Suitability of Brisbane Rock Conditions to Roadheader Excavation

by Jody Herley

Roadheader excavation has typically been limited in its ability to cut hard rock. Despite this, a number of tunnelling projects being implemented in South-East Queensland are utilising roadheaders to excavate sections of the tunnel which pass through the characteristically strong Brisbane Tuff rock.

Laboratory testing has been conducted on this rock with the objective of applying the results to previously derived models in order to determine the suitability of the Brisbane Tuff to roadheader excavation. This paper describes the results of this research.

INTRODUCTION

South-East Queensland is currently witnessing the implementation of a number of tunnel projects in an attempt to reduce deficiencies in the Brisbane road network system. The tunnelling methods being used for these projects include roadheader excavation, which has a number of advantages over drill and blast and tunnel boring machine techniques including compactness, mobility, relatively little lead times and simultaneous mucking. Despite these key advantages, the main disadvantage recognised is that roadheaders have limited hard rock cutting ability and have in the past been suited to excavation of soft to medium rocks only.

A number of models exist to predict roadheader performance based on key rock properties. In performing laboratory tests on samples of the Brisbane Tuff, these rock properties could be found, allowing the objective of determining the suitability of Brisbane rock conditions to roadheader excavation, to be achieved.

LABORATORY TESTING

Rock Properties

There are a number of factors that affect the application of roadheaders to rock cutting. It is important that the most influential rock material properties are known so that laboratory tests can be conducted to determine these properties for the Brisbane rock. The following rock material properties have all been examined by a number of authors with regards to their affect on roadheader performance:

- Uniaxial compressive strength (UCS);
- Brazilian tensile strength (BTS);
- Fracture toughness;
- Specific energy;
- Hardness
- Abrasiveness; and
- Rock mass characteristics.

Rock Samples

The rock chosen to be tested is the Brisbane Tuff which comes from the North-South Bypass Tunnel (NSBT) as this project is currently underway and the geology is known for the areas being excavated by roadheader. The Brisbane Tuff formation is the result of violent explosive eruptions of rhyolitic magma that produced extremely hot ash flows nearly 220 million years ago (Stevens, 1984). The rock is known as welded tuff or ignimbrite, which is what the Brisbane Tuff formation consists of. For the North-South Bypass Tunnel project, the roadheaders will be excavating predominantly Brisbane Tuff rock and so the laboratory testing for this paper will be of this rock in order to determine the important rock properties which can be used to predict the suitability of the roadheader to this excavation.

Three samples of this rock were sourced from the Bowen Hills NSBT site; a highly weathered sample from the portal excavation (Rock 1), a more characteristic, unweathered sample from deeper in the portal (Rock 2), and cores from the face of the tunnel (Rock 3). The samples were prepared at the University of Queensland's Experimental Mine (UQEM) in accordance with the specifications outlined in the International Society for Rock Mechanics (ISRM) standards (ISRM, 1981). Samples were prepared for the following tests:

- UCS;
- BTS;
- Fracture toughness;
- CERCHAR abrasive index;
- Schmidt hammer hardness; and
- Shore scleroscope hardness.

Test Results

The six rock properties listed above were all found through laboratory testing. The average results for each rock can be seen in Table 1. As can be seen, Rock 3 was only tested for the UCS and BTS as it was provided in the form of cores. Along with these six rock properties, the specific energy and rock mass characteristics were also determined. The specific energy was found using the theoretical equation $SE = UCS^2/E$, where E is the Young's Modulus in MPa. The Rock Quality Designation (RQD) number and Rock Mass Rating (RMR) were found for Rock 3 only, in the form of 26 mappings taken at regular intervals along the tunnel. These results are also displayed in Table 1 below.

Table 1
Summarised average results

Test	*Rock 1*	*Rock 2*	*Rock 3*
UCS (MPa)	25.72	86.27	78.83
BTS (MPa)	1.81	8.44	7.33
Fracture Toughness (MPa√m)	0.59	1.45	-
CERCHAR Abrasive Index	0.40	2.71	-
Schmidt Hammer Hardness	39.60	49.30	-
Shore Scleroscope Hardness	34.01	59.33	-
Specific Energy (MJ/m^3)	0.0472	0.5316	0.4438
Rock Quality Designation	-	-	95.33%
Rock Mass Rating	-	-	71.33

Discussion

As can be seen from Table 1, there is a significant difference in the results obtained for the weathered rock sample (Rock 1) compared with the two other samples. This was true for all of the laboratory tests performed. This may be attributed to the fact that Rock 1 came from the portal excavation and was a highly weathered sample. Rocks 2 and 3 showed similar results for the UCS and BTS values obtained.

ROADHEADER RELATIONSHIPS

A number of models have been developed for predicting roadheader cutting performance. These models utilise the rock properties mentioned earlier and have been broken down into the following four groups:

- UCS Relationships;
- Specific Energy Relationships;
- Rock Mass Relationships; and
- Pick Wear Relationships.

UCS Relationships

As most authors believe that UCS alone is insufficient to predict roadheader performance, most of the relationships utilising the UCS also take into account other rock properties or machine specifications. These models are discussed briefly below.

Nelson, Sinha and Handewith's Model

Nelson, Sinha and Handewith (1991), developed a plot of rock strength (UCS) versus mining rate for very abrasive, medium abrasive and non abrasive rocks.

Voest-Alpine Model

Voest-Alpine created a model for their Alpine Miner and Alpine Tunnel Miner 105 roadheaders. These machines are 300 kW transverse roadheaders and the relationship developed plots the net cutting rate (NCR) against the rock UCS. The model is further refined into three separate plots based on the UCS to BTS ratio.

Thuro and Plinninger's Model

Thuro and Plinninger (2003) developed a relationship derived from 26 rock samples for a 130 kW roadheader. It plotted UCS versus cutting performance. The plot showed wide scatter and Thuro and Plinninger (2003) concluded that the UCS was not able to effectively describe the energy used for rock fragmentation during the excavation process.

Specific Energy Relationships

As was discussed, many authors agree that the specific energy, or destruction work, can be used to predict roadheader performance. The model found to utilise specific energy is given below.

Farmer and Garrity's Model

Farmer and Garrity (1987) developed a model to show the relation between σ_{cf}^2 / 2E and the volume excavation rate for two roadheaders: the Thyssen-Paurat Titan and the DOSCO MK 3. They then developed a second relationship which uses a constant value of σ_{cf}^2 / 2E to show that the range of data can be related to the rock type. This model was used as the two roadheaders used for their first model are not being used to excavate the Brisbane Tuff.

Rock Mass relationships

There has been a number of models developed relating roadheader performance to rock mass properties such as the RMR and RQD values. These models are given below.

Fowell and Johnson's Model

Fowell and Johnson (1982) developed a model to predict the cutting rate for roadheaders based on the rock mass rating (RMR) number. The relationship is based on 20 field results and is remarkably consistent.

Bilgin, Yazici and Eskikaya's Model

Bilgin, Seyrek and Shahriar (1988) developed a model at the Instanbul Technical University to estimate roadheader production in terms of the instantaneous cutting rate. In 1996, Bilgin, Yazici and Eskikaya improved the equations through analysing more data. The model utilises the UCS, RQD and machine power to predict the instantaneous cutting rate.

Sandbak's Model

Sandbak (1985) developed a model that utilises the RMR value to predict the bit usage in bits/foot. The model also predicts the machine cutting rate in feet per hour.

Pick consumption relationships

Along with the cutting rate, the prediction of tool consumption is also fundamental to any assessment of machine performance and as such, a number of models have been produced to calculate this. These models are discussed further below.

Copur, Ozdemir and Rostami's Model

Copur, Ozdemir and Rostami (1998) developed a set of models to predict the bit consumption rate (BCR) during roadheader excavation.

Thuro and Plinninger's Model

Thuro and Plinninger (2004), discuss the application of the Cerchar abrasive index (CAI) in the estimation of tool wear rates for hardrock operations.

PERFORMANCE PREDICTION

The primary objective of the project was to predict the performance of roadheaders in the Brisbane Tuff rock, thereby determining it's suitability to roadheader excavation. This was done using the relationships discussed. Many of the models required specific information relating to the roadheader being used to excavate the rock and so the specifications used were taken from the Alpine Tunnel Miner (ATM) 105 ICUTROC as this roadheader was used to excavate part of the North-South Bypass Tunnel.

Cutting Rate

Based on the relationships discussed above, the results for the predicted cutting rates for each model found in the literature can be seen below in Table 2. As can be seen in Table 1, the rock mass properties were not known for Rocks 1 and 2 and as such, the cutting rate could not be predicted using the rock mass models for these two rocks.

Table 2
Cutting rate prediction summary

Model	*Cutting rate prediction (m^3/h)*		
UCS	*Rock 1*	*Rock 2*	*Rock 3*
Nelson, Sinha and Handewith (1991)	34	11	13
Voest-Alpine	95	26	32
Thuro and Plinninger (2003)	30	12	15
Specific Energy	*Rock 1*	*Rock 2*	*Rock 3*
Farmer and Garrity (1987)	50	7	8
Rock Mass Characterisitics	*Rock 1*	*Rock 2*	*Rock 3*
Fowell and Johnson (1982)	-	-	20
Bilgin, Yazici and Eskikaya (1996)	-	-	28
Sandbak (1985)	-	-	7

As can be seen from Table 2, there were significant differences noted in the cutting rates predicted from each model. For each model, Rock 1 had the highest predicted cutting rate, followed by Rock 3 and then Rock 2. However for the same rock there were large variances in the predicted cutting rates between the different models. The only similarities that could be drawn were between Nelson, Sinha and Handewith's (1991) model and Thuro and Plinninger's (2003) model which gave very similar predicted cutting rates for all three rocks. The differences between the other models can be attributed to the fact that each model draws on different rock properties in determining the cutting rates.

Pick Consumption

Along with the cutting rate, the prediction of tool consumption is also fundamental to any assessment of machine performance and as such, two models were used to calculate this value. The average predicted pick consumptions can be seen in Table 3.

Table 3
Pick wear prediction summary

Model	*Pick wear prediction (picks/m^3)*		
	Rock 1	*Rock 2*	*Rock 3*
Copur, Ozdemir and Rostami (1998)	0.003	0.012	0.011
Thuro and Plinninger (2004)	0.003	0.600	-

As can be seen from Table 3, the predicted pick wear values were the same for both models for Rock 1, but showed significant differences between the two models for Rock 2. The pick wear for Rock 3 was unable to be determined from Thuro and Plinninger's (2004) model as the abrasivity of Rock 3 was not known. The differences between the two models for Rock 2 may be attributed to the fact that Thuro and Plinninger's (2004) model takes into account the high abrasivity of Rock 2, whereas Copur, Ozdemir and Rostami's (1998) model does not consider the abrasiveness at all.

Validation

The predicted cutting rates and pick wear values could finally be validated based on actual data obtained from the roadheaders while they were cutting the NSBT. The average cutting rates and pick consumptions achieved at the NSBT were taken during the period from 21/02/07 to 04/10/07 and can be seen in Table 4 along with the range of each. The core UCS values can also be seen.

Table 4
Actual performance values

	Average value	*Range of values*
Cutting rates (m^3/h)	15.5	5.8 – 43.8
Pick consumption (picks/m^3)	0.2432	0.0121 – 0.7949
Core UCS (MPa)	66	22 – 122.5

From Table 4, it can be seen that the average cutting rate achieved at the NSBT was 15.5 m^3/h. This is expected to be similar to the theoretical values obtained for Rock 3, as this rock came from the face of the tunnel. In comparing this value with the values obtained in Table 2, it can be said that Nelson, Sinha and Handewith's (1991) model and Thuro and Plinninger's (2003) model provide the most accurate results for prediction of roadheader cutting rates.

The average actual pick consumption was found to be approximately 0.2432 picks/m^3. In comparing the actual values with the predicted values, it can be seen that Copur, Ozdemir and Rostami's (1998) model gave predicted consumption rates for all three rocks that are lower than even the minimum actual consumption rates being achieved. Thuro and Plinninger's (2004) model on the other hand, gave a value for Rock 1 which was very low and a value for Rock 2 which was unusually high. It can therefore be said that neither of these models are accurate in predicting the pick consumption for the Brisbane Tuff.

CONCLUSIONS

From the results, it can be seen that the Brisbane Tuff shows a wide range of rock properties throughout the rock mass. This will in turn lead to a wide range of cutting rates and pick consumptions that are able to be achieved.

The most accurate cutting rate predictor models were found to be those by Nelson, Sinha and Handewith (1991) and Thuro and Plinninger (2003), as the predictions from these models were very similar to the actual rates being achieved at the NSBT. Due to this, it can be concluded that the UCS is the most influential rock property in predicting roadheader performance, as both of these models were developed from the rock UCS.

The pick consumption relationships found in the literature did not give accurate results compared with the actual pick consumptions being achieved and it can therefore be concluded that they are inaccurate models and should not be used to predict pick consumption in the Brisbane Tuff.

Finally, it can be concluded that with average actual and predicted cutting rates of 15 m^3/h and the ability to achieve even higher cutting rates in more favourable conditions, the Brisbane Tuff is well suited to roadheader excavation.

ACKNOWLEDGEMENTS

The author acknowledges support by the Leighton contractors and Baulderstone Hornibrook Bilfinger Berger Joint Venture in supplying core samples along with other data regarding the Brisbane Tuff. The project was also assisted by Eric Muhling and Graham Ruhle who aided with the laboratory testing. The author also wishes to thank Dr. Shivakumar Karekal for supervising the project.

REFERENCES

Bilgin, N, Yazici, S and Eskikaya, Ş, 1996. A model to predict the performance of roadheaders and impact hammers in tunnel drivages, in *Proceedings of the Eurock '96 on Prediction and Performance in Rock Mechanics and Rock Engineering* (ed: G Barla) pp 715-720 (Balkema: Rotterdam).

Copur, H, Ozdemir, L and Rostami, J, 1998. Roadheader applications in mining and tunnelling, *Mining Engineering,* 50(3):38-42.

Farmer, I W and Garrity, P G, 1987. Prediction of roadheader cutting performance from fracture toughness considerations, *Sixth International Congress on Rock Mechanics,* 6(1):621-624.

Fowell, R J and Johnson, S T, 1982. Rock classification and assessment for rapid excavation, in *Strata Mechanics – Developments in Geotechnical Engineering vol 32* (ed: I W Farmer), pp 241-244 (Elsevier Scientific Publishing Company: Amsterdam).

International Society for Rock Mechanics, 1981. *Rock Characterisation Testing and Monitoring – ISRM Suggested Methods,* 211 p (Pergamon Press: Oxford).

Nelson, P P, Sinha R S and Handewith, H J, 1991. Machine excavation, in *Underground Structures: Design and Construction* (ed: R S Sinha), pp 227-307 (Elsevier: Amsterdam).

Sandbak, L A, 1985. Roadheader drift excavation at San Manuel, Arizona. RETC Proceedings, 1(2): 903-916.

Stevens, N, 1984. *Queensland Field Geology Guide,* pp 1-20 (Adam Advertising: Queensland).

Thuro, K and Plinninger, R J, 2003. Hard rock tunnel boring, cutting, drilling and blasting: rock parameters for excavatability, in *Proceedings 10th ISRM Congress,* pp 1227-1234 (SAIMM: Johannesburg).

Thuro, K and Plinninger, R J, 2004. Wear prediction in hardrock excavation using the CERCHAR Abrasive Index (CAI), in *Rock Engineering – theory and practice* (ed: Schubert), pp 599-604.