AMAR PRAKASH
VMSR MURTHY
KALENDRA BAHADUR SINGH
and
AKELLA SATYA VENKATESH

Effect of rock fracture toughness and mineralogy on cutting performance of surface miner – some investigations

Cuttability of rocks is intimately related to the variation in fracture and micro-petrographic properties of the rocks. An understanding of fracture mechanism and fracture toughness (FT) of rocks is useful to evaluate production performance of rock cutting machines. A study was conducted on rock samples collected from two limestone mines located in India where surface miner (SM), a popular drum type cutting machine, was used for excavation of rock. FT in Mode I was measured by Chevron edge notched round bar (CENRB) method. A simple and accurate procedure of sample preparation of specified dimension, and experimental approach for determining the FT has been discussed in this paper. The study also covers the relation between fracture toughness and mineralogy of limestone as well as their role in estimating production performance by SM. FT was found to be strongly related to uniaxial compressive strength (σ_c), point load strength index (I_s) and Young's modulus (E). The study shows that the fracture toughnessof the rock is governed by the configuration of carbonate grains, grain texture and grain matrix. FT was also found to decrease with increase in marl content resulting in increase of production performance of SM. Principal component analysis (PCA) was also conducted to develop a correlation matrix for FT and its inter-relationships with other influencing parameters. Critical strain energy release rate (G_{IC}) was also found to be related with production performance of SM.

Key words: Fracture toughness; mineralogy; surface miner; limestone; production

1. Introduction

Fracture mechanics has evolved as a theory to solve many rock engineering problems such as rock cutting, rock blasting, hydraulic fracturing and rock mass structure stability (Ke et. al., 2008). It deals with facture initiation and crack propagation, and provides quantitative methods for characterizing the behaviour of an intact material as it fractures due to crack growth (James, 2003). Fracture toughness, a fundamental parameter in fracture mechanics, is defined as the critical value of the stress intensity factor when a crack propagates. FT of rock is also influenced by the mineralogical composition, shape of grains, texture, crystallinity, stratification, lamination and modification by heat or pressure. Characterization of FT and micro-fractures is required for determining the cutting performance of machines. FT was determined with a simple and precise approach and was correlated with varied rock properties. The same was also compared to the production performance of SM.

2. Fracture toughness

2.1 Applicability

Determination of FT of rocks has wide application for classification of rock material (Gunsallus and Kulhawy, 1984); index of fragmentation processes such as tunnel boring (Lindqvist, 1982) and model scale blasting (Rustan et al., 1983); material property in the modelling of rock fragmentation like rock cutting (Saouma and Kleinosky, 1984), hydraulic fracturing (Rummel and Winter, 1982), gas driven fracturing (Nilson and Griffiths, 1986), explosive stimulation of gas wells (McHugh and Keough,1982), radial explosive fracturing (Grady, 1985) and crater blasting (Adams et al., 1985) as well as instability. Franklin et al. (1971) suggested a bivariate rock mass classification in which two rock properties, namely, Fracture Index and Point Load Index play a major role. These two parameters can be plotted on a classification diagram to predict rippability as shown in Fig.1. Differences in cuttability of various rocks are related to the variation of fracture properties among the rocks (Nelson and Fong, 1986). Deliac (1986) analyzed the chip formation due to drag picks and found that for sharp, rigid picks operating in brittle rocks the cutting force can be expressed as a function of the FT of the rock and the cutting depth. Guo (1990) related the FT to the penetration rate of a diamond-coring machine and found that rocks with higher

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Messrs. Amar Prakash and Kalendra Bahadur Singh, Scientists, Central Institute of Mining & Fuel Research, Dhanbad 826 015, V.M.S.R. Murthy, Professor, Dept. of Mining Engg, Indian School of Mines, Dhanbad 826 004 and Akella Satya Venkatesh, Professor, Department of Applied Geology, Indian School of Mines, Dhanbad 826 004, India. e-mails: amar_cmri@yahoo.co.in, kbsingh. cimfr@ gmail.com, vmsr_murthy @yahoo.com, and asvenkatesh@hotmail.com

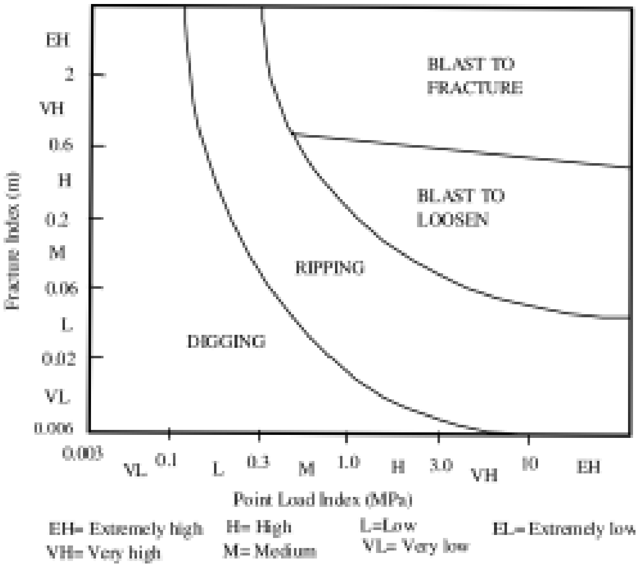


Fig.1 Discontinuity strength classification (after Franklin et al., 1971)

FT are harder to penetrate resulting in lower penetration rates.

Ingraffea et al. (1982) has proposed using the FT of different rocks encountered during three tunnel boring projects to predict the performance of the TBMs (tunnel boring machines). Bearman et al. (1991) correlated various rock strength parameters to power consumption of a laboratory cone crusher with a statistical significance of 99.9% and FT was among those parameters.

2.2 Influencing parameters

FT is influenced by many factors such as microstructure, thickness of rock and constraints, strain rate, environment and temperature. FT increases with increasing confining pressure (Rao, 1999). Temperature and moisture content have also shown to influence fracture toughness (Al-Shayea et al., 2000). FT increases with decreasing temperature and can be related to physico-mechanical properties of rock like E, σ_c, tensile strength, I_s, Poisson's ratio, compressional wave velocity (C_p), grain size, grain contact length, or dry density (Alber and Brardt, 2003). Fracture roughness increases with increasing loading rate (Marder and Fineberg, 1996). If a material has a large value of FT it is prone to ductile fracture. Brittle fracture is a characteristic of materials with a low FT value (Kanninen and Popelar, 1985).

Intact rock material or rock mass invariably consists of micro-cracks in general and the ability of a material to resist the growth of a crack depends on a number of factors. Larger flaws work to reduce the permitted stress; brittle rock has lower strain energy absorption capacity than ductile rock and hence the former breaks early as represented in Fig.2 (area under the load deflection curve denotes the energy required to cause fracturing). Thicker and more rigid rocks have lower FT than thin rocks. Increasing the rate of application of the load, such as an impact test, typically reduces the FT of the rock. Increasing the temperature normally increases the fracture toughness, just as in the impact test. A small grain size normally improves fracture toughness, whereas more point defects and dislocations reduce fracture toughness. Thus, a fine-grained rock may provide improved resistance to crack growth.

2.3 Modes of fracturing and fracture propagation

There are three different modes of fracturing in fracture mechanics: Mode I opening (tensile), Mode II in-plane shear and Mode III out-of-plane shear. The modes are illustratively presented in Fig.3.

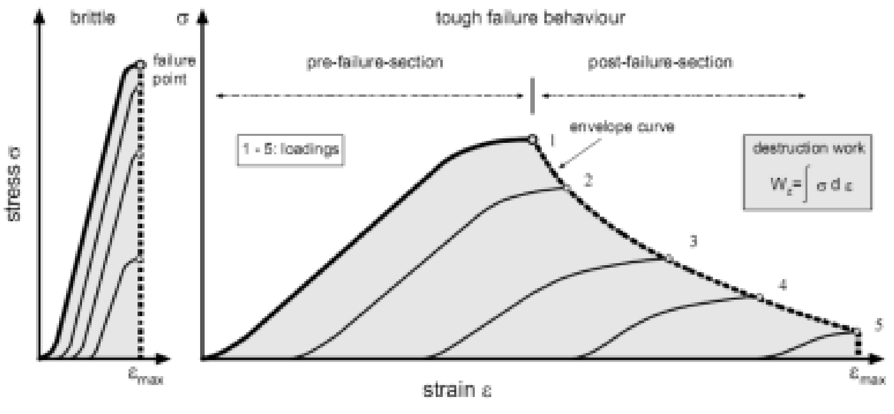


Fig.2 Strain energy absorption behaviour for different rock types (Thuro and Spaun, 1996)

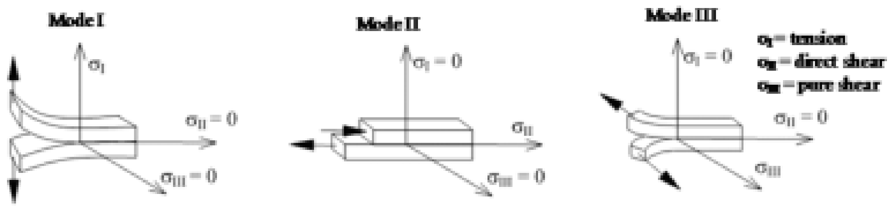


Fig.3 Fracture propagation modes (Artur, 2003)

In Mode I, the crack tip is subjected to displacements perpendicular to the crack plane. The crack propagation is in crack plane direction. The lateral and the directional stress component (f_{xx}) are symmetric with respect to the crack trace. The crack carries no shear traction and no record of shear displacement is visible. In Mode II, the crack faces move relative to each other in the crack plane. Crack propagation is perpendicular to the crack front. Shear traction parallels the plane of the crack. The lateral (f_{yy}) and the directional stress component (f_{xx}) are point-symmetric. The shear stress component (f_{xy}) is the only component to be symmetric with respect to the crack trace. In Mode III, shear displacement acts parallel to the front in the crack plane. f_{yz} appears to be symmetric with respect to the crack trace while f_{xz} shows point-symmetry. Any combination of the three basic modes is referred to as mixed mode. Critical FT values of the fracture propagation for each mode separately, can be tested using several different methods. Backers (2004) describes multiple possibilities to test Modes I and II, but states that there are a very few methods available that provide Mode III loading conditions.

2.4 METHOD OF DETERMINATION

In this study, Mode I testing method was carried out to determine the FT in the laboratory. In several testing methods for determination of the Mode I fracture toughness, namely, the SCB (Semi-circular core in three point bending) test (Chong and Kuruppu,1984), the chevron-notched SCB test (Kuruppu, 1997), the BD (Brazilian Disc) test (Guo et al., 1993), the RCR (Radial Cracked Ring) test (Shiryaev and Kotkis, 1982), the MR (Modified Ring) test (Thiercelin and Roegiers, 1986) and the DT (Double Torsion) test (Evans, 1972) K_{IC}, has been introduced. CENRB of Mode I testing method was conducted in the Rock Excavation Laboratory of Indian School of Mines, Dhanbad, as per ISRM (1995) suggested methods to determine fracture toughness.

The core axis was oriented either parallel or perpendicular to any anisotropic feature such as planes of weakness. The present method used a specimen, called the chevron bend specimen, with a chevron or V-shaped notch cut perpendicular to the core axis. The chevron notch causes crack propagation to start at the tip of the V and proceeds transverse to the core axis in a stable fashion until the point where the FT is evaluated. The specimen dimensions used are given in Table 1. The experimental set-up and preparation of precise specimen geometry are illustrated in the following section.

2.5 SAMPLE PREPARATION AND TESTING PROCEDURE

In order to determine the FT of rock by CENRB test, the size specifications of the sample (Table 1) needs to be fulfilled. A diamond wheel saw can be used to cut the required notch. Since limestone samples are relatively soft, a hacksaw blade was used to prepare the notch precisely. The following steps were adopted to prepare the notch (Prakash, 2013):

TABLE 1: SPECIMEN DIMENSIONS FOR CENRB TEST

Geometry parameter	Value	Tolerance
Specimen diameter	D	>10 × grain size
Specimen length, L	4D	>3.5D
Support span, S	3.33D	$\pm 0.02D$
Subtended chevron angle, θ	90^{o}	$\pm 1.0^{o}$
Chevron V tip position, a_0	0.15D	$\pm 0.10D$
Notch width, t	$\leq 0.03D$ or 1 mm*	
Depth of notch, C	$0.25 \leq C/D \leq 0.5$	

* whichever is greater

(a) The diameter (D) of the core sample is measured and the depth of the notch is marked on the sample such that it lies between 0.25 and 0.5 times the diameter of core as shown in Fig.4. The projection of the notch line must pass through the center of the core.

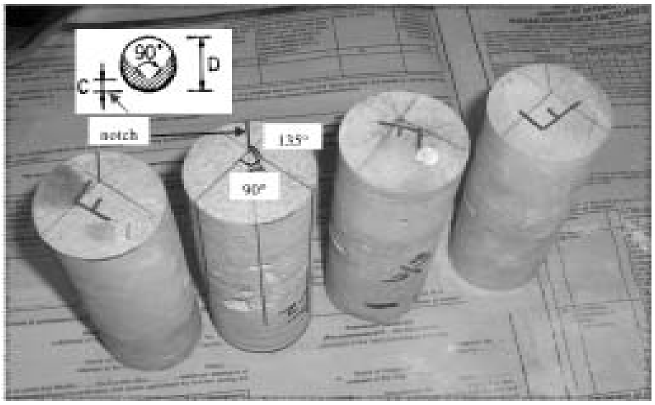


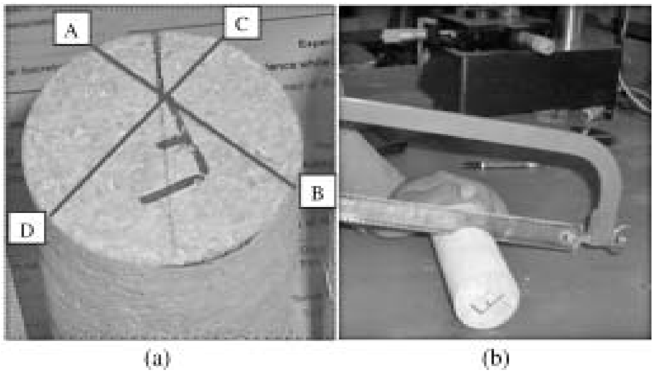
Fig.4 Process for preparing notch

(b) A line is drawn at an angle of 135° from the inner end of the notch line with the help of protractor and extended up to the edge of the core. Then a 90° line is drawn from the intersection of these two lines. This line is also extended to the other edge of the core. All the lines touching the edge of the core are extended along the axis of the core as shown in Fig.4.

(c) Mid-point of the length of the core is marked on each extended line. These intersected points are joined together, which would be the line for cutting the rock. This line helps in cutting the rock in a straight line.

(d) The marked lines guide in preparing the notch as shown in Fig.5. Initially, the sample is cut at the mid-length of the core parallel to line AB (Fig.5b). The depth of cut should stop as it touches the extended lines of A and B along the length of the sample. Similar cut is made parallel to CD from the other side using hacksaw blade.

(e) The sample is placed on the testing apparatus. Care is taken before applying the load that the sample touches



(a) (b)

Fig. 5. Process for notch cutting

the support rollers placed at equidistance. The loading roller must lie vertically above the notch.

(f) Load is gradually applied till the sample breaks along the notch as shown in Fig.6. The applied breaking load is measured in MPa.

Fig.6 Status of sample before and after applied load

(g) K_{IC} for CENRB geometry is calculated in MPa-$^{m1/2}$as:

$$K_{IC} = \frac{10.617\left[\left(\frac{C}{D}\right)+19.646\left(\frac{C}{D}\right)^{5.5}\right]^{0.5} P}{\left(1-\frac{C}{D}\right)^{0.25} D^{0.5}} \quad \ldots \quad (1)$$

where,

C = depth of notch (mm),

D = specimen diameter (mm) and

P = load (MPa).

K stands for stress intensity factor at the crack tip, I denotes that the FT test is performed in tensile mode and C denotes that the value of K is "critical". When K attains critical value then crack propagation becomes unstable and results in fracture of the components (Nath and Das, 2006).

2.6 Fracture energy release rate

Fracture energy is defined as the amount of energy necessary to create one unit area of a crack (Rilem, 1985). There is a relationship between G_{IC} and stress intensity factor (K_{IC}) in Mode I failure under plane strain condition (Schreurs, 2011) expressed as:

$$G_{IC} = \frac{\left(1-\upsilon^2\right)K_{IC}^2}{E} \quad \ldots \quad (2)$$

where,

G_{IC} = critical strain energy release rate (J/m^2),

E = Young's modulus (GPa),

υ = Poisson's ratio and

K_{IC} = stress intensity factor corresponding to the initiation of the crack.

If a stress is applied to a sample with a thickness greater than some critical value B, the material is in a state called plane strain. This limiting value of B is given in equation below:

$$B \geq 2.5\left(\frac{K_{IC}}{\sigma_Y}\right)^2 \quad \ldots \quad (3)$$

where,

K_{IC} = fracture toughness, when the sample has a thickness less than B and

σ_y = yield stress of material.

3. Study sites

For analysing the cutting performance of SM, a study was conducted in two sites, namely, Dalavoi limestone mine of India Cements Limited (ICL) and Alathiyur limestone mine of Madras Cements Limited (MCL) located in Tamil Nadu, India. The details of geology, petrography and performance of SMs deployed in different mines are detailed in the following sections.

3.1 Dalavoi mine

(a) Geology

The Dalavoi limestone mine is situated in the revenue village of Dalavoi in Perambalur district of Tamil Nadu at the intersection of 78°53' E longitude and 11°14' N latitude. In the mining area, limestone beds of Niniyur formation are associated with partings of calcareous marl, below a cover of black-red soil of 2 to 5 m thickness on an average. Limestone with marl and clay is generally off-white to brownish yellow in colour, fine to medium grained and soft amorphous. Clay and marl are found in various proportions. Marl is buff to yellow in colour, fine-grained and compact in nature. The lithological unit of clay is less calcarious and is yellow to buff in colour, highly plastic and becomes hard on sun drying and occurs in association with marl and limestone. The rock formation in the study area was of marine sedimentary origin and consists of limestone, shell limestone, arenaceous limestone, sandstone, clay and marl. Limestone was found in

Fig.7 Alternate bands of limestone and marl in Dalavoi mine, ICL, India

the form of alternative bands of boulder limestone and marl or massive limestone with intercalations of marl. An alternate band of limestone and marl is shown in Fig.7. Fossil contents were dominantly present in the entire area of limestone deposit.

(b) Petrography

Petrography study was conducted using Trinocular polarizing microscope (Olympus make) under transmitted light with image analyser software (5 Rule) to analyse the variation of FT with respect to the mineralogy of rock. The rock was medium to coarse-grained, massive rock with abundant fossils (Fig.8). At places, finely crushed grains of carbonates were seen along with elongated to circular shaped fossils.

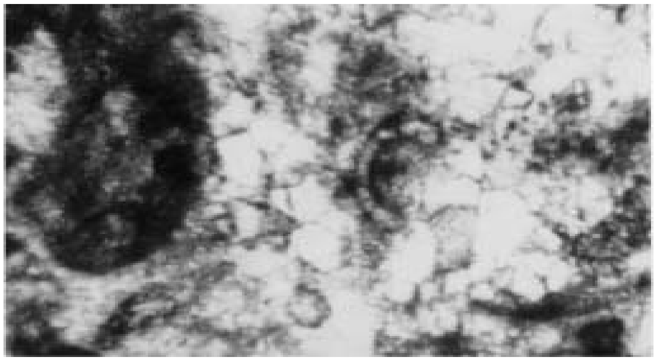


Fig.8 Microscopic view of rock sample of Dalavoi mine, ICL, India

The rock was predominantly constituted of carbonate grains with very few dispersed grains of quartz and clayey matrix. The carbonates were about 65-70% of rock volume whereas quartz, mica and opaques constitute only 5% and fine-grained matrix forms the rest. Some of the solution cavities were filled with finer secondary calcite and quartz grains. Overall, the rock was a hard limestone with well-cemented marl matrix. Other rock sample consisted predominantly of carbonates (70-80%), quartz (10%), mica and fine Fe-oxide grains (opaque 2-3%) and clayey matrix along with fossils. The quartz and Fe-oxide grains constitute the hard mineral population. Texturally, the rock showed very good expression of marginal granulation and grain size reduction along the boundary of larger grains. The rock was having overall higher matrix percentage of clayey material with calcareous matter and embedded with microfossils. The rock was fossiliferous limestone.

(c) Surface miner

Two models of SMs, namely, 2100SM (3 nos.) and 2200SM (1 no.) manufactured by Wirtgen GmbH were deployed in Dalavoi mine. Production of limestone with these machines varied between 140 and 240 t/h.

3.2 ALATHIYUR MINE

(a) Geology

The Alathiyur mine is located in Sendurai Taluk, Perambalur district of Tamil Nadu. Geology and lithology of this limestone deposit closely resembles to that of ICL mines with minor variations in silica percentages. The average depth of groundwater from surface was 7 to 8 m. Continuous pumping of water was done to control the water levels. At places, hard limestone bands with an average thickness of 20 cm were embedded into thin layers of marl, whereas at other places thin bands of hard limestone were embedded into thick layers of marl as shown in Fig.9 and Fig.10 respectively.

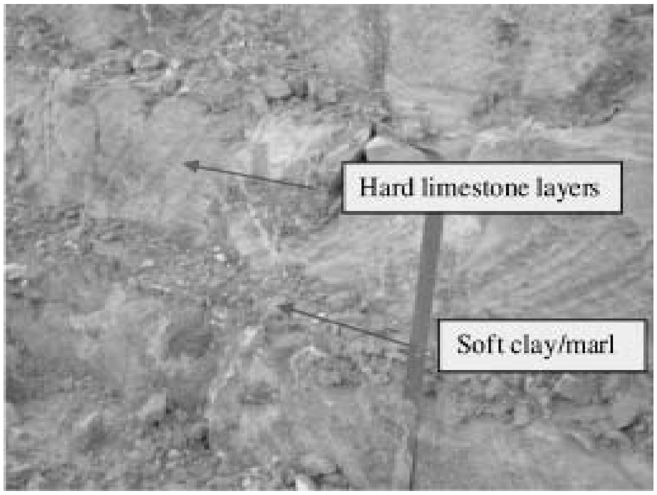


Fig.9 Thin layers of marl intercalated in thick layer of hard limestone, MCL, India

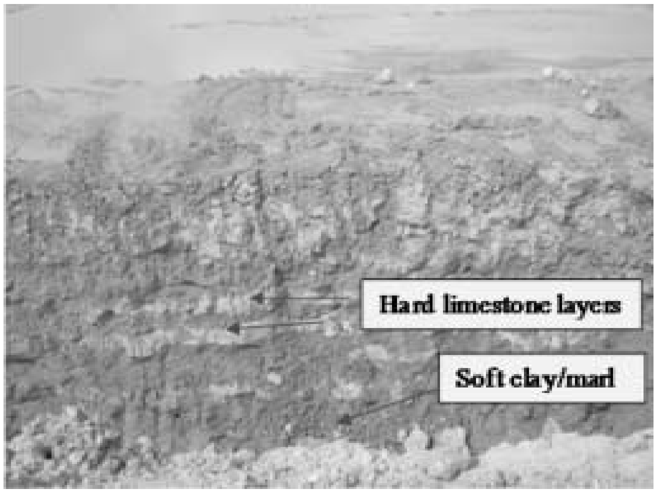


Fig.10 Thin layers of hard limestone embedded in thick layer of soft clay, MCL, India

(b) Petrography

Analysis through petrographic studies indicates that the sample was light coloured, fine and friable natured soft rock. At places loose fragments of larger lithic fragments were seen. Secondary fine-grained calcite veinlets were also noted. Microscopically, the rock was medium grained interspersed with microfossils. The rock predominantly constituted of fine clayey matrix with dispersed grains of carbonate, quartz and opaques (Fig.11). The carbonates were about 40-50% of rock volume whereas clay, quartz, mica and opaques constitute 40-50%.

(c) Surface miner

Two models (2100SM and 2200SM) of Wirtgen make SMs were deployed in Alathiyur mine. SM was deployed under wet ground condition. The production of limestone ranged from 166 to 351 t/h. Conveyor discharge system was adopted in the mine.

Fig.11 Microscopic view of rock sample of Alathiyur mine, MCL, India

4. Results and discussion

4.1 Influence of intact rock parameters

Rock properties of the limestone samples, collected from various working sites of Dalavoi and Alathiyur mine, were determined as given in Table 2. K_{IC} test ranged from 0.008 to 0.03 MPa-m$^{1/2}$. K_{IC} showed good correlation with σ_c, I_s and E. The corresponding relationships developed are presented in Figs.12, 13 and 14 respectively. K_{IC} was found to be directly proportional to these rock properties.

The value of K_{IC} was also correlated with limestone production (TPH) and it was observed that TPH was inversely proportional to K_{IC} as shown in Fig.15. The power form showed the best fit curve between TPH and K_{IC} and is expressed as:

$$TPH = 17.86 K_{IC}^{-0.58} \quad (R^2 = 0.62) \quad \dots \quad (4)$$

where,
TPH = production (t/h) and
K_{IC} = fracture toughness (MPa-m$^{1/2}$)

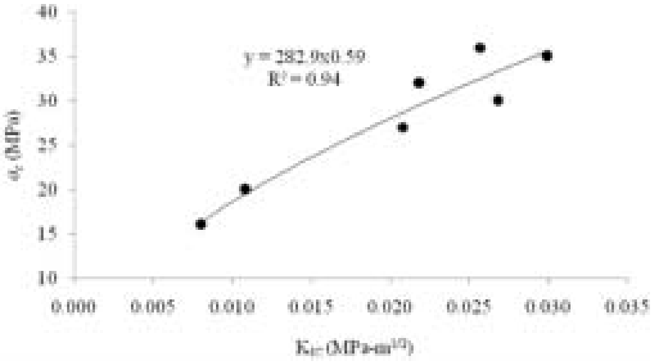


Fig.12 Relation between K_{IC} and σ_c.

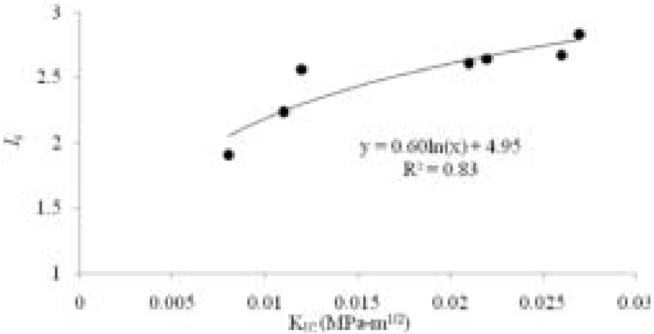


Fig.13 Relation between K_{IC} and I_s

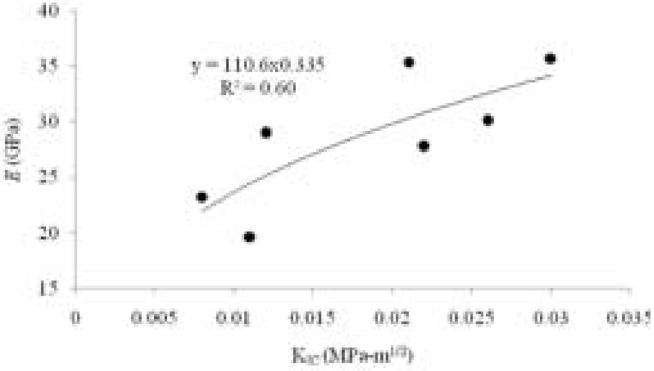


Fig.14 Relation between K_{IC} and E

TABLE 2: ROCK AND MINERALOGICAL PROPERTIES WITH PRODUCTION DATA OF LIMESTONE MINES

TPH	σ_c	I_s	E	PR	K_{IC}	G_{IC}	Carbonate grains
163	36	2.67	30.11	0.34	0.026	0.0000194	Confined
240	20	2.23	19.62	0.14	0.011	0.0000059	Dispersed
351	34	2.56	28.98	0.28	0.012	0.0000046	Dispersed
140	27	2.60	35.40	0.23	0.021	0.0000115	Confined
185	30	2.83	26.12	0.18	0.027	0.0000266	Confined
176	32	2.64	27.77	0.24	0.022	0.0000162	Confined
172	35	2.32	35.76	0.31	0.030	0.0000226	Confined
192	16	1.90	23.27	0.22	0.008	0.0000026	Confined

TPH = production in tonnes per hour, σ_c = uniaxial compressive strength (MPa), I_s = point load strength index, E = Young's modulus (GPa), PR = Poisson's ratio, K_{IC} = fracture toughness (MPa-m$^{1/2}$), G_{IC} = critical strain energy release rate (J/m^2)

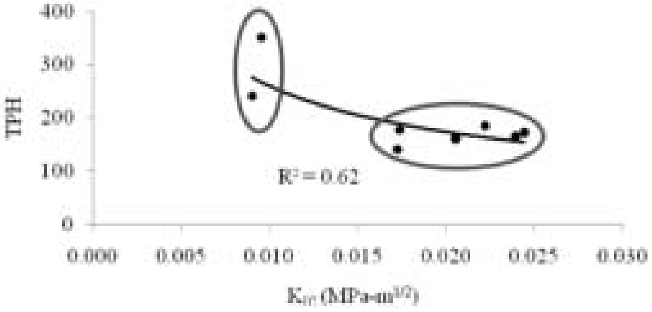


Fig.15 Influence of K_{IC} on limestone production

4.2 Influence of geological parameters

Marls are composed mainly of clay minerals and carbonate in varying proportions, normally between 35% and 65% (Bellair and Pomerol, 1980). Marl, dominating with clay, was present as a coating on the layer of limestone preventing the water to percolate to limestone bed in Alathiyur mine. Thus, dry limestone was easily cut and loaded by the conveyor directly on to the hauling equipment. Carbonates dominate in rock samples ranging from 40 to 70%. Degree of compactness is determined by the carbonate content. Al Jassar and Hawkins (1977) showed that the engineering properties of several lithological types in carboniferous limestone have an influence on the strength and deformation characteristics of carbonate rocks. Production was high and the FT was less in areas having dispersed grains of carbonates especially in Alathiyur mine and the condition was reverse in confined carbonate grains with fine grained matrix areas (Fig.15). It was found that FT was less in areas dominating with more marl formation (Fig.16). The nature of marly-clayey fraction affects strength of cohesion as well as grain size.

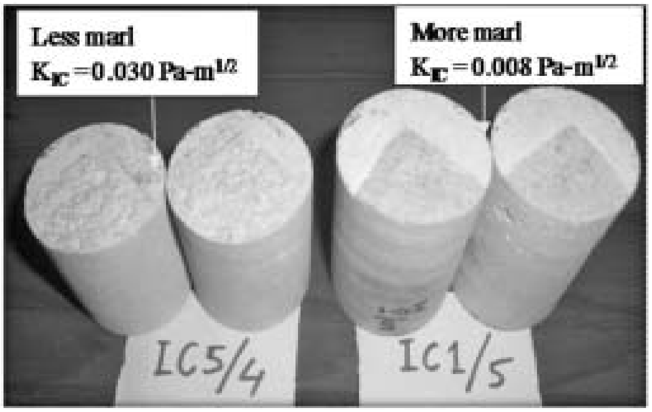


Fig.16 Variation in FT due to marl

Colour can be an indication of the weathered state of the rock and in turn its strength. The degree of discolouration may provide an indication of the degree of stability of minerals in rocks. Marl was buff to yellow, clay was yellow to buff and limestone with marl and clay showed off-white to brownish yellow in colour. However, it was practically difficult to infer the performance of SM through colour variation.

4.3 Statistical analysis

PCA is generally used to develop the correlation matrix. As K_{IC} is related to multiple rock parameters and influences TPH, PCA was conducted to assess their inter-relationships. The amount of information carried by each component was identified by eigenvalues generated through PCA (Fig.17). The inter-relationships of multiple parameters were assessed from the plot of highest two factor coordinates as shown in Fig.18.

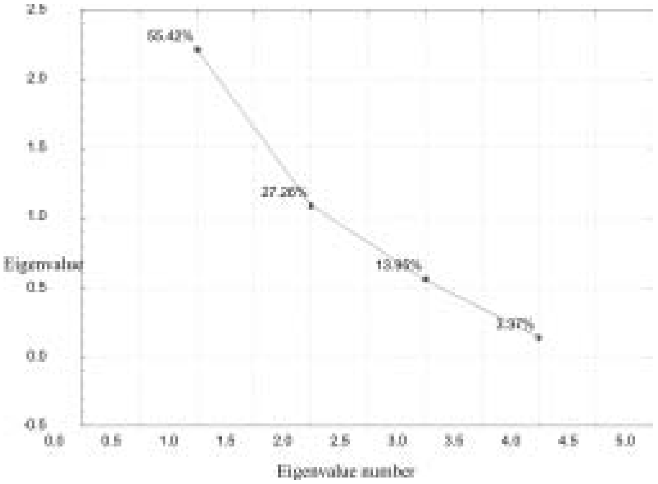


Fig.17 Eigenvalues of correlation matrix for fracture toughness

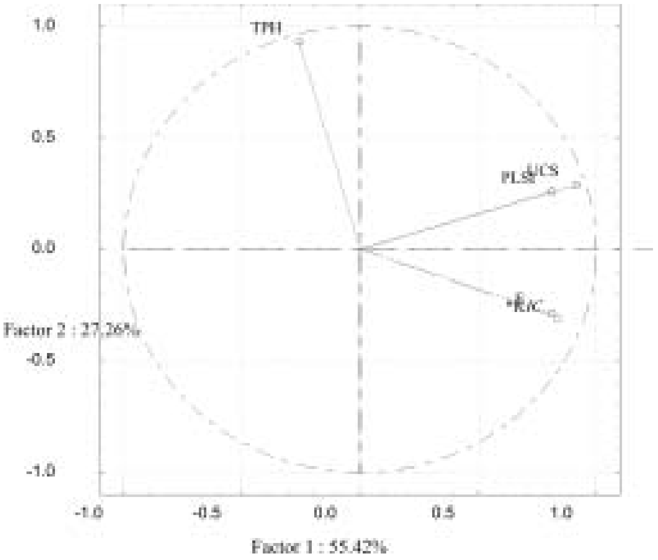


Fig.18 Projection of parameters on factor plane for KIC

It can be interpreted from the correlation circle that K_{IC} was inversely related to production as it is positioned in diagonal quadrant and directly proportional to E as it falls in the same quadrant. The σ_c and I_s did not show any conclusive relation as they were placed in the side quadrant with respect to K_{IC}. The points of each variable were far from the origin of the circle, indicating greater correlation of the corresponding variable with the factor axes.

G_{IC} was calculated from equation 2. TPH was found to be inversely proportional to G_{IC} (Fig.19) and the relation is expressed as:

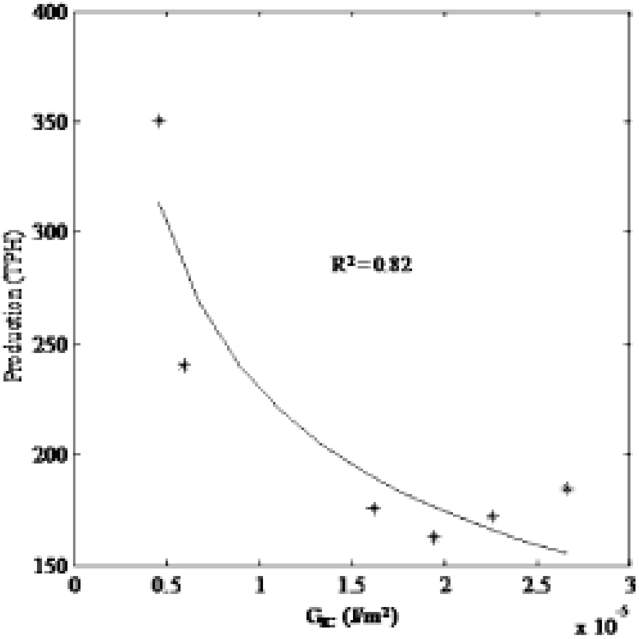


Fig.19 Influence of GIC on limestone production

$$TPH = 2.37 G_{IC}^{0.4} \exp\left(-3.93 G_{IC}^{0.6}\right) \quad \left(R^2 = 0.82\right) \ldots \qquad (5)$$

where,

TPH = production (t/h) and

G_{IC} = critical strain energy release rate (J/m^2).

It can be interpreted from Fig.19 that TPH was on higher side when the G_{IC} was less than 0.00001 J/m^2.

5. Conclusion

Determination of FT involves preparation of samples to required specific dimensions as per standard norms. An easy technique adopted in sample preparation, as detailed stepwise in this paper, was found to be expediently accurate. K_{IC} was found directly proportional to σ_c, I_s and E having 0.94, 0.83 and 0.60 index of determination respectively. K_{IC} was inversely related to production of SM (TPH) expressed in the power form with 0.62 index of determination, which was also supported by PCA. Variation in the rock composition especially in terms of marl threw significant influence in the fluctuation of K_{IC}. K_{IC} decreased with increase in marl. High TPH with low value of K_{IC} was observed in the rock formations having dispersed grains of carbonates. PCA revealed that K_{IC} was inversely related to production of SM (TPH) and directly proportional to E. G_{IC} can be used to estimate TPH as it was observed to be inversely related with 0.69 index of determination. Thus, FT and mineralogy were found useful in evaluating production performance of SM.

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