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FUELS AND MINING PRACTICE DIVISION

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EXPERIMENTAL CRITERIA FOR CLASSIFICATION OF ROCK SUBSTANCES

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Abstract—The classification system previously suggested for consideration uses categories describing both the rock substance and the rock mass. The rock substance was to be classified with respect to strength, pre-failure deformation characteristics and failure characteristics. The divisions within these categories were to be kept to a minimum owing to the much greater importance of structural features in determining the behaviour of most rock masses. Also, the detailed rock properties appropriate for specific problems cannot be considered in a classification system which must be based on information that can be easily obtained.

Since the original proposal, many research workers have offered criticisms and alternate suggestions. Also, extensive testing has been done on a wide range of rock substances to determine if the previously suggested criteria produced classifications that are acceptable from a common-sense point of view.

As a result of the suggestions by others and the classification testing, it is now recommended that the previous proposal be modified to include the geological name of the rock and to change the dividing line between *weak* and *strong* to 700 ksc (10,000 psi). In addition, owing to the variety of patterns of rheological behaviour, it is thought that instead of trying to distinguish between *elastic* and *viscous* substances and *plastic* and *brittle* failure based on deformation characteristics, it might be better simply to classify the substance as either *elastic* or *yielding* with the term *yielding* meaning a certain minimum time-dependent strain rate or a certain proportion of total strain being permanent. Further criticisms and suggestions are invited.

1. PREVIOUS WORK

A CLASSIFICATION system for rocks was previously suggested to promote discussion and research [1]. The proposed system separated the classification categories between those describing the rock substance and those describing the rock mass, i.e. Items 1–3 and Items 4–5 respectively as follows:

Substance: (i) Uniaxial compressive strength of the rock substance:
- (a) Weak (less than 350 ksc i.e. 5000 psi),
- (b) Strong (between 350 ksc i.e. 5000 psi and 1760 ksc i.e. 25,000 psi),
- (c) Very Strong (greater than 1760 ksc i.e. 25,000 psi).

(ii) Pre-failure deformation of rock substance:
- (a) Elastic,
- (b) Viscous (at a stress of 50 per cent of uniaxial strength the strain rate is greater than 2 micro-strain per hour).

(iii) Failure characteristics of the rock substance:
- (a) Brittle,
- (b) Plastic (more than 25 per cent of the total strain before failure is permanent).

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Formation: (iv) Gross homogeneity of formation:
(a) Massive,
(b) Layered.
(v) Continuity of the rock substance in the formation:
(a) Solid (joint spacing greater than 1·8 m i.e. 6 ft),
(b) Blocky (joint spacing between 76 mm and 1·8 m i.e. 3 in. and 6 ft),
(c) Broken (in fragments that would pass through a 76 mm i.e. 3 in. sieve).

Whereas for ground control problems a classification system ideally should indicate the order of magnitude of its strength, compressibility and continuity, it is very difficult to determine these properties for the *in situ* rock mass. The best that can be done on a routine basis at the present time is to establish the strength and compressibility of the rock substance and to add to this some geological survey information on the rock mass.

The properties of the rock substance provide only limited information for field problems as the properties of the rock mass may vary through a range of values varying from those of the substance to those of the infilling material in the joints of a loose formation. For example, if the substance is weak, then the rock mass will certainly be weak. On the other hand, if the substance is strong the rock mass may be strong or it may be weak, but it would be known that the weakness in the latter case arises from structural features.

Since the publishing of the above suggested classification, research work has been done on measuring the properties of the rock mass together with some laboratory testing of a wide spectrum of rock substances. The development of techniques for measuring the properties of rock masses *in situ* is still in process so that little useful information has as yet been gathered, On the other hand, the data obtained from testing rock substances can now be reviewed to determine if the previously suggested criteria produce classifications that are acceptable from a common-sense point of view.

2. EXPERIMENTAL DATA

Other research programmes in our laboratories have required the determination of either the uniaxial compressive strength or the modulus of deformation of a variety of rock substance. Supplementary testing has been conducted on a limited number of additional samples of these rocks so that the substance could be classified according to the above system, not only with respect to strength but also as either elastic or viscous and as either brittle or plastic. Table 1 shows the results of this testing plus some comparable data gathered from the literature. The common field geological names have been used. Appendix A includes some information on the origin and composition of these rock specimens.

The uniaxial compressive strengths, Q_u, shown in Table 1 were obtained following the test specifications presented in Appendix B. In some cases, fewer than the desirable minimum of 10 samples were tested owing to the limitations on the amount of core available of the particular rock type.

The modulus of deformation, E, has been determined from the compression test by taking the tangent of the stress-strain curve at a stress of 50 per cent Q_u. However, for highly viscous rocks this is not a satisfactory procedure unless a very crude value is of some use as a starting point for further studies. For the Potash and Halite samples, the reported E is based on the final unloading cycle. In the cases of data taken from the literature, i.e. in Table 1 from Shale 2 down to Marble, the modulus of deformation is that characterizing the immediate deformation as represented by the first spring in a Burgers model.

TABLE 1. ROCK SUBSTANCE CLASSIFICATION TESTING

Name	Density (g/cm³)	Q_u (ksc)	$E10^5$ (ksc)	$\dot{\epsilon}$ (μ/hr)	$\bar{\epsilon}_p$ (%)	Substance classification
Quartzite	2·66	2600	8·14	0	2·9	VS, E, B
	((112))	((112))	((112))	((6))	((10))	
	(2·25)	(15·8)	(2·5)	—	(42·5)	
Conglomerate	2·76	2220	7·60	1·0	1·8	VS, E, B
	((32))	((32))	((32))	((3))	((2))	
	(4·0)	(22·5)	(15·7)	(40)	—	
Diabase	2·96	2180	9·48	0·9	0·7	VS, E. B
	((23))	((23))	((23))	((4))	((3))	
	(4·6)	(35·2)	(11·5)	(33)	(90)	
Peridotite	2·62	1970	5·52	1·21	0·7	VS, E, B
	((18))	((18))	((18))	((6))	((8))	
	(1·61)	(28·0)	(7·7)	(100)	(67·4)	
Chlorite	2·78	1120	6·09	1·42	4·7	S, E, B
	((10))	((10))	((10))	((4))	((6))	
	(1·8)	(8·0)	(8·81)	(6·60)	(40)	
Siderite	3·59	2790	9·05	0	0·40	VS, E, B
	((10))	((7))	((8))	((2))	((3))	
	(1·32)	(17·1)	(3·97)	—	(64)	
Granite 1	2·61	1720	6·58	0	1·0	S, E, B
	((11))	((7))	((8))	((2))	((2))	
	(8·15)	(17·4)	(10·7)	—	—	
Specularite-Magnetite	3·84	2360	8·72	0·77	2·24	VS, E, B
	((9))	((11))	((11))	((10))	((7))	
	(14·5)	(20·1)	(8·0)	(133)	(40)	
Hematite	4·19	1940	7·45	<1	1·4	VS, E, B
	((9))	((9))	((9))	((3))	((3))	
	(0·36)	(6·57)	(11·3)	—	(8·0)	
Shale 1	2·90	1500	3·52	10·8	7·4	S, V, B
	((7))	((9))	((9))	((4))	((9))	
	(11·0)	(11·0)	(27·2)	(19·7)	(35)	
Blastonite	3·02	1190	4·53	1·75	7·3	S, E, B
	((7))	((8))	((8))	((2))	((9))	
	(0·8)	(45·0)	(32·1)	—	(72)	
Limestone 2	2·81	1340	7·10	0·7	2·9	S, E, B
	((6))	((7))	((7))	((7))	((8))	
	(8·9)	(37·2)	((33·5)	(117)	(46)	
Limestone 1	2·69	2780	5·89	3·6	1·5	VS, V, B
	((6))	((6))	((6))	((2))	((5))	
	(0)	(13·7)	(17·8)	—	(86)	
Sandstone 1	2·28	920	3·60	1·75	0·5	S, E, B
	((6))	((5))	((6))	((2))	((3))	
	(0·36)	(3·8)	(3·00)	—	(25)	

TABLE 1.—*cont.*

Name	Density (g/cm³)	Q_u (ksc)	$E10^6$ (ksc)	$\dot{\epsilon}$ (μ/hr)	$\bar{\epsilon}_p$ (%)	Substance classification
Granite 2	2·59 ((5)) (5·8)	2760 ((5)) (4·0)	7·38 ((5)) (4·8)	0·8 ((4)) (91)	1·8 ((10)) (108)	VS, E, B
Potash	2·10 ((4)) (2·9)	127 ((7)) (20·7)	0·73* ((4)) (19·2)	20·0 ((7)) (56)	44·0 ((7)) (47)	W, V, P
Granite 3	2·73 ((3)) (0·29)	1440 ((4)) (30·2)	7·16 ((4)) (9·8)	0·4 ((3)) (82·5)	4·1 ((6)) (82)	S, E, B
Flourite	2·27 ((2)) 14·3	1020 ((2)) —	5·17 ((2)) —	0·25 ((2)) —	10·8 ((2)) —	S, E, B
Shale 2 [2]	—	1100	1·8	4·9	—	S, V
Shale 3 [2]	—	600	1·3	100·4	—	S, V
Shale 4 [2]	—	600	1·3	45	—	S, V
Shale 5 [2]	—	600	1·3	180	—	S, V
Sandstone 2 [3]	—	850	1·0	115	31	S, V, P
Rhyolite [4]	—	—	2·6	0·16	—	
Basalt [4] (Ref. 4)	—	—	5·5	1·5	—	
Andesite [4]	— —	— —	3·8 9·7	2·4 0·06	— —	
Granite 4 [4]	—	—	3·8	1·1	—	
Granite 5 [5]	—	1400	5·4	1·4	—	S, E
Marble [6]	2·70	883	6·4	13·1	18	S, V, B
Halite	2·13 ((5)) (3·24)	156 ((4)) (11·0)	1·84* ((5)) (19·8)	92·8 ((5)) (21·6)	83·9 ((5)) (5·48)	W, V, P
Shale 6	2·07 — —	20·2 ((2)) —	— — —	230 ((1)) —	30·5 ((2)) —	W, V, P

* Based on final unloading cycle.

Q_u = uniaxial compressive strength, ((= number of specimens)), (= coefficient of variation); E = modulus of deformation; $\dot{\epsilon}$ = strain rate, μ = microstrain; $\bar{\epsilon}_p$ = the ratio of irrecoverable strain to total strain; VS = very strong, S = strong, W = weak, E = elastic, V = viscous, B = brittle, P = plastic.

The strain rate, $\dot{\epsilon}$, has been determined, as suggested in Appendix B, by extrapolating the creep data to 200 min and using this as a rough measure of its probable behaviour over longer periods of time [7]. We have found in some cases that the actual strain at 200 min, as determined in longer duration tests, is not accurately predicted by extrapolating from the data obtained from the initial 30 min. Also, the decrease in strain rate with increase in stress level for the Andesite (from 99 ksc to 225·5 ksc) is rather curious [4]. However, we believe for purposes of classification of the rock substance that the procedure recommended in Appendix B is practical.

The relative plastic or permanent strain, $\bar{\epsilon}_p$, was obtained in different ways. Cycling tests were used both before and after the creep test, with a duration of the few minutes required to apply the load and take intermediate readings up to the ultimate stress level and the few minutes required to do the same on unloading. In other cases, the plastic strain has been determined from the strain remaining after a creep test has been conducted. Where alternate methods were used on the same sample, different ratios of permanent to total strain were obtained. The suggested procedure quoted in Appendix B was evolved towards the end of the programme.

3. DISCUSSION

The use of the simple field geological name of a rock clearly adds useful information as opposed to being completely functional and talking about strong or weak rocks as previously suggested [1]. There will probably always be significant properties of rocks that are intangible or unmeasurable by practical means, so that the guidance of a name indicating general composition will continue to be helpful. It is to be hoped that the sophisticated arguments of the specialized geologists on correct terminology can be avoided.

The strength of the rock substance is seldom a critical quantity in problems of ground control. Consequently, the original concept was that this property might be usefully divided simply into two groups: *weak* and *strong* or possibly with a third group of *very strong*. With such a simple division, it was considered probable that most individuals with experience in this work could classify the substance with respect to strength either by visual examination or at least with the assistance of some simple empirical test such as a hardness or rebound test. We still believe this approach to be valid.

Many individuals who reviewed our original report suggested that the dividing line between *weak* and *strong* ought to be somewhere around 700 ksc (10,000 psi) rather than 350 ksc (5000 psi) [8]. We are inclined to agree with this suggestion. Also, it permits an additional sub-division, if desired, of *very weak* for strengths less than 5000 psi. With this change Shales 3, 4 and 5 would be classified as *weak*, instead of *strong*, which would be more in line with a common-sense description.

However, we would re-emphasize the two important factors on this matter: the strength of the rock mass is the really significant property, which only in a few cases will be governed by the strength of the rock substance, and detailed information about the material should be considered as engineering data required for design or appraisal purposes, which cannot be expected to be given in a classification system.

The purpose of the pre-failure category was to indicate whether the rock can be expected to creep. Again, recognizing that the properties of the rock substance in most cases will only be of minor significance compared to structural aspects that might cause the rock mass to creep, a simple testing procedure has been evolved to divide substances into *elastic* and *viscous* types as suggested in Appendix B. The figure of 2 μ/hr was based on the amount of creep that would be required during one month in a typical drift to produce visual distress in tightly placed sets. This concept still seems valid and, in addition, the division of the spectrum of rock substances contained in Table 1 into *elastic* and *viscous* materials appeals to one's judgement as reasonable.

The nature of failure was originally conceived as being important but not easy to characterize. Furthermore, the type of failure was recognized as being sensitive to the stress regime. However, this property was included in the original proposal as the violence of rupture of different rock masses does vary, and it is conceivable that this could be related to some other property of the rock substance.

As the violence of failure presumably varies with the amount of stored energy before failure in the rock substance, it was envisaged that a measure of this quantity could be obtained by determining the amount of plastic, or irrecoverable, strain as a proportion of the total strain in a compression test. The dividing line of 25 per cent of the total strain before failure being permanent was judged to be an appropriate quantity for differentiating rock substances into two groups. However, Table 1 shows that with this criterion only four of the rocks, Potash, Sandstone 2, Shale 6 and Halite, are classified as *plastic* rather than *brittle*.

Furthermore, some of the rock substances are classified as *viscous* and *brittle*, which superficially might seem inconsistent. However, if it were assumed that all rocks that are *viscous* should also have a *plastic* classification, this would be equivalent to assuming that the two properties are necessarily related and consequently only one category would be required. Some of our correspondents have suggested that this may be so. However, our testing indicates that rock substances may or may not creep at stresses below failure, but that this type of reaction to sustained stress does not necessarily indicate whether the material would have a significant amount of plastic strain as soon as an increment of stress is applied. In addition, it does not necessarily indicate whether failure will be brittle with the release of substantially the entire amount of strain energy put into the material on the application of stress.

Consequently, we still visualize the plastic or permanent strain as resulting from some inter-granular or slippage-type mechanism that occurs almost instantaneously on the application of an increment of stress. Furthermore, it is these types of rocks that should have significantly less violent failure characteristics. Thus, in bursting conditions rocks with significant plastic strain may not produce the explosive effects common to distinctly brittle rocks. Also, yielding rocks in slopes might produce rotational shear failure when some average shear stress exceeds the average shear strength, as opposed to a block flow failure that is conceived as being initiated by stresses at a point exceeding the strength at a point in a brittle rock [9].

Although we are still not certain that the property of "failure characteristics" can be adequately characterized by the relative permanent strain and whether this category can be included in a simple classification system, we are not inclined to eliminate it at the present time without additional work. Furthermore, we are not certain that the criterion figure of 25 per cent is the right quantity; however, as we have little evidence that would support an alternate figure, we are inclined to leave it at its present level.

It is conceivable that the pre-failure deformation and failure characteristics in the proposed classification system might preferably be combined and the two classifications of *elastic* and *yielding* used, with the criterion being that a rock would be classified as yielding if either the relative permanent strain at any stress level exceeded something like 25 per cent or if the creep rate under sustained loading exceeded something like 2 μ/hr. The sorting out of the detailed behaviour of the rock substance, and in particular of the rock mass, would then be relegated to the activity described as engineering studies required for a particular problem. The classification of Shale 1, Limestone 1 and the Marble would then be *yielding* instead of *viscous* and *brittle*.

4. CONCLUSION

We would now recommend, that where a simple field geological name can be easily determined, it should be used together with the previously proposed mechanical categories of classification.

We would also recommend that the dividing line between *weak* and *strong* for Item 1 be changed from 350 ksc (5000 psi) to 700 ksc (10,000 psi).

Items 2 and 3 on the pre-failure deformation and ostensibly on failure characterics of the rock substance might be combined to classify, in effect, the deformation characteristics, recognizing that these properties might also serve to indicate the type of failure that is likely to occur.

The system would then be:

Substance: Geological Name
Strong or Weak
Elastic or Yielding.

The term *weak* would mean that the uniaxial compressive strength is less than 700 ksc (10,000 psi), and the term *yielding* would mean that the relative permanent strain is greater than 25 per cent or the creep rate is greater than 2 μ/hr.

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REFERENCES

1. Coates D. F. Classification of rocks for rock mechanics, *Int. J. Rock Mech. Min. Sci.* 1, 421–429 (1964).
2. Nishihara M. Creep of shale and sandy-shale, *J. geol. Soc. Japan* 58, (683) 373–377 (1952).
3. Nishihara M. Rheological properties of rocks, *Doshisha Engng Rev.* 8, (2) 32–55; (3) 85–115 (1957).
4. Iida K. *et al.* Measurements of creep in igneous rocks, *J. Earth Sci.* (Nagoya University) 8, No. 1 (1960).
5. Matsushima S. *On the Flow and Fracture of Igneous Rocks*, Disaster Prevention Research Bulletin, No. 36, Kyoto University (1960).
6. Hardy H. R. Jr. *Inelastic Behavior of Geological Materials*, unpublished report (1965).
7. Ladanyi B. *Uniaxial Testing of Rocks for Classifications Purposes*, unpublished report (1964).
8. Bergman S. *Funktionell bergklassificering*, Ingeniorsvetenskapsakademieus Meddelande 142, Stockholm (1965).
9. Coates D. F. and Brown A. Stability of rock slopes at mines, *Bull. CIMM* (July 1961).

APPENDIX A

Description of Test Specimens

Quartzite: A Pre-Cambrian Proterozoic sedimentary rock from the Elliot Lake, Ontario, area; composed of moderately well-rounded quartz grains with a silica cement; grain size is from 0·2 to 1·5 mm; feldspar present in amounts up to 5 per cent; sericite alteration can be seen along many of the grain boundaries; pyrite in present in amounts up to 1 per cent.

Conglomerate: A Pre-Cambrian Proterozoic sediment from the Elliot Lake, Ontario, area; quartz pebbles occur in a quartz matrix made up of the above Quartzite with the exception that pyrite, both as disseminated grains and as bands parallel to the bedding, can be as much as 15 per cent.

Diabase: A Pre-Cambrian Keweenawan intrusive from the Elliot Lake, Ontario, area; consists of plagioclase, pyroxene and hornblende; varying from an almost vitreous type near the contact to a coarse-grained variety in the centre of large dikes containing 2 mm feldspar phenocrysts.

Periodite: A Post-Ordovician intrusive rock from Thetford Mines, Quebec, area; consisting mainly of olivine and pyroxene with alteration to serpentine; the unaltered olivine crystals are about 0·5 mm in diameter

Chlorite: A Pre-Cambrian Huronian rock from Wawa, Ontario; consists mainly of chlorite and 10–30 per cent calcium carbonate generally disseminated throughout.

Siderite: From the same formation as the Chlorite; a compact mixture of iron carbonate and calcium carbonate; the grain size is fine enough not to be discernible to the eye, and the material breaks with a conchoidal fracture.

Granite 1: A Pre-Cambrian intrusive near Grenville, Quebec, consists of about 80 per cent orthoclase feldspar, 5 per cent quartz, the remainder being hornblende and biotite with an average grain size of 2 mm.

Specularite-Magnetite: A Pre-Cambrian Proterozoic metamorphosed sediment from Wabush, Quebec; consists of 99 per cent magnetite, specularite and quartz. The silica content varies between 10 and 60 per cent between specimens. The quartz grains are 0·1 mm in size, the specularite grains are elongated with an average length of 0·5 mm, and the magnetitite grains are anhedral with an average diameter of 0·1 mm.

Hematite: A Lower Ordivician sedimentary rock from Bell Island, Newfoundland; a red, compact oolitic iron ore consisting of hematite and chamosite.

Shale 1: A Jurassic rock of the Kootenay formation from Michel, British Columbia; a carbonaceous shale varying from very fine-grained to a somewhat siliceous variety with a grain size of 0·1 mm.

Blastonite: A Devonian intrusive rock from St. Lawrence, Newfoundland; consists of a fine-grained mixture of fluorite and quartz; the shape of the quartz crystals is irregular with length-to-width ratios being as much as 10 and the average length being 0·5 mm; quartz clusters around the well-rounded fluorite crystals which are approximately 2·5 mm in size.

Limestone 1: An Ordovician rock from Ottawa, Ontario; a fine-grained grey-black calcium carbonate with a maximum grain size of 0·01 mm.

Limestone 2: A Pre-Cambrian altered sedimentary rock from Gagnon, Quebec, consists of calcium carbonate with various degrees of alteration to dolomite and serpentine with dolomite being the predominant mineral.

Sandstone 1: An Ordovician rock from Ottawa, Ontario; consisting of rounded quartz grains 0·2 mm in diameter in a porous silica cement.

Granite 2: An intrusive rock of Devonian age from St. Lawrence, Newfoundland; consisting mainly of coarse-grained orthoclase and microcline of 2 mm crystals; some specimens have as much as 30 per cent quartz; the matrix consists of quartz and microcline.

Potash: A Middle Devonian evaporite from Esterhazy, Saskatchewan; consists of crystals of sylvite and carnallite with an average size of 8 mm and some as large as 15 mm; a film of iron oxide surrounds many of the crystals giving the rock a red colour.

Granite 3: A Devonian rock from St. Lawrence, Newfoundland; consists of nodules of granite and fluorite ranging in size from 1 mm to 20 mm surrounded by concentric growths of calcium fluoride; the matrix is fluorite and/or calcium carbonate with variable amounts of fine-grained silica.

Fluorite: A Devonian vein-type mineral from St. Lawrence, Newfoundland; consists of the single mineral calcium fluoride.

Shale 2: A Tertiary rock from Kyushu, Japan; test specimens were 1 cm^3 and dry [2].

Shale 3: A Tertiary sandy shale from Kyushu, Japan; test specimens were 1 cm^3 and saturated [2].

Shale 4: As for Shale 3 with the exception that the applied stress was 160 ksc perpendicular to the bedding [2].

Shale 5: Same as Shale 4 with the exception that the stress was applied parallel to bedding.

Sandstone 2: An Upper Cretaceous rock from Osaka, Japan; consists of medium-grained quartz, feldspar and chlorite-like minerals; test specimens were 2 cm in diameter 4 cm long and saturated [3].

Rhyolite: From Taguchi, Japan; consisting of phenocrysts of plagioclase and quartz with calcite and goethite as secondary minerals and a groundmass of anorthoclase, quartz, plagioclase, and hematite; the test was conducted with an applied stress of 145·5 ksc [4].

Basalt: From Genbudo, Japan; consisting of phenocrysts of olivine in a groundmass of plagioclase, magnetite and pyroxene; the test was conducted with an applied stress of 32·6 ksc [4].

Andesite: From Komori, Japan; consisting of phenocrysts of plagioclase and chlorite in a groundmass of plagioclase, clinopyroxene and chlorite; the test was conducted with applied stress of 99·0 and 225·5 ksc respectively [4].

Granite 4: From Taguchi, Japan; consisting of plagioclase, quartz, biotite, microcline and muscovite; the test was conducted with an applied stress of 35·6 ksc [4].

Granite 5: A Kitashirakawa biotite granite, Japan [5].

Marble: A Silurian rock from close to Wombeyan, New South Wales, Australia; consisting of 96 per cent calcium carbonate, 2·5 per cent magnesium carbonate and 0·2 per cent silica with an average grain size of 1 mm [6].

Shale 6: From the Bearpaw formation (Upper Cretaceous); a uniform medium-grey clay shale with montmorillonite the main constituent. The wet density of the shale is 129 pcf (2·07 g/cm^3) and the water content of the test specimens was approximately 20 per cent.

Halite: From the Silurian evaporite deposits of Goderich, Ontario; a very pure halite deposit with an average grain size of 8 mm. Although the formation is closely bedded, no bedding is visible in the test specimens.

APPENDIX B

Conventional Uniaxial Compression Testing

1. A suite of at least ten samples of the same rock substance should be tested to obtain a significant mean and a measure of the dispersion of strength values.
2. Roller lap the specimens, if necessary, so that the maximum difference in diameter over the length of the sample is less than 0·001 in. Lap the ends of the samples on a wheel so that they are parallel within 0·001 in. A standard length–diameter ratio is 2:1, but a ratio down to a minimum of 1:1 can be used. After lapping, allow the samples to dry at room temperature for at least 24 hr.
3. Measure the samples to 0·0001 in. at three points for the lengths and at three points for the diameter. Weigh samples to the nearest 0·01 g. Measure strain either with two strain gauges cemented at the mid-height of the specimen and on opposite sides or with a compressometer that measures the change in length over a 1-in. gauge length. The modulus of deformation is determined by the slope of the stress-strain curve at 50 per cent of the strength.
4. Apply the load at a rate of 500–1000 psi/sec until failure occurs. Record the maximum load and the duration of the test. Describe qualitatively the type of failure as indicated by the noise produced, e.g. very violent, violent and quiet. Describe the orientation of the fractures, e.g. top cone, bottom cone, longitudinal, diagonal, irregular; along with a description of the fragment size, e.g. powdered, highly fragmented, quarter inch with silvers. Where possible determine the fracture angle.

Suggested Classification Uniaxial Compression Testing

1. Unless otherwise stated the specifications for Conventional Uniaxial Compression Testing apply; however, when Classification testing is to be done one Conventional test plus nine Classification tests will normally be sufficient.
2. Apply a stress equal to approximately 0·5 Q_u. During the loading cycle record strain readings continuously or at every $\frac{1}{5}$th of the increment of load. When the load has been established at the increment value, keep constant until the strain rate is less than 2 μ/10 min or a maximum duration of 1 hr.
3. After maintaining the load increment, unload the specimen as quickly as possible, and then maintain the specimen at zero stress until the strain rate is less than 2 μ/10 min or a maximum duration of 1 hr.
4. Reapply the load to 0·5 Q_u, read the strain; then unload and read the strain.