# A new methodology for the analysis of the relationship between rock brittleness index and drag pick cutting efficiency

by R.M. Goktan* and N. Gunes Yilmaz*


## Synopsis

**Rock brittleness plays an important role in the cutting action of picks on rock surfaces. It controls the ease with which cracks can propagate through the rocks. Although rock brittleness is known as a property that contributes to the cuttability of rocks, despite considerable research effort, there is still much uncertainty about the relation between rock brittleness and rock cutting efficiency. This fact can be attributed to the lack of a universally accepted brittleness concept and a brittleness measurement method.**

**The existing publications of some researchers have, in a way, tended to confuse the understanding of brittleness in the general field of rock excavation where it is expected that the energy consumption of cutting should decrease with increasing brittleness of rock, other conditions being equal. However, this sometimes conflicts with the brittleness concept commonly used in rock mechanics, where the more brittle the rock the higher its mechanical strength. The ratio of rock compressive strength to tensile strength is considered by many authors to give a valuable brittleness index for drag pick operations.**

**Hence, in this contribution the ratio of uniaxial compressive strength to tensile strength BI is considered as an index of rock brittleness, and a new methodology is proposed for its use in rock cutting efficiency analyses of drag tool operations. Validation of the suggested approach is supported by available experimental data in the literature. Contrary to the conclusions reached previously by other authors, it is shown that an increase in rock brittleness is accompanied by an increase in the cutting efficiency, other conditions being equal.**


**Keywords: brittleness index, rock brittleness, cutting efficiency, specific energy, rock excavation.**

## Introduction

Rock cutting is a breakage process with the formation of rock chips caused by crack propagation due to the action of the cutter picks. The brittleness of the rock plays an important role in the cutting action of the picks, controlling the ease with which cracks propagate through the rock to be cut. Crack propagation is the basic phenomenon for rock disintegration during the cutting process of mechanical excavators. Although rock brittleness is generally accepted as a property that contributes to the cuttability of rocks, the relationship between brittleness and rock cutting efficiency has not been fully established. Relatively little published material is available on the relationship between rock brittleness and rock cutting efficiency. This fact can be attributed to the lack of a universally accepted brittleness concept and a measurement method. Altindag[1] gave various definitions for rock brittleness, but a more common definition may be given as: the tendency to fracture without appreciable deformation under low stress[2]. Andreev[3] has reviewed about 20 different formulations and definitions of rock brittleness existing in the literature.

Perhaps due to the differences in the employed brittleness measurement methods, the existing publications of some researchers have, in a way, tended to confuse the understanding of brittleness in the general field of rock excavation. As indicated by Pozin *et al.*[4], rock brittleness is generally used in two different ways by different authors:

- as a physical measure of rock mechanical strength, or
- as a measure of energy consumption in the process of rock cutting or drilling.

Therefore, it is not surprising to find conflicting statements about the effect of rock brittleness on various cutting/drilling operations in the general field of rock excavation. For example, Cigla *et al.*[5] considers brittleness as a rock property, which the rock exhibits when subjected to the mechanical forces generated by the cutting action of an excavator, where cutting efficiency improves with increasing rock brittleness. However, according to some other authors[1,6], an increase in the rock brittleness is found to be accompanied by a higher specific energy of cutting, indicating low cutting efficiency. This fact can be attributed to the differences in the brittleness measurement methods employed by the authors.

---

* *Department of Mining Engineering, Osmangazi University, Eskisehir, Turkey.*

© *The South African Institute of Mining and Metallurgy, 2005. SA ISSN 0038–223X/3.00 + 0.00. Paper received Apr. 2005; revised paper received Aug. 2005.*

Although the concept and measurement method of rock brittleness has long been discussed and is not yet made precise, it is stated[7] that with higher brittleness the following facts are observed: formation of cracks in indentation, low values of elongation, fracture failure, formation of fines, and a higher ratio of compressive strength to tensile strength. Due to its wide use in the general field of rock excavation and rock mechanics, in this paper the ratio of uniaxial compressive strength to tensile strength is considered as a measure of rock brittleness, which herein will be named the brittleness index BI. The basic idea of the present study is to examine the relationship between BI and the rock cutting efficiency of drag tools. As the definition and measurement method of rock brittleness differs from one author to another and is still much discussed[1,8], the implication of whether BI could be used as a true representative of rock brittleness is beyond the scope of this paper.

An extensive literature survey carried out by the present authors reveals that, despite the wide use of BI in the general field of rock excavation and rock mechanics[1,3-29], there appears to be very few studies[1,6] in the published literature examining the relationship between BI and rock cutting efficiency. However, it may be interesting to note that so far no meaningful correlations could be found between BI and rock cutting efficiency in the published literature. In view of this fact, in this contribution a new methodology is suggested for the analysis of relationships between these two parameters. The presented approach is then confirmed by evaluating some available experimental data from the literature. It is strongly emphasized that the concept of brittleness adopted in this study is from the point of view of relative energy consumption of rock cutting, where it is expected that the cutting efficiency should improve with increasing rock brittleness.

## The brittleness index

The so-called BI (also termed *brittleness ratio*, the *brittleness coefficient* or the *ductility number* in the literature) is the ratio of uniaxial compressive strength $\sigma_c$ to tensile strength $\sigma_t$. It is perhaps the most widely used parameter for the quantification of rock brittleness. The higher the magnitude of BI, the more brittle the rock. A general rock classification based on brittleness index values is given in Table I.

The brittleness index is also accepted as an indicator for the mode of rock cutting. According to Gehring[18]; a value less than 9 indicates ductile cutting behaviour, 9–15 is average and > 15 indicates brittle cutting behaviour. Typical force displacement curves for a cutting tool cutting a ductile and a brittle rock are illustrated in Figure 1. It has been reported[30] that the forces needed to excavate a rock, which had failed in a ductile mode, were substantially higher than those required for a rock of comparable unconfined compressive strength, which had failed by brittle fracture.

*Table I*

**Rock brittleness classes[26]**

| Class | BI | Description |
|---|---|---|
| 1 | >25 | Very brittle |
| 2 | 15<BI<25 | Brittle |
| 3 | 10<BI<15 | Moderately brittle |
| 4 | BI<10 | Low brittleness |

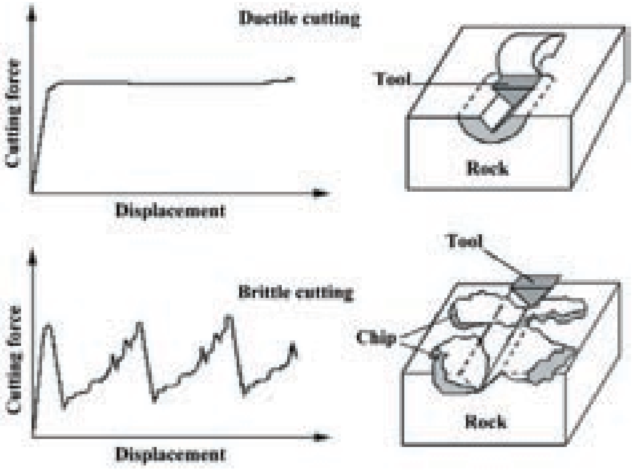


**Figure 1—Brittle and ductile mode of cutting[30]**

A comprehensive literature study conducted by Johnston[31] reveals that BI usually ranges from 5 to 35, and varies considerably as a function of uniaxial compressive strength $\sigma_c$ and rock type. For a given rock group, an increase in the brittleness index is accompanied by an increase in uniaxial compressive strength as follows:

$$BI = 2.065 + k(log\ \sigma_c)^2 \qquad [1]$$

where $k$ is dependent on rock type as grouped by Hoek[32] (Table II) taking values from 0.170 to 0.659 , and $\sigma_c$ is expressed in kilopascals. As will be discussed later, the relationship given in Equation [1] is of great consequence in analyses of the effect of brittleness on relative rock cutting efficiency.

## Rock cutting efficiency

The efficiency of a given rock cutting process is measured by the parameter specific energy SE, which is defined as the amount of work done in excavating a unit volume of rock. Specific energy is the most widely used parameter to measure the efficiency of a rock cutting system within a given rock, with lower values indicating higher efficiencies. In the field, it can be calculated by relating the energy absorbed by the cutter motor to the measured volume of rock[33]. Using a standard rock cutting rig, it can also be used to compare the relative cuttability of different rock types in the laboratory. SE is calculated as follows[34]:

$$SE = FC/Q \qquad [2]$$

where SE is the specific energy (MJ/m$^3$), FC is the mean cutting force (kN), and Q is the volume of excavated material per unit length of cut (m$^3$/km).

A review of the literature shows that SE is not a fundamental intrinsic property of rock. It is greatly influenced by the cutting depth and cutting geometry of the tool, as well as the mechanical strength of the rock. An extensive research by Roxborough[35], conducted under standard laboratory cutting test conditions, indicated that SE increases linearly with the uniaxial compressive strength of rock in the form:

*Table II*

**Grouped rock types[32]**

| Rock group | Material type |
|---|---|
| Group a | Carbonate materials with well-developed crystal cleavage (e.g., limestone, dolomite and marble) |
| Group b | Lithified argillaceous materials (e.g., mudstone, shale, clay) |
| Group c | Arenaceous materials with strong crystals and poorly developed crystal cleavage (e.g., sandstone and quartzite) |
| Group d | Fine-grained polymineralic igneous crystalline materials (e.g., andesite, dolerite, diabase and rhyolite) |
| Group e | Coarse-grained polymineralic igneous and metamorphic materials (e.g., granite, gabro, gneiss) |

$$SE = 0.25\,\sigma_c + C \qquad [3]$$

where $C$ is a material constant. Roughly similar trends emphasizing the effect of compressive strength on SE can also be found in the works of other researchers[36–39].

Perhaps the most widely recognized and most frequently cited drag pick theory was presented by Evans[40]. The model is based on tensile failure of rock under the action of a cutter pick. As the pick moves into the rock, tensile cracks radiate from the tip of the wedge until they meet a free surface, whereupon failure occurs (Figure 2a). Roxborough[34] used the basic features of this failure model to determine the specific energy SE of rock cutting theoretically:

$$SE = FC/R\left(Wd + d^2 tan\theta\right) \qquad [4]$$

where $FC$ is the mean peak cutting force, $R$ is the ratio between mean peak cutting force and mean cutting force, $W$ is the pick width, $d$ is the depth of cut, and $\theta$ is the breakout angle for rock. It is now well established that the cutting action of picks is primarily an indentation action. As the development of cracks in indentation is a direct function of rock brittleness, it can be expected that a more brittle rock is characterized by larger breakout angle values (Figure 2b). Consequently, Equation [4] implies that, other conditions being equal, the specific energy will decrease in the case of higher brittleness, indicating higher cutting efficiency.

## Proposed methodology for the analysis of the relationship between brittleness index and rock cutting efficiency

From the brief review above, it is possible to draw the following important conclusions:

- an increase in the brittleness index of a rock material is generally accompanied by an increase in its mechanical strength such as the uniaxial compressive strength
- brittleness index is a function of the rock type
- rock cutting specific energy is directly proportional to the uniaxial compressive strength of rock.

These findings point out the necessity of adopting a different methodology to relate rock brittleness to cutting efficiency, rather than following the conventional means. The details of such an approach are given below.

Laboratory rock cutting experiments can provide the fundamental information for choosing and designing the most efficient cutting system for a particular rock type. A common criterion adopted for the efficiency of cutting is the specific energy obtained from standard laboratory cutting tests. In this work, in an attempt to examine the relationship between brittleness index and specific energy, data derived from some available standard laboratory rock cutting experiments[41,42] were evaluated. The experimental conditions for the standard cutting tests are given in Figure 3. Mechanical properties of the tested rocks and the measured specific energy values are given in Table III.

Valid for the standard cutting conditions and for all types of tested rocks, the variation of brittleness index with specific energy is illustrated in Figure 4. As can be seen from Figure 4, the data show significant scatter, not allowing any trends to be deduced between brittleness index and specific energy. So far, this finding is in agreement with the results obtained from previous works of other researchers[1,6], where no meaningful correlations could also be found between these two parameters.

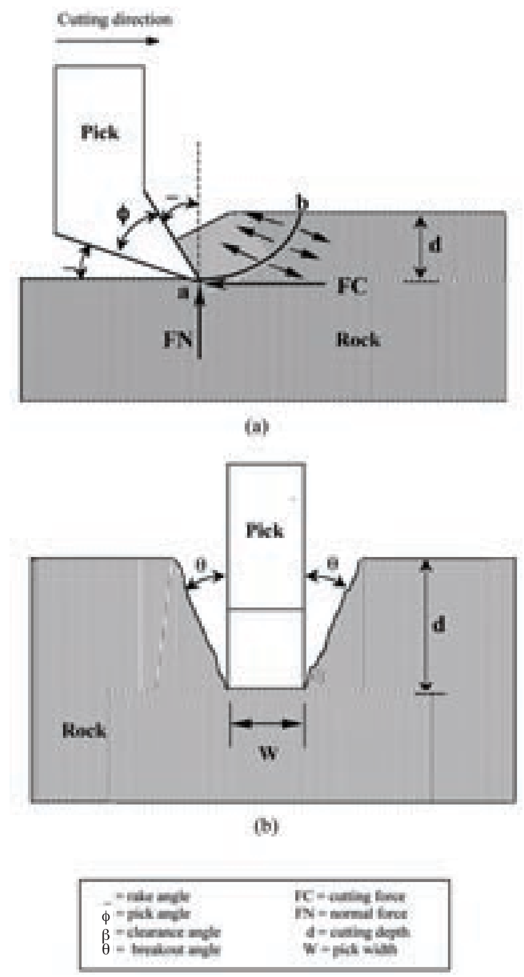


**Figure 2—Tensile breakage model of Evans (a), simplified groove geometry (b)**

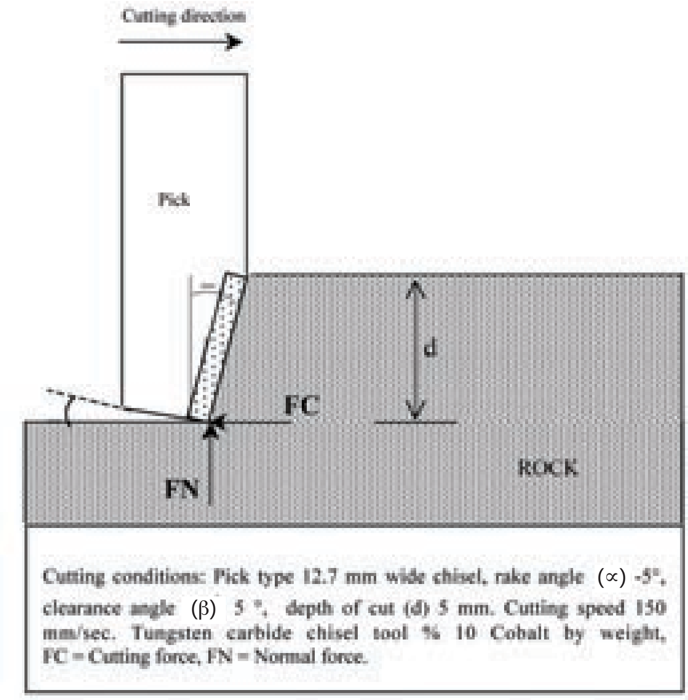


**Figure 3—Details of standard laboratory cutting conditions**

*Table III*

**Rock properties and specific energy values of the tested rocks**

| Rock type | Uniaxial compressive strength $\sigma_c$, Mpa | Tensile strenght* $\sigma_t$ MPa | Brittleness index** BI | Specific energy SE, MJ/m$^3$ |
|---|---|---|---|---|
| 1. Sandstone | 8.0 | 1.1 | 7.27 | 5.60 |
| 2. Sandstone | 7.0 | 1.0 | 7.00 | 6.10 |
| 3. Sandstone | 41.0 | 1.8 | 22.70 | 7.70 |
| 4. Sandstone | 18.0 | 2.4 | 7.50 | 9.40 |
| 5. Sandstone | 23.0 | 3.9 | 5.89 | 15.40 |
| 6. Sandstone | 48.0 | 2.7 | 17.70 | 11.50 |
| 7. Sandstone | 120.0 | 7.7 | 15.58 | 4.30 |
| 8. Sandstone | 37.0 | 7.8 | 4.74 | 20.50 |
| 9. Grit | 58.0 | 4.2 | 13.80 | 18.50 |
| 10. Grit | 37.0 | 2.5 | 14.80 | 14.40 |
| 11. Sandstone | 156.0 | 7.3 | 21.36 | 26.40 |
| 12. Sandstone | 117.0 | 8.9 | 13.15 | 22.10 |
| 13. Mudstone | 18.0 | 5.1 | 3.53 | 9.60 |
| 14. Mudstone | 32.0 | 3.7 | 8.45 | 9.00 |
| 15. Mudstone | 23.0 | 7.4 | 3.10 | 5.30 |
| 16. Mudstone | 47.0 | 6.9 | 6.81 | 6.90 |
| 17. Seatearth | 24.0 | 6.6 | 3.64 | 4.60 |
| 18. Seatearth | 27.0 | 6.6 | 4.10 | 5.70 |
| 19. Limestone | 170.0 | 9.2 | 18.47 | 30.30 |
| 20. Limestone | 133.0 | 6.4 | 20.78 | 28.10 |
| 21. Limestone | 144.0 | 7.9 | 18.23 | 32.30 |
| 22. Limestone | 134.0 | 8.6 | 15.58 | 25.80 |
| 23. Sandstone | 62.0 | 3.5 | 17.71 | 9.75 |
| 24. Sandstone | 21.3 | 1.9 | 11.21 | 6.87 |
| 25. Sandstone | 48.2 | 2.5 | 19.28 | 9.97 |
| 26. Sandstone | 87.5 | 6.3 | 13.88 | 20.78 |
| 27. Sandstone | 55.7 | 4.3 | 12.95 | 12.00 |
| 28. Sandstone | 44.3 | 4.5 | 9.84 | 17.07 |

Raw test data from 1 to 22 were referred to McFeat-Smith and Fowell[41], and from 23 to 28 were referred to Tiryaki *et al.*[42].
*Measured in the Brazilian test
**Calculated by the present authors

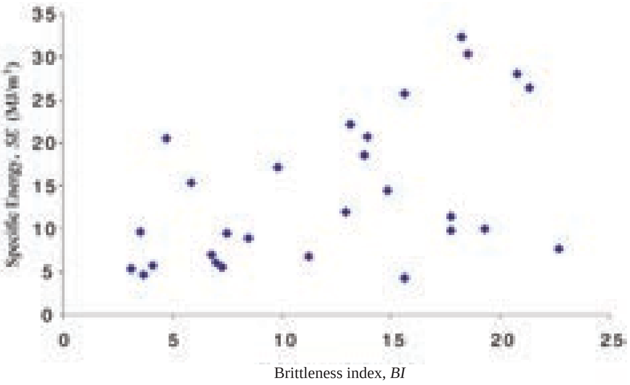


**Figure 4—Relation between BI and SE for all tested rock types**

Figure 5 shows the relation between uniaxial compressive strength and specific energy for all tested rock types, where specific energy increases in a linear manner with increasing compressive strength. Considering this fact, in order to be able to eliminate the effect of rock mechanical strength, and thus obtain comparable relations between brittleness index and specific energy, normalization of specific energy with respect to uniaxial compressive strength is thought to be a convenient approach. The normalization process seems to be logical because of the good linear relation between these two parameters.

The variation of the brittleness index BI with normalized specific energy $SE_n$, for all tested rock types, is presented in Figure 6. As can be seen from Figure 6, following the normalization process the data still shows significant scatter, not allowing an accurate expression of any relation between these two variables. Therefore, considering that BI is also a function of rock type, the normalization process is now applied for a particular group of rocks, namely the arenaceous rocks given in Table II. After separation of the data given in Table III for arenaceous rocks, the correlation is significantly improved (Figure 7). Obviously, normalization with respect to uniaxial compressive strength and the subsequent categorization of data for a particular rock group has resulted in a better defined correlation between these two variables. Figure 7 indicates that relative cutting efficiency improves with an increase in the brittleness index.

The presented methodology is particularly important from the point view of providing a suitable means of relating rock brittleness to cutting efficiency. Furthermore, the trend obtained is in line with the common expectation among the researchers that the relative energy consumption of cutting should decrease with increasing brittleness. As the brittleness of rock is not the only rock property affecting specific energy in a particular application, the established degree of correlation between BI and $SE_n$ in Figure 7 may be regarded as satisfactory for this field of rock cutting mechanics.

Although the relations in Figure 7 refer specifically to only one group of rocks, it is considered that the approach adopted can also be successfully applied for other rock groups, as categorized in Table II. As there is statistically insufficient data, no attempt was made to examine the correlations between BI and $SE_n$ for other rock groups given in Table III.

Finally, it may also be interesting to note that the brittleness index BI adopted in this work may be correlated with another brittleness index B often mentioned in the literature[1,3,6,7,10,11,43], which is formulated as:

$$B = (\sigma_c - \sigma_t)/(\sigma_c + \sigma_t) \quad [5]$$

Figure 8 indicates that BI is highly correlated with B for the arenaceous rock group given in Table III. However, a high correlation between these two variables was also found in a previous study[10] for other rocks that belong to different groups. As can be expected, a similar trend to that illustrated in Figure 7 was also observed between B and $SE_n$ for arenaceous rocks (Figure 9 ).

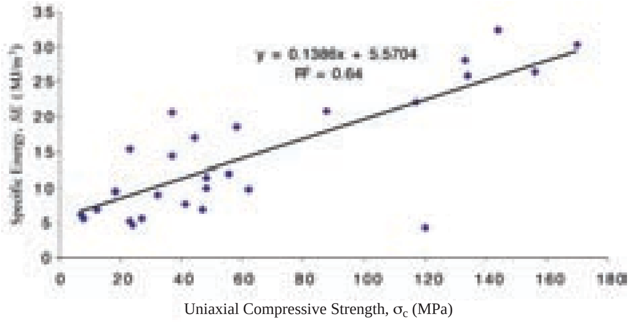


**Figure 5—Relation between $\sigma_c$ and SE for all tested rock types**

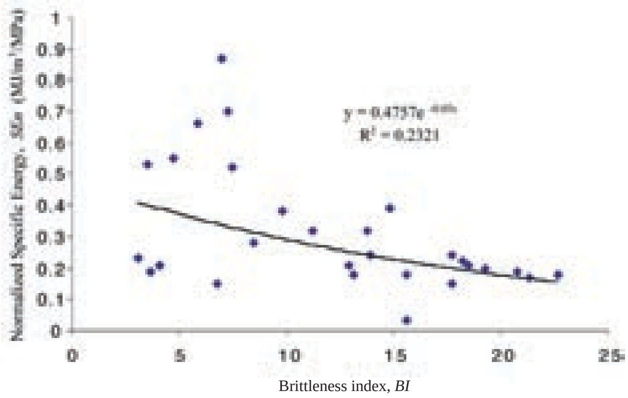


**Figure 6—Relation between BI and $SE_n$ for all tested rock types**

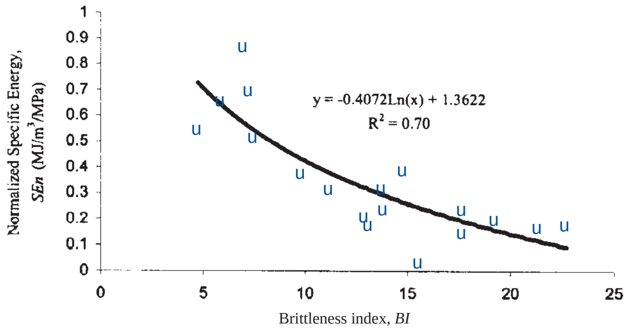


**Figure 7—Relation between BI and $SE_n$ for arenaceous rocks**

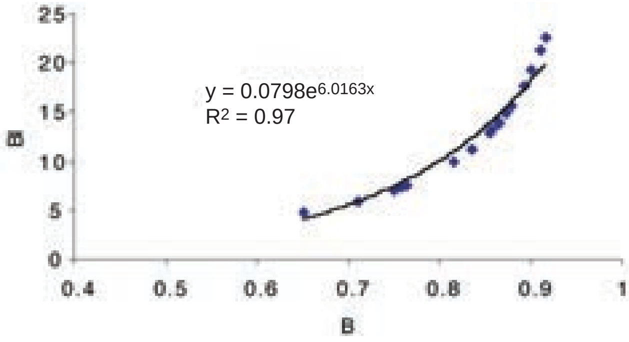


**Figure 8—Plot of B versus BI for arenaceous rocks**

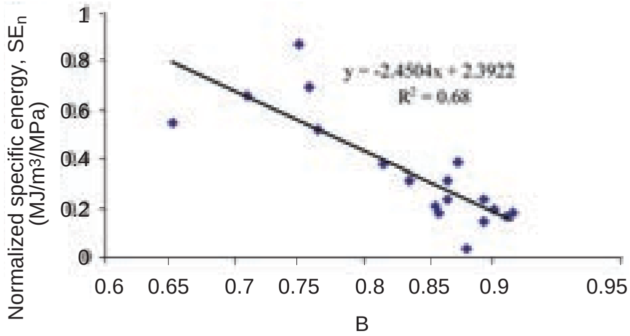


**Figure 9—Relation between B and SE$_n$ for arenaceous rocks**

## Conclusions

In order to be able to gain a better understanding of the cutting process and to create an optimum pick design, there is a need to examine the relationships between rock properties and cutting efficiency of mechanical excavators. Although brittleness is one of the most important properties of rocks, relatively little published material is available on its relationship with rock cutting efficiency. This fact can be partly attributed to a lack of a universally accepted brittleness concept and a measurement method. There is a large number of tests for the determination of rock brittleness, but none has yet gained general acceptance for a particular application. Therefore, it seems that a brittleness concept and a measurement method relevant to rock excavation need to be established. This contribution is a step in this direction.

In this study it was intended to examine the relationships between rock brittleness and cutting efficiency of drag picks. To achieve this goal, the raw data obtained from two independent standard laboratory rock cutting experiments were evaluated in this respect. The ratio of rock uniaxial compressive strength to tensile strength, namely the brittleness index, was adopted for the quantification of rock brittleness. Also, specific energy of rock cutting SE was adopted for the quantification of cutting efficiency. In the first stage of the analysis, valid for all tested rock types, no meaningful correlations could be found between BI and SE, which is in line with the findings of other researchers surveyed in the literature. However, after normalization of SE by uniaxial compressive strength and classification of test data for a particular rock group, the correlation is significantly improved. In this case, the established correlation indicates that relative rock cutting efficiency improves with increasing rock brittleness, other conditions being equal.

Considering the unsuccessful attempts of previous authors to establish correlations between rock brittleness and cutting efficiency, the results so far obtained in this contribution suggest that the proposed methodology could be a useful tool in this field of rock cutting mechanics.

It should be pointed out that the basic aim of this study was to analyse the fundamental relationship between rock brittleness and cutting efficiency based on laboratory determinations, without taking into account the possible effects of various *in situ* conditions. While it shows a promising technique, it is emphasized that the validity of the presented approach should be further investigated for other rock types and cutting conditions.

## References


1. ALTINDAG, R. Correlation of specific energy with rock brittleness concepts on rock cutting. *The Journal of the South African Institute of Mining and Metallurgy*, vol. 103, no. 3, 2003, pp. 163–171.
2. *Chambers Dictionary of Science and Technology*. Chambers Harrap Publishers, vol. 1, 1978, p. 156.
3. ANDREEV, G.E. *Brittle failure of rock materials*. Balkema/Rotterdam,1995, p. 446.
4. POZIN, E.Z., MELAMED, V.Z., and AZOVTSEVA, S.M. Towards a method of quantitative assessment of the cuttability of coals. *Soviet Min. Sci.*, vol. 15, 1979, pp. 573–581.
5. CIGLA, M., YAGIZ, S., and OZDEMIR, L. Application of tunnel boring machines in underground mine development. *17th International Mining Congress and Exhibition of Turkey*, Ankara, Turkey, 2001, pp. 155–164.
6. COPUR, H., BILGIN., TUNCDEMIR, H. and BALCI, C. A set of indices based on indentation tests for assessment of rock cutting performance and rock properties. *The Journal of the South African Institute of Mining and Metallurgy*, vol. 103, no. 9, 2003, pp. 589–600.
7. HUCKA, V. and DAS, B. Brittleness determination of rocks by different methods. *Int.J.Rock Mech.Min.Sci. and Geomech. Abstr.* vol. 11, 1974, pp. 389–392.
8. DENKHAUS, H.G. Comment on 'The evaluation of rock brittleness concept on rotary blast hole drills and correlation of specific energy with rock brittleness concepts on rock cutting', in *The Journal of the South African Institute of Mining and Metallurgy*, vol. 103. no. 8, 2003, pp. 523–525.
9. ALTINDAG, R. The evaluation of rock brittleness concept on rotary blast hole drills. *The Journal of the South African Institute of Mining and Metallurgy*, vol. 102, no. 1, 2002, pp. 61–66.
10. KAHRAMAN, S. Correlation of TBM and drilling machine performances with rock brittleness. *Eng.Geol.*, vol. 65, 2002, pp. 269–283.
11. GOKTAN, R.M. Brittleness and micro-scale rock cutting efficiency. *Mining Science and Technology*, vol. 13,1991, pp. 227–241.
12. GOKTAN, R.M. Rock brittleness ratio and its applicability on percussive drilling performance analyses (In Turkish), *Journal of Engineering and Architectural Faculty of Anadolu University*, vol. 8, no. 1, 1992, pp. 90–99.
13. YOSHINA, R. and YAMABE, T. A strength criterion of rocks and rock masses. *Proc. of the Int. Symp. on Weak Rock*, Tokyo, 21–24 Sept. 1981, pp. 613–618.
14. INYANG, H.I. Development of a preliminary rock mass classification scheme for near-surface excavation, *Int. J. of Surface Mining and Reclamation*, vol. 5,1991, pp. 65–74.
15. ROGERS, S and ROBERTS, B. Wear mechanisms associated with rock excavation using point attack picks. *Mining Science and Technology*, vol. 12, 1991, pp. 317–323.
16. ATCHISON, T.C. Fragmentation principles. *Surface Mining*, E.P, Pfleider, (ed.) AIME, Seeley Int. Mudd Ser., 1968.
17. SATAKE, M. and TANO, H. Consideration on the fracture modes and strength of rocks under compression test. *Rock Mechanics in Japan*, vol. 2, 1974, pp. 52–54.
18. GEHRING, K. Rock testing procedures at VA's geotechnical laboratory in Zeltweg. Internal report TZU 41, Voest Alpine Zeltweg, Austria, 1987.
19. VERHOEF, P.N.W. Abrasivity of Hawkesbury sandstone in relation to rock dredging. *Quart. J. of Engng. Geo.*, vol. 26, 1993, pp. 5–17.
20. MITANI, I. and KAWAI, T. Experimental study on relationship between engineering properties of rock and mechanical drilling characteristics. *Rock Mechanics in Japan*, 1974, vol. 2, pp. 124–126.
21. BECKER, H., LEMMES, F., and SCHOMER, M. Testing of rock mechanics as a basis for improved cutting technology. *Gluckauf + Translation*, vol. 120 no. 8, 1984, pp. 122–124.

22. BARDET, J.P. Numerical modeling of a rockburst as surface buckling, *Rockbursts and seismicity in mines*, Fairhust (ed.), Balkema, Rotterdam, 1990, pp. 81–85.

23. GOKTAN, R.M. Prediction of drag bit cutting force in hard rocks, *Proc. of the 3rd Int. Symp. on Mine Mechanization and Automation*, Golden, Colorado, USA, vol. 1, 1995, pp. 10–31/10–38.

24. GOKTAN, R.M. A theoretical performance comparison of drag picks in relation to coal strength parameters, *Journal of the South African Institute of Mining and Metallurgy*, vol. 92, no. 4,1992, pp. 85–88.

25. HAGAN, P.C. Some aspects of the application of high pressure water jets to rock cutting. PhD thesis, The University of South Wales, Australia, 1990.

26. AFTES, Guidelines for characterization of rock masses useful for the design and the construction of underground structures, *Tunnels et ouvrages Souterrains*, no. 177, Mail / Juin, 2003, p. 49.

27. KRAMADIBRATA, S. The influence of rock mass and intact rock properties on the design of surface mines with particular reference to the excavatability of rock. PhD thesis, Curtin University of Technology School of Civil Engineering, 1996, p. 492.

28. THURO, K. Drillability prediction: geological influences in hard rock drill and blast tunneling. *Geol.Rundsch*, vol. 86, 1997, pp. 426–438.

29. ALTINDAG, R. The estimate of rock brittleness concepts in percussive drilling performance. *ISRM Regional Symposium on Advancing Rock Mechanics Frontiers to Meet the Challenges of 21st Century*, 24–27 September 2002, New Delhi.

30. DEKETH, H.J.R., ALVAREZ GRIMA, M., HERGARDEN, I.M., GLEZEN, M., and VERHOEF, P.N.W. Towards the prediction of rock excavation machine performance. *Bull. Eng. Geol. Env*., vol. 57, 1998, pp. 3–15.

31. JOHNSTON, I.W. Strength of intact geomechanical materials. *Journal of Geotechnical Engineering ASCE*, vol. 3, no. 6, 1985, pp. 730–747.

32. HOEK, E. Strength of jointed rock masses. *Geotechnique*, vol. 33, no. 3, 1983, pp. 187–223.

33. FOWELL, R.J. and MCFEAT-SMITH, I. Factors influencing the cutting performance of a selective tunnelling machine. *Tunnelling '76 Symposium*, London, March 1976, pp. 301–309.

34. ROXBOROUGH, F.F. Cutting rock with picks. *Min. Engr*., vol. 132, 1973, pp. 445–454.

35. ROXBOROUGH, F.F. The role of some basic rock properties in assessing cuttability. *Seminar on Tunnels, Wholly Engineered Structures*, I.E Aust/A.F.C.C, Sydney, Australia, April 1987, p. 21.

36. BALCI, C., DEMIRCAN, M.A., COPUR, H., and TUNCDEMIR, H. Estimation of optimum specific energy based on rock properties for assessment of roadheader performance. *The Journal of the South African Institute of Mining and Metallurgy*, vol. 104, no. 11. 2004, pp. 633–645.

37. COPUR, H., TUNCDEMIR, H., BILGIN, N., and DINCER, T. Specific energy as a criterion for the use of rapid excavation systems in Turkish mines. *Mining Technology: IMM Transactions Section A*, vol. 110, no. 3, 2001, pp. 149–157.

38. KEL, K. Investigation of the cuttability of coal measure rocks in Zonguldak coal basin. PhD thesis (In Turkish), Zonguldak Karaelmas University, 2003, p. 181.

39. SNOWDEN, R.A., RYLEY, M.D., and TEMPORAL, J. A study of disc cutting in selected British rocks. *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr*., vol. 19, 1982, pp. 107–121.

40. EVANS, I. A theory on the basic mechanics of coal ploughing. *Proc. Int. Symp. On Min. Res*., London, Pergamon Press, Oxford, vol. 2, 1962, pp. 761–798.

41. MCFEAT-SMITH, I. and FOWELL, R.J. Correlations of rock properties and the cutting performance of tunnelling machines. *Proc. of Conf. Rock Engineering*, University of New Castle Upon Tyne, 4–7 April, 1977, pp. 585–602.

42. TIRYAKI, B., DIKMAN, A., KADIOGLU, Y.K., OZBILGIN, D., TIRYAKI, N., and BOLUKBASI, N. Application of texture coefficient concept for the prediction of pick performance in rock cutting (in Turkish). *The Journal of the Chamber of Mining Engineers of Turkey*, vol. 42, 2003, pp. 27–43.

43. KAHRAMAN, S. and ALTINDAG, R. A Brittleness index to estimate fracture toughness. *International Journal of Rock Mechanics and Mining Sciences*, vol. 41, Feb. 2004, pp. 343–348. u


Transaction Paper

# Mintek's 'Smartbolt' wins an SABS 2005 Prototype Award*

Fatal accidents caused by gas explosions, rock falls, breaches of health and safety regulations, not to mention seismic activities, remain a grim reality for the South African mining industry, resulting in the death of hundreds of miners every year.

An innovative safety monitoring device has now been designed and developed for the mining industry by Mintek to warn of changing mine roof conditions. For the development of this innovation in mine safety, Mintek's Smartbolt' prototype has won a coveted SABS 2005 Prototype Award.

Due to the large number of rockfall events that occur in South Africa's mines, and the danger associated with such events, Mintek, together with the Safety in Mines Research Advisory Committee (SIMRAC) have for the past few years been involved in a research project focusing on the development of a Smartbolt for underground rock monitoring operations.

The Smartbolt is installed along with conventional carbon steel rock bolts in mine roofs for added protection and safety underground. It enables rock engineers to measure changes in sound velocity in the bolt, with an ultrasound monitoring device.

This technique will help to promote safety in the mining industry. Information can be gathered and logged quickly to determine whether any bolts have been bent, broken or overloaded. Here the Smartbolt will be an extension of applying good safety practices in the mining environments.

If a Smartbolt was located in an area that collapsed, and one was able to recover the bolt, it would also be possible to determine the extent of damage from the information that was recorded earlier, prior to the rockfall.

Features and benefits of the prototype include that when stressed, this metastable bolt undergoes a microstructural transformation. Depending on the degree of loading, the bolt's properties will change from non-magnetic to magnetic, resulting in a change in longitudinal sound velocity, which warns of changing mine roof conditions.

Where the conventional steel rockbolt will equalize the tension in the mine, the Smartbolt will enable rock engineers to anticipate and record rock movement. The two systems are expected to complement one another. A portable ultrasonic (USM 25 DAC) monitoring device is used to measure sound velocity along the length of the bolt. Its probe is applied to the head of the Smartbolt, which enables rock engineers to monitor the change in the microstructure that results from the stresses exerted on the Smartbolt by the changing mining roof conditions.

The Smartbolt acts as a sensor for the determination of stresses in mine workings. An additional attribute of the Smartbolt alloy is that its chemical composition allows it to be functional in mines containing highly corrosive mine water. In addition, the results from the characterisation programme also show that the Smartbolt alloy has a good combination of high strength and durability. This makes it a suitable sensor candidate for extreme conditions of high tensile and shear stresses, similar to conventional roof bolts.

Smartbolt technology was developed based on the use of metastable austenitic materials and the concept of integrated 'smart' structures/sensors. The structural monitoring systems that are currently being developed around the world are mainly based on the use of new sensor technology/capabilities. The materials used for the production of these sensors are commonly known as 'smart' materials.

A Smartbolt is a metastable austenitic stainless steel alloy with a smooth metallic surface finish. Its length varies according to different mine roof requirements. Its shape and form is different from the conventional carbon steel bolts because its outer is not ribbed.

Unique features and benefits of the Smartbolt include:

The Smartbolt is interrogated with a portable ultrasonic USM 25 DAC device, which measures the longitudinal sound velocity to assess any structural change. The probe is applied to the head of the Smartbolt and the sound velocity feedback is used to assess microstructural changes that have accorred in the roof bolt as a result of the stress exerted on it

- It is durable and permanent
- It requires no active (unreliable, bulky) circuitry or online monitoring. Calibration is done at the factory
- Variation of the alloy compositions can provide a wide range of measurable strains
- It has a good environmental stability such as corrosion resistance
- Minimal space is required
- It is installed in the conventional way along with the other rockbolts.

The alloy of the Smartbolt is ideally suited to be used as a strain monitor in tunnelling and mining applications as it meets the following requirements:

- A yield strength similar to existing carbon steel rockbolts
- The ability to withstand conditions of high tensile and shear stress
- Resistant to corrosion in the mining industry
- Low incubation strain for transformation
- Ease of manufacturing and monitoring using a simple conventional technique.

Smartbolts are cement bonded and mechanically anchored so that when the rocks become loose during blasting, the cement can hold the bolts.

The smartbolts are currently being tested at one of the local gold mines on the West Rand. Further work is planned to gather complete and definitive field test data using the Smartbolt technology to demonstrate the efficacy of using the developed rockbolt alloy as a monitoring device for varied mining loading conditions covering the following possible situations:

- Underloading/no rockfalls;
- Moderate loading/no rockfalls
- Overloading/rockfalls.

After this the product will be introduced to mining companies on a commercial scale with a commercialization partner.

---

* *Issued on behalf of: Mintek, Johannesburg, Erna Harmse, Tel: (011) 709-6035*
*Issued by: Hans Alink, Tel: (011) 709-4265, Cell: 082 551 6857, e-mail: hansa@mintek.co.za*