Classification of Rock for Engineering Purposes

By

Leonard Obert, Ph.D.
(Science Adviser—Mining Research, U.S. Bureau of Mines)
and
Charles Rich
(Mining Engineer, U.S. Bureau of Mines)

SUMMARY -- Although a number of classifications for both intact rock and rock masses have been proposed, these classifications, in general, do not relate to specific engineering applications. This report outlines research in progress by the U.S. Bureau of Mines to develop rock mass classifications related to two ground support problems, namely, caveability of ground (as in a block caving mine), and attainable unsupported spans, (as in an open-stope mine). The mechanical and geological property data used in these classifications are obtained from cores taken from operating mines. Techniques for quantizing geological features in the cores are briefly described.

Many investigators have considered ways of classifying rock on the basis of some mechanical or quantifiable geological property of the rock, or some combination of these factors. These classifications can be divided into two categories; (1) classification of intact rock, and (2) classification of rock masses. The intact properties used in these classifications include the laboratory-determined unconfined compressive and tensile strengths, triaxial (confined) strengths and friction, deformation moduli, seismic velocities, and indentation (or hardness). Rock mass classifications have used, in addition to the intact mechanical properties, in-hole and cross-hole seismic velocities, and geological factors such as the percentage core recovery and joint (or fracture) spacing. These mechanical and geological properties can be obtained from measurements in exploration holes or cores taken from these holes.

However, a review of the literature disclosed that there is only very limited information on how these classifications relate to specific mining problems or applications. For example, it is logical to suppose that because processes such as pneumatic drilling, diamond drilling, or large-diameter boring (as with a tunneling machine) create mostly fresh rock surfaces, a classification based on the properties of intact rock should relate to drilling and boring capabilities or rates. There is very little information in the literature showing such a relationship and, in fact, a questionnaire sent to tunneling machine manufacturers revealed that they do not use any such classification. Some manufacturers do rate their machines in terms of an upper limit on the unconfined compressive strength of the rock that the machine will bore, but properties other than compressive strength affect boring rates. These manufacturers are more likely to estimate bore rates on the basis of an index established by boring in an equivalent rock type with a model drill.

The use of classifications for rock masses is almost as indefinite. For example, it might be expected that ground support requirements would relate to some rock mass classification based on measured rock properties. One report (1)[3] does classify "rock quality" in terms of RQD (rock quality designation)[4] and presents a chart, Table I, giving "Guidelines for Selection of Primary Support for 20-ft to 40-ft Tunnels in Rock." However, the literature does not contain any equivalent tables for support requirements for chambers or mine openings classified in terms of RQD or any other measured rock property. Moreover, as will be indicated later in this report, RQD may not be satisfactory for such purposes.

If geomechanics is to serve the excavation industry, it should answer such questions, because the most critical decision-making period is when the exploration cores from a project become available for observation and test. For example, consider a tunneling project: At the conclusion of exploration the following decisions must be made; can the tunnel be machine bored and, if so, will machine boring be economically favorable in comparison to conventional mining? What will be the expected rate of progress? Will the ground stand unsupported, or will support ranging from rock bolts, to heavy sets and concrete lining be required? Errors in judgment at this point can result in substantial delays that can be costly to either the contractor or owner, or both.

---

[1] Science Adviser-Mining Research, Office of Science Adviser-Mining Research, U.S. Bureau of Mines, Denver, Colo.

[2] Mining Engineer, Office of Science Adviser-Mining Research, U.S. Bureau of Mines, Denver, Colo.

[3] Underlined numbers in parentheses refer to items in the list of references at the end of this report.

[4] Rock quality designation (RQD) is the ratio of length of core recovered, counting only those pieces of intact rock 4 inches in length or longer, to the total length or core run.

Table I--Guidelines for selection of primary support for 20-ft. to 40-ft. Tunnels in Rock [Deere, et al (1)]

Rock Quality	Construction Methods	Steel Sets			ALTERNATIVE SUPPORT SYSTEMS(5)				
					Rock Bolts(3) (Conditional use in poor & very poor rock)		Shotcrete Conditional use in poor & very poor rock(4)		
							Total Thickness		
		Rock Load (B-Tunnel Width)	Weight of Sets	Spacing(2)	Spacing of Pattern Bolts	Additional Requirements and Anchorage Limitations(a)	Crown	Sides	Additional Support(4)
Excellent(1) RQD > 90	Boring Machine	(0.0 to 0.2)B	Light	None to Occasional	None to Occasional	Rare	None to occ. Local Application	None	None
	Drilling & Blasting	(0.0 to 0.3)B	Light	None to Occasional	None to Occasional	Rare	None to Occ. Local App. 2 to 3 in.	None	None
Good RQD = 75 to 90	Boring Machine	(0.0 to 0.4)B	Light	Occasional to 5 to 6 ft.	Occasional to 5 to 6 ft.	Occasional mesh & straps	Local App. 2 to 3 in.	None	None
	Drilling & Blasting	(0.3 to 0.6)B	Light	5 to 6 ft.	5 to 6 ft.	Occasional mesh & straps	Local App. 2 to 3 in.	None	None
Fair RQD = 50 to 75	Boring Machine	(0.4 to 1.0)B	Light to Medium	5 to 6 ft.	4 to 6 ft.	Mesh & straps as required	2 to 4 in.	None	Provide for rock bolts
	Drilling & Blasting	(0.6 to 1.3)B	Light to Medium	4 to 5 ft	3 to 5 ft.	Mesh & straps as required	4 in. or more	4 in. or more	Provide for rock bolts
Poor RQD = 25 to 50	Boring Machine	(1.0 to 1.6)B	Medium Circular	3 to 4 ft.	3 to 5 ft.	Anchorage may be hard to obtain. Considerable mesh and straps required.	4 to 6 in.	4 to 6 in.	Rock bolts as required (~4-6 ft. oc.)
	Drilling & Blasting	(1.3 to 2.0)B	Medium to Heavy Circular	2 to 4 ft.	2 to 4 ft.	Anchorage may be hard to obtain. Considerable mesh and straps required	6 in. or more	6 in. or more	Rock bolts as required (~4-6 ft. oc.)
Very Poor RQD < 25 (Excluding Squeezing & Swelling ground)	Boring Machine	(1.6 to 2.2)B	Medium to Heavy Circular	2 ft.	2 to 4 ft.	Anchorage may be impossible. 100% mesh and straps required.	6 inches or more on whole section		Medium sets as required
	Drilling & Blasting	(2.0 to 2.8)B	Heavy Circular	2 ft.	3 ft.	Anchorage may be impossible. 100% mesh and straps required.	6 inches or more on whole section		Medium to heavy sets as required
Very poor, Squeezing or Swelling gr.	Both Methods	Up to 250 ft.	Very Heavy Circular	2 ft.	2 to 3 ft.	Anchorage may be impossible. 100% mesh and straps required	6 inches or more on whole section		Heavy sets as required

NOTES:

(1) In good and excellent quality rock, the support requirement will in general be minimal but will be dependent upon joint geometry, tunnel diameter and relative orientations of joints and tunnels.

(2) Lagging requirements for steel sets will usually be minimal in excellent rock and will range from up to 25% in good rock to 100% in very poor rock.

(3) Bolt diameter = 1 in. Length = 1/3 to 1/4 tunnel width. It may be difficult or impossible to obtain anchorage with mechanically anchored rock bolts in poor and very poor rock. Grouted anchors may also be unsatisfactory in very wet tunnels.

(4) Because shotcrete experience is limited, only general guidelines are given for support in the poorer quality rock.

(5) Table reflects 1963 technology in U. S. A. Groundwater conditions and the details of jointing and weathering should be considered in conjunction with these guidelines, particularly in the poorer quality rock. See Deere et al. (1) for discussion of use and limitations of the guidelines for specific situations.

In an exploratory investigation for an underground chamber such as that for a power station, the principal problem is to determine the span that will stand either unsupported, or with minimum support such as rock bolts and a wire-mesh-shotcrete surface treatment. Considering that spans ranging from 50 to 80 ft or more are generally required for such chambers, a critical evaluation of the rock that will form the roof of the chamber must be made.

In mining the problem is even more complex. Presuming that an ore body has been delineated by exploration, a mining method must be selected that will provide for a satisfactory recovery and rate of production from the deposit, and be otherwise economic. The selection of this method will be determined primarily by the properties of the rock that comprise the ore body, the immediate rock surrounding the deposit, and the rock forming the overlying cover. Assuming that a rational selection of the mining method can be made, it is generally necessary at this time to decide on production capabilities and hence the size of the shaft, the mill capacity, and other surface facility requirements. Also, a substantial part of the mining machinery must be ordered considerably in advance of the start of production. These decisions must be made almost immediately following exploration because of the large capital investment that is involved in bringing a modern mine into production. This capital investment may be in excess of $10 million, and in some instances over $100 million. Thus, the judgments that must be made on the basis of observations and tests on core or boreholes must be reliable or costly delays, and losses incurred in the purchase of improper equipment will result.

Because previous classifications based on observations and tests on exploration cores or in exploration cores or in exploration holes have been only indefinitely related to specific excavation problems, an investigation was initiated in which the problem was approached from a different direction. Two geomechanical problems were selected; namely, the caveability of rock (as experienced in block caving mines), and the attainable unsupported span (as experienced in open stope mines). Operational data related to ground support were collected (and are continuing to be collected) from a number of operating mines. Also, exploration cores were obtained from these mines (either from past explorations or from present borings). The cores included the rock types that comprise the ore body, the immediate rock surrounding the ore body and, whenever possible, from the overlying cover. A routine set of geological observations and mechanical property tests are performed on these cores. These data are than analyzed to ascertain which or what combination of these measured properties are significant in relation to the specified excavation problem. These selected data will form the basis for classification.

In so far as possible the mines selected for study have been chosen to include operations in a variety of rock types. Also, preferential consideration has been given to mines in which uncontrolled failures have been experienced, that is, failures due to misjudgments, because these failures are in effect a limiting test of the rock structure.

The combination of operational and geomechanical data that have been collected to date are much too extensive to present in detail. However, Table II includes the more significant operation data obtained from a number of block caving mines, together with a part of the geomechanical data. Table III presents the same information obtained from open stope mines.

Several interesting inferences already have been made from the analysis of these data. First, the unconfined compressive strength of the rock comprising or surrounding the ore body is only secondarily related to the unsupported span that can be mined. For example, borax ore (see Row 1, Table II), which is a combination of borax, kernite, and shale, is one of the weakest rock tested to date, having an unconfined compressive strength ranging from 1100 to 6000 psi. However, an unsupported area approximately 140 x 270 ft. has been mined in this rock type (2). Rooms 150 ft. wide are routinely mined in dome salt (halite), a rock that has an unconfined compressive strength of about 5000 psi and, hence, would be rated as one of the weaker rocks. On the other hand, a monzonite porphyry with a compressive strength of about 20,000 psi taken from a block caving mine (see Row 9, Table II), will cave freely if the span exceeds 10 ft. A comparison of these results leads to the rather obvious conclusion that some factor other than compressive strength dominates the length of span that can stand unsupported. As might be expected, in the cases cited this factor is the absence or occurrence of joints and fractures. Both borax ore and salt are virtually massive and unfractured rock types, whereas the monzonite porphyry has a joint and fracture spacing of about 3 to 24 inches. However, in an open-stope mine (see line 11, Table III) rooms with a span of 75 ft. have been mined and remained stable for many years in a jaspilite (roof rock) that has a joint spacing of 4 to 6 inches. Thus, there is some other factor than joint spacing that must be considered in relation to unsupported spans. This factor is not attributed to the type and extent of fill materials in joints and fractures, and the degree to which these fill materials indurate and recement.

The strengthening ability of even a weak bond across a joint plane is not too surprising if one considers that an average bond strength of, say, 5 psi across a horizontal joint plane will support 5 feet of underlying rock against the force of gravity. It is improbable that a diamond drill core can be taken across a joint plane that only has a bond strength of 5 psi.

Unfortunately, there has been no means of numerically evaluating the bond strength across joints except when the bond is strong enough so that a core can be taken across the joint plane. A research project, under the direction of Pincus[5] and Wipf[6], has been started to identify the alteration and decomposition products that form on joint planes and to determine which of these materials tend to indurate and recement. The rock materials used in these studies

---

[5] Howard J. Pincus, Dean and Professor, College of Letters and Science, The University of Wisconsin, Milwaukee; and U.S. BuMines Consultant.

[6] Robert A. Wipf, Graduate Student, University of Wisconsin, Milwaukee; and Intermittent employee, U.S. BuMines.

TABLE II - Characteristics of Caving Stopes

Mine and Location	Mining Method	Minimum Span or Area to Cave (ft)	Maximum Unsupported Span or Area (ft)	Stope Depth (ft)	Ore Deposit			Surrounding Rock			Overburden		
					Rock Type (Gangue)	Partings or Joints	Cohesion	Rock Type	Partings or Joints	Cohesion	Rock Type	Partings or Joints	Cohesion
Jennifer Boron, Calif.	Experimental block cave	?	113 - 149 x 272 Arching	300+	Borax C_o 1,100-6,600 CR 100	Clay fractures, borax-filled	Weak	Shale C_o 900-1,200	Partings, thin-bedded	Weak	Playa C_o 745-3.353 (CR ~ 5)	None	----
Grace Morgantown, Pa.	Continuous block cave	Undercut 15 x 25	4 x 6 Drift	1500+	Limestone, chlorite	4 Joint systems	Weak-medium	Limestone	4 Joint systems	Weak-medium	Sandstone, shale, quartzite		Weak
Climax Climax, Colo. **Area A**	**Block cave assisted by longholing**	> 200 x 200	200 x 200 No cave	1460+	Unmineralized quartz, granite, schist gneiss	Quartz-pyrite-filled JS 6-24	Strong	Granite, schist	Pyrite-, gouge-filled or open JS 1-24	Weak	Granite, schist	Weathered, gouge-filled or open JS 1-24	Weak
Area B	**Block cave assisted by longholing**	200 x 200	12 - 14 Drifts	1460+	Quartz, porphyry granite CR 84 - 98 RQD 68	Quartz-molybdenum-pyrite-filled JS 6 - 24	Strong	do.	do.	do.	do.	do.	do.
Area C	**Block cave**	100 x 200	< 12 ? Drifts	1460+	Quartz, porphyry, granite (C_o 17,680) CR 84, RQD 16	Sericite-molybdenum-pyrite-filled JS 1-24	Medium	do.	do.	do.	do.	do.	do.
Area D	**Block cave**	> 25	0	1460+	Quartz, porphyry, granite CR 86 - 84 RQD 8	Sericite-molybdenum-pyrite-filled or open JS > 1	Weak	do.	do.	do.	do.	do.	do.
Crestmore Riverside, Calif.	**Block cave assisted by shrinkage stopes**	80 x 200	60 x 200	730-915	Limestone (marble) C_o 4,430-19,900 RQD 55-70	Sporadic, tight, well-healed	Strong	Limestone (marble) C_o 4,430-19,900 RQD 55-70	Sporadic, tight, well-healed	Strong	Grano-diorite 0 - 200 ft	Solution channels, weathered or tight (JS 1-24)	Strong
White Pine White Pine, Mich.	Experimental longwall	125 x 320	> 80	400+	Shale C_o 12,750-26,050	Calcite-quartz-filled (JS > 12)	Weak-medium	Shale, laminar C_o 11.680-30.920	Calcite-quartz-filled (JS > 12)	Weak-medium	Sandstone C_o 16,940-23,720 CR 95+	Calcite-quartz-filled (JS > 12)	**Weak-medium**
San Manuel San Manuel, Ariz.	Block cave	> 10	0	1100+	Monzonite porphyry C_o 17,240-21,360 quartz monzonite C_o 10,909-27,625 rhyolite dikes C_o 20.000-39,960	Sericite-chlorite-clay-filled with hypothermal alteration 8 systems JS < 3-24	Weak	Monzonite porphyry C_o 17.240-21.360 quartz monzonite C_o 10,909-27,625 rhyolite dikes C_o 20,000-39,960	Sericite-chlorite-clay-filled with hypothermal 8 systems JS < 3-24	Weak	Conglomerate silt and marl C_o 541	Occasional fault	**Medium-strong**
Mather A and B Negaunee, Mich.	Block cave	< 6	0	2000+	Hematite, soft and plastic	Diorite dikes	----	Iron formation	3 Systems of joints diorite dikes (JS < 24)	Weak	Iron formation, greenstone C_o 26,200-39,800	**3 Systems of joints (JS < 24)**	**Strong**

( )	Estimated
JS	Average joint spacing (in.).
RQD	Rock Quality Designation (pct).
C_o	Compressive strength (psi).
CR	Core recovery (pct).

TABLE III - Characteristics of Self-Supported Stopes

Mine and Location	Mining Method	Extraction (%)	Maximum Unsupported Span or Area (ft)	Stope Height (ft)	Stope Depth (ft)	Ore Deposit			Surrounding Rock			Overburden		
						Rock Type	Partings or Joints	Cohesion	Rock Type	Partings or Joints	Cohesion	Rock Type	Partings or Joints	Cohesion
Hockley Hockley, Tex.	Room and random or regular pillar	60	70 x 130	40+ Flat roof	1400+	Dome salt CR 100	None	----	Dome salt	None	----	Massive anhydrite	?	----
Friedensville Friedensville, Pa.	Room and regular pillar	60	38	25 Arched roof	225+	Dolomite and quartz breccia	Sphalerite-pyrite-calcite-filled ($JS > 12$)	Weak-medium	Dolomite, limestone	Calcite-pyrite-mud-filled	Weak-medium	Sandstone, limestone	Calcite-clay-filled	Weak
Jennifer Boron, Calif.	Room and regular pillar	30-40	17	8 - 32 Flat roof	300+	Borax C_o 1,100-6,600 CR 100	Clay fractures, borax-filled	Weak	4-5 ft. Borax, then shale C_o 900-1200	Partings, thin-bedded	Weak	Playa C_o 745-3,353 ($CR \sim 5$)	None	----
Lead Hill #10 Federal Flat River, Mo.	Room and random pillar	90+	180 x 430	11-28 Flat arched roof	348+	Dolomite CR 90+	Partings, calcite-filled PS 6-24	Weak-medium	Dolomite CR 90+	Partings, calcite-filled PS 6-24	Weak-medium	Dolomite CR 90+	Partings, calcite-filled PS 6-24	Weak-medium
Tri-State District Mo., Kans., Okla.	Room and random pillar	60+	50	17+ Flat arched roof	400-700	Dolomite, chert	Occasional joints	----	Dolomite, chert	Occasional joints	----	Dolomite chert	Occasional joints	----
Clonan Mineville. N. Y.	Room and random pillar	67-80	125 - 200	150-200 Arched roof	400+	Massive magnitite C_o 20,500	Occasional joints	Strong	Massive gneiss C_o 27,100-34,300	$JS > 24$	Strong	Gneiss gabbro C_o 27,100-34,300	Occasional joints	Strong
Plasterco Saltville, Va.	Room and random pillar	80+	60 x 110	30-100 Arched roof	200+	Shale, gypsum	Calcite-filled ($JS > 12$)	Medium	Shale	Calcite-filled ($JS > 12$)	Weak-medium	Sandstone, limestone	Blocky	Weak-medium
Rifle Rifle, Colo.	Room and regular pillar	75	80 - 200	73 Flat roof	700-900	Marlstone C_o 16,600	Partings and occasional joints ($PS > 18$)	Weak-strong	Marlstone (shale) C_o 16,600	Partings and occasional joints ($PS > 24$)	Weak-strong	Marlstone $C_o > 16,000$	Partings $PS > 24$	Weak-strong
Crestmore Riverside, Calif.	Room and regular pillar	75+	60 - 200	25 Arched roof	730-915	Limestone (marble) C_o 4,430-19,900 RQD 55-70	Sporadic, tight, well-healed	Strong	Limestone (marble) C_o 4,430-19,900 RQD 55-70	Sporadic, tight, well-healed	Strong	Grano-diorite 0-200 ft.	Solution channels. weathered. tight (JS 1-24)	Weak-medium
White Pine White Pine, Mich.	Room and regular pillar	70-75	> 80	15-20 Flat roof	400+	Shale C_o 12,750-26,050	Calcite-quartz-filled ($JS > 12$)	Weak	Shale laminar C_o 11,680-30,920	Calcite-quartz-filled ($JS > 12$)	Weak-strong	Sandstone C_o 16,940-23,720 CR 95+	Calcite-quartz-filled ($JS > 12$)	Weak-medium
Cliffs Shaft Ishpeming, Mich.	Room and random pillar	75	65 x 75 90 x 230 rock bolted	90-100 Arched roof	850+	Specular hematite C_o 47,800	Tight ($JS > 12$)	Weak-medium	Argellaceous, slate C_o 47,800 Jaspilite C_o 49,600	Tight ($JS > 12$) Silica-filled (JS 4-6)	Weak-medium Medium	Massive quartzite C_o 43,200	Tight $JS > 24$	Medium

( )	Estimated	RQD	Rock Quality Designation (pct)
PS	Average parting separation (in.)	C_o	Compressive strength (psi)
JS	Average joint spacing (in.)	CR	Core recovery (pct)

Fig. 1 -- Photograph made from acetate peel (2X), Granite No. 1.

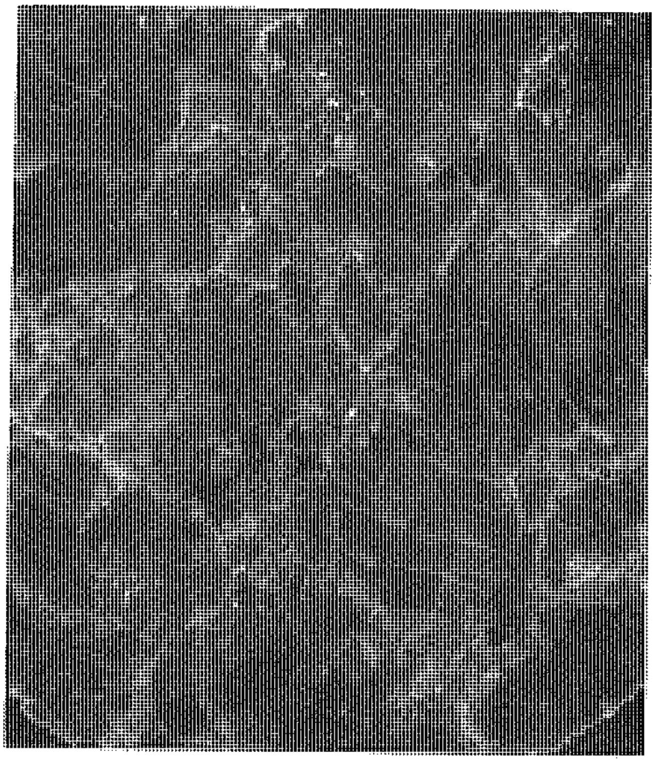

Fig. 2 -- Photograph made from acetate peel (2X), Granite No. 2.

are from the various mines in which other operational and geomechanical data are obtained. If this study can lead to even a rough quantitative classification of joint filling materials it would assist in assessing the ground supportability of the rock materials in exploration cores.

In block caving mines it is frequently reported that some areas are easy to cave, whereas others are more difficult to cave. This difference is due in part to the degree in spacing of joints and fractures. However, it is also due in part to the degree of alteration in the host rocks which, in turn, is probably related to the rock strength. An investigation, also under the direction of Pincus and Wipf, is in progress to determine if an alteration index for rock can be developed, that is, some quantitative measure of the degree of alteration. It is hypothesized that alteration is accompanied by the development of microfractures, and that the degree of microfracturing is related to the degree of alteration. Also, alteration may produce preferred spatial orientations of microfractures. The degree of microfracturing is being investigated by two techniques. The first involves applying a fluorescent dye penetrant to a sawed rock surface and observing the microcrack in this surface under ultraviolet light. In the second technique an acetate sheet softened in acetone is pressed against a sawed rock surface. When the sheet hardens it is peeled from the rock and the fractured detail observed on the peel.

The dye penetrant-ultraviolet light technique produces some visual enhancement of the microfractures, and even better detail is shown in the photograph of the peel. Photographs of peels taken from two granite specimens are shown in Figs. 1 and 2. The peel has a further advantage in that it can be subjected to an optical processing technique developed by Pincus (3,4), a technique that is helpful in determining if the microcracks lie in preferred directions. Using these methods, both the extent and orientation of microfractures can be quantized.

An up-hole or cross-hole seismic method is also being developed for evaluating in situ "rock quality." In this method a small charge is detonated in an exploration hole and the generated seismic signal picked up either at distant points within the same hole (up-hole) or in other exploration holes (cross-hole). From an analysis of the amplitude-frequency spectrum of the received signals, a seismic absorption coefficient for some specified frequency can be determined. This coefficient is sensitive to both rock type (5) and the degree of jointing and fracturing within a given body of rock (6). A "rock quality" index is being developed by comparing the absorption coefficient for a rock mass to the coefficient for an intact specimen taken from the same mass.

Collectively, the results from these studies indicate that at least three factors affect the caving properties of rock, or the ability of rock to sustain a specified unsupported span; namely, and in order of importance, the joint and fracture spacing, the degree of bonding across joints and fractures, and the rock strength or the degree of alteration.

In relation to problems other than ground support, this investigation suggests that there will probably be as many rock classifications as there are engineering problems. Thus, there may be a classification for pit slope angles, drillability, boreability and blastability of rock, as well as other factors that enter into the excavation process. Also, it would appear that performing mechanical property or geological tests on rock is an unprofitable exercise unless the test results are related to some specific engineering problem.

REFERENCES

1. DEERE, D. U.; PECK, R.B.; MONSEES, J.E.; PARKER, H. W.; and SCHMIDT, B. - "Design of Tunnel Support Systems," Proc. 49th Annual Meeting, Highway Research Board, Jan. 1970.

2. OBERT, LEONARD and LONG, ALBERT E. - "Underground Borate Mining, Kern County, Calif.," BuMines Rept. of Investigation 6110, 1962, 67 pp.

3. PINCUS, HOWARD J. and DOBRIN, MILTON B. - "Geological Applications of Optical Data Processing," J. Geophys. Res., Vol. 71, No. 20, October 1966, pp. 4861-4869.

4. PINCUS, HOWARD J. - "Sensitivity of Optical Data Processing to Changes in Rock Fabric," Int'l. J. Rock Mech. & Min. Sci."; Vol. 6, 1969; Part I--Geometric Patterns, pp. 259-268. Part II--Standardized Grain Patterns, pp. 269-272. Part III--Rock Fabrics, pp. 273-276.

5. OBERT, LEONARD. - "Seismic Tests at the Pre-Gondola II and Buggy Sites, Final Report," BuMines, Denver Mining Res. Center, Rept. No. OSA-E-59-2, May 1969, 50 pp.

6. NICHOLLS, HARRY R.; SCHMECHEL, FRANK W.; and MUNSON, ROBERT D. - "Strength Properties of the Phillipson, Storke, and Ceresco Ridge Levels as Determined by Seismic Absorption Techniques," BuMines, Denver Mining Res. Center, November 1970, 11 pp.