Energy, Mines and Resources Canada
Énergie, Mines et Ressources Canada

CANMET
Canada Centre for Mineral and Energy Technology
Centre canadien de la technologie des minéraux et de l'énergie

La caractérisation de la roche par la technique de micro-dureté.

ROCK CHARACTERIZATION THROUGH MICROHARDNESS TECHNIQUE

B. Das
Calgary Coal Research Laboratory

March 1986

For presentation to the 27th U.S. Symposium on Rock Mechanics, the University of Alabama, Alabama, June 23-25, 1986.
Format dictated by the Conference Organizing Committee.

11pg

ENERGY RESEARCH PROGRAM
COAL RESEARCH LABORATORIES
DIVISION REPORT ERP/CRL 86-31(OP,J)

CONTENTS

TABLES

FIGURES

Abstract. Rock characterization for geotechnical purposes using the microhardness technique is discussed in this paper. The concept of rock characterization and its steps are logically developed. The geotechnical properties should be functionally tethered to the technological problems for characterization. The overriding geotechnical concern is rock mass stability. The important factors in this respect are rock properties, structural discontinuities, ground water, field stress, temperature and technological factors. The rock properties are the primary factors and the other factors generally affect rock properties. Of the rock properties the strength and elastic properties can form a basis for rock characterization. The microhardness technique can provide these two properties. Study on coal shows that the microhardness impressions can be used for this purpose.On the basis of this study coals of all ranks can be divided into distinct geotechnical groups. The details of these are discussed in this paper.

INTRODUCTION

Of all different properties of rocks, for example, optical, magnetic, decorational, chemical, geotechnical and others, only the geotechnical properties are of real significance in mining and civil engineering. These properties govern the behaviour of rocks and the rock mass.

Most of the activities in mining and some in civil engineering are essentially working with rock and rock mass. More specifically, it means cutting or breaking rocks, designing and developing engineering structures in rocks, supporting these structures for a short or a long period according to specific requirements, and letting or forcing them to collapse when so required. In all cases, the emphasis is upon predicting performance of the rocks being excavated and the surrounding rock mass. It also means transporting the broken rocks to the surface or to a place where they will be prepared, processed or used. Again, this should be carried out with the formation of minimum amounts of undesirable dust in cutting and during transportation. The main objective is to design the operation at the highest level of productivity and recovery and at minimum cost without sacrificing safety.

It is therefore important that the properties influencing rock mass stability, rock fragmentation and others are clearly identified and their effects on specific geotechnical problems are given a characterization rating.

Several rock classification/characterization systems have gradually evolved with different test methods or parameters used to establish different systems (Terzaghi, 1946; Lauffer, 1958; Coates, 1964; Barton, Lien and Lunde, 1974; Bienawski, 1975). These are general rock classification systems that were developed for civil engineering purposes. There are some other systems developed specifically for mining applications (Vinacour, 1964; Pawlowicz, 1967; USBM, 1973; Laubscher, 1977; Hybert, 1978; Korovkin, 1980; China Coal Soc., 1982; CANMET, 1983).

There is a long list of rock classification systems other than those cited above. The reasons for this long list are: (a) rock classification is still in the development stage, and (b) no single classification system is universally applicable to satisfy the needs for different technological problems. Therefore a few different classification systems are required to cover the entire spectrum of the technological problems.

The microhardness technique offers a simple method for characterizing rocks. Although it is suitable for most rocks this paper discusses the results on coals.

THE CONCEPT OF ROCK CHARACTERIZATION

Like any other scientific study rock characterization should also be conceived with respect to some reference framework. Here the reference framework is the practical application of rock characterization. Only geotechnical applications have been considered in this study as they constitute the major applications in mining and civil engineering.

The Basic Steps

Rock characterization is meaningful only when the factors involved are functionally tethered to practical problems for applications. In view of this, a sound rock characterization method should have the following steps.

- sorting out the geotechnical problems into functional groups,

- identifying the rock properties and other factors affecting these problems,

- developing suitable test methods for determining these properties,

- establishing functional correlations between a set of properties or factors and the problems, and

- verifying these correlations in practice.

Geotechnical Problems

Almost all geotechnical problems can broadly be divided into the following major groups; (a) Rock mass stability, (b) Rock breakage and handling and (c) Environmental problems. The details of these groups are shown in Table 1.

Rock Properties and Other Factors Affecting Geotechnical Problems

The geotechnical characteristics of rocks mainly depend on the following: (a) Rock properties, (b) Structural discontinuities in the rock mass, (c) Ground water, (d) Field stress, (e) Temperature and (f) Technological factors.

Rock properties are divided into the following principal groups: (a) Standard static properties, (b) Rheological properties, (c) Dynamic properties, and (d) Triaxial and penetration properties. Structural discontinuities include faults, joints, cleats, other slip planes, etc. The effects of ground water on rocks are due to pore pressure and physico-chemical alteration. Field stress and temperature directly affect rock properties. The technological factors include excavation geometry, rate and method of excavation, dynamic stresses due to blasting and load transfer, etc. Some examples of geotechnical problems affected by rock properties, structural discontinuities and ground water, etc. are presented in Table 1.

The Principal Property Groups for a Basic Rock Characterization System

Of the five factors influencing geotechnical characteristics of rocks as stated before, only the rock properties may be considered as the primary factor. Leaving aside the effects of any dominant geologic features, the influences of other factors on geotechnical characteristics are generally indirect and mainly through their effects on rock properties. If the properties are determined through in situ tests some of these effects are automatically accounted for. But as the in situ tests are difficult and not always possible, rocks are often characterized on the basis of laboratory tests after making adjust-

Table 1 - Some important geotechnical problems in mining and civil engineering and the properties affecting them.

FIELD	PROBLEM GROUP	SPECIFIC PROBLEM/ACTIVITY	IMPORTANT GEOTECHNICAL PROPERTIES AFFECTING THE PROBLEMS
Surface mining/ surface excavation	Rock mass stability	- highwall stability - base/floor stability - waste dump stability	- shear strength, geologic features, ground water - penetration strength/hardness - cohesion, friction
	Rock breakage and handling	- coal cutting/digging - soil stripping - coal/rock blasting - rock handling	- penetration hardness/strength - cohesion - dynamic strength - different strength and elastic properties
Underground mining/ civil engineering tunnel	Rock mass stability	- shaft, roadway and face design/support - pillar design/strength - floor strength - load transfer and pressure readjustment - roof caving/void filling - surface subsidence and subsurface movement - rockburst - backfill	- different strength and elastic properties - triaxial/tensile strength, Young's modulus - penetration hardness/strength, ground water - triaxial strength, Young's modulus - shear/bending strength, coefficient of loosening - coefficient of loosening, uniaxial compressive strength - brittleness, reversible energy capacity - triaxial strength
	Rock breakage and handling	- coal cutting - coal/rock blasting - rock handling	- penetration hardness/strength - dynamic strength - different strength and elastic properties
Surface/ underground excavation	Environmental problems	- dust formation and gas emission control - control of ground water movement	- brittleness, reversible energy capacity, joints - geological features , permeability

ments for different field factors.

The rock properties are further divided into the following main two groups: (a) Strength properties, (b) Elastic properties. Strength properties include different properties as mentioned before and represent resistance to deformation. Elastic properties govern the mode of deformation/failure, such as elastic or plastic, brittle or ductile, etc. Also, elastic properties provide a measure of modulus and limit of elasticity. Thus if a technique can determine some of the properties in the above two groups that method will serve as a basis for rock characterization.

The influence of all the factors on the geotechnical characteristics of rocks can mathematically be expressed as follows:

$$G = F(R) = f(R_s, Re) \qquad (1)$$

where, G - Geotechnical characteristics
R - Rock properties
R_s - Strength properties of rocks
R_e - Elastic properties of rocks

Therefore,

$$\frac{\partial G}{\partial R_s} = \frac{dG}{dR} \cdot \frac{\partial R}{\partial R_s} \qquad (2)$$

and

$$\frac{\partial G}{\partial R_e} = \frac{dG}{dR} \cdot \frac{\partial R}{\partial R_e} \qquad (3)$$

Also,

$$R = (R_s, Re) = F(D, W, S, T, O) \qquad (4)$$

where, D - Structural discontinuities
W - Ground water
S - Field stress
T - Temperature
O - Technological factors

Therefore,

$$\frac{\partial G}{\partial D} = \frac{\partial G}{\partial R_s} \cdot \frac{\partial R_s}{\partial D} + \frac{\partial G}{\partial R_e} \cdot \frac{\partial R_e}{\partial D} \qquad (5)$$

Similar relations are true for W,S,T,O

These relationships are important in developing various functions, vectors or matrices on rock characterization based on a detailed study of those variables.

THE MICROHARDNESS TECHNIQUE

The standard form of microhardness in practice is the micro-indentation hardness. The specimen to be tested is subjected to a given load applied onto a microindenter. The hardness, in this case, is known as microhardness and is expressed as the ratio of the applied load to the total slant area of the permanent impression.

The two common type of indenters are known as Vicker's pyramid and Knoop's pyramid. The microhardness determined using these two pyramids are respectively known as Vicker's microhardness (Morley,1944) and Knoop's microhardness (Knoop, Peters and Emerson,1939). The indenter in Vicker's hardness is a square based diamond micropyramid whose opposite faces form an angle of 136° (Figure 1-a). Knoop's indenter on the other hand is a rhombus based diamond micropyramid with longer diagonal approximately seven times the shorter diagonal (Figure 1-b). The angle subtended by the longer and the shorter edges are 172° 30′ and 130° respectively.

Microhardness Equations

The derivation of the microhardness equations (Vicker's and Knoop's) from the definition of hardness provides a very clear understanding of the physical meaning of hardness. This is of significance when using the microhardness technique for rock characterization. This aspect is discussed later under this major subheading.

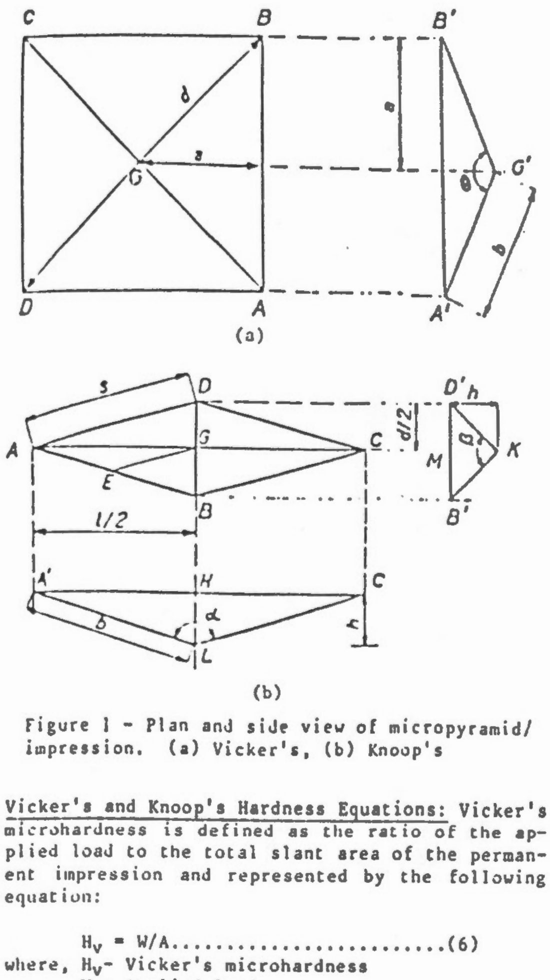


Figure 1 - Plan and side view of micropyramid/impression. (a) Vicker's, (b) Knoop's

Vicker's and Knoop's Hardness Equations: Vicker's microhardness is defined as the ratio of the applied load to the total slant area of the permanent impression and represented by the following equation:

$$H_v = W/A \qquad (6)$$

where, H_v - Vicker's microhardness
W - Applied load
A - Total slant area of permanent impression

The area A can be expressed in terms of the diagonal of the impression as follows:

Area of contact is the sum of the four slant triangles: Δ GAB, Δ GBC, Δ GCD AND Δ GAD = 4.Δ GAD (as all the triangles are congruent). (Figure 1-a)

Now ΔGAD = 1/2 AD. A'G' = 1/2 (2ab) =

$$\frac{a.a.}{\sin\theta/2} = \frac{a^2}{\sin\theta/2} \tag{7}$$

$$\text{but } a = \frac{d}{2\sqrt{2}} \tag{8}$$

Therefore the total area of contact

$$A = \frac{4d^2}{8\sin\theta/2} = \frac{d^2}{2\sin\theta/2} \tag{9}$$

Therefore,

$$H_v = \frac{W}{A} = \frac{W}{d^2/2\sin\theta/2} = \frac{2W}{d^2}.\ \sin\theta/2$$

$$= \frac{KW}{d^2} \tag{10}$$

where, K is a constant and θ and d are shown in Figure 1-a.

It may now be said that in calculating Vicker's hardness the total area of the permanent impression is the basis, and not just the diagonals. The occurrence of the diagonals in the formula is a geometrical fact. In reality, however, the diagonals are measured irrespective of the fact whether the area is fully or partly developed or whether only the diagonals remain as the residual impressions. Further work, which will be the subject matter of a future research paper, will explain the reason for the morphological variation of the impression.

Knoop's hardness equation can similarly be derived as follows:

$$H_k = \frac{W}{A} \tag{11}$$

where,

- H_k - Knoop's microhardness
- W - Applied load
- A - Total slant area of permanent impression

Substituting the value of A which can be determined from Figure 1-b, Knoop's microhardness is represented by the following equation:

$$H_k = \frac{4W \operatorname{Cot}^2\beta/2}{\ell^2\sqrt{(\operatorname{Cot}^2\alpha/2+\operatorname{Cot}^2\beta/2)(\operatorname{Cot}^2\alpha/2+4\operatorname{Cot}^2\alpha/2\operatorname{Cot}^2\beta/2+\operatorname{Cot}^2\beta/2)}}$$

$$= \frac{CW}{\ell^2} \tag{12}$$

where, C, is a constant and ℓ, α and β are shown in Figure 1-b.

Physical Concept of Vicker's Microhardness

The microhardness equations as derived above indicate that microhardness can be determined from the applied load and the length of the permanent impressions irrespective of the morphology of the impressions. It has been observed that impressions under a given load having nearly identical size of diagonals had different morphology as shown in Figure 2 (Das,1985). Therefore, an analysis of the impression morphology is also important for characterizing the material. Whereas Vicker's microhardness is a measure of strength properties, the impression morphology is a reflection of elastic properties. All these aspects are discussed under the next major subheading.

THE MICROHARDNESS TECHNIQUE FOR COAL CHARACTERIZATION

As discussed before the strength and elastic properties of rocks can serve as a basis for rock characterization. The microhardness technique can provide the essential components of these two groups of properties directly and some other components through indirect correlations. Therefore this technique can be used for rock characterization.

Properties from Microhardness Test

Theoretical analysis of the microhardness technique as well as experimental study on coals using this technique indicates that some strength and elastic properties can precisely be determined. Although Knoop's microhardness method has also been investigated, the results of Vicker's microhardness study on coals are discussed here.

The following important properties can be determined from microhardness test: (Table 2):

- Vicker's microhardness (H_v): This is an index of strength
- Uniaxial compressive strength (σ_u) and penetration strength (σ_p):correlations have been established between, these two quantities with Vicker's microhardness (Das and Hucka, 1975)
- Youngs modulus (E): It has been theoretically established (Honda and Sanada,1956) that: $E = 2.71\ H_v$
- Penetration modulus (E_p) and penetration brittleness (B_p): Correlations have been established between these two quantities and Vicker's microhardness (Das and Hucka, 1975)
- Brittleness (B):An index of brittleness can be established from the morphological analysis of the Vicker's microhardness impressions. Also, a quantitative measure of brittleness as a function of microhardness and macrohardness has been established (Hucka and Das,1974). A similar quantity, the so called, fissure factor was also established as a function of Vicker's microhardness and macrohardness (Heinze,1958).

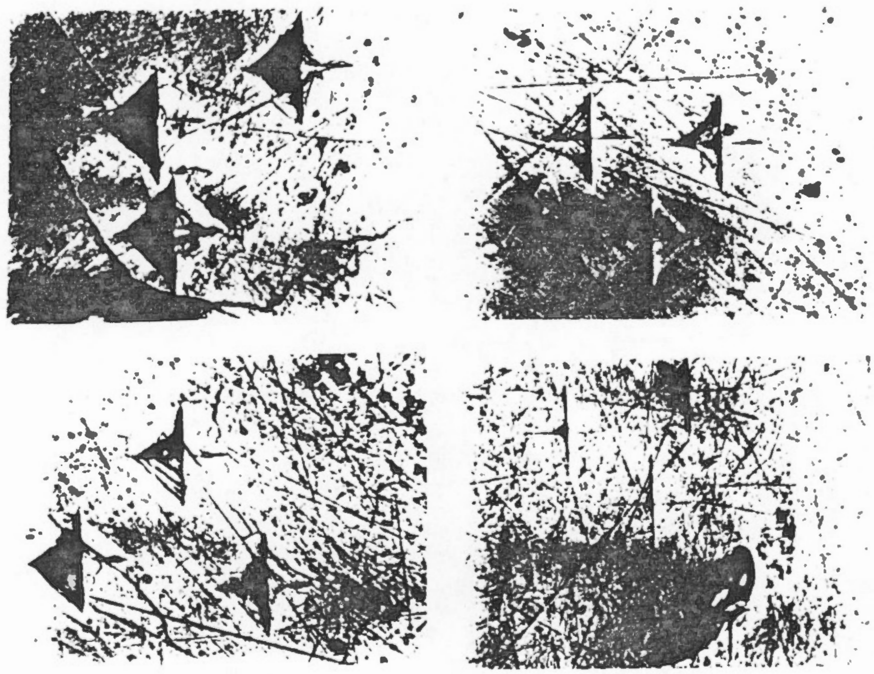


Figure 2 - Vicker's microhardness impressions showing identical diagonal size but different morphology

The brittleness index determined from the morphology of the microimpressions are shown in Figure 3. The following aspects of the microimpressions are studied in giving a brittleness rating: size, shape, depth, boundary, microcracks and external area. The rating ranges from 1 to 10 where 1 indicates lowest brittleness and 10 the highest. Some representative photographs of Vicker's microimpressions are presented in Figures 4-11.

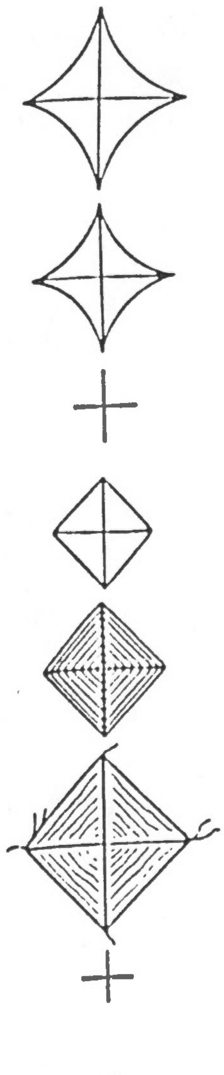
Characterization of Coals

The results of the microhardness study on coals of all ranks from lignites to anthracites indicate that a basic characterization system can be developed from the strength and elastic properties of coal.

The microhardness of coal varies with coal rank producing an oscillating curve (Figure 12).On the other hand, brittleness increases steadily with rank (Table 2, Figure 3). Accordingly, coals of all ranks can be divided into four broad groups (Table 3). This system can be easily extended by forming different other sub groups with intermediate values. Some geotechnical characteristics of each group are indicated in Table 3. Some nongeotechnical characteristics, for example, susceptibility to spontaneous heating, methane capacity, coking characteristics, etc. can also be predicted for the groups. Thus the coals in Group I are highly susceptibile to spontaneous heating, almost free of methane and are non-coking (Figure 4). Again, those in Group III have low susceptibility to spontaneous heating, a high methane risk and are prime coking (Figure 11).

Table 2 - Vicker' microhardness tests results and other mechanical properties for different ranks of coal.

Serial No.	Carbon % of the coal substance (d.m.f.)	Volatile % of the coal substance (d.m.f.)	Vicker's microhardness (H_v) (kg/mm^2=9.8MN)	Penetration strength (σ_p) (kg/mm^2=9.8MN)	Penetration brittleness (B_p)%	Brittleness Index (B)
1	61.23	62.14	18.21	17.00	10.21	1
2	64.72	64.24	19.32	19.25	10.56	2
3	66.46	59.99	19.78	20.78	10.68	3
4	68.23	56.39	22.52	20.52	13.53	
5	71.13	55.42	25.09	21.64	14.75	
6	72.05	50.80	26.24	25.00	18.23	
7	74.12	51.95	31.06	26.37	18.22	4
8	76.88	49.99	35.10	27.93	21.57	
9	76.98	36.48	37.17	28.34	24.10	
10	78.50	40.52	38.62	29.00	26.22	
11	80.62	37.09	25.35	20.86	41.97	5
12	81.28	35.83	41.97	31.53	30.23	
13	81.58	36.28	40.25	33.26	32.20	
14	82.03	36.52	42.03	34.77	32.29	
15	82.12	37.30	39.24	34.09	33.77	
16	82.34	36.53	38.07	34.85	34.19	
17	82.95	36.67	35.02	34.13	35.00	
18	83.12	34.88	39.11	32.09	35.62	
19	83.15	36.91	35.23	35.69	35.42	6
20	83.23	32.57	35.62	32.42	35.73	
21	84.51	32.80	35.60	33.33	39.72	
22	86.06	32.08	31.52	31.28	41.33	
23	86.33	31.24	26.87	31.74	41.39	
24	86.44	23.68	24.42	22.45	48.44	
25	86.96	27.65	26.16	26.24	40.00	7
26	87.92	30.57	24.55	24.00	45.21	
27	88.39	23.13	23.80	22.15	48.33	
28	89.17	17.12	23.22	21.24	49.95	8
29	89.58	18.54	24.41	20.73	49.82	
30	90.46	15.54	26.75	22.52	51.08	
31	90.61	14.84	27.72	22.79	52.73	9
32	91.74	5.52	No	37.00	52.67	
33	92.47	12.38	impress-	41.18	54.03	
34	94.22	5.21	ion	63.38	53.26	10



Lignite
C - 65%
B - 3

Sub-bituminous Coal
C - 75%
B - 4

Sub-bituminous Coal
C - 80%
B - 5

Caking Coal*
C - 83%
B - 6

Coking Coal
C - 87%
B - 7

Prime Coking Coal
C - 89.5%
B - 8

Semi-anthracite
C - 91.5%
B - 9

Anthracite
C > 93.3%
B - 10

Figure 3 - Brittleness of coal from Vicker's microimpressions. C - Carbon percentage in coal (dmf), B - Brittleness index (Brittleness increases with index)(*Caking ≠ Coking).

Figures 4-11 (Further reduced by 60%)

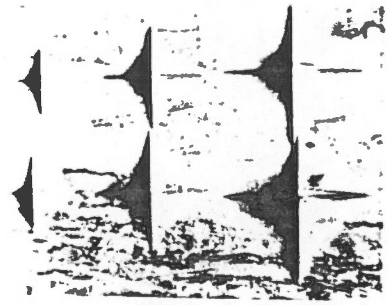


Figure 4 - Vicker's microhardness impressions. (Load: 20g, 50g, 100g); magnification - 350X; low rank lignite.

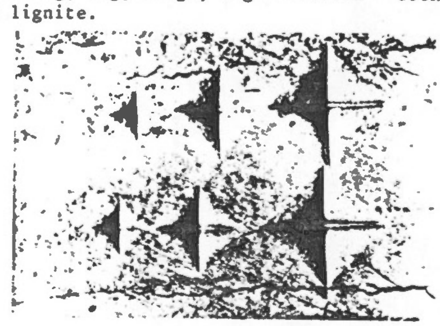


Figure 5 - Vicker's microhardness impressions. (Load: 20g, 50g, 100g); magnification 350X; high rank lignite.

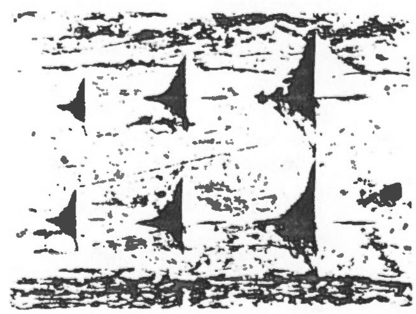


Figure 6 - Vicker's microhardness impressions. (Load: 20g, 50g, 100g); magnification 350X; medium rank sub-bituminous coal.

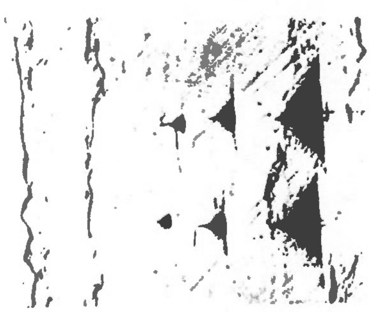


Figure 7 - Vicker's microhardness impressions. (Load: 20g, 50g, 100g); magnification 350X; high rank sub-bituminous coal.

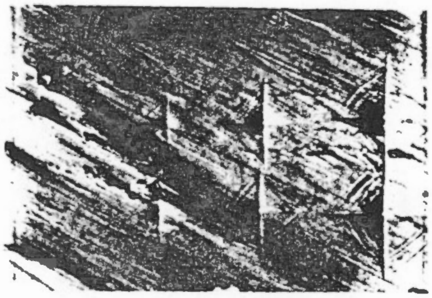


Figure 8 - Vicker's microhardness impressions. (Load: 20g, 50g, 100g); magnificaiton 350X; low rank bituminous coal.

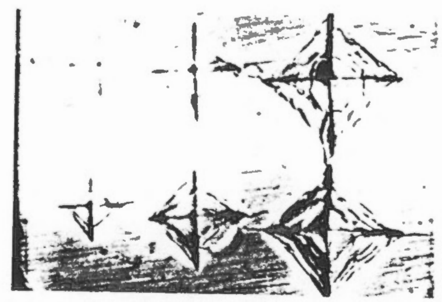


Figure 10 - Vicker's microhardness impressions. (Load: 20g, 50g, 100g); magnification 350X; low rank coking coal.

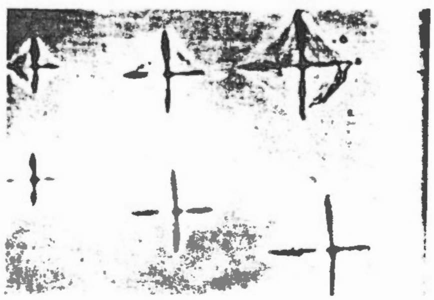


Figure 9 - Vicker's microhardness impressions. (Load: 20g, 50g, 100g); magnification 350X; caking coal.

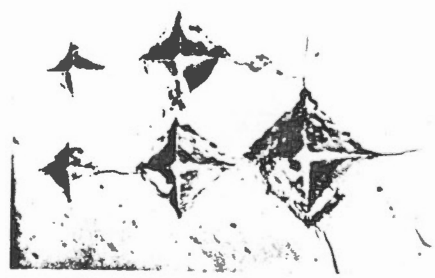


Figure 11 - Vicker's microhardness impressions. (Load: 20g, 50g, 100g); magnification 350X; prime coking coal.

Table 3 - Geotechnical classification of coal based on Vicker's microhardness tests

GROUP	TYPICAL COAL	GEOTECHNICAL PROPERTIES	GEOTECHNICAL CHARACTERISTICS
I	Lignites, low rank sub-bituminous coals	$H_v < 20$ $B < 4$	Soft and ductile coal, difficult to cut, no cracks, less fines or dust, low abutment pressure
II	Low volatile sub-bituminous and high volatile bituminous coals	$H_v = 40$ $B = 5$	Hard and elastic coals, blocky pieces, less cracks, less fines, out burst prone
III	Coking coals	$H_v < 25$ $B = 7$ to 8	Soft friable coals, highly fractured, high amount of fines, higher permeability and methane emmission rate
IV	Semi-anthracites and anthracites	$H_v > 60$ $B = 9$ to 10	Very hard and brittle coals, dusty but not to an extreme degree, high abutment pressure, highly prone to rock burst

H_v - Vicker's microhardness (kg/mm^2 = 9.8 MN), B - Brittleness index

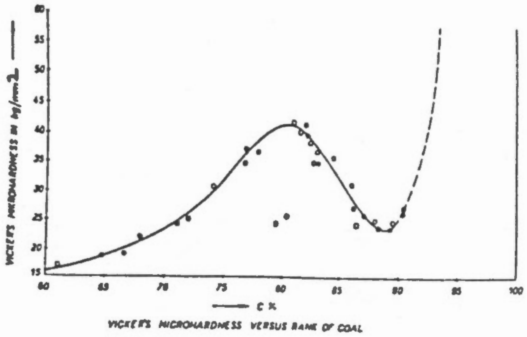


Figure 12 - Vicker's microhardness versus rank of coal expressed as the percentage of Carbon (C)(dmf)

CONCLUSIONS

The microhardness technique provides a simple and reliable tool for rock characterization. Microhardness as a penetration property is a better representative of the strength characteristics than uniaxial compressive strength for such factors as cutting resistance, floor bearing capacity, and roof resistance. Also, the microhardness represents some sort of triaxial strength due to self-confinement and therefore will serve as a better index in many practical problems involving self-confinement. The microhardness impressions are of great value in determining strength and elastic properties. Only a skeleton classification system which can be filled or extended through further study is developed in this paper. With modern microhardness testers the work on microhardness is expected to advance by leaps and bounds.

REFERENCES

Barton, N., Lien, R. and Lunde, J., 1974,"Engineering Classification of Rock Masses for the Design of Tunnel Support", Rock Mechanics, Vol. 6. No. 4, pp. 189-236.

Bienawski, Z.T., 1974,"Geomechanics Classification of Rock Masses and Its Application in Tunnelling - Advances in Rock Mechanics", Proc. of 3rd Cong. of Int. Soc. Rock Mech., Vol. 6, No. 4.

CANMET, 1983,"A Rock Classification System for Application in Underground Coal Mining", CANMET Contract-Report, Micromedia Ref. No. 84-1281/2.

China Coal Society, 1982,"Classification of Roofs Overlying Gently Inclined Coal Seams in China", Proc. 11th World Mining Congress, Belgrade, Yugoslavia.

Coates, D.E., 1964, "Classification of Rocks for Rock Mechanics", Rock Mechanics and Mining Sciences", Vol. 1, 421-429.

Das, B. and Hucka, V., 1975, "Laboratory Investigation of Penetration Properties of the Complete Coal Series," Int. J. Rock Mech. Min. Sci. and Geomech. Absts., Vol.12, July, No. 7, pp.213-217.

Das, B., 1985, "The Microhardness Technique and Its Applications to Coal and Coal Mining," Division Report ERP/CRL 85-51 (OP), Canada Centre for Mineral and Energy Technology, Fed. Dept. of Energy Mines and Resources, Calgary, Canada.

Deer, D.U., Peck, R.B., Parker, H.W. and Monsees, J.H., 1970, "Design of Tunnel Support Systems", Highway Research Record, Vol. 339, pp. 26-33.

Heinze, G., 1958, "Die Mikroharte der Kohle", Bergbau Archive., Vol. 19, pp. 71-93.

Honda, H. and Sanada, Y., 1956, " Hardness of Coal," Fuel, London, Vol 35, pp. 451-462.

Hucka, V. and Das, B., 1974, "Brittleness Determination of Rocks by Different Methods", Int. J. Rock Mech. Min. Sci. and Geomech. Abstr., Vol. 11, No. 11, pp. 389-392.

Hybert, D.K., 1978, "The Classification, Evaluation, and Projection of Coal Mine Roof Rocks in Advance of Mining", Min. Eng., 1667-1676, Dec.

Knoop, F., Peters, C.G. and Emerson, W.D., 1939, J.Res. Nat. Bur. Standard., Vol. 23, pp.39.

Korovkin, J.A., 1980, "Coal Mine Roofs Classification in Mechanized Longwalls", UGOL, Vol. 1, pp. 18-22 (in Russian).

Laubscher, D.H., 1977, "Geomechanics Classification of Jointed Rock Masses - Mining Applications", Trans. Instn. Min. Metall, Vol. 86, A1-8.

Lauffer, H., 1958, "Gebirgsklassifizierung fur den Stollenham", Geologie und Bauwesen; Vol. 24, pp. 46-51.

Morley, A., 1944, "Strength of Materials", Longman, Green and Co., New York, pp. 527-528.

Pawlowicz, K., 1967,"Classification of Rock Caveability of Coal Measure Strata in Upper Silesia Coalfield", Prace GIG, Komunikat, 429, Katowice (in Polish).

Terzaghi, K., 1946, "Rock Defects and Loads on Tunnel Supports", Rock Tunnelling with Steel Supports, Ed. Proctor and White, Commercial Shearing Co., Youngstown, pp. 15 - 99.

USBM., 1973, "Ground Control Aspects of Coal Mine Design", Proceedings: Bureau of Mines Technology Transfer Seminar, Lexington, Kentucky, March 6, (Washington, D.C., Bureau of Mines, U.S. Department of the Interior, 1974).

Vinokur, B.S., 1964,"Classification of Rock Caveability in Pitching Seamns of the Kisielov Coalfield During Manless Coal Extraction", Trudy Wnimi, 53 Izd. Niedra, Leningrad (in Russian).