Sawability prediction of carbonate rocks from brittleness indexes

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Synopsis

Performance measurements of large-diameter circular saws were conducted on eight different carbonate rocks in marble factories located in some areas of Turkey. Rock samples were collected from these factories for laboratory tests. Uniaxial compressive strength, tensile strength and impact strength were determined in the laboratory. The brittleness of B_3 (the ratio of compressive strength minus tensile strength to compressive strength plus tensile strength), the brittleness of B_5 (the product of percentage fines in the impact strength test and compressive strength) and the brittleness of B_8 (half of the product of compressive strength and tensile strength) were calculated from the test results. Hourly slab productions were correlated with brittleness indexes. It was concluded that sawability of carbonate rocks can best be predicted from the brittleness of B_8.

Introduction

Large-diameter circular saws drills have been extensively used in stone processing plants. The prediction of rock sawability is very important in the cost estimation and the planning of the plants. Rock sawability depends on machine characteristics, type and diameter of saw, depth of cut, rate of sawing and tool wear, and rock properties. Some researchers have investigated the relations between sawability and rock properties. Norling (1971) correlated sawability with petrographic properties and concluded that grain size was more relevant to sawability than the quartz content. Burgess (1978) proposed a regression model for sawability, which was based on mineralogical composition, hardness, grain size and abrasion resistance. Wright and Cassapi (1985) tried to correlate the pertographic analysis and physical properties with actual sawing results. The research indicated that cutting forces have the closest correlation. Hausberger (1989) concluded, by studying work by other authors, that the higher the proportion of minerals with well-defined cleavage planes, the easier the stone is to cut. Unver (1996) developed predictive equations for the estimation of specific wear and cutting force in rock sawing. Clausen *et al*. (1996) carried out a study of the acoustic emission during single diamond scratching of granite and suggested that acoustic emission could classify the sawability of natural stone. They also concluded that the cutting process is affected by the properties and frequency of minerals, grain size and degree of interlocking. Ceylanoglu and Gorgulu (1997) correlated specific cutting energy and slab production with rock properties and found good correlations. Brook (2002) developed a new index test, called Brook hardness, which has been specifically developed for sliding diamond indenters. The consumed energy is predictable from this new index test.

Brittleness is an important mechanical property of rocks. However, there is no available published material on the relationship between brittleness and sawability. In this study, the correlations between sawability and different brittleness were analysed using regression analysis.

Brittleness

Brittleness is one of the most important mechanical properties of rocks. Nevertheless, there is no agreement between different authors as to definition, concept or measurement of brittleness. Different researchers mean, express and use it differently. Morley (1944) and Hetényi (1966) define brittleness as the lack of ductility. Materials, such as cast iron and many rocks that usually fail by fracture at or only slightly beyond the yield stress, are defined as brittle by Obert and Duvall (1967). Ramsay (1967)

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defines brittleness as follows: 'when the internal cohesion of rocks is broken, the rocks are said to be brittle.' The definition of brittleness as a mechanical property varies from author to author. However, it may be stated that with greater brittleness the following facts are observed (Hucka and Das, 1974):

- low values of elongation
- fracture failure
- formation of fines
- higher ratio of compressive to tensile strength
- higher resilience
- higher angle of internal friction
- formation of cracks in indentation.

Different definitions of brittleness summarized by Hucka and Das (1974) are formulated as follows:

$$B_1 = \frac{\varepsilon_r}{\varepsilon_t} \quad [1]$$

where B_1 is the brittleness determined from the percentage of reversible strain determined from the stress-strain curve, ε_r is the reversible strain, and ε_t is the total strain.

$$B_2 = \frac{W_r}{W_t} \quad [2]$$

where B_2 is the brittleness determined from the percentage of reversible energy determined from the stress-strain curve, W_r is the reversible energy, and W_t is the total energy.

$$B_3 = \frac{\sigma_c - \sigma_t}{\sigma_c + \sigma_t} \quad [3]$$

where B_3 is the brittleness determined from compressive and tensile strengths, σ_c is the uniaxial compressive strength, and σ_t is the tensile strength.

$$B_4 = Sin\theta \quad [4]$$

where B_4 is the brittleness determined from Mohr's envelope (at σ_n=0) , and θ is the angle of internal friction.

$$B_5 = q\sigma_c \quad [5]$$

where B_5 is the brittleness from the Protodyakonov (1963) impact test, σ_c is the uniaxial compressive strength, and q is the percentage of fines (-28 mesh) formed in the Protodyakonov impact test.

$$B_6 = \frac{H_\mu - H}{K} \quad [6]$$

where B_6 is the brittleness from macro-hardness and micro-hardness, H_μ is the micro-indentation hardness, H is the macro-indentation hardness, and K is a constant.

Hucka and Das (1975) defined a brittleness obtained from load-deformation curves. This definition of brittleness can be formulated as follows:

$$B_7 = \frac{W_{rs}}{W_t} \quad [7]$$

where B_7 is the penetration brittleness determined from the percentage of reversible energy in the load-deformation curve, W_{rs} is the reversible strain energy just before failure, and W_t is the total energy supplied just before failure.

Altindag (2000) suggested a new brittleness obtained from compressive and tensile strength. This new brittleness is defined as the area under the curve of the compressive strength-tensile strength plot and can be formulated as follows:

$$B_8 = \frac{\sigma_c \sigma_t}{2} \quad [8]$$

where B_8 is the brittleness determined from compressive and tensile strength, σ_c is the uniaxial compressive strength, and σ_t is the tensile strength.

Evans and Pomeroy (1966) theoretically showed that the impact energy of a cutter pick is inversely proportional to brittleness. Singh (1986) indicated that cuttability, penetrability, and the Protodyakonov strength index of coal strongly depended on the brittleness of coal. Singh (1987) showed that a directly proportional relationship existed between *in situ* specific energy and brittleness of three Utah coals. Goktan (1991) stated that the brittleness concept adopted in his study might not be a representative measure of rock cutting specific energy consumption. Altindag (2000, 2002, and 2003) found significant correlations between his new brittleness concept (Equation [8]) and the penetration rate of percussive drills, the drillability index in rotary drilling, and the specific energy in rock cutting. Kahraman (2002) statistically investigated the relationships between three different brittleness and both drillability and borability using the raw data obtained from the experimental works of different researchers. He concluded that each method of measuring brittleness has its usage in rock excavation, depending on practical utility, i.e. one method of measuring brittleness shows good correlation with the penetration rate of rotary drills, while the other method does not. Kahraman and Altindag (2003) correlated fracture toughness values with different brittleness values using the raw data obtained from the experimental works of two researchers. They indicated that the Altindag's brittleness concept (Equation [8]) can be used as a predictive rock property for the estimation of the fracture toughness value.

Field studies

Marble factories in the Kayseri, Konya and Antalya areas of Turkey were visited and the sawing performances of large-diameter circular saws were measured on eight different carbonate rocks. Performance studies were carried out on the machines operating under approximately the same conditions. The diameter and the revolution per minute of the saw in cutting, the advance rate of the saw, the depth of the cut, the dimensions of the slabs, the number of slabs cut per hour, etc. were recorded in the performance forms (Table I) during performance studies. The revolutions per minute of the saws were measured with a stroboscope. Factory names, the locations and the names of the rocks sawn, and the hourly slab production are given in Table II.

Laboratory studies

Rock blocks were collected from the factories for laboratory tests. An attempt was made to collect rock samples that were large enough to obtain all of the test specimens of a given rock type from the same piece. Each block sample was inspected for macroscopic defects so that it would provide

Table I

The performance forms for observations

Observation no.	1	2	3	4	5	6	7	8
Date	25 October 2001	26 October 2001	26 October 2001	25 August 2001	4 September 2001	26 July 2001	28 July 2001	26 August 2001
Factory name	Kamer Mermer	Derinkok Mermer	Toros Mermer	Akmera,s	Model	Kombassan	Kombassan	Kombassan
Factory location	Kayseri (Turkey)	Kayseri (Turkey)	Kayseri (Turkey)	Konya (Turkey)	Antalya/ (Turkey)	Konya (Turkey)	Konya (Turkey)	Konya (Turkey)
Machine model	MKS-four footed	Breton-two footed	Two footed footed	MKS-four footed	Esmas-four footed	Breton-two footed	Mermak-four footed	Breton-two footed
Saw diameter (mm)	1200	1200	1400	1200	1200	1400	1400	1400
Saw model	Sonmak	Guclu	Sonmak	Topas	Topas	Sonmak	Diabo	Zess
Rotational speed of saw (rpm)	2418	2565	2407	2640	2315	2200	2600	2170
Advancing rate of saw (cm/s)	2.3	2.2	2.2	2.7	2.4	2.8	2.6	2.7
Motor current for saw (A)	105	120	–	72	120	115	158	120
Rock type	Dol. Limestone	Limestone	Travertine	Travertine	Travertine	Travertine	Limestone	Travertine
Rock location	Yahyali/Kayseri	Bunyan/Kayseri	Yildizeli/Sivas	Godene/Konya	Bucak/Antalya	Karaman/Konya	Bursa	Mut/Icel
Slab dimension (cm)	135x30	210x30	285x30	200x30	150x30	220x30	200x30	200x30
Slab number cut per hour	26.5	21	14.6	29	43.6	28.3	22.5	28
Hourly slab production (m^2/h)	10.7	13.23	12.5	17.4	19.6	18.7	13.5	16.8

Table II

The results of performance studies*

Factory name and location	Rock location	Rock type	Slab production (m^2/h)
Kamer Mermer/Kayseri	Yahyali/Kayseri	Dolomitic limestone	10.7
Derinkok Mermer/Kayseri	Bunyan/Kayseri	Limestone (Bunyan rose)	13.2
Toros Mermer/Kayseri	Yildizeli/Sivas	Travertine	12.5
Akmera,s Mermer/Konya	Godene/Konya	Travertine	17.4
Model Mermer/Antalya	Bucak/Antalya	Travertine (Limra)	19.6
Kombassan Mermer/Konya	Karaman	Travertine	18.7
Kombassan Mermer/Konya	Bursa	Limestone (Bursa beige)	13.5
Kombassan Mermer/Konya	Mut/Icel	Travertine	16.8

* Saw diameter: 1200–1400 mm; rotational speed of saw: 2200–2600 rpm; advancing rate of saw: 2.2–2.8 cm/s; depth of cut: 30 cm

test specimens free from fractures, partings or alteration zones. Then, standard test samples were prepared from these block samples, and compressive strength, tensile strength and impact strength tests were carried out. The summaries of the test results are given in Table III.

Uniaxial compressive strength

Uniaxial compression tests were performed on trimmed core samples, which had a diameter of 38 mm and a length-to-diameter ratio of 2. The stress rate was applied within the limits of 0.5–1.0 MPa/s.

Brazilian tensile strength

Brazilian tensile strength tests were conducted on core samples having a diameter of 38 mm and a thickness-to-diameter ratio of 1. The tensile load on the specimen was applied continuously at a constant stress rate such that failure will occur within 5 min of loading.

Impact strength test

The device designed by Evans and Pomeroy (1966) was used in the impact strength test. A 100 g sample of rock in the size range 3.175 mm–9.525 mm is placed inside a cylinder of 42.86 mm diameter and a 1.8 kg weight is dropped 20 times from a height of 30.48 cm on to the rock sample. The percentage of rock remaining in the initial size range after the test is termed as the impact strength index.

Statistical analysis

Because the data used in this study were taken from the authors' continuing research project, only three brittleness concepts were available. Therefore, the brittleness B_3, B_5 and B_8 were used in the statistical analysis. The brittleness values given in Table IV and hourly production values were analysed using the method of least squares regression.

Table III

The results of the tests

Rock location	Rock type	Uniaxial compressive strength (MPa)	Brazilian tensile strength (MPa)	Impact strength (%)
Yahyali/Kayseri	Dolomitic limestone	136.7	10.2	81.4
Bunyan/Kayseri	Limestone (Bunyan rose)	175.0	7.4	86.6
Yildizeli/Sivas	Travertine	83.3	5.8	76.4
Godene/Konya	Travertine	45.4	4.6	75.2
Bucak/Antalya	Travertine (Limra)	50.3	2.8	71.3
Karaman	Travertine	50.3	4.1	76.5
Bursa	Limestone (Bursa beige)	128.8	5.6	78.8
Mut/Icel	Travertine	60.0	2.2	66.6

Table IV

Calculated brittleness values

Rock location	Rock type	Brittleness B_3	Brittleness B_5	Brittleness B_8
Yahyali/Kayseri	Dolomitic limestone	0.86	11128.7	697.2
Bunyan/Kayseri	Limestone (Bunyan rose)	0.92	15155.0	647.5
Yildizeli/Sivas	Travertine	0.87	6363.3	241.2
Godene/Konya	Travertine	0.82	3415.4	104.4
Bucak/Antalya	Travertine (Limra)	0.89	3586.9	70.4
Karaman	Travertine	0.85	3848.0	103.1
Bursa	Limestone (Bursa beige)	0.92	10149.4	360.6
Mut/Icel	Travertine	0.93	3996.0	66.0

Hourly production values were correlated with the corresponding brittleness values. The equation of the best-fit line, and the correlation coefficient were determined for each regression.

There is no significant correlation between hourly production value and the brittleness B_3 (Figure 1). However, there is a strong correlation between hourly production value and the brittleness B_5 (Figure 2). The relation follows a logarithmic function. Hourly production decreases with increasing brittleness B_5. The equation of the curve is

$$P_h = -4.63 \ln B_5 + 55.69 \quad r = 0.85 \qquad [9]$$

where P_h is the hourly production (m^2/h) and B_5 is the brittleness.

A very strong correlation between hourly production value and the brittleness B_8 was found (Figure 3). The relation follows a logarithmic function. Hourly production decreases with increasing brittleness B_8. The equation of the curve is

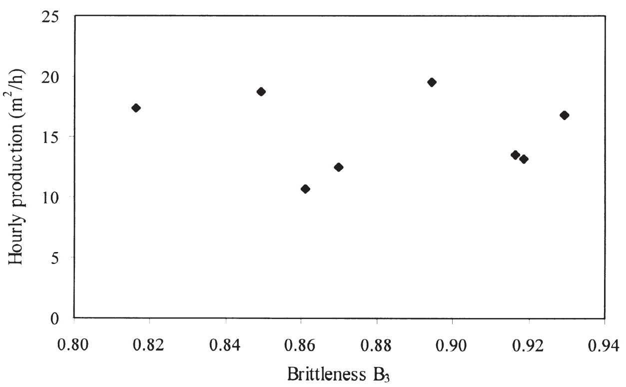

Figure 1—Hourly production versus brittleness B_3

$$P_h = -3.01 \ln B_8 + 31.14 \quad r = 0.90 \qquad [10]$$

where P_h is the hourly production (m^2/h) and B_8 is the brittleness.

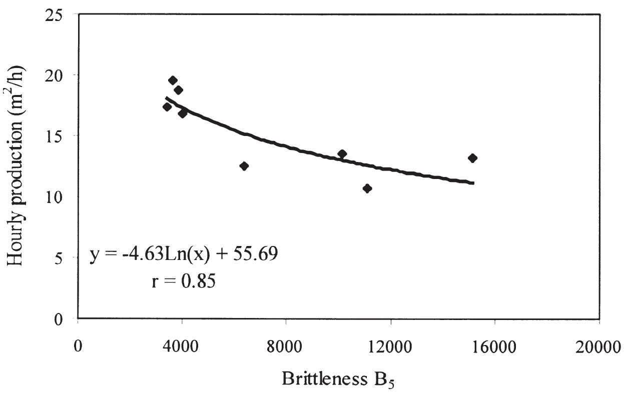

Figure 2—Hourly production versus brittleness B_5

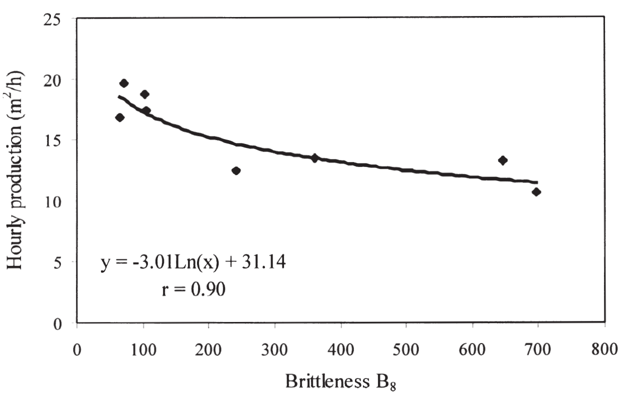

Figure 3—Hourly production versus brittleness B_8

Discussion

The values of brittleness B_3 range from 0.82 to 0.93. The lack of the correlation between hourly production and the brittleness B_3 may be due to this narrow range. In addition, the rocks tested in this study are only carbonate rocks. If the other rock types are tested, a significant correlation may be obtained. That the number of rock types tested is limited may be another reason of the lack of the correlation. Nevertheless, a correlation may not be obtained for other rocks types and a wider range of brittleness values because, as stated above, each method of measuring brittleness has its usage in rock excavation, depending on practical utility, i.e. one method of measuring brittleness shows good correlation with the penetration rate of rotary drills, while the other method does not (Kahraman, 2002). Similarly, while one method of measuring brittleness indicates good correlation with sawability of rocks, the other method does not.

Both brittleness B_5 and B_8 exhibit significant correlation with sawability. Because the impact strength test is practical and economical according to the tensile strength test, the use of brittleness B_5 is more advantageous than brittleness B_8.

Conclusions

Sawability prediction is very important for the cost estimation and the planning of stone processing plants. The prediction models for sawability will help the engineers working in the plants. For the derivation of prediction models, three different brittleness indexes correlated with the sawability of rocks. Any significant correlation between hourly production and brittleness of B_3 was not found. However, a strong correlation between hourly production and brittleness of B_5 was found. Also, a very a strong correlation between hourly production and brittleness of B_8 was found. It can be said that the brittleness of B_8 is the most reliable index among the brittleness indexes adopted in this study.

Sawability of carbonate rock can be predicted from some brittleness indexes. Further study is required to investigate the validity of the derived equation for other rock types.

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Barloworld rebuilds LHDs for lower mine profiles*

Barloworld Equipment now rebuilds flameproof LHDs to accommodate lower profile underground coal mining conditions on South African mines.

The first rebuild—a Wright 356B LHD, owned by Sasol and used for coal loading in a fiery application at the Brandspruit mine near Secunda—was done last year at Barloworld Equipment's Boksburg facility in 39 days and at a cost of about R1 million, half the price of a new unit (costed and conducted using Barloworld Equipment's newly commissioned SAP business solutions system).

It involved lowering the profile of the machine from 1.84 m to 1.65 m with the bucket flat. The machine was rebuilt to a Caterpillar design, with new bucket, loader frame, tower and front cylinders, as well as reconfigured piping. The new bucket is lower but longer, reducing capacity from four cubic metres to 3.8 cubic metres, but with an improved rack back to reduce spillage.

'In rebuilding the machine for Sasol to accommodate lower profiles, we converted the 356B into a 356C,' explains Mossie Mostert, Barloworld Equipment Mining underground coal account manager. 'The new lower-profile model design by Cat will soon replace the older, taller model,' he adds. 'In fact, the last new 356Bs to be built are now coming off our assembly line, while a prototype of the new 356C has gone to Australia, where it is proving successful.'

There are around 200 Wright 356B LHDs running in South Africa at present, as well as a few in Australia and Siberia. The rebuilt 356Cs will be assembled at Barloworld Equipment's Middelburg facility, where four LHDs have been overhauled since the first rebuild for Sasol.

Wright LHDs come with certified SABS hydraulic brakes, a specially designed cab built to withstand an impact of 10 tons from the top and 2.5 tons from the side, and an optional quick coupler attachment for fast changeovers between attachments.

'Together with Caterpillar we have geared up to provide total solutions to the mining industry,' says Mostert. 'The Wright 356B has undergone modifications in the past to lower its back end from 1.9 metres to 1.71 metres,' he adds. 'With the new front end modification, the flameproof Wright LHD is now able to accommodate lower seams without reducing machine capacity.'

Barloworld Equipment recognizes the cost of downtime to any mining operation should a machine require a component replacement or, alternatively, a complete rebuild. As a result, Barloworld has geared up to work with the mines and best manage down-time situations and resultant loss with a number of 'smart initiatives'. ◆

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