2015

Changes in Cutter Performance with Tool Wear

Esmat Sarwary
University of New South Wales

Paul Hagan
University of New South Wales

Publication Details

Esmat Sarwary and Paul Hagan, Changes in Cutter Performance with Tool Wear, 15th Coal Operators' Conference, University of Wollongong, The Australasian Institute of Mining and Metallurgy and Mine Managers Association of Australia, 2015, 283-290.

CHANGES IN CUTTER PERFORMANCE WITH TOOL WEAR

Esmat Sarwary and Paul Hagan

ABSTRACT: Mechanical excavators such as shearers, road-headers, and continuous miners that utilise conical picks are increasingly being used in civil construction and mining. Their application has broadened to include stronger and more abrasive rock types that result in higher wear rates and considerably shorter life span. This results in a bottleneck resulting in lower utilization and lower productivity. An understanding of the factors that cause high wear rates is crucial in the selection and design of an excavator, selection of cutter tools, and definition of optimum cutting geometry. All these parameters can contribute to major cost savings for companies using mechanical excavators. This paper explores how tool wear affects the cutting performance of a point attack pick with changes in the depth of cut. Linear rock cutting tests were performed using samples of Gosford Sandstone and Gambier Limestone at a constant speed of 0.06 m/s and pick attack angle of 55°. The rock samples were cut at depths ranging between 5 mm and 20 mm using a standard conical pick having tip angles of 70°, 90° 100° and 110°. The cutting forces and normal forces, specific energy, and yield were correlated against depth of cut. The results reveal that for each rock type, the specific energy increases at a decreasing rate with pick wear, confirming cutting efficiency decreases with increasing pick wear whereby a slight increase in pick wear resulted in a significant reduction in cutting efficiency. There was a near two to threefold decrease in efficiency between a sharp pick and worn out pick. The cutting and normal forces were also found to increase at a decreasing rate with pick wear.

INTRODUCTION

Most mechanical rock cutting machines in coal mining use tungsten-carbide conical picks, mounted on a cutting head to fracture the rock *in situ* prior to its removal and further processing (Lloyd, 1985). As theory relating to the mechanical excavation of rock has emerged and evolved over time, so too has the utilisation of these machines, often replacing traditional drill and blast methods, resulting in an increase in safety performance and a reduction in operating cost. As a consequence, laboratory-scale rock cutting facilities such as the Portable Linear Rock Cutting Machine (PLCM) in the Machine Cuttability Research (MCR) facility within the School of Mining Engineering at UNSW Australia are able to provide data for machine selection, design, and performance prediction for a given rock formation (Balci and Bilgin, 2006; Jacobs and Hagan, 2007; Langham-Williams and Hagan, 2014).

Normal force measured by the PLCM can be used to estimate the effective mass and thrust required of an excavator. This is a crucial parameter as it provides an insight into the range of necessary forces provided by the excavator in order for the cutter to effectively penetrate the rock and maintain the cutting depth. Furthermore, the cutting force measured by the PLCM is crucial to evaluating the energy requirements for excavating the rock. Cutting force is used to calculate the specific energy requirements, defined as the amount of energy required in excavating a unit volume of rock. Specific energy is a direct measure of cutting efficiency. Lower specific energy correlates to more material being produced by a given machine; therefore, lower specific energy indicates an increase in cutting efficiency (Roxborough, 2009).

Despite picks being typically constructed from tungsten carbide due to its hardness, thermal resistance, high compressive strength and high impact resistance; they are still susceptible to wear (Hudson *et al.*, 1993). There are several mechanics of wear, such as frictional wear, abrasive wear, microfracturing, thermal fatigue, impact damage, and chemical erosion, all of which contribute to tool wear. The consequence of wear on the cutting is familiar in the mining and tunnelling industry, since the performance of the machine deteriorates significantly as the tools become blunt. The mining output will fall, repairable dust production will rise, and the risk of incendive sparking increases (Roxborough, 2009).

PROJECT OBJECTIVES

The objective of this project was to determine how tool wear of a point attack pick impacts on cutting performance in two different rock types. Cutting tests were undertaken in a combination of a pick of differing tool angles and at differing depths of cut. Changes in cutting performance were assessed in

School of Mining Engineering, UNSW Australia, Sydney, NSW 2052, Australia, E-mail:p.hagan@unsw.edu.au

terms of changes in:

- Cutting force, F_C
- Normal force, F_N
- Specific Energy, *SE*, and
- Yield, *Q*

METHODOLOGY

The research involved tests conducted using the newly installed the newly commissioned PLCM as shown in Figure 1. The linear rock cutting tests were performed using blocks of Gosford Sandstone and Gambier Limestone at a constant cutting speed of 0.06 m/s and attack angle of 55°. Tests were undertaken at depths ranging from 5 mm to 20 mm with conical picks at four different pick angles. A data acquisition system was used to record the cutter forces measured by a triaxial dynamometer during linear rock cutting tests.

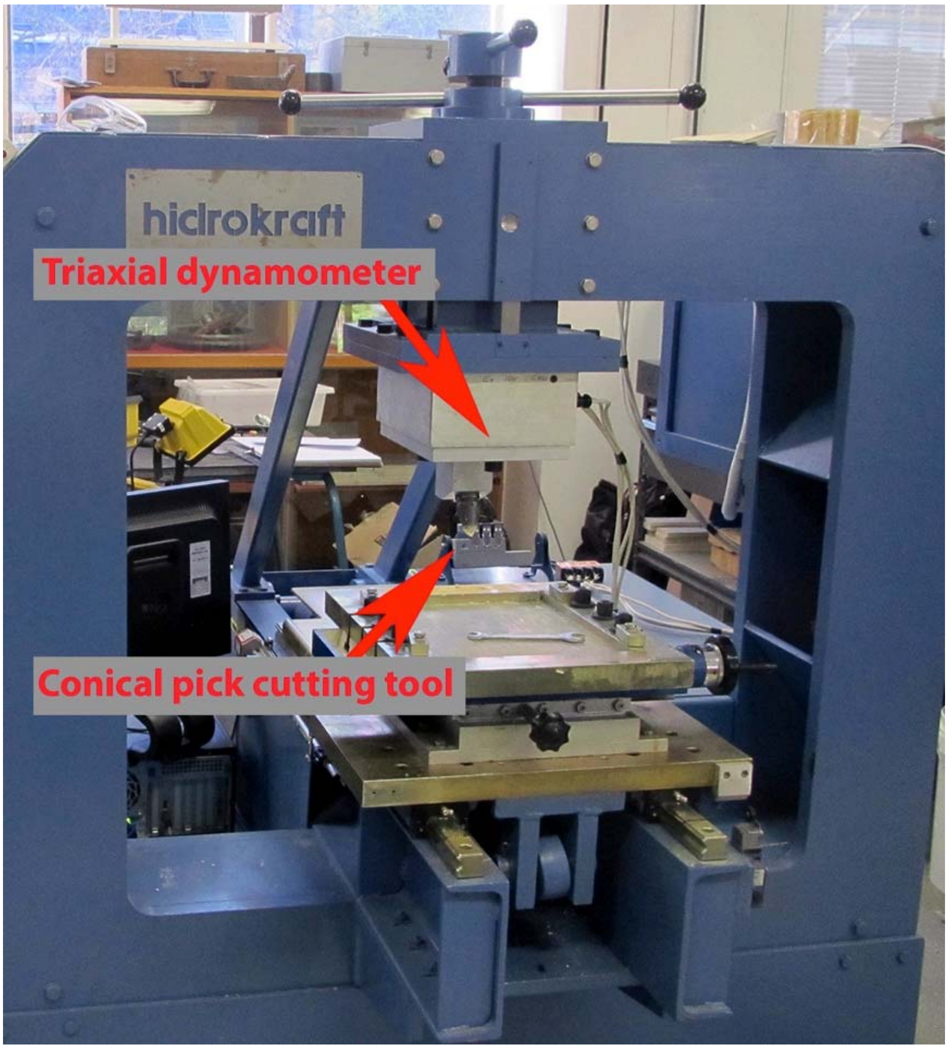

Figure 1: Portable Rock Cutting Machine in the Machine Cuttability Research facility at UNSW

Sample preparation

Blocks of test samples having dimensions of 260 × 180 × 100 mm were set in plaster within a small steel box frame to provide the necessary confinement during testing, as depicted in Figure 2. The preparation of the plaster involved mixing with water at a ratio of 5:3.25 (that is 5 kg of powder to 3.25 kg of water).

The samples were cured for at least 24 hrs prior to any testing to ensure the plaster had hardened sufficiently.

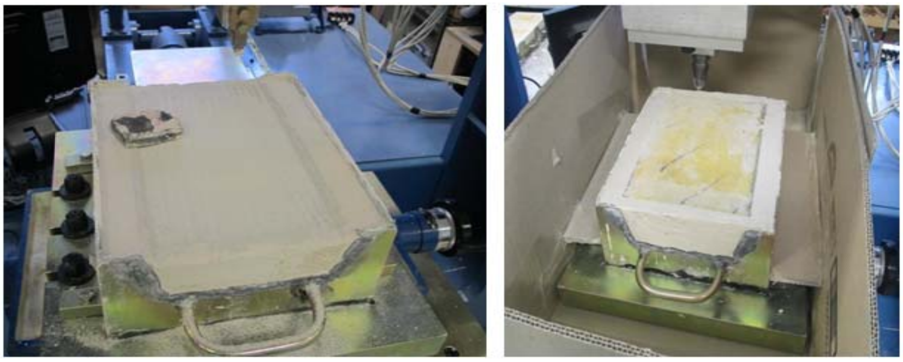

Figure 2: Method of securing the blocks of rock samples for cutting tests

Preparation of test picks

New Sandvik conical picks with short-tailed 25 mm shank were machined to provide four different pick tip angles of 70°, 90° 100° and 110° representing a pick at various states of wear. An illustration of the pick used in the tests is shown in Figure 3 with dimensions provided in Table 1.

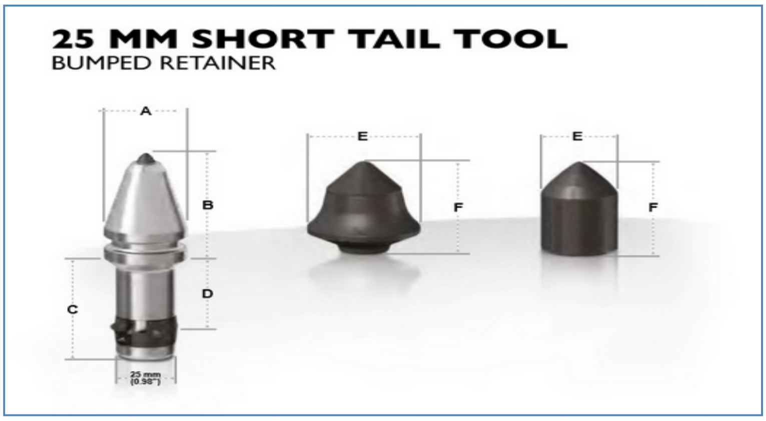

Figure 3: The short tail pick used in the tests (Sandvik Mining, 2013)

Table 1: Specifications of 25 mm Short Tail Pick

Product Code	*Dimensions (mm)*					
	A	*B*	*C*	*D*	*E*	*F*
P9QA-2560-3562	35	58	58	42	12	19

(Source: Sandvik Mining, 2013)

The pick holder system was designed with a fixed insert as shown in Figure 4. The design allowed the pick to be mounted at an attack angle of 55°. According to Mostafavi *et al.,* (2006) this is within the range of angles when mounting picks on continuous miners, road-headers, and shearers.

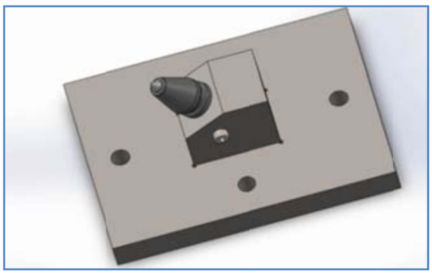

Figure 4: Design of conical tool holding unit that is mounted directly on the dynamometer

Data analysis

The cutting (F_C) and normal (F_N), forces were measured using the integrated triaxial dynamometer. The length of the cut was measured using a Linear Variable Displacement Transducer (LVDT). The LabView software package was used for real time monitoring and recording of the forces and displacement.

The force values in conjunction with mass of collected debris were used to calculate the specific energy and yield based on the following formulas:

$$Q = (m / \rho) / l \quad (1)$$

where:
Q: yield (m^3/km)
ρ: density of the rock (kg/m^3)
m: weight of the debris collected (kg)
l: length of cut (km)

$$SE = Fc / Q \quad (2)$$

where:
SE: Specific energy (MJ/m^3),
Fc = cutting force (kN)

Strength and density of test samples

Compressive strength tests were conducted on specimens of Gambier Limestone, in accordance with the ISRM suggested method for uniaxial compressive strength determination (Brown, 1981).

The testing procedure involved six limestone rock specimens with a diameter and length of 52 mm and 104 mm respectively using an MTS universal test machine. The tests were conducted at a constant displacement rate of 0.003 mm/sec. The strength of the Gosford Sandstone was earlier determined by Masoumi (2013).

Nine core samples were weighed and the diameter and length of each sample recorded. Sufian and Russell (cited in Masoumi, 2013) conducted an X-ray CT scan on Gosford Sandstone. By using a resolution of 5 *μ*m they calculated the porosity to be approximately 18.5% with density of 2.5 × 103 kg/m3. Table 2 summaries the strength and density of the two of rock types. As shown in Table 2, there is over a ten-fold difference in strength and near doubling in rock density between the sandstone and limestone samples.

Table 2: Strength and density of Gosford Sandstone and Gambier Limestone samples

Rock type	*UCS (MPa)*	*Density (t/m^3)*
Gosford Sandstone	52.3	2.5
Gambier Limestone	5.0	1.4

RESULTS

A series of cutting tests were conducted in the sandstone and limestone with typical results as shown in Figure 5.

The results of the cutting and normal forces, specific energy, and yield were correlated against picks at different tool angles representing various states of wear. Figures 6 and 7 show the effects of pick wear on cutting and normal force for the two rock types. The trends in each of the graphs indicate cutting and normal force increase with pick wear. The magnitude of forces is much greater for Gosford Sandstone compared to Gambier Limestone, nearly three times greater for cutting force and six times greater for normal force. This is in line with the sandstone's much greater strength and density. It is also evident that the magnitude of cutting force for both types of rock is greater than the magnitude of normal force. Cutting force is also approximately 1.6 times greater than the normal force for sandstone and 2.8 times greater for limestone.

Figure 5: Cutting with a pick tip angle of 70˚ at 15mm depth of cut in Gosford Sandstone (left) and Gambier Limestone (right)

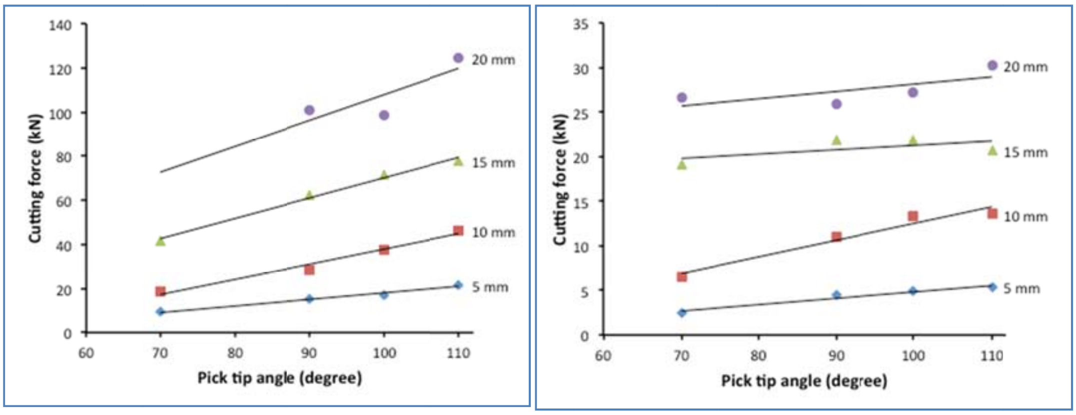

Figure 6: Effect of wear on cutting force at varying depths of cut for Gosford Sandstone (left) and Gambier Limestone (right)

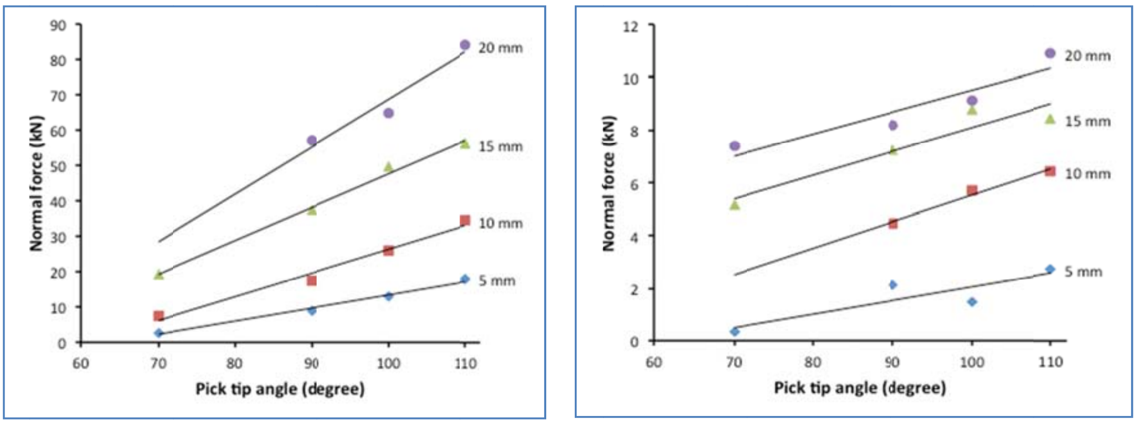

Figure 7: Effect of wear on normal force at varying depths of cut for Gosford Sandstone (left) and Gambier Limestone (right)

Table 3 shows the variation in cutting force and normal force with tool angle at increasing depths of cut in the two rock samples. In the case of sandstone, the gradient increases with depth of cut indicating the impact of wear increases with depth of cut. The gradients are of similar magnitude level for cutting force and normal force.

The situation is not as consistent for the softer limestone whereby there is little significant change in gradient with depth and the values for cutting and normal force are again comparable. Earlier work has found that increasing wear usually has a much more deleterious effect on normal force than on cutting force (Roxborough, 2009). The consequence of this effect is that machines, such as continuous miners and road-headers, become thrust limited rather than torque limited with increasing wear.

Table 3: Variation in forces with tool angle and depth of cut

Rock type	*Depth of cut (mm)*	*Cutting force gradient (kN/deg)*	*Normal force gradient (kN/deg)*	*Ratio C:N*
Sandstone	5	0.30	0.37	1.5
	10	0.69	0.67	1.6
	15	0.92	0.95	1.6
	20	1.18	1.34	1.7
Limestone	5	0.07	0.05	2.7
	10	0.19	0.10	2.3
	15	0.05	0.09	2.9
	20	0.08	0.08	3.2

Figure 8 shows specific energy increase with pick tip angle and hence wear. Hence as would be expected cutting efficiency decreases with increasing wear. Also specific energy decreases with increasing depth of cut and hence cutting efficiency increases with increasing depth of cut

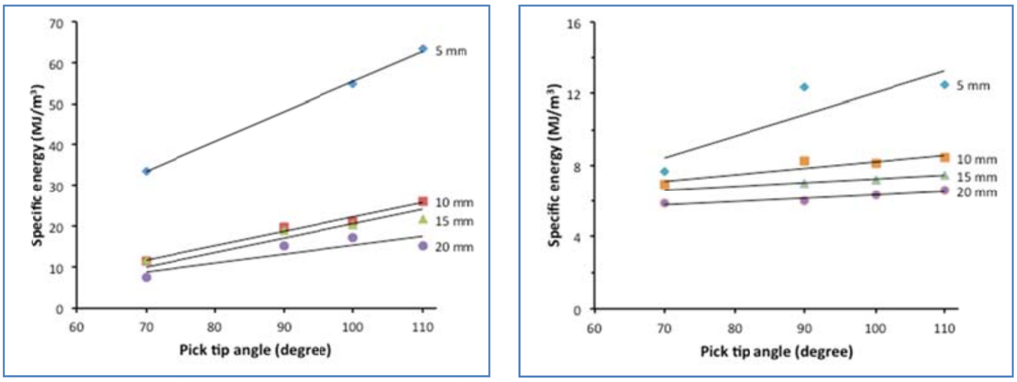

Figure 8: Effect of wear on specific energy for Gosford Sandstone (left) and Gambier Limestone (right)

The increase in normal force required to successfully achieve pick penetration will result in the machine becoming thrust limited, consequently leading to eventual stalling.

Although the general trend indicates that wear has a negative impact on cutting efficiency, there are some outlier results. Closer analysis of the result reveal that cutting sandstone with pick tip angle of 110° at 20 mm depth of cut results in a slightly lower specific energy compared to cutting with pick tip angle of 90° and 100° which represent a slightly less worn out pick. A possible explanation is that not only the groove cut with a 110° pick tip angle is wider but it has been able to achieve the same penetration depth as a sharp pick under the same constant thrust force provided by the PLCM, resulting in greater yield which consequently would have yielded a lower efficiency. These variations may also be due to differences in microfractures, grain size distribution, and varying joint structure within the different rock samples, suggesting that the rocks tested are not perfectly homogenous. There are also similar outliers observed when cutting sandstone with a pick tip angle of 90° and cutting limestone at a pick tip angle of 110° at 5 mm depth of cut which suggests that it is more efficient to cut with a more worn out pick.

From Figure 8, it is evident that the trend indicates that it is more cost effective because it requires less energy to excavate Gambier Limestone than Gosford Sandstone. However, whether it is more efficient to mine the two different types of rock would require further exploration. It is further observed that wear has a dramatic effect on cutting efficiency at shallow depths of cut and higher specific energy, but at the deeper depths of cut, such as 15 mm and 20 mm, a more worn out pick (φ = 110°) has little effect on cutting efficiency. This indicates that a slightly more worn pick will perform just as well at a higher depth of cut.

Table 4 shows the percentage decrease in specific energy from 5 mm to 10 mm depth of cut for both limestone and sandstone. The data outlined in the table shows that a specific mechanical excavator capable of mining both limestone (soft rock) and sandstone (hard rock) will have a higher efficiency when mining sandstone compared to limestone as depth of cut increases, given that all other conditions are constant. This is due to the percentage drop in specific energy when transitioning from a 5 mm depth of cut to 10 mm being significantly higher in sandstone regardless of pick's state of wear. This trend concerns the brittleness of the rock, which is a function of compressive and tensile strength of the rock (Goktan and Yilmaz, 2005). Generally, if the tensile strength of the rock is similar, a higher compressive strength value means that the rock would be more brittle (Goktan and Yilmaz, 2005). Since the strength of Gosford Sandstone is 50.3 MPa, it is more brittle compared to the Gambier limestone of 5.0 MPa. In this case, when a pick penetrates the rock at the same depth of cut, the ease with which fractures propagate with sandstone is higher compared to limestone, thus resulting in more rock fragments. This is consistent with experimental results for this research project. More fragments indicate a higher yield, given that other parameters are constant, which leads to a lower specific energy.

Table 5: Variation in specific energy with tool angle

Rock type	*Tip angle (degrees)*	*Reduction in specific energy (%)*
Limestone	70	9
	90	33
	100	49
	110	32
Sandstone	70	58
	90	23
	100	61
	110	58

CONCLUSIONS

A series of rock cutting tests was conducted with two rock types of different strengths and picks with four levels of pick tip angle to simulate wear of the pick cutting tool. It was found that cutting and normal force increased with pick tip angle and hence with pick wear but the rates of increase varied between the two rocks types. As the depth of cut increased there was a rise in the forces. In the weaker Gambier Limestone, there was little change in the effect of wear on the rate of increase in forces with depth of cut. Whereas for the stronger Gosford Sandstone, the effect of wear on forces was more enhanced and this was compounded at larger depth of cut. Mirroring the difference in compressive strength between the two rock types, there was a near three-fold difference in cutting forces and six-fold difference in normal between the two rock types.

Specific energy also increased with wear, indicating that cutting efficiency decreased with pick wear. A two to threefold increase in specific energy was observed between a sharp pick (70°) and a mostly worn pick (110°). The percentage drop in specific energy transitioning from a 5 mm to 10 mm depth of cut in sandstone is always higher, regardless of the pick's state of wear. This suggests that mechanical excavators capable of mining both limestone (weak rock) and sandstone (strong rock) will have a higher efficiency when mining sandstone compared to limestone, given all other conditions held constant

ACKNOWLEDGEMENTS

The authors would like to thank Mr Kanchana Gamage and Mr Mark Whelan for their tireless efforts and assistance in getting the Portable Linear Rock Cutting Machine (PLCM) fully commissioned.

REFERENCES

Balci, C and Bilgin, N. 2006, Correlative study of linear small and full-scale rock cutting tests to select mechanized excavation machines, *International Journal of Rock Mechanics & Mining Science*, pp 468-476.

Brown, E T. 1981, *Rock Characterisation Testing and Monitoring: ISRM Suggested Methods*, pp 111-137 (Pergamon Press: Oxford).

Goktan, R M and Yilmaz, N G. 2005, A new methodology for the analysis of the relationship between rock brittleness index and drag pick cutting efficiency, *Journal of The South African Institute of Mining and Metallurgy*, pp 727-733.

Hudson, J, Brown, E T, Fairhurst, C and Hoek, E. 1993, *Comprehensive Rock Engineering*, Volume 3, pp 155-175 (Pergamon Press: New York).

Jacobs N and Hagan P. 2009, The effect of stylus hardness and some test parameters on CERCHAR Abrasivity Index, in *Proceedings 43rd US Rock Mechanics Symposium*, Asheville, NC, USA, June.

Langham-Williams J and Hagan P. 2014, An assessment of the correlation between the strength and cuttability of rock, *in Coal 2014: Proceedings 14th Underground Coal Operators' Conference,* University of Wollongong, Feb, (eds: N Aziz, B Kininmonth, J Nemcik and T Ren) 12-14 February (Australasian Institute of Mining and Metallurgy.

Lloyd, M J A. 1985, An investigation into the effect of the angle of attack on the cutting performance of a point attack cutting pick, Honours thesis (unpublished), University of New South Wales, Sydney.

Masoumi, H. 2013, Investigation into the mechanical behaviour of intact rock at different sizes, Doctor of Philosophy thesis (unpublished), University of New South Wales, Sydney.

Mostafavi, S, Yao, Q Y, Zhang, L C, Li, X S, Lunn, J and Melmeth, C. 2006, Effect of attack angle on the pick performance in linear rock cutting, in *Proceeding 45th US Rock Mechanics/Geomechanics Symposium*, San Francisco, California, pp 11-14 (American Rock Mechanics Association: California).

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

Roxborough, F F. 2009, Principles of machine mining, *Monograph 12 - Australasian Coal Mining Practice*, Chp 11. (AusIMM: Melbourne).

Sandvik Mining. 2013, Mining tools [online], Available from < www.miningandconstruction.sandvick.com/sandvick> [Accessed: 18 of March 2014].