The assessment of rock cutability, and physical and mechanical rock properties from a texture coefficient

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Synopsis

Determining the cutability and mechanical properties of rocks is vital for the feasibility studies of a mine or tunnel projects. Many scientists have investigated the correlation between these parameters in order to predict specific energy (SE) and other important rock cutability properties for many years. On the other hand, textural properties of rocks have been quantified in detail by Howarth and Rowlands (1987). Hence, it was possible to correlate mechanical and textural properties of rocks by using a parameter known as the texture coefficient (TC).

The main objective of this study was to use the test results taken from a research project carried out by Bilgin and Shahrair[1] to correlate the mechanical and cutability properties of rocks with textural properties of rocks. For this purpose, uniaxial compressive strength (UCS), uniaxial tensile strength (UTS), cone indentor (CI), point load index (PLI), unit volume weight (γ), porosity, SE, and normal and cutting force values, were correlated with textural properties of rocks. Hence it was possible to make illuminating interpretations about the relationships between the mechanical and cutability with the textural properties of rocks.

Keywords: Cutting properties, mechanical properties, specific energy, texture coefficient.

Introduction

The effect of textural properties on the physical and mechanical properties of rocks has been investigated for many years, and studies have shown that there is a close relationship between these parameters. Ehrlich and Weinberg[2] proposed a grain roughness coefficient. Olsson[3] proposed that a linearly increasing relationship exists between yield stress and the square root of the mean grain size for marble. Bell[4] noticed that the strength properties may be correlated with packing density of rocks (space in a given area occupied by grains). Onodera and Kumara[5] found that uniaxial compressive strength (UCS) of rocks is related to the grain roughness coefficient (proposed by Ehrlich and Weinberg[2]). However, texture is defined as the degree of crystallinity by Williams *et al.*[6].

Howarth and Rowlands[7] developed the theory of texture coefficient (TC), which made it possible to understand the variations of mechanical properties of rocks with rock textural properties. In this research, they investigated the correlation between the mechanical properties such as UCS, modulus of elasticity, drillability and TC for ten different rock types, and they found the drilling rate and TC were highly correlated. They also correlated the mechanical and textural properties of rocks, and they found that there is a close relationship between rock mechanical properties and TC with high correlation coefficients (r^2). Similar investigations have also been carried out by Ersoy and Waller[8]. It should be added that Azzoni *et al.*[9]. investigated the correlation between TC and uniaxial compressive strength and rock weathering for different rock types. The results are similar to those of the previous researchers.

The cutting of a rock formation in a mechanical excavation application is realized by using cutters that are mounted on the cutting head of a cutting machine. For a typical cutting machine, the cutting head must have enough applied power in order to excavate a given rock formation. Hence, cutting and normal forces should be determined prior to excavation; however, there are always differences between theoretical and actual values. Evans[10] proposed a cutting theory that used UTS and UCS as input variables for determing the cutting and normal forces, whereas Nishimatsu[11] had a different approach of using shear strength in high strength rocks to determine the relevant forces.

McFeat and Fowell[12], Fowell and Pycroft[13], and Fowell and Johnson[14] found high correlations between SE and some of the geotechnical properties of rocks. Fowell and

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McFeat-Smith[15] found that SE can be calculated by using the value of NCB (National Coal Board—England) cone indentor (CI), UCS, Shore Sclereroscope hardness, and the packing density of rock. SE is energy spent in excavating the unit volume of rock and is used in determining the performance of roadheaders. This is an important point, since all the parameters included in this formula are found to be related to textural properties of rocks. However, prediction of SE is found to be a useful tool in order to estimate the efficiency and cutting rate of any excavator for a tunnel and mine planning project. The research results of Atkinson *et al.*[16] and Poole[17] showed that there is a close relation between the advance rate of a cutting machine and the ratio between UCS to the elasticity modulus of rocks.

It is simple to conclude from all of these aforementioned research results that the estimation of SE is important before starting an excavation project. The main objective of this research is to investigate the relationships between textural properties of rocks and some mechanical and cutability properties of rock, especially for SE. The relation between cutability and textural properties of rock has been preliminarily investigated as the main scope of this research.

Experimental studies

Bilgin and Shahriar[1] carried out an extensive rock cutability test on samples taken from Zonguldak Coalfield. They used an experimental technique and procedure described by Fowell and McFeat-Smith[15]. The samples were taken from a borehole, drilled in this region to a depth of nearly 1 000 m. The most important point arising from this research is that all rock samples have been kept for further analysis, and as such, it was possible to conduct image analysis by using thin slices from these samples, taken from depths ranging between 40 m and 399 m. Mineralogical and petrografical properties of these samples are given in Table I.

Mechanical and physical properties

Standard test procedures were carried out to determine the physical and mechanical properties of the rocks tested. The results are shown in Table II.

Cutability properties

Experimental techniques and procedures developed in Newcastle upon Tyne University by Fowell and McFeat-Smith[15] were used throughout the experiments. The equipment used at the Istanbul Technical University for rock cutability tests is shown in Figure 1.

Cutting parameters are as follows:
Cutting depth : 5 mm
Cutting angle : -5°
Cleaning angle : 5°
The width of cutting : 12.7 mm
Cutter tip properties : Tungsten carbide, 10% cobalt.

A shaping machine of 9 kW and a triaxial force dynamometer was used to measure the following parameters:

F_C = Mean cutting force acting in the direction of cutting in kN

$F`_C$ = Mean cutting peak force acting in the direction of cutting in kN

Table I

Mineralogical and petrografical properties of tested samples[1]

Depth of Samples (m)	Definition
40–71	Microfossilized micritic limestone
221–240–259	Porphyritic basaltic andesite
278–336	Andesitic crystaline tuff
315	Altered andesitic crystaline tuff
355–367–397–399	Micritic

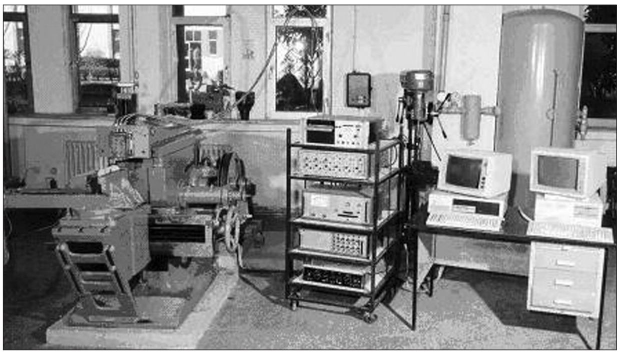

Figure 1. Schematic view of cutting machine

Table II

Physical and mechanical properties of rock samples[1]

Depth (m)	UCS (kg/cm^2)	UTS (kg/cm^2)	CI	PLI (kg/cm^2)	BS	γ (gr/cm^3)	Porozite (%)
40	537.10	21.0	1.8	7.2	77.7	2.40	2.1
71	522.90	19.8	1.5	41.0	67.6	2.40	2.1
221	496.20	31.4	2.0	47.0	86.3	2.19	5.6
240	522.64	49.0	2.7	47.6	90.0	2.21	4.1
259	530.30	23.0	2.2	40.0	85.4	2.17	–
278	446.90	28.3	1.8	21.8	75.6	2.38	2.4
315	526.20	19.1	2.1	21.8	72.4	2.28	–
336	350.00	26.4	0.9	13.8	72.0	2.32	2.9
355	383.50	22.2	1.6	8.2	82.0	2.27	2.5
367	279.10	25.2	1.4	15.0	73.5	2.34	1.7
397	288.40	35.5	2.3	–	82.6	2.34	1.7
399	432.50	48.4	2.8	–	82.6	2.34	1.7

F_N = Mean normal force acting normal to the direction of cutting in kN
$F`_N$ = Mean normal of peak force acting normal to the direction of cutting in kN
Q = Yield, in m³/km
SE = Energy required in order to cut the unit volume of rock in MJ/m³. SE is calculated as
SE = FC/Q

Textural analysis

As mentioned above, the most important development for describing the textural properties of rocks occurred in 1987 after Howarth and Rowlands[7] proposed the theory of TC. Hence, it is possible to make quantitative assessment of rock texture. TC is formulated as :

$$TC = AW\left[\left(\frac{N_o}{N_o+N_1}\times\frac{1}{FF_o}\right)+\left(\frac{N_1}{N_o+N_1}\times AR_1\times AF_1\right)\right] \quad [1]$$

where :
TC = texture coefficient
AW = grain packing weighting
N_0 = number of grains whose aspect ratio (AR) is below a pre-set discrimination level
N_1 = number of grains whose aspect ratio (AR) is above a pre-set discrimination level
FF_0 = arithmetic mean of discriminated form factors,
AR_1 = arithmetic mean of discriminated ARs,
AF_1 = angle factor (Howarth and Rowlands[7]).

Some other sub-equations are derived for solving Equation [1]. Form factor, which is a parameter of the grain's deviation from circularity, can be determined by using Equation [2]. If FF is equal to 1.0, it means that the particle is a perfect sphere. In this application an AR discrimination level of 2.0 is used as assumed in literature[7]. The values of FF_0 are calculated for all grains falling below this level.

$$FF = 4\times\prod\times\frac{Area}{(perimeter)^2} \quad [2]$$

AW can be determined by using Equation [3] for every grain viewed and analysed as part of the rock texture imaging step.

$$AW = \frac{\sum\left(\begin{array}{c}\text{grain areas within the}\\ \text{reference area boundary}\end{array}\right)}{\begin{array}{c}\text{area bounded by the}\\ \text{reference area boundary}\end{array}} \quad [3]$$

AF and other parameters which constitute Equation [1] can be calculated as given in literature[7]. After that, it is possible to determine the value of TC for every thin slice and make a quantitative assessment of rock texture.

In this study, the image analysis procedure is applied to every thin slice of rock that had been used in the project referred to above (Zonguldak Coalfield). In this procedure, the images that are quantified are taken from a camera that is mounted on a microscope, and after taking photographs of the thin slices, every desired property of the grains are determined by using the Leica Qwin computer program. These properties are: area, perimeter, length, width, and orientation (only for elongated grains). After the completion of the procedure, every thin slice has a unique value. These values per rock type are averaged to produce the TC values shown in Table IV.

Comparison of textural and other properties of rocks

In order to understand the relation between the parameters that are investigated within the scope of this research, regression analysis is carried out for different pairs of parameters. The correlation coefficient (r^2) value of the regression line is used to understand the reliability of the correlation between the parameters. The relations between the investigated parameters are given in Figures 2–13.

As can be seen from Figure 2, there is a strong correlation between SE and TC. Figures 3, 4, 5, and 6 show that cutting and normal forces are related to TC with a statistically high level of confidence (r^2 = 0.82) (r^2 = 1 is a perfect

Table III

Cutability properties of rocks[1]

Depth (m)	$F`_C$ (kN)	F_C (kN)	$F`_N$ (kN)	F_N (kN)	SE (MJ/m³)
71	3.08	1.35	1.61	0.96	8.16
221	4.29	2.42	2.27	1.53	29.89
240	4.51	2.01	2.46	1.17	22.40
259	4.15	1.69	2.27	1.13	19.85
278	2.67	1.33	1.09	0.63	16.84
336	3.13	1.77	1.47	0.91	19.16
355	3.85	2.00	1.96	1.05	16.03
367	2.42	1.42	1.15	0.89	16.22

Table IV

TC values of rock samples

Depth (m)	TC	Depth (m)	TC
40	0.53	315	0.23
71	0.41	336	1.02
221	2.54	355	0.67
240	1.34	367	0.24
259	1.06	397	0.21
278	0.91	399	0.38

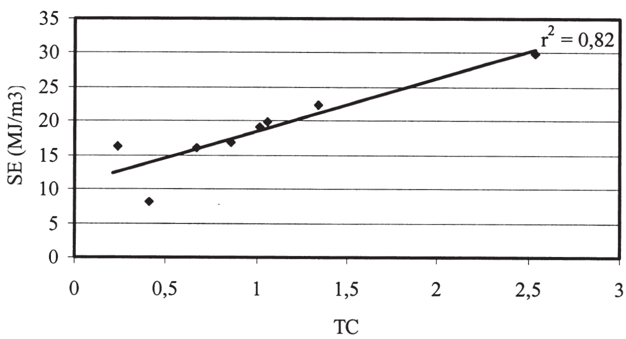

Figure 2 . Correlation between SE and TC

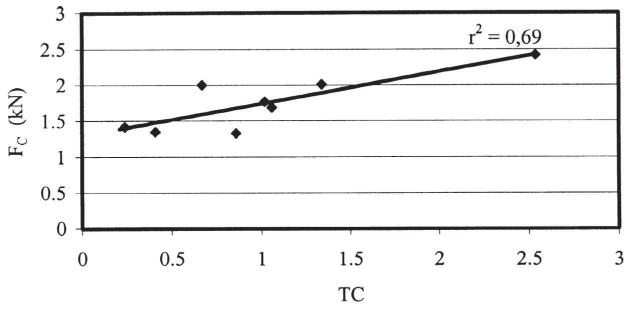

Figure 3. Correlation between F_C and TC

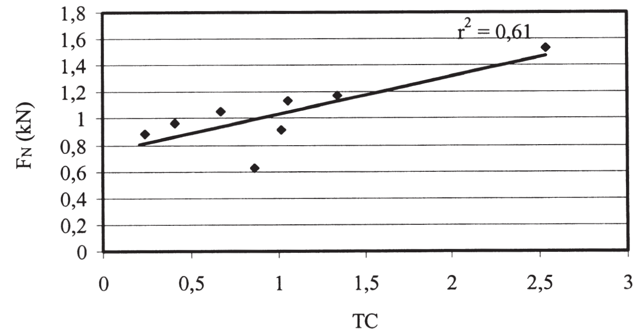

Figure 4 . Correlation between F_N and TC

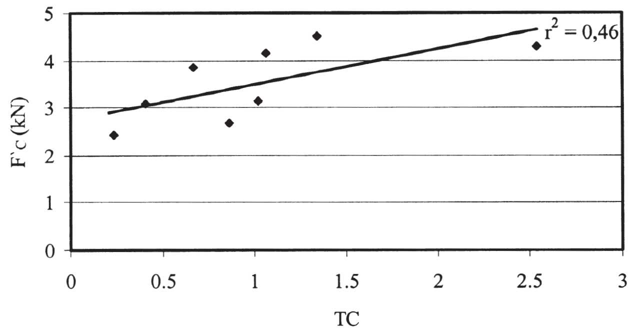

Figure 5 . Correlation between $F`_C$ and TC

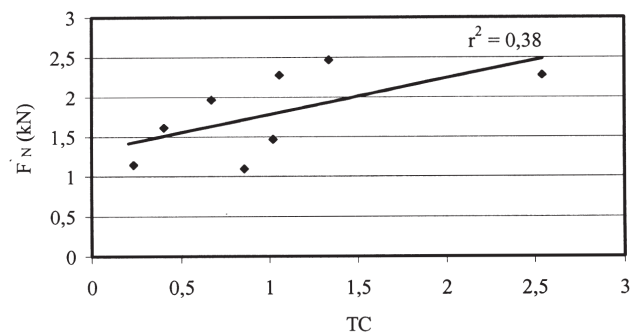

Figure 6 . Correlation between $F`_N$ and TC

correlation). However, the relation between $F`_N$ and TC is less clear. Hence, as a result of this, it is possible to say that the higher values of TC indicate a difficulty in rock cutability. The higher values of SE and F_C means that they are more affected by rock texture.

In addition to these results mentioned above, it may be concluded that one of the physical properties of rocks shows a good relation to TC; however, the other cannot show the same high correlation. Porosity has the best correlation among the all rock parameters with the highest r^2 (0.96) (Figure 7). This result is expected, since the increasing porosity number indicates the increasing of the number of elongated grains, which causes the increasing TC. On the other hand, the correlation between γ and TC is less significant, as seen in Figure 8.

As can be seen from Figures 9–13, the relation between TC and mechanical properties is not statistically significant in most cases. The highest correlation was found between PLI and TC with a correlation coefficient, r^2, of 0.67. Controversially, the correlations between TC and other mechanical properties are not very significant when the relevant coefficients of correlation are taken into consideration. These results differ from the results given in previous research studies. For example, Howarth and Rowlands[7] found a good relation between TC and UCS and TC and UTS with a high coefficient of correlation, r^2. However, Ersoy and Waller[8] found these relationships to have a lower coefficient of correlation, r^2. This can be explained by the fact that in most cases UCS, UTS and other mechanical properties of rocks are closely related to the mineralogical and petrografical properties of rocks. However, the magnitude of mechanical, physical, and textural properties of rock can be changed in a wide range, even for the same type of rock material because of the uncertainty of the rock material. Some of the possible reasons for such uncertainty situations can be summarized as anisotropy, metamorphisms, nature, etc.

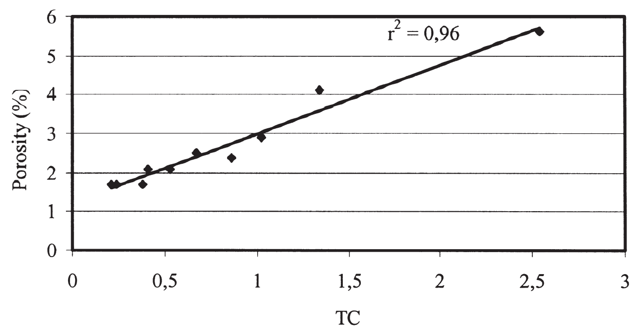

Figure 7. Correlation between porosity and TC

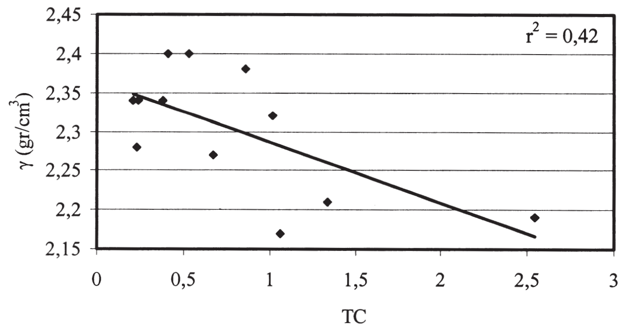

Figure 8 . Correlation between γ and TC

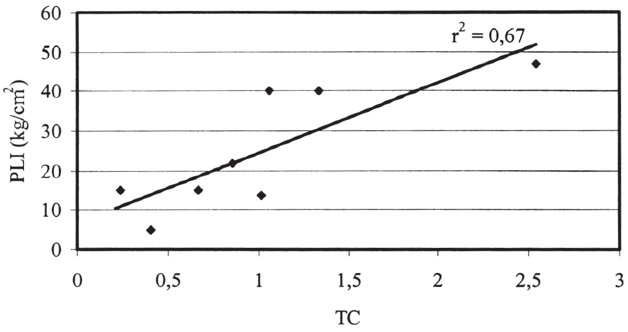

Figure 9. Correlation between PLI and TC

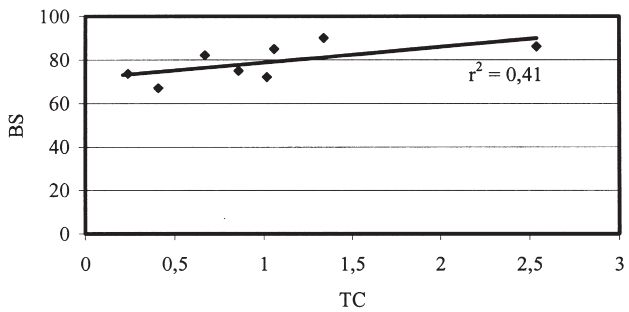

Figure 10. Correlation between BS and TC

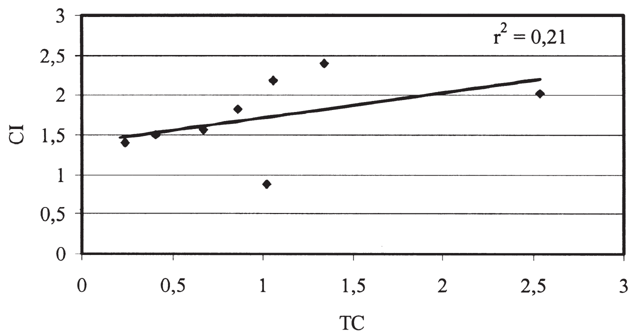

Figure 11. Correlation between CI and TC

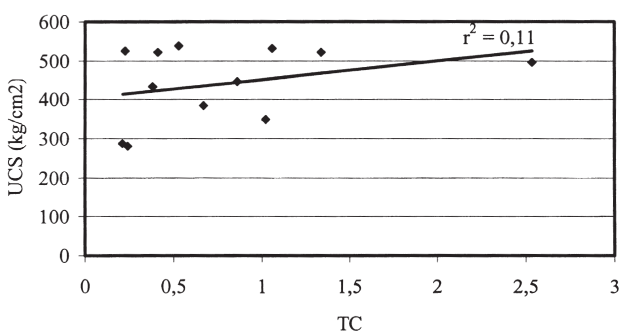

Figure 12. Correlation between UCS and TC

Conclusion

Some of the mechanical and cutability properties of rocks are used intensively in mining and tunneling projects. The relationships between these parameters have been investigated by Bilgin and Shahriar[1] in a project carried out on rocks from the Amasra bituminous coal basin of Turkish Hard Coal Enterprise (TTK). In this project, for rock cutability tests, they used a test rig similar to the one described by Fowell and McFeat-Smith[15].

Textural properties of rocks have been quantified firstly by Howarth and Rowlands[7]. Since then, the relation between textural and other properties of rocks such as physical, mechanical, and cutability can be better explained by using the texture coefficient (TC). This paper has shown this to be the case.

The relations between the mechanical properties, physical properties, and the cutability of rocks with textural properties are investigated within the scope of this research. The thin rock slices are used to make textural analysis by using an image analysis methodology. Hence, it was possible to obtain a unique value for every thin slice section of the rocks investigated. Later, a standard statistical analysis was run in order to understand the correlations between TC and other properties of rocks. Consequently, this research has shown that there is a good correlation between rock cutability properties and TC—especially for SE. In addition to this, some of the physical properties of the rocks tested have shown a good relation to the TC, as expected. The research has, however, also shown that this may not necessarily be the case when it comes to the correlation of TC to the mechanical properties of rocks.

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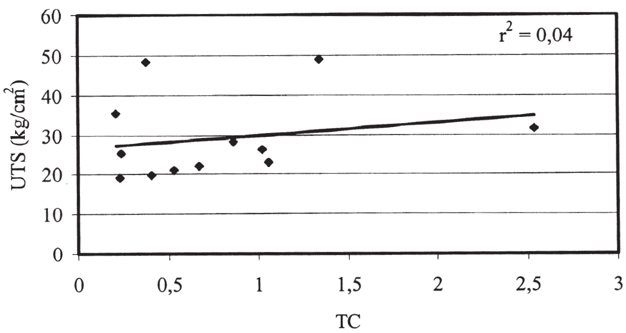

Figure 13 . Correlation between UTS and TC

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JK researchers 'on-the-ball' with blast movement monitoring*

In the relatively short period of just under 18 months, the JKMRC has developed a system to enhance the mining industry's ability to track and monitor the movement of ore and waste material 'blown up' and shifted during production scale blasting operations.

The JKMRC responded to the mining industry's need to have a system that replaces existing methods to track ore and waste movement, which were either less accurate or less practical.

Current methods used by the mining industry to monitor muck pile movement include the use of sand bags, poly pipe and chains as displacement markers. Muck piles are the broken fragments of rock resulting from blasting.

JKMRC senior researcher Darren Thornton said that mining operations want to be able to track movement within the muck pile so that they know exactly where the orebody moves.

'It is often the case that an ore block moves several metres during blasting,' Darren said. 'If the ore is excavated in its original position, much of this material will actually be waste.'

He said that the mining crew might not know this and inadvertently dig waste material instead of the ore in the wrong place.

'A state-of-the-art monitoring system should tell you exactly where to mine after a blast.'

JKMRC researcher Darren Thornton and his colleagues Michael Wortley, Graham Sheridan and David La Rosa came up with the Blast Movement Monitor—or BMM—which is a plastic ball-shaped transmitter placed in holes within a blast area.

Up to fifteen transmitters have been used in each blast. After each blast sequence, the BMMs are quickly located within the muck pile using a detector, and three-dimensional vectors for each transmitter's movement are available within two hours of the blast.

According to Darren Thornton, the key to the success of the prototype device was the ability of a small transmitter to send signals through at least ten metres of rock after surviving a production blast.

The first trial of the monitors occurred at a Brisbane quarry late in 2002. Encouraged by the results, the research team took the BMMs to a gold mine in Western Australia for a series of trials, which began in February 2003. These trials successfully demonstrated that the electronics in the balls would survive a full scale production blast at a mine site.

Much of the electronics-based gadgetry has been developed by JKMRC Ph.D. researcher Michael Wortley who came up with the robust transmitting system small enough to fit inside a blast hole. The holes vary in size from 80 mm to 300 mm.

Test work scaled up in June 2003 with the deployment of 15 monitors in two blasts, followed by a project in August where 65 BMMs were used to quantify the ore loss and dilution across a whole bench.

Darren Thornton said the use of the BMMs—also known in the mining industry as blast vector indicators—are particularly useful in selective mining operations, such as narrow vein gold mining.

He said BMMs were an obvious choice over current movement monitoring methods as they gave the excavation team the required results before they started digging.

'Quick and accurate information from a practical system is the major advantage.' ◆

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