure 5 - Linear rock cutting machine

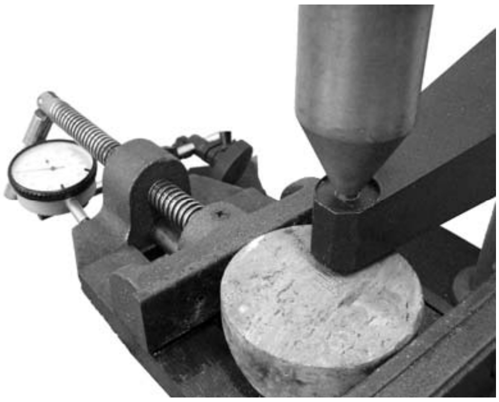

Figure 6 - Cerchar test apparatus

In order to promote more even distribution of the water absorbed by a sample, each sample to be used in the cutting tests would after being removed from water at the pre-determined time indicated in Table 2 be wrapped in plastic and left for at least 72 hours prior to testing. This would allow time for the moisture to diffuse evenly throughout the sample.

Test apparatus

The assessment of changes in cutting performance was undertaken using equipment in the Machine Cuttability Test Facility at UNSW. A modified linear shaping machine with a tri-axial dynamometer as shown in Figure 5 was used to measure the forces and energy of cutting. An Instron test machine with a 500 kN capacity was used for the compression strength tests.

The Cerchar Abrasivity Index test was performed with standard Cerchar testing apparatus as shown in Figure 6.

RESULTS

Material properties changes in the strength of the samples at various levels of moisture content were undertaken with the small samples. Three levels of moisture content were examined, these being:

- oven dried condition, 0% moisture content;
- "air-dried" condition, 0.2% moisture content; and
- saturated condition, 5.2% moisture content.

Results of testing at the three levels are summarised in Table 3.

The results indicate a significant reduction in the compressive strength of the rock with the saturated sample of 68%. It was found a significant reduction in strength of 63% occurred even at the lowest level of moisture content compared to oven dried test rock sample. This finding is in line with that observed by Vasarhelyi and Van (2006).

Table 3 - Summary of effect of moisture content on material properties

moisture content	*UCS (MPa)*	*strength reduction*	*Young's Modulus (GPa)*
0.0%	60.3	-	6.3
0.2%	22.1	63%	4.1
5.2%	19.4	68%	3.2

Cutting performance

A summary of the effect of changes in moisture content on rock cutting performance is summarised in Table 4.

For each of the "dry" results (0.0%) and the "saturated" results (4.6%), the values stated in Table 4 represent an average of four replications of linear cutting tests undertaken in each of two test samples; that is eight replications in all for each of the dry and saturated samples. This large number of replications was undertaken so as to increase confidence in the results at both extremes in moisture content. In the case of all other results, the values represent the average of four linear cutting tests made with each sample.

In terms of cutting force and normal force, there were significant reductions between the dry and saturated samples of approximately 40% and 49% respectively for the cutting and normal forces.

Table 4 - Effect of moisture content on cutting performance

test sample condition	*moisture content*	*Force (kN)*		*Yield (m^3/km)*	*SE[1] (MJ/m^3)*	*CAI[2]*	*Wear (mg/m)*
		Cutting	*Normal*				
dry	0.0%	1.24	0.89	0.0713	17.3	2.7	7.1
	0.2%	0.88	0.57	0.0463	18.1	-	1.5
	1.2%	0.91	0.50	0.0656	13.6	2.6	-
	1.7%	0.77	0.41	0.0671	11.3	2.5	0.2
	2.5%	0.89	0.66	0.0695	12.9	2.6	4.5
	3.3%	0.74	0.45	0.0719	9.0	1.5	0.8
saturated	4.6%	0.74	0.45	0.0691	10.8	2.4	1.8

Note: 1. Specific Energy 2. Cerchar Abrasivity Index value

As indicated in Figure 7, the greatest reductions in force were registered at the smallest level of moisture content of 0.2% level which was when the rock was in the air-dried or ambient conditions. At this level of moisture content the reductions were 29% and 36% respectively for cutting and normal forces which represent nearly 72% of the total force reductions. Consequentially by the time the sample contains even the smallest amount of moisture, there is a step change with most of the gains in terms of a reduction in force having been achieved. Any further increase in moisture content did not result in any further significant perceived changes given the scatter in test results though on average there were further reductions of 11% and 14% respectively in cutting and normal force.

The results indicate no further step changes as the sample becomes fully saturated once the sample has absorbed even the smallest amount of water. In summary, given the range of moisture content examined in this study it would seem that it is not the quantum of water that is not important but whether the rock contains any water at all.

In terms of the yield of material from rock cutting, the results indicate moisture content had little impact within the bounds of experimental error. There was little significant difference in yield between the dry and saturated samples.

In terms of Specific Energy, which is a function of cutting force and yield, since yield was found to have no effect then any variation in Specific Energy with moisture content should mimic that of cutting force. This was found to be the case as shown in Figure 8. The difference in Specific Energy between the dry and saturated rocks was 38% which is similar to that determined for cutting force.

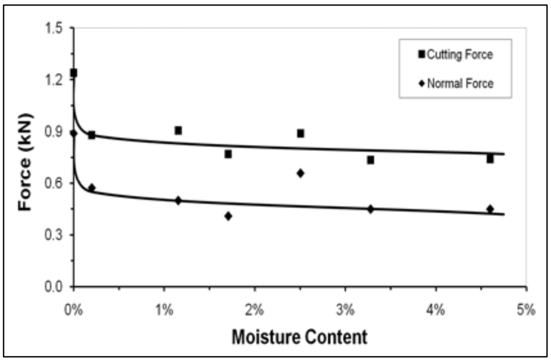

Figure 7 - Effect of moisture content on forces in rock cutting

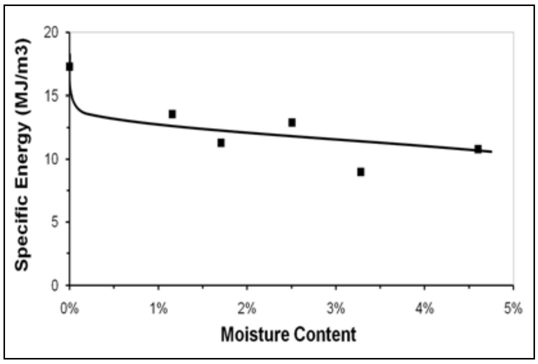

Figure 8 - Effect of moisture content on Specific Energy of rock cutting

In terms of CAI, there was a slight reduction of 13% between the dry and saturated samples. However unlike the nature of reduction in forces, there was no evidence of any major step change, CAI seemed to decrease steadily with moisture content.

Finally with respect to impact wear as a result of rock cutting, there was again a step change although on a much greater scale. Wear of the tool in the saturated sample was about 20% of that found in cutting the dry sample. As shown in Figure 9, similar reductions were observed in all cases of the sample containing water. It should be cautioned though that in the case of wear, only one measurement was determined for each sample as it represents the cumulative wear from all four replications of cutting tests.

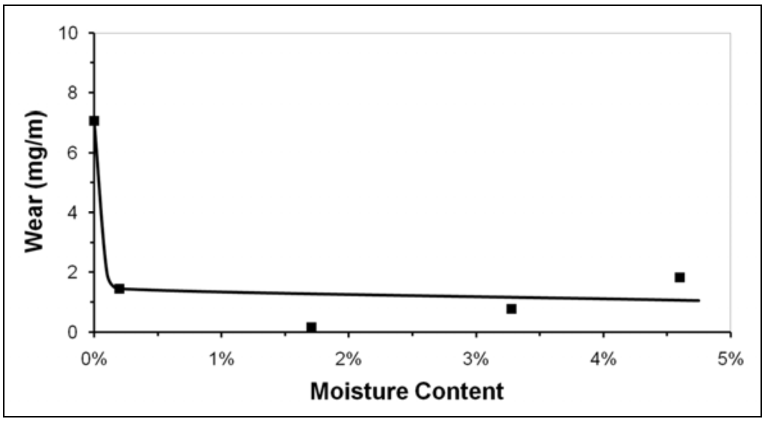

Figure 9 - Effect of moisture content on wear of the cutting tool

CONCLUSIONS

In conclusion, it was observed that there was a significant decrease in most of the rock cutting performance parameters with moisture content. The difference in performance was greatest when comparing cutting a dry sample to a saturated sample. The test samples used in the study were 57 mm sandstone cores.

Reductions of up to 40% and 49% were found for cutting and normal forces, 38% for Specific Energy, 80% for impact wear of the cutting tool and, 68% in compressive strength. There was little evidence of any significant change in rock abrasiveness as measured by CAI and, in rock yield.

Significantly in most cases the magnitude of the reduction in performance parameters was greatest with only the slightest addition of water to the rock. The inherent moisture content of the sandstone test samples if left at ambient conditions was found to be 0.22%; as opposed to a saturated sample containing 4.6 to 5.2% water. Even at the low moisture content of 0.22%, the reduction in both cutting and normal forces was nearly 72% of the total potential reduction in forces.

Whether there is a causal relation between the reduction observed in compressive strength and in the rock cutting performance parameters was determined in this study. A common mechanism that may account for these reductions may be found in fracture mechanics and the part that water plays in modifying the characteristics of crack propagation.

The results indicate that it is not so much that the rock needs to be saturated but that any minor amount of water in the rock is sufficient to reduce the levels of the various cutting performance parameters.

Interestingly this would suggest that as rock in its natural state is likely to contain some moisture then there is unlikely to be any significant change in performance as a cutting machine excavates rock. Importantly also there is unlikely to be any benefit from introducing water to the cutting face for the purpose of reducing performance parameters.

An exception to this general rule might be if rock excavation takes place in or adjacent to high temperature rock resulting in the *in situ* moisture content of the rock being negligible. In this case there would benefit from the addition of water at the face that would lead to a reduction in cutting forces and the other performances parameters.

Amongst some of the many questions that arise from this study, the following merit follow-up work.

- Can the results be duplicated in different sandstones and other rock types? What effect does permeability and porosity have on the magnitude of reduction in performance parameters?
- Can the performance benefits be repeated in the same rock after more test replications?
- What is the effect on the performance parameters with rock at very low moisture content?
- Are there any differences between free water on the rock surface and water within the rock matrix? This would impact on whether water sprays at the face would be sufficient to gain any benefit or whether water has to be injected into the rock mass.
- Are the test results sensitive to the method of achieving a dried test sample?
- How sensitive are the test results to the testing environment and what effect do environmental factors such as temperature and pore water pressure have on the results?

ACKNOWLEDGEMENTS

Acknowledgement is given to Victor Lau with whom there was some collaboration in determining the material properties of the sandstone samples used in this study.

REFERENCES

Brady, B H G, and Brown, E T, 2004. *Rock Mechanics for Underground Mining*, 3rd ed (Kluwer Academic Publishers).

Budhu, M, 2000. *Soil Mechanics and Foundations*, (John Wiley and Sons).

Fowell, R J, 1993. The mechanics of rock cutting, in *Comprehensive Rock Engineering* (ed: J A Hudson), 4(7):155-176.

Hood, M, and Roxborough, F F, 1992. Rock breakage: mechanical, in *SME Mining Engineering Handbook,* (ed: H L Hartman), 1(9.1):680-721 (SME: Littleton).

ISRM, 1981. Suggested methods for determining water content, porosity, density, absorption and related properties, in *Rock Characterization Testing and Monitoring: ISRM Suggested Methods* (ed: E T Brown), pp 81 -88 (Pergamon Press).

Nishimatsu, Y, 1993. Theories of rock cutting, in *Comprehensive Rock Engineering* (ed: J A Hudson), 1(26):647-662.

Roxborough, F F, 1987. The role of some basic rock properties in assessing cuttability, in *Seminar on Tunnels: Wholly Engineered Structures,* (The Institute of Engineers Australia / A.F.C.C.).

Vasarheyli, B, and Van, P, 2006. Influence of water content on strength of rock, *Engineering Geology*, 84(1-2):70-74 (Elsevier).