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THE EFFECT OF WATER SATURATION IN SANDSTONE AND LIMESTONE SAMPLES ON DISC CUTTING PERFORMANCE

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ABSTRACT: A study was undertaken to quantify the changes in disc cutter performance between dry and saturated rock. The tests were conducted using samples of limestone and sandstone to determine whether changes in performance are consistent across rock types. A linear rock cutting machine was used to conduct the tests with a rolling disc cutter. The tests were performed at varying depths with fixed disc spacing. Cutting forces were measured in the different rocks and cutting depths with rock yield determined and specific energy calculated.

Comparing the results between cutting in dry and saturated rock showed reductions in cutting forces of 52% and 7% respectively for sandstone and limestone. That is the magnitude of the reduction in forces when cutting saturated rock was not consistent with a significant difference between the two rock types. The changes in specific energy were similar with a 43% and 9% reduction in sandstone and limestone. This difference in behaviour between the two rocks was also reflected in rock strength. A comparison of the strength between dry and saturated rock found the change was non-uniform with a 64% and 17% reduction in uniaxial compressive strength in the saturated sandstone and limestone samples respectively. When using a rolling disc cutter, rock cutting performance and rock strength were found to alter between dry and saturated conditions. In the case of a sandstone sample there were significant reductions in cutting forces, specific energy and strength whereas in limestone there were only marginal reductions in these parameters.

INTRODUCTION

The growth in global population has brought many challenges, including mounting pressure on developing infrastructure as well as increased demands on mineral consumption. These relate to both developed as well as developing countries. As the population continues to grow the supporting infrastructure must keep abreast in maintaining a sustainable standard of living. Much of this growth will occur in urbanised areas where there are already limitations on surface land use consequently there is likely to be more subsurface infrastructure development. In recent decades there has been a commensurate increase in the amount of underground construction despite its high cost. The North West Rail Link in Sydney, Australia, is one example of how high human densities are forcing infrastructure underground with the development of Australia's largest public transport project consisting of twin 15 km railway tunnels (Transport for New South Wales, 2015).

Minerals and metals are the building blocks for our modern society. They are key to all services, infrastructure and technologies as we know today (International Council on Mining and Metals, 2012). As near-surface mineral resources are depleted the mining sector faces the major challenge of discovering and accessing deposits that are deeper underground. It is critical that new tools and methods be developed to enable the economic recovery of these deep deposits. Mining methods such as block caving are in use in many parts of the world, which allows the economic extraction of deep underground ore deposits. However, the costs and advance rates related to underground development are significantly under par (Albanese and McGagh, 2011). Actual mine data reveals that even though equipment technology in the mining industry has improved, development performance has not kept paced and is substantially less compared to those achieved in the civil industry. Underground development rates in the mining industry are typically 5 m/d whereas civil projects

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achieve on average 10 m/d. The implementation of proven civil tunnelling technologies such as Tunnel Boring Machines (TBM) and the reliable prediction of rock behaviour and cutter performance will improve the speed and quality of underground development in the mining industry. TBMs have been used in mining operations as early as the 1950s (Cigla, *et al*, 2001). The Grosvenor Mine owned by Anglo American Metallurgical Coal is one of the few examples that show the effectiveness of bringing together previous experience and knowledge from the civil tunnelling industry and implementing it in the mining industry with the development of two access drifts using a TBM (Donnelly, *et al*, 2014).

Machines such as raise borers and TBMs are used to excavate hard rock. These excavators usually employ disc cutters which have proven their effectiveness in hard rock conditions, both in the civil and mining industries. Disc cutting excavators are attractive for hard rock applications because they provide: higher advance rates; safer and more stable excavations; and, can create smooth tunnel profiles (Wilson and Graham, 1972). Information about the forces that act on a disc cutter and their performance is predominantly based on testing conducted in dry rock. While in some cases disc cutters are used in dry rock, more often development occurs in wet conditions in which rock strength properties and cutting performance can be markedly different hence it is important to assess disc cutting behaviour in these conditions (Mammen *et al*, 2009; Summersby, 2013; Abu Bakar, *et al*, 2014). Increased knowledge and quantification of how cutting performance changes in dry and saturated rock will improve the reliable estimation of production and development rates. In turn this will enhance the ability to develop accurate schedules and plans reducing potential financial project risk (Abu Bakar, 2012).

TEST SAMPLE PREPARATION

Rock properties

Testing was undertaken to assess the changes in uniaxial compressive strength and tensile strength of limestone and sandstone samples with moisture content. Testing was conducted to determine the key properties of four different rock conditions i.e. dry limestone, saturated limestone, dry sandstone and saturated sandstone. In total, 40 rock specimens were tested. The limestone and sandstone had average dry densities of 1.60 t/m^3 and 2.22 t/m^3 and saturated moisture contents of 25% and 4% respectively. Table 1 and Table 2 indicate the strength reduction while roughly consistent for each rock type, varied dramatically between the two rock types.

Table 1: Reduction in uniaxial compressive strength when saturated

	Limestone (MPa)	*Sandstone (MPa)*
Dry specimen	5.3	67.4
Saturated specimen	4.4	24.1
Strength reduction	17%	64%

Table 2: Reduction in tensile strength when saturated

	Limestone (MPa)	*Sandstone(MPa)*
Dry specimen	0.4	1.2
Saturated specimen	0.3	0.3
Strength reduction	14%	76%

Sample preparation

The preparation of the dry test block samples involved oven drying at 105° for seven days. This temperature and duration was to minimize if not eliminate moisture in the samples, the blocks were then stored in a cool dry place until they were tested.

Other sample blocks were saturated through a technique known as incremental saturation. This involved placing the blocks in a large plastic box. The box was then filled with water. The water level was increased incrementally for seven days until the block was completely submerged. This technique allows capillary forces to act, drawing water into the pore spaces in the rock while allowing air to escape. This incremental saturation method ensured that the center of the block was completely saturated. After seven days of incremental saturation, the blocks were submerged for eight weeks before being tested. Each of the sample blocks was encased in a medium hardness casting plaster. The plaster was mixed in small quantities in a steel bowl, to ensure an accurate measurement of the water-to-plaster ratio and then added to each block that had been placed in each mould. Foam sheets were used to cover the bottom and sides of the mould. The dry block samples were first placed in plastic to avoid moisture contamination from the plaster as shown in Figure 1. The plaster was allowed to cure for a minimum of 24 hours before being tested.

Figure 1: Dry block samples wrapped in plastic and ready for casting

EXPERIMENTAL PROCEDURES

The testing procedure followed for linear rock cutting tests was as follows:

1. After the plaster had cured for 24 hours, the excess plaster was scrapped to create a flat even surface on the bottom of the mould.
2. The mould was then placed on the table of the Liner Rock Cutting Machine (LRCM). A steel plate was placed in the block to measure the level of the block. This allowed the average level of the block to be measured. A magnetic digital protractor was used to record the average levels along the *x* and *y* axis. The mould was then fastened to the LRCM table with screws and tightened to level the block as much as possible as shown in Figure 2.
3. The distance between the disc and the block was adjusted precisely to ensure a consistent depth of penetration. This was achieved by measuring the distance offset between the disc and the block and setting the depth of penetration accordingly.
4. The block was then marked out to ensure that the first cut was 65 mm from the edge of the block in sandstone and 45 mm in limestone. Due to the hardness to the sandstone the distance between the edge and the cut was larger to prevent the sample from failing at lower depths of cut.
5. A foam containment structure was placed around the mould. This foam containment structure contained all chips and fine material that were ejected during a cut.
6. The cut was performed and data from the load cell acquired.

7. The ejected rock chips and fine material was collected using a vacuum collection device. This vacuum device was created to fit onto the end of a conventional vacuum cleaner. The device was able to achieve a material recovery of approximately 98 %.
8. The collected material was then weighed. The debris was then placed in the oven at 105° for 24 hours and weighed again to determine the moisture content of the cut.
9. The LRCM table was then setup for the next cut at a spacing of 40 mm. Due to the distance left from the edge of the blocks, two adjacent cuts were performed per block in the sandstone and three in the limestone;
10. This process was then repeated for different penetration increments with several passes to investigate the effect of groove deepening. Figure 3 shows a schematic of this nomenclature.

Figure 2: Block sample fastened to LRCM table prior to cutting (left) and foam containment structure to retain cutting debris (right)

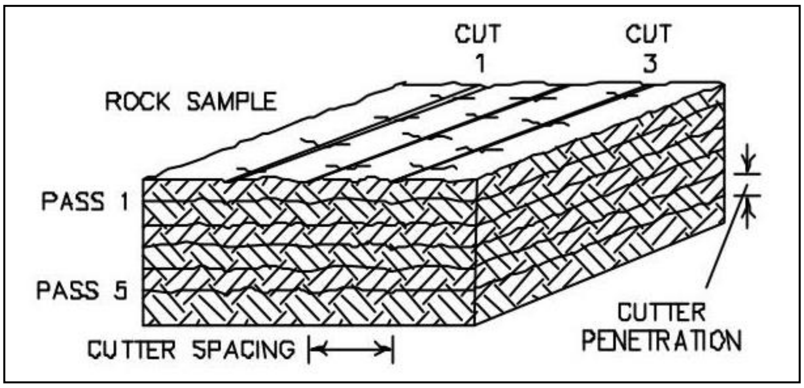

Figure 3: Schematic of the LRCM sample and nomenclature (Balci, 2013).

EXPERIMENTAL RESULTS

Observations

Figure 4 shows the force profiles observed from a cut in limestone and in sandstone. The primary difference between the two force profiles is the magnitude of the forces. The force in cutting the sandstone is nearly an order of magnitude much greater than the limestone. In addition, the force trace is also noticeably different. The limestone force trace is relatively uniform and flat whereas the sandstone trace shows distinct peaks and troughs. Due to the low strength of the limestone, the thrust force applied by the disc caused localised crushing (Figure 5). The peaks and troughs in the sandstone trace indicate the formation of chips. As the disc passes through the rock there is a build-up of elastic energy in the rock indicated by the peaks. This build of elastic energy is then suddenly released resulting in a sudden drop in cutting forces. This mechanism is what causes chips to form in the sandstone

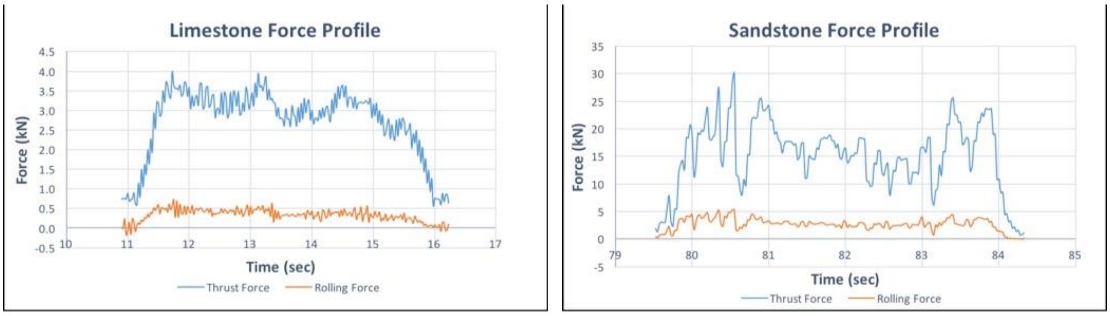

Figure 4: Typical force profile during cutting in limestone (left) and sandstone (right)

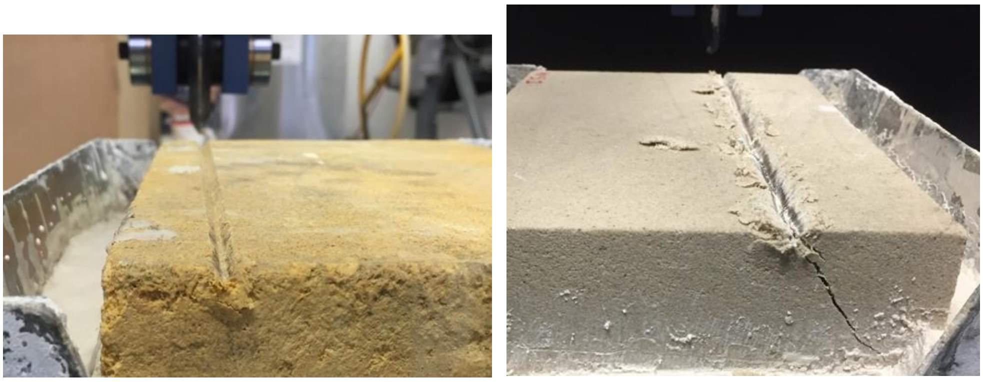

Figure 5: Localised crushing in limestone (left) compared to substantive rock chips in cutting sandstone (right)

RESULTS

Cutting is classified as either unrelieved or relieved. Unrelieved cutting in rock occurs in the absence of any previous cutting whereas relieved cutting refers to the situation that occurs when a previous cutting has been made that can lead to formation of microfractures that can assist subsequent cutting.

Three cuts were made across the surface per incremental penetration in the limestone samples while only two cuts were made in the sandstone sample. This was due to the different edge spacing used in the sandstone and limestone to prevent the samples from failing at low depths of cut. The first cut in the surface was made as unrelieved cut and subsequent cuts were relieved cuts. Since three cuts were made in the limestone, the average of the two relieved cuts was calculated. However, since only two cuts were made in the sandstone, there was only one data measurement for the relieved cut.

The effect of water saturation on thrust force in unrelieved cutting in sandstone and limestone is summarised in Table 3. The results show an increase in forces over the limited range of penetration but that the effect of water had a different effect in the two rock types. As shown in Figure 6 there was a significant reduction in thrust force that tended to increase with penetration when cutting in the saturated sandstone sample as compared to the dry sample. However, the reduction in thrust force in the saturated limestone was minor over the range of penetration as shown in Figure 7. Similar reductions were in rolling force in the saturated sandstone as shown in Figure 8.

Table 3: Reduction in unrelieved thrust force in two rock types with water content

Penetration (mm)	Limestone				Sandstone		
	Dry (kN)	*Saturated (kN)*	*Reduction*		*Dry (kN)*	*Saturated (kN)*	*Reduction*
4	3.1	2.7	13%		14.9	7.6	49%
5	3.2	2.9	9%		16.6	9.2	45%
6	4.7	4.2	11%		26.1	10.8	59%
7	5.1	5.2	0%		29.7	13.7	54%

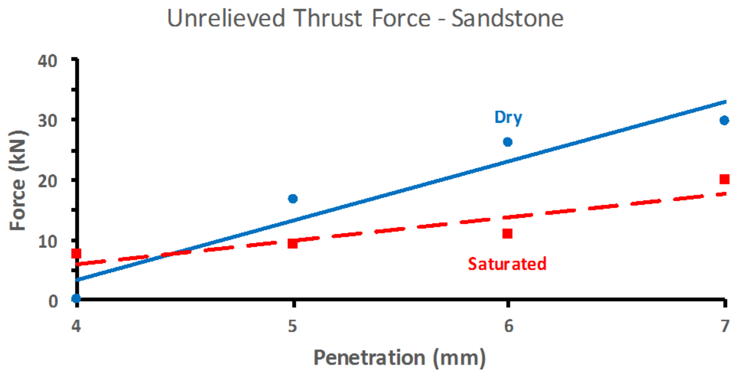

Figure 6: Variation in thrust force with depth in cutting sandstone

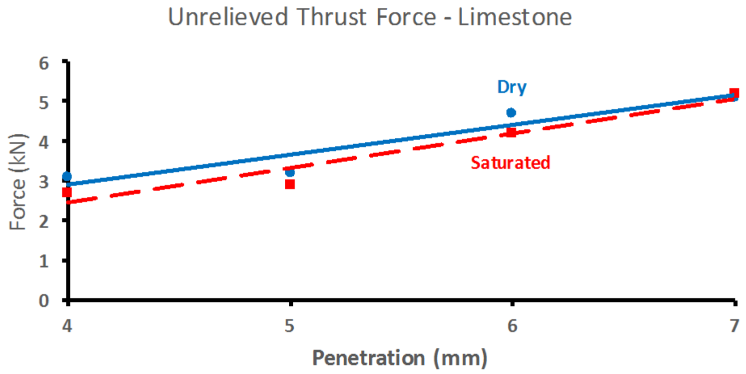

Figure 7: Variation in thrust force with depth in cutting limestone

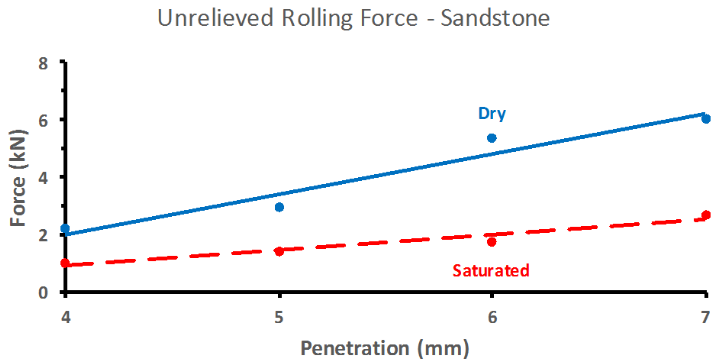

Figure 8: Variation in rolling force with depth in cutting sandstone.

CONCLUSION

The study was conducted to better understand how cutting performance with a rolling disc cutter might change when cutting in dry and saturated rock. It involved a comprehensive program of linear rock cutting tests to evaluate the differences in performance between cutting dry and saturated rock samples. The test sample blocks of two rock types, a limestone and a sandstone were used to gauge whether there might be any differences in effect with rock type.

Data collected from the linear rock cutting tests was analysed to find differences in cutting performance in dry and saturated rock conditions. An average reduction of 52% and 8% was observed in thrust force in the saturated sandstone and limestone samples respectively. Similar levels of reduction were found in rolling force. The average reduction in specific energy was 43% and 9% in sandstone and limestone. These reductions in forces and specific energy correspond with the 64% and 17% reduction in UCS in the saturated sandstone and limestone samples respectively.

The yield produced in the limestone at low depths during cutting was observed to consist predominantly of fine material. This was caused by localised crushing under the disc due to the low UCS of the limestone. However, the chip size when formed in sandstone chips increases proportionally with the depth of cut.

Compared to the reduction in cutting performance in the saturated sandstone sample, the change in cutter performance in limestone was less substantial. The effect of water saturation varies directly with penetration, indicating greater levels of cutting performance can be achieved with a disc cutting machine such as a TBM. Performance changes appear to be less effected in limestone.

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