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THE CHARACTERIZATION OF ROCK FOR CIVIL ENGINEERING PRACTICE IN BRITAIN

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ABSTRACT

Characterization of rock can be approached from the point of view of geology, and for engineering purposes from the contrasting needs of rock mechanics and engineering geology.

The geological approach is usually concerned with the study of samples of fresh rock and classification is based on mode of origin, mineral content and a variety of textural features. The bases of the classification of the three genetic groups—the igneous, the sedimentary and the metamorphic rocks—are discussed and simplified versions of classifications are presented for each group.

A rock classification to meet the requirements of rock mechanics is concerned with both the rock as a material and the rock in the mass. In particular an essential ingredient is information on physical and mechanical properties, and parameters of use in engineering design. After a review of the development of ideas in classification and characterization, in which the need for cheap index tests to supplement expensive and elaborate engineering design tests as a means of characterizing large areas for design purposes, work carried out on all these aspects in the United Kingdom is discussed.

Acknowledgement of the significance of geological processes in determining how rock masses achieved their present condition highlights the importance of understanding all aspects of the geology of a particular engineering site as a prerequisite of engineering-geological classification and characterization of rock. The engineering-geological approach has high powers of discrimination, and is invaluable in the relatively inexpensive assessment of rock-mass properties of large areas and volumes of *in situ* rock.

After briefly reviewing early work, a geological classification of rock material simple enough for engineering application, but nonetheless comprehensive, is given. The classification table may be used as an aid to identification with minimal geological knowledge. Provision of a rock name, combined with selected quantified descriptive terms and engineering properties is proposed as a basis for the engineering-geological description of *in situ* rock and rock material.

Examples are given of the application of engineering-geological characterization of rock in British engineering practice and research.

INTRODUCTION

As commonly understood, rock is a natural hard material derived from the Earth. It would be generally appreciated that rock or, as it is more likely to be

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called, stone is used in large slabs or pieces for decoration or construction or both, and in small pieces as an aggregate for use in concrete or as a material for road construction. Hardness and durability, and in some situations a pleasing appearance, are the obviously desirable properties which cannot readily be achieved in alternative man-made materials, most of which in any case use natural stone as an essential ingredient. Stone of requisite quality would be obtained from a limited number of isolated quarries; rock would be seen in some road cuttings and in natural exposures along shore line and river bank, and in hilly and mountainous places. Similarly, in common experience soil, clay, sand and gravel would be considered a different type of material, certainly not rock.

This practical distinction is based on an understanding of the properties of the material in the mass; a soil and other related materials can be easily dug or moved; a rock must be treated specially if it is to be excavated. Civil engineers make the same division of natural materials, but to a geologist rock, whether hard or soft, coherent or incoherent, is simply an aggregate of minerals and differences result from different modes of origin. Unlike the geologist, the engineering geologist is concerned with the application of geology to Civil Engineering particularly as applied to design, construction and performance aspects of engineering structures in an on the ground. Therefore, for engineering geological purposes the engineering, as opposed to the geological, connotation of the term "rock" has to be adopted simply because the engineering properties and behaviour of the two types of material are so different.

The study of the engineering behaviour of soil, the science of soil mechanics, and the parallel study of rock mechanics, are based on the application of the laws of hydraulics and mechanics to engineering problems related to the two materials. There can be no true understanding of the behaviour of soils or rocks without a clear knowledge of the nature and variability of the materials themselves. The initial stage in the study of naturally occurring materials must be that of classification, the methodical arrangement of the materials into distinct classes on the basis of one or more characteristic properties.

Characterization of rock, the topic of this paper, can be approached in several ways. There is, firstly the purely petrological or petrographic side in which the genetic aspects are of prime importance; how was the rock formed, what is the genetic significance of its mineral assemblage, its texture and structure? Petrological studies place the rock firmly within the genetic framework of its original geological environment, and only in very exceptional circumstances is the petrologist concerned with the fact that the rock may be weathered or altered, and hardly ever with the fact that the rock is jointed. On the other hand, for the purposes of rock mechanics rock tends to be treated as a material with definable mechanical properties; the material *in situ*, including its structural discontinuities is referred to as the rock mass. Rock material and rock mass properties are both of importance in understanding the engineering behaviour of rock.

The engineering geological approach seeks to place geological materials in the context of their past and present geological environments; this will lead to an understanding of how the rock arrived at its present physical state both in the hand specimen and in the mass. Concern will be less for the genesis of the original rock material, although this is still important, than for its subsequent evolution to the rock material and mass present in the particular engineering situation. Engineering geological classification of rock integrate both the petrological and the rock mechanics aspects within a broader geological framework.

From the practical point of view, rock characterization in engineering geological terms ensures uniformity in description from one worker to another. Once basic laboratory determinations have been made, it provides a short-cut to those properties requiring sophisticated tests and sample preparation and thus is of great assistance in field and site work including core logging and mapping in engineering geological terms. There is also the difficult problem of deciding for contractual purposes what materials should be considered as rock rather than as soil in an engineering undertaking.

Requirements are the development of a simplified version of the geological approach to rock classification that is acceptable to the geologist, and to the specialists in rock mechanics and engineering geology. In the following sections there is discussion first of geological classifications of rocks, followed by a review of the rock mechanics approach, and finally the engineering geological approach to rock classification and characterization.

Characterization of rock for engineering purposes implies a two-stage operation. The first is simply the description of the rock in terms of significant properties, while the second stage involves naming the rock in such a way that, when used the name brings to mind as accurately and as unambiguously as possible the distinctive properties of that rock. Such an analytical system is likely to be very unwieldy, bearing in mind the great variety of naturally occurring rocks, and therefore some form of classification has to be attempted. A classification arranges rocks methodically into distinct categories or classes each of which have arbitrarily determined boundaries. Determination of these boundaries, the limiting properties of a class, depends to a large extent on the purpose of the classification. A rock classification for petrological purposes, for general geological mapping purposes, or for engineering-geological purposes, are each likely to be based on different parameters, some of which of course may be common to more than one or all of the different classifications.

To be workable, a classification should be based on a small number of significant properties which determine, if practicable, a relatively small number of classes; irrelevant properties should be ignored. The main problem is where to set the boundaries between classes. In engineering a classification is likely to find a place, eventually, in a Code of Practice (Anon., 1957); class boundaries will then have been defined by agreement among the interested parties: geologists, engineering geologists and engineers. Hopefully, discussions leading to agreement or compromise would have ranged over aspects of traditional usage, the desirability or otherwise of having equal class divisions, and the need for easily remembered class boundary limits. Boundaries selected for use in such a pragmatic classification should correspond reasonably closely to important changes in rock properties. This is the case, for example, with the system adopted by the British Standards Institution for engineering soils (Anon., 1957). Glossop and Skempton (1945) discussed this and other systems of particle size classification in relation to the physical properties of the fractions. They concluded that the B.S. system is best suited for engineering purposes, since the boundaries of the main divisions correspond approximately to important changes in soil properties. It also has the advantage that, at each stage, the various categories increase by a multiple of about three. Thus, for example, in plotting grading curves logarithmic paper is not needed, and ordinary graph paper may be used. The divisions are close to the grain-size limits chosen for igneous rocks (Hatch *et al.*, 1949) and acceptance of the same grain-size class boundaries for all groups of rocks would bring order to an otherwise rather chaotic situation. The change could be made without affecting the petrological basis of a geologically acceptable classification. But whether such attributes are applicable to the three main genetic groups of rocks, and whether the class boundaries correspond to important changes in rock properties, still have to be determined.

Rock classifications are needed both for scientific and practical purposes, and if the same classification will serve both functions so much the better. However, more than one scheme is needed even for the geologist. For example, an understanding of chemical composition of igneous rocks is essential for a quantitative classification suitable for the petrologist; non-specialists are better served by a classification based on visible characters such as mineral content and texture; while for the purposes of rock mechanics and engineering geology an essential requirement is a quantitative indication of rock quality related to engineering use.

Geological nomenclature tends to emphasize the solid constituents of a rock, whereas the engineering performance of a rock is likely to be strongly influenced by the pores, fissures and other discontinuities present in the rock. A geological classification supplemented by information on the mechanical properties of rocks could provide a rock quality classification for engineering application. What is required is the equivalent for rocks of the soil classification which is used by the engineer, in conjunction with simple field tests, as a rapid quantitative guide to the engineering performance of soil. Determination of the mechanical properties of rocks implies the need for testing; for the purpose of classification rapid and inexpensive tests may be distinguished from the more sophisticated and expensive design tests that are required to provide quantitative data for design calculations. Much research has been undertaken on the design of index tests for rock, and the main requirements are that the tests should be rapid, simple, relevant to rock properties, relevant to engineering performance, and finally, discriminating (Cottiss *et al.*, 1971).

THE GEOLOGICAL CLASSIFICATION OF ROCKS

Introduction

In the geological sense a rock is an aggregate of minerals; it may consist of one mineral species or many, and it may be crystalline or amorphous. Later it will be necessary to modify this definition for engineering purposes, but it will suffice for the present purpose which is to show how rocks may be classified in geological terms. This should form the basis for a requisite engineering classification.

The Three Genetic Rock Classes

There are three great genetic classes of rocks, the igneous, the sedimentary and the metamorphic. An igneous rock is one that has solidified form molten or partly molten material; it may be entirely crystalline, part crystalline and part vitreous, or entirely vitreous.

A sedimentary rock is more difficult to define as there is a great variation in mode of origin and in the nature of the materials involved. Broadly there are two main groups, the detrital sediments and the chemical sediments; the latter include the biochemical or organic sediments. The fragmented or detrital rocks are composed principally of broken fragments (clastic texture) that are derived from any pre-existing rock, or from the solid products formed during the chemical weathering of such rocks, and that have been transported mechanically to their places of deposition. A chemical sedimentary rock is composed primarily of organic or inorganic material formed directly by precipitation from solution or colloidal suspension. It usually has a non-clastic, frequently crystalline, texture. There are detrital rocks with a significant non-detrital content, and vice versa. Finally sediments are subject to physical and chemical changes after they have formed, so that original minerals, textures and structures may be greatly modified after the formation of the sediment. These diagenetic changes, as they are called, take place under near-surface temperatures and pressures, and result finally in lithification.

A metamorphic rock is any rock derived from pre-existing igneous, sedimentary and metamorphic rocks by mineralogical, chemical and structural changes brought about essentially in the solid state by marked changes in temperature, pressure, shearing stress and chemical environment at depth in the Earth's crust. The processes of weathering and diagenesis are excluded. Thermal metamorphism is normally associated with igneous intrusions. Dynamic metamorphism involves intense localized stresses which tend to break up the rocks, often to a very fine-grained state. Regional metamorphism is a general term for metamorphism affecting an extensive area and involving the effects of directed pressures and shearing stress and a wide range of temperatures and confining pressures.

Rock Properties Suitable for Classification Purposes

Rock properties suitable for rock classification are:

(a) chemical composition, reflected in the minerals present and their relative abundances, and

(b) rock texture, wich is the mutual relationships between the individual mineral components.

Identification of minerals is based on determination of their optical properties using the polarizing microscope. Examination of mineral fragments or mineral grains present in thin sections of a rock requires specialist knowledge and training. With some very fine-grained rocks even this may not be sufficient and other methods including X-ray diffraction and differential thermal analysis may be necessary.

However, the number of commonly occurring rock minerals is small. It includes:

quartz, including the cryptocrystalline varieties;

feldspars, orthoclase and plagioclase; the feldspar-like minerals (felspathoids) may be included here;

micas, including the light-coloured muscovite and the dark-coloured biotite;

ferromagnesian minerals, amphibole, pyroxene and olivine;

carbonates, calcite, dolomite, siderite;

sulphates and chlorides, gypsum, anhydrite, halite;

hydrated oxides;

clay minerals;

metamorphic minerals.

Identification of these mineral species and groups in a hand specimen of a rock requires some specialist training, but, with the requisite background knowlegde, a hand lens and a knife or mounted steel needle may be the only aids that are needed. Dilute acid will determine and if need be discriminate between the carbonates.

The most useful diagnostic characteristics of minerals are: shape, colour and transparency, cleavage and hardness. On the basis of light or dark coloured, hard or soft, cleaved or non-cleaved, carbonate or not, simple visual determinations can be made. Metamorphic minerals present difficulties, but they are relatively rare and metamorphic rocks are predominantly composed of the common light and dark coloured minerals. In any case, the classification of metamorphic rocks is more dependent on textural than mineralogical characteristics.

Textural features are as varied as mineral composition and need to be considered in some detail before significant diagnostic textures can be selected for each of the main rock groups and for the discrimination of different classes in each main group.

At this point it is necessary to define certains terms. *Texture*, in petrological terms, is "The general physical appearance or character of a rock, including the geometric aspects of, and the mutual relations among, the component particles or crystals; e.g. the size, shape, and arrangement of the constituent elements of a sedimentary rock, or the crystallinity, granularity, and fabric of the constituent elements of an igneous rock. The term is applied to the smaller features as seen on a smooth surface of a homogeneous rock or mineral aggregate." (Gary *et al.*, 1972). *Fabric*, a term used in the definition of texture, is not easily understood. From the same glossary, the fabric of an igneous rock is defined as the external appearance or pattern produced by the shapes and orientation of the crystalline and non-crystalline parts of the rock; it is dependent on the relative sizes and shapes of the parts and their positions with respect to one another and to the groundmass when present. The same definition would be acceptable for metamorphic rocks, but a slight modification is needed for sedimentary rocks in which fabric refers to the orientation (or lack of it) in space of the elements (discrete particles, crystals, cement) of which the rock is composed.

Texture is all important in naming a rock type since there are examples of igneous, metamorphic and sedimentary rocks which have the same, or at least very similar, mineral assemblages; textural differences serve to distinguish them in samples of the rock material. Textural and other terms used later are defined in Gary *et al.* (1972) and other geological dictionaries.

Classification of Igneous Rocks

In igneous rocks mineral composition is the visible expression of chemical composition, but because of variation in conditions during cooling, a magma of a certain composition may give rise to several distinct mineral assemblages. An igneous rock may be too fine-grained or even glassy for the minerals to be determined; a chemical analysis is then the only way of placing the rock in its correct category. For the non-specialist chemical analysis is usually out of the question and for classification purposes and nomenclature reliance has to be placed on mineral composition. Fortunately most igneous rocks consist predominantly of a small number of common minerals, and identification can be based on the recognition of quartz, the feldspars orthoclase and plagioclase and feldspar-like minerals, the micas, and the ferro-magnesian minerals olivine, pyroxene and amphibole. These minerals fall into two classes, those that are light and those that are dark coloured, and the ratio between the two can be used in rock classification.

Relative abundance of light-coloured and dark-coloured minerals is reflected in the colour of the rock. The percentage of dark minerals in a rock is termed the colour-index; applied to igneous rocks the index has considerable petrological significance and three descriptive terms are used for specified ranges of the colour-index:

light-coloured rock (leucocratic): with less than 30 per cent dark minerals;
medium-coloured rock (mesocratic): with between 30 and 60 per cent dark minerals;
dark-coloured rock (melanocratic): with more than 60 per cent dark minerals.

Grain size will affect the visual impression produced by different colour-indices; colour-index can also be applied to the other major rock groups.

A simple classification of the common igneous rocks may be based on mineralogy and grain-size (Table 1). Igneous rocks that are completely crystalline may be identified by means of criteria such as:

(a) the presence or absence of quartz;

(b) the proportions and kinds of feldspar present, and

(c) the proportions and kinds of ferromagnesian minerals.

It appears to be generally accepted that grain-size is defined by reference to the largest common grains, approximate divisions being

(a) fine-grained < 1 mm;

(b) medium-grained 1-5 mm;

(c) coarse-grained > 5 mm.

When crystals reach dimensions of several centimetres the rock becomes a pegmatite. Glassy varieties, obsidian, pitchstone and tachylyte occur.

Classification of Sedimentary Rocks

No classification of the sedimentary rocks can be all embracing because of the polygenetic nature of the sedimentary materials. One important group contains sediments made by the accumulation of fragments of minerals or rocks and newly formed transported clay particles. These are the detrital sediments and subdivision is made on grain size. The other group contains sediments precipitated from solution or produced by organic agencies; these are the chemical-organic sediments subdivided by composition. Even these broad divisions are not clear cut, particularly in the classification of the limestones, which are best treated as a separate group.

The Detrital Sedimentary Rocks

Detrital sedimentary rocks are classified on the basis of grain size, on the nature and proportions of the mineral or rock type constituting the bulk of the rock, and on the type of cement or matrix material. A classification is set out in Table 2.

As with unconsolidated sediments (soils) the grain-size ranges of the three main classes may be further subdivided.

TABLE 1. — *Classification of common igneous rocks on the basis of mineralogy and grain-size* (after HOLMES, 1965)

Feldspars Other minerals	**Orthoclase sodic plagioclase**	**Sodic plagioclase orthoclase**	**Sodic plagioclase (andesine) predominant**	
Quartz essential Ferro-magnesian minerals: **biotite** or **hornblende** or both	*Rhyolite* Quartz porphyry **Granite**	*Rhyodacite* Granodiorite porphyry **Granodiorite**	*Dacite* Quartz porphyrite **Quartz-diorite**	
Feldspars Other minerals	**Orthoclase predominant**	**Orthoclase and plagioclase roughly equal**	**Sodic plagioclase (andesine) predominant**	**No feldspar**
Little or no quartz Ferro-magnesian minerals: **hornblende and/or biotite and/or augite**	*Trachyte* Porphyry **Syenite**	*Trachy-andesite* Monzonite porphyry **Monzonite**	*Andesite* Porphyrite **Diorite**	**Hornblendite**
Feldspars Other minerals			**Calcic plagioclase predominant**	**No feldspar**
Little or no quartz Ferro-magnesian minerals: **augite and iron ores**			*Basalt* Dolerite or diabase **Gabbro**	**Pyroxenite**
No quartz Ferro-magnesian minerals: **augite, olivine and iron ores**			*Olivine-basalt* Olivine-dolerite or olivine diabase **Olivine-Gabbro**	**Peridotite**

Fine-grained types in italics.
Medium-grained types in ordinary type.
Coarse-grained types in bold type.

TABLE 2. — *Classification of the detrital sedimentary rocks*

Grain-size (mm)	Class	Class name	Varieties			
Coarse-grained	Rudaceous (Rudite)	**Conglomerate** **Breccia**	Conglomerates, with rounded pebbles, and breccias, with angular pebbles, may be oligomict (pebbles of one rock type) or polymict (pebbles of more than one rock type). Additional descriptive terms may relate to pebble size, pebble composition, cement. Conglomeratic mudstones have more fine-grained detrital matrix than pebbles			
2						
Medium-grained	Arenaceous (Arenite)	**Sandstone**		Cement or matrix	Medium-grained fraction	
					Quartz	Other
			Greywacke	Fine detrital matrix prominent > 15 %	< 75 %	Rock and other
			Arkose	Detrital matrix absent or scanty < 15 %. Voids empty or cemented	< 75 %	Feldspar exceeds rock fragments
			Quartz sandstone **Orthoquartzite**		> 95 %	Rock and feldspar
0.062						
Fine-grained 0.004	Argillaceous (Argillite)	**Mudstone**	**Shale** is fissile mudstone	**Siltstone**, with more than 50 % silt-sized particles		
				Claystone, with more than 50 % clay-size particles		

TABLE 3. — *Classification of pyroclastic rocks*

Grain-size (mm)		Class	Class name	Diagnostic features and varieties	Reworked sedimentary types < 50 % Pyroclast	Reworked sedimentary types > 50 % Pyroclast
Coarse-grained	64, 32, 16, 8, 4, 2	Rudaceous (Rudite)	Agglomerate	Composed of bombs of magmatic material which solidified in flight	Polymict Conglomerate	Volcanic Conglomerate
			Volcanic breccia	Composed of rock fragments that were solid at the time of ejection		
			Lapilli tuff	Fragments of the erupting lava are termed essential; accessory if they are fragments of earlier lavas or the cone; accidental if composed of other rocks		
Medium-grained	1, 0.5, 0.25, 0.125, 0.062	Arenaceous (Arenite)	Tuff	According to the source of material, tuffs may be essential, accessory or accidental. Fragments may be of glass, crystal, or rock debris, so that vitric, crystal and lithic tuffs may be recognised depending on the proportions of each component	Tuffaceous Sandstone	Arenaceous Tuff
Fine-grained		Argillaceous (Argillite)	Fine tuff		Tuffaceous Mudstone	Argillaceous Tuff

The Pyroclastic Rocks

Pyroclastic deposits are classified on grain-size and on the character of the material. A classification is set out in Table 3, and includes descriptive terms for reworked sediments derived from pyroclastic deposits. It is to be noted that the commonly accepted grain-size ranges for the different classes of pyroclastic rocks do not correspond with those for the detrital sediments in Table 2.

Limestones

As with the terrigenous detrital sediments, limestones may be classified on the bases of texture and composition. There are two types of constituent. Allochemical constituents, or "allochems," are those materials which have formed by chemical or biochemical precipitation within the basin of deposition but which are organized into discrete bodies which have suffered some degree of transport. On the other hand, orthochemical constituents, or "orthochems," are materials precipitated in the basin of deposition.

Allochems provide the structural framework of limestones and typically are of sand and gravel size. Four common types may be recognized:

(a) intraclasts, fragments of reworked penecontemporaneous carbonate sediment;

(b) oolites;

(c) fossils, and

(d) pellets, rounded aggregates of microcrystalline aggregates in the size-range 0.03-0.15 mm.

Orthochems are analogous to the clay and chemical cement of sandstones, and are of two types:

(a) 1-4 micron microcrystalline calcite, representing calcite ooze, may recrystallize to 5-15 micron microspar, and

(b) coarser, greater than 0.01 mm, and clearer sparry calcite, commonly present as a simple pore-filling cement; may form by recrystallization but this is not common.

Four major limestone families may be recognized:

I. Abundant allochems cemented by sparry calcite;

II. Variable amounts of allochems in microcrystalline calcite matrix;

III. Microcrystalline limestones, and

IV. Limestones composed of organisms in their growth positions.

By comparison with detrital sediments, I is equivalent to well sorted, clay free sandstones; II to clayey poorly sorted sandstones; and III to terrigenous claystones, and siltstones.

Table 4 is a classification of limestones simplified from Folk (1959). The grain-size range of the rudites, arenites and lutites, as well as that of the sparry cement, may be further subdivided (Folk, 1959, table II).

Recrystallization and inversion of the carbonate content of limestones introduce difficulties in classification, as these processes induce changes in grain size which may affect matrix, allochems, or both. The original limestone texture may be entirely obliterated.

TABLE 4. — *Classification of limestones*

Grain-size (mm)	Class	Class name	Allochems	Orthochems Cement, sparry calcite		Matrix, micro-crystalline calcite		Organisms in growth position	
Coarse-grained	Rudaceous (Rudite)	Calcirudite	Intraclasts Oolites	I	INTRASPARITE OOSPARITE	II	Intramicrite Oomicrite	IV	BIOLITHITE
1.0									
Medium-grained	Arenaceous (Arenite)	Calcarenite	Fossils Pellets	I	BIOSPARITE PELSPARITE	II	BIOMICRITE Pelmicrite	IV	BIOLITHITE
0.0625									
Fine-grained	Lutaceous (Lutite)	Calcilutite	None	III	DISMICRITE	III	MICRITE		

Notes. — Names in capitals are the common rock types. Proportions of allochems should be determined: compound types may be described, for example, as "intra oosparite." Micrites and dismicrites with 1-10 % intraclasts are referred to, for example, as "fossiliferous micrite." Dolomites are classified on allochems and crysta size. Terrigenous admixtures, with less than 50 % of such materials, are indicated by the prefixes "clayey," "silty," "sandy." If it is important to differentiate the rudites on grain-size, then the word is added: e.g. intrasparudite.

The Chemical Sedimentary Rocks

Excluding limestones, the chemical organic sediments may be classified by their chemical composition into:

(i) Siliceous: radiolarite, flint, chert;
(ii) Ferruginous: iron carbonates, oxides, silicates, sulphites;
(iii) Aluminous: laterite, bauxite;
(iv) Phosphate: phosphorite;
(v) Saline: halite, gypsum, anhydrite;
(vi) Carbonaceous: lignite, coals.

They include chemical precipitates, organic accumulations, and secondary segregations having distinctive mineral assemblages and textures which, although useful for diagnostic purposes, are not further described here. Reference may be made to standard texts (e.g. Pettijohn, 1957) if there is a need to discriminate these volumetrically insignificant but economically highly important rock types.

Classification of Metamorphic Rocks

Mineral composition is not an essential factor in the basic classification of metamorphic rocks. Varieties are distinguished by texture, but the general appearance of the texture depends to some extent on the general mineralogical composition of the rock. Specific varieties are then distinguished by prefixing the names of conspicuous mineral components.

Typical textural varieties are:

Mylonite has a cataclastic texture resulting from the mechanical breakdown of rock under stress. Bent and fractured mineral grains are in mechanical contact with one another. A mylonite is a microbreccia composed of microscopic angular particles bound together by dust; the particles may be welded together by heat.

Hornfels possesses no foliation or lineation, and comprises a regular mosaic of mineral grains in random orientation. Essentially, the rock is isotropic.

Slate is a very fine-grained, very strongly foliated rock possessing the property of fissility along planes independent of the original bedding, whereby it can be split (cleaved) into lustrous plates which are lithologically indistinguishable.

Phyllite is a rock intermediate between slate and schist but the minerals are usually not distinguishable by the naked eye.

Schist, a strongly foliated medium to coarse-grained rock which can readily be split into thin flakes due to a parallelism of lamellar minerals such as micas, or amphiboles and other acicular minerals.

Gneiss is a foliated rock in which there are alternate bands or lenticles of granular minerals and flaky or acicular minerals. Gneisses are coarse-grained rocks that split readily along the schistose bands. The name is usually restricted to rocks containing felspar as an obvious constituent.

Granulite consists of roughly equidimensional, interlocking mineral grains; scattered flaky minerals may have a parallel orientation which produces a rough parting or schistosity.

The mineralogy and texture of a metamorphic rock are determined by the nature and chemical composition of the parent rock, and by the character and intensity of the metamorphic process. Mineral growth takes place in rocks that are solid. As a result the mineral grains are generally anhedral, and grain boundaries are sinuous and interlocked. Good crystal faces may be shown by some minerals, and these frequently are large grains or porphyroblasts set in the finer minerals of the body of the rock.

Most metamorphic rocks are derived from a small number of common rock types, and parentage may be used as another basis of classification. It is evident that any attempt at classification of a metamorphic rock must take into account not only texture and mineralogy, but also the geological setting in which it is found. In this way, thermally metamorphosed rocks are recognized by their proximity to an igneous rock; crystalline limestones formed by regional metamorphism are distinguished from sedimentary limestones; and slate is distinguished from fissile very fine-grained sedimentary rocks.

CHARACTERIZATION OF ROCKS FOR ROCK MECHANICS

The geological classification of rocks, based on mode of origin, mineralogy and texture provides very little, and possibly misleading information for the engineer. For designing in rock, whether it is a foundation, an excavated slope or an underground opening, the classification should provide information on design criteria including deformation characteristics, and strength and failure characteristics. All this the classification should provide in addition to characterizing the rock as a geological substance, the rock material, forming part of a geological body, the rock mass, with all its inherent geological imperfections.

The requirements of a rock classification for rock mechanics go beyond the usual bases of a geological classification, and in this section the early growth of ideas is first discussed. This is followed by an account of British work which is illustrated later (page 24) by selected examples of field applications. A summary is then provided of the observations and tests needed for the classification and characterization of intact rock material and the *in situ* mass, and the laboratory and *in situ* tests which may be used to provide engineering design data.

The Development of Ideas on Rock Classification

Concern in the United Kingdom with the nomenclatural problems confronting the rock mechanician seems to stem from the challenging series of papers (John, 1962; Deere, 1963; Coates, 1964, 1965; Coates and Parsons, 1966) in which basic classifications of rock material and the rock mass were developed. Terzaghi (1946) of course had very early developed a system for classifying rock for the purpose of predicting tunnel support requirements. His descriptive categories are based on joint spacing and weathering, but are not defined by measurements. His descriptive terms for rock conditions are summarized in Table 5.

In practice there are no sharp boundaries between these rock categories and the properties of the rocks indicated by each term can vary between wide limits.

TABLE 5. — *Classification of* in situ *rock for predicting tunnel support requirements* (TERZAGHI, 1946)

Term	Description
Intact	Rock contains neither joints nor hair cracks
Stratified	Rock consists of individual strata with little or no resistance against separation along the boundaries between strata
Moderately jointed	Rock contains joints and hair cracks, but the blocks between joints are locally grown together or so intimately interlocked that vertical walls do not require lateral support
Blocky and seamy	Rock consists of chemically unweathered intact rock fragments which are entirely separated from each other and imperfectly interlocked. In such rock vertical walls may require support
Crushed	Chemically unweathered rock has the character of crusher run material
Squeezing	Rock that slowly advances into the tunnel without perceptible volume change
Swelling	Rock that advances into the tunnel chiefly on account of expansion caused by minerals with a high swelling capacity

In 1962, John presented a review of the fundamental rock mechanics concepts developed over more than a decade by the Salzburg study group. It was recognized that *in situ* rock is rarely homogeneous, that rock mechanics is the study of a jointed structure, a discontinuum. In this context the strength of a rock mass is related to the degree of decomposition or the resulting compressive strength of the rock material, and the spacing of the joints. What is clearly brought out is the range of properties in the hypothetical rock mass he is discussing (fig. 1); a range of joint spacing is defined and within that range the statistical distribution is stated. Strength is approached in the same way, but what is lacking is any indication of the distribution or localization in the rock mass of significantly low or high values of material properties. In other words, the geological appraisal is missing from the classification of a rock mass, illustrated in fig. 1, as being moderately sound, with blocky appearance which would allow underground excavations of moderate spans without support. The difficulty with the John classification, and it is obvious from fig. 1, is that a rock described as sound on the basis of its intact strength may have a range of joint spacing from 20 feet to several inches; it would be misleading to define a rock mass with joints as closely spaced as one inch as a sound rock with close jointing. There is an obvious need for a rock quality classification related to use.

However, John clarified the rock mechanics approach to geological materials, and in particular underlined the importance not only of geological discontinuities but also the fundamental importance of rock homogeneity (or inhomogeneity for the two are but different sides of the same coin) and the full details of the nature of discontinuities, and their three-dimensional characteristics.

There followed the series of papers already mentioned which are clearly derivative but explore certain aspects in greater depth. Deere (1963), for example, considered further the concept of homogeneity of the rock mass, recognition of which could lead to the selection of a single (complex) design value. The important step that Deere took was the recognition of the significance of geological factors. He suggested that the lithological description of the rock mass should be based on a geological name assigned on an understanding of the mineralogical composition, texture and mode of origin of the rock. He recommended that the rock name should be supplemented by descriptive terms for grain size, colour and minor constituents. But he went further than this and suggested that for rocks an *index property*, that might be correlative to other more important mechanical properties, might be provided by a numerical hardness value in conjunction with a textural classification.

This latter concept harks back to John who correlated "rock classification" with the compressive strength of the rock; a visually assessable physical property, in this case degree of decomposition, could be used as an estimate of a significant mechanical property without the need for laboratory testing of specially prepared specimens (fig. 1).

Texture is a most important criterion applied to the geological classification of rock (p. 6) and Deere suggested that three types could be recognized:

Interlocking texture shown by rock salt, limestone, dolomite, quartzite, basalt and granite;

Cemented texture of sandstone, conglomerate, some limestones, tuffs, and

Laminated foliated texture for rocks which contain minerals with a preferred orientation, such as shale, slate, phyllite, schist, gneiss. Such rocks have an obvious anisotropy even in the hand specimen.

Strength, on the other hand, does not enter into geological appraisal except as a qualitative test using a knife or a hammer to place a rock within an arbitrary soft: medium: hard category. But there is a need to quantify strength values for soil and rock even though large variations only are important in rock engineering.

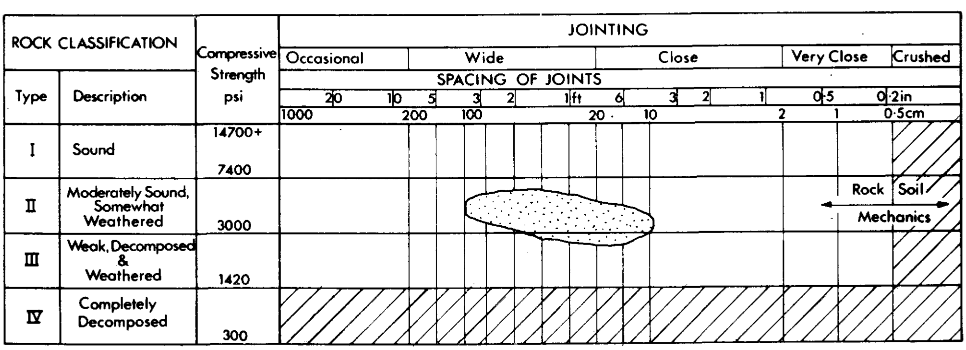


FIG. 1. — *Representation of the strength of a rock mass (after John, 1962, table 2).*

Or when the strength of part of a rock mass is markedly different from the main mass. Here Deere injected geological concepts into rock mechanics by stating that in many situations geological bodies are inherently inhomogeneous. The concept of inhomogeneity is obviously dependent on scale, but he quoted, as examples, interbedded shales and sandstones, limestones with solution widened and clay-filled joints, altered rocks along fault zones, and spheroidal weathering remnants of rock surrounded by soil.

Granite would be described as "coarse-grained, light grey, biotite granite with interlocking texture, hard." The only need to retain the rock name is that it provides so much more information about the geological setting and associations than does the use of the term "rock." For this reason, Deere recommended that geological names should be retained, but pleaded that they should be simple.

In this paper, which was concerned with the technical description of rock cores for engineering purposes, Deere also gave a semiquantitative descriptive terminology for joint spacing and the thickness of bedding units:

Descriptive term (joints)	Joint spacing or thickness of beds	Descriptive term (bedding)
Very close	< 2 in	Very thin
Close	2 in-1 ft	Thin
Moderately close	1 ft-3 ft	Medium
Wide	3 ft-10 ft	Thick
Very wide	> 10 ft	Very thick

Descriptions of geological planes should include information on tightness, irregularity, and filling material.

By the following year Deere had developed RQD (Rock Quality Designation) as a descriptive measure or rock quality inferred from rock cores:

RQD per cent	Description of rock quality
0- 25	Very poor
25- 50	Poor
50- 75	Fair
75- 90	Good
90-100	Excellent

RQD is a measure of the total length of all unweathered pieces of core greater than or equal to 4 inches in length, divided by the length of the particular core run. Lengths may be influenced by drilling method and technique, including removal of the core from the core barrel, so that some discrimination is needed.

The technique of determining a *fracture-index* of *in situ* rock by seismic methods was suggested by Onadera in 1963 as a basis for the *soundness* classification of *in situ* rock (Table 6).

TABLE 6. — *Dynamic soundness classification of rocks* in situ *on the basis of the ratio between* in situ *dynamic Young's modulus and the dynamic Young's modulus of the corresponding rock sample* (ONADERA, 1963, table 3)

Symbol	Grade	Soundness (e_d/E_d)
A	Excellent	0.75
B	Good	0.50-0.75
C	Available	0.35-0.50
D	Deficient	0.20-0.35
E	Bad	0.20

Geological diagnostics. — A. Fresh, with no alteration; almost no joints, cracks, etc. — B. More or less jointed and cracked, but with only slight parting; more or less weathered only on the surface along the parting, but inner part is fresh and intact. — C. More or less parted by joints or cracks with or without minor amounts of interstitial clayey matter, but rock itself is rather fresh with its surface weathered. — D. Partings are rather open and wide, and usually contain clay or muddy materials accompanied by fissure water; rock itself may be partly hard, but generally somewhat weathered or altered and jointed or cracked. — E. Weathering advanced; rock materials altered or weathered as a whole; conspicuously jointed, cracked or crushed. — e_d : *in situ* dynamic Young's modulus. — E_d : laboratory sample, dynamic Young's modulus.

Onadera suggested that the method could be used as an *in situ* test of the effectiveness of consolidation grouting.

Using the "fracture-index" Knill (1970) established a relationship between curtain grout take and longitudinal wave velocity for the rock adjacent to 89 concrete dams in the United Kingdom. The method can also be used in the evaluation of dam foundations on rock, in terms both of design and construction, at the site investigation stage. But the method, used at Latiyan dam (Knill and Jones, 1965), does not have the discriminating power of visually assessed engineering-geological grades (Table 14).

Coates (1964, 1965) and Coates and Parsons (1966), with a comment by Burton (1965), proposed a method of classifying *in situ* rock on the basis of material and mass properties. In the first paper there is no mention of a rock name, but later it is accepted that a simple field name clearly adds useful information, and that the guidance of a name indicating general composition would be useful. The recommended system of nomenclature for *rock* substance is:

Geological name;
Strong or weak (compressive strength greater or less than 10 000 lb/in^2);
Elastic or yielding.

The rock formation would be described in terms of the continuity of the rock substance in the formation. A granite would be desribed as "Granite, strong elastic, massive;" a shale as "Shale, weak, plastic, broken."

Strength and deformation characteristics would be defined by laboratory tests on prepared specimens: the degree of continuity of the mass would be determined by field measurements. Important and determinable rock characteristics are set out in Table 7.

A description of the strength of the rock substance would indicate whether the rock is *weak enough* to be a possible source of trouble. Assessment of deformation properties would indicate whether creep could be expected in the rock material at stress levels less than those required to cause failure; if creep occurs with an elastic material, then the deformation is a function of mass and not material property. The nature of failure is important, whether by rupture or flow, as this

TABLE 7. — *Classification of rocks for rock mechanics*
(COATES, 1964 and COATES and PARSONS, 1966)

I. Strength of the rock material

Description	*Unconfined compressive strength lb/in²*
Very strong	More than 25 000
Strong	10 000-25 000
Weak	5 000-10 000
Very weak	Less than 5 000

II. Deformation properties of the rock material

A. Elastic

— no creep or swelling tendencies
— large amount of stored strain energy
— brittle fracture failure with explosive energy release

B. Plastic

— more than 25 per cent total strain at any stress level is irrecoverable
— some material will creep or swell on exposure and some will fail by yielding or rupture
— includes viscous or time dependant strain materials (at constant stress)

III. Continuity in the rock mass

Description	*Joint spacing*
Massive	More than 6 feet
Blocky	1 ft-6 ft
Broken	3 in-1 ft
Very broken	Less than 3 inches

would influence the working factor of safety; if rupture with very violent release of stored clastic strain is likely, than a high factor of safety is desirable.

Coates, on publication of his 1964 classification, invited comment. This early version contained two sections dealing with the homogeneity of the rock mass:

Gross homogeneity:

(a) Massive;

(b) Layered. (Generally including sedimentary and schistose, as well as other, layering effects which would produce parallel planes of weakness.)

Continuity of the rock substance in the formation:

(a) Solid (joint spacing greater than 6 ft);

(b) Blocky (joint spacing between 3 inches and 6 feet);

(c) Broken (in fragments that would pass through a 3 inch sieve).

Burton (1965) commented on these two items in the original classification. His principal ground for criticism was that insufficient account had been taken of the present usage of some of the descriptive terms. "For example *massive* is used by geologists to describe thick beds of sedimentary rocks as well as bodies of igneous rocks. In Coate's classification the former would be included in the *layered* group. Again the term *layered* is used quite frequently in connexion with certain basic/ultrabasic igneous complexes." He goes on to give other examples and to suggest alternative solutions. The solution adopted by Coates and Parsons was to leave out altogether gross homogeneity, and to deal with continuity in the rock mass in terms of a slightly revised joint spacing classification and slight alterations to the descriptive terms.

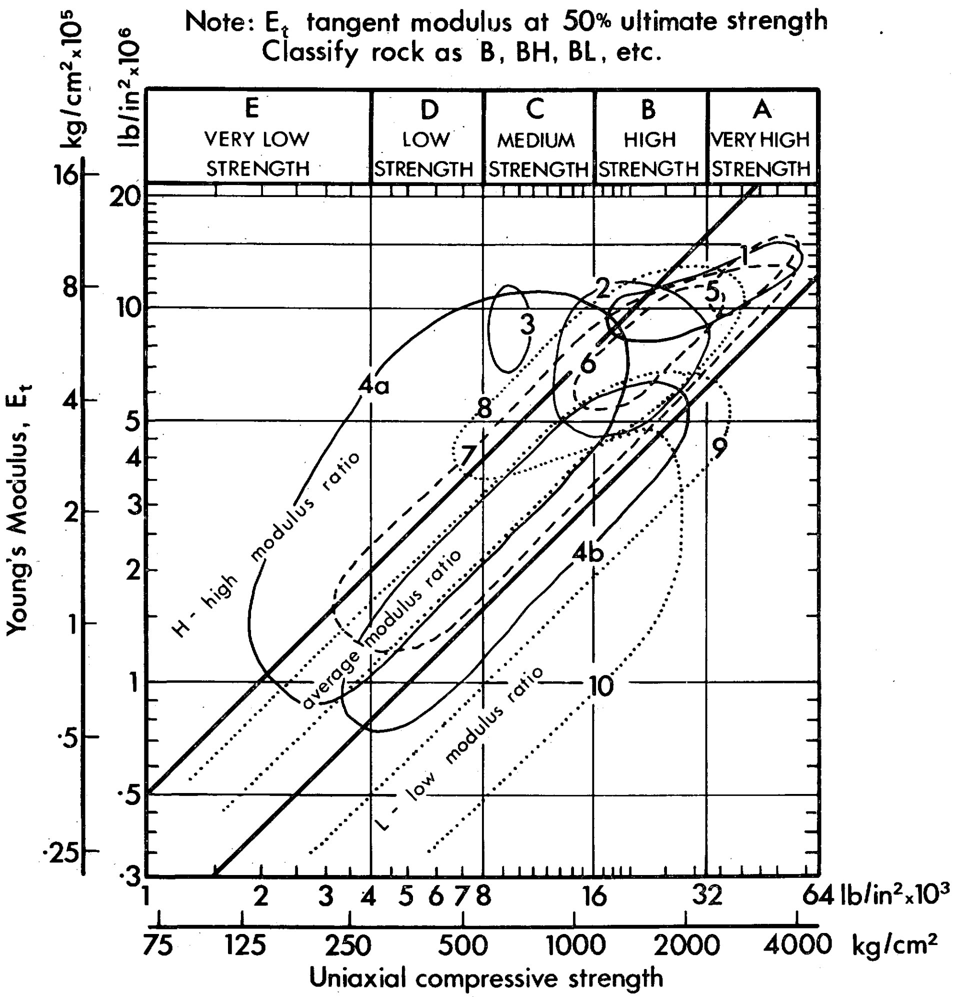
But the issue raised by Burton is an important one. Descriptive terms should convey to the reader, or user, a clear mental picture of, in this case, the rock conditions they are intended to describe. Additionally, and perhaps ideally because geologists are not entirely without fault in this respect, terms should be used in an accepted and standard geological sense; otherwise the term should be redefined or preferably a new term devised.

In 1966, Deere and Miller proposed an engineering classification of rock material based on unconfined compressive strength and Young's modulus. The physical and elastic properties of thirteen rock types were determined on specimens of NX-size core. Laboratory tests included determination of density, water absorption, shore scleroscope hardness, Schmidt hammer hardness, abrasion hardness, sonic-velocity, stress-strain under cyclic loading to 5 000 lb/in^2, uniaxial stress-strain to failure, and point-load tensile strength. Classification was based on the relationship between uniaxial compressible strength and modulus ratio (Table 8). Specific rock types fall within certain areas on the classification plot (fig. 2).

TABLE 8. — *Engineering classification of intact rock proposed by Deere and Miller (1966). Modulus ratio is the tangent modulus at 50 % ultimate strength divided by the uniaxial compressive strength. Rock would be classified as AH, A, AL, for example*

Class	Uniaxial compressive strength	
	Term	Value (lb/in^2)
A	Very high strength	32 000
B	High strength	16 000-32 000
C	Medium strength	8 000-16 000
D	Low strength	4 000- 8 000
E	Very low strength	4 000
Class	**Modulus ratio**	
	Term	**Value**
H	High	500
	Average	200-500
L	Low	200

By examining a range of simple, inexpensive and rapidly performed tests which could be carried out in the field, Deere and Miller were able to select the Schmidt



Metamorphic: —1— Quartzite, —2—Gneiss, —3— Marble, —4a— Schist, steep foliation, —4b— Schist, flat foliation.
Igneous: --5-- Diabase, --6-- Granite, --7-- Basalt and other flow rocks.
Sedimentary: ····8···· Limestone and dolomite, ····9···· Sandstone, ···10···· Shale.

FIG. 2. — *Engineering classification of intact rock based on uniaxial compressive strength and modulus ratio. Fields are shown for igneous, sedimentary and metamorphic rocks (after Deere and Miller, 1966, figs. 6.4, 6.8 and 6.13).*

hammer test as a simple index test that together with density determination would provide an approximate value of the strength and modulus of deformation of intact rock (fig. 3). Thus a simple test could be used to provide an index to material properties which could be used by the engineer in solving design problems.

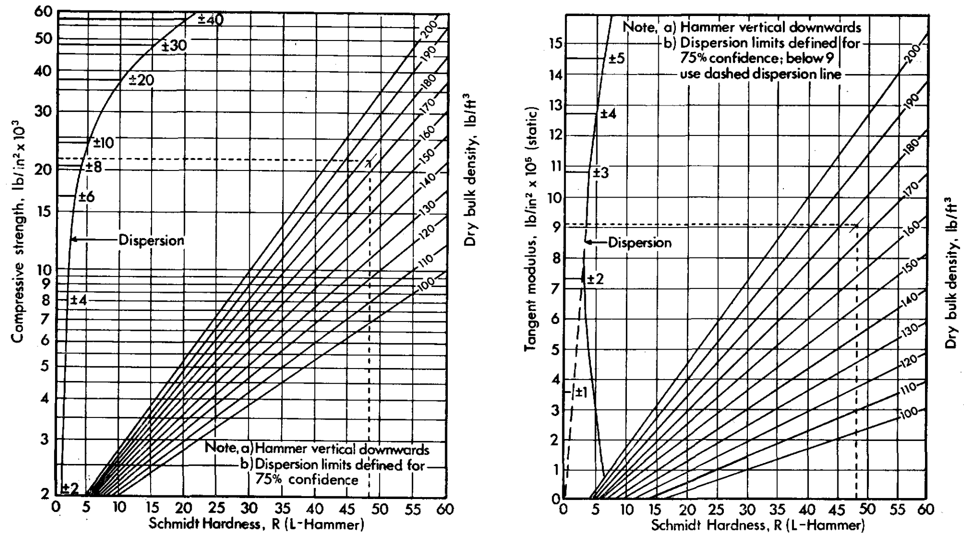


FIG. 3. — *Rock strength charts based on Schmidt hammer value, dry bulk density, and (a) compressive strength, and (b) deformation modulus (after Deere and Miller, 1966, figs. 6.20 and 6.25).*

It was emphasized that in order to allow realistic estimates to be made of the expected engineering behaviour of *in situ* rock, the system developed for intact rock material would have to be extended to include the influence of geological discontinuities. As Deere in 1963 had recognized, both the spacing and the mechanical properties of discontinuities might have a greater influence on design parameters than a detailed knowledge of strength and modulus values for the rock material.

In 1969, Deere *et al.* proposed that an engineering classification of *in situ* rock could be based on two indices of rock quality, the RQD and the Velocity Index. The RQD is the percentage of solid core recovered greater than 4 in. in length. The Velocity Index is the square of the ratio of the field velocity to laboratory velocity. Correlation of *in situ* test data with the two rock quality indices suggest that the rock classification can be used to estimate *in situ* deformability, rate of tunnelling, and underground support requirements (Table 9).

Measurements of *in situ* deformability were made by static tests, including the plate jack, pressure chamber, radial jack, borehole deformation, and cable tests. Dynamic moduli were calculated from seismic tests and sonic logging in exploratory boreholes. Because the loading conditions in static tests are closer to those of engineering structures, Deere *et al.* propose that these should be used for engineering design, whereas the dynamic moduli should be used as an index of rock quality.

Nearly all of the data presented in the report relate to rock classed as Fair to Excellent; difficult ground conditions represented by highly weathered and highly disintegrated rock still require investigation. Deere *et al.* again emphasize the need for geological assessments of degree of openness and type of infilling of

TABLE 9. — *Correlation of engineering properties and the engineering classification of rock* (from DEERE *et al.*, 1969, table 18.1)

Rock Quality Classification	RQD	Velocity Index	Deformation Ratio S_e/S_t	Engineering Properties of *in situ* Rock		
				Deformability		Permeability
				E_d/E_{t50}	E_e/E_{t50}	
Excellent	90-100	80-100	0.8-1.0	0.8-1.0	0.9	Moderate to low
Good	75- 90	60- 80	0.6-0.8	0.5-0.8	0.7-1.0	High to low
Fair	50- 75	40- 60	0.4-0.6	0.1-0.5	0.1-0.7	High to low
Poor	25- 50	20- 40	0.1-0.4	0.2	0.2	High to low
Very poor	0- 25	0- 20	0.1	0.2	0.2	High to low

S_e : elastic or recoverable deformation, field static test. S_t total deformation, field static test. E_d : modulus of deformation, field static test. E_e : modulus of elasticity, field static test. E_{t50} : tangent modulus of elasticity at 50 % unconfined strength, laboratory static test.

TABLE 10. — *The field description and classification of rocks by Duncan (1966, 1969). An abbreviated rock description may be given by selecting one term from each column and using the figure or letter for each, e.g. I h C l a, a crystalline, homogeneous, calcareous, light coloured, coarse-grained rock*

Group Number	Texture	Structure
I	*Crystalline* Rock consists entirely of interlocking crystals which are visible to the naked eye No particles freed when samples scratched with blade of knife	*Homogeneous (h)* Crystals and grains arranged randomly. No visible linear or planar structure
II	*Crystalline-indurated* Isolated crystals visible to the naked eye and embedded in an indurated matrix No particles freed when samples scratched with blade of knife	*Lineated (l)* Particles show a preferred orientation but of a linear rather than a planar nature
III	*Indurated* Interlocking crystals are not visible to the naked eye. The samples may be coarse, medium or fine grained No particles freed when samples scratched with blade of knife	*Intact-foliated (i)* A planar structure is visible in the rock but closed or incipient fracture is absent. The intact foliation may be produced by the alternation of layers of different colours
IV	*Compact* Individual crystals and grains not visible to the naked eye Particles freed when samples scratched with blade of penknife	
V	*Cemented* Crystal grains visible to the naked eye Particles freed when samples scratched with blade of penknife	
VI		*Fracture-foliated (f)* A planar structure is visible associated with closed or incipient fracture, e.g. cleavage planes or bedding planes

Composition	Colour	Grain Size
Non-calcareous Calcium carbonate is absent. The sample will not react with dilute HCl. Place (*N*) after the Group Number	The specific colour of the rock should be noted as an aid in assessing its composition and also for purposes of correlation The general light or dark nature of the rock should be noted	*Coarse-grained (a)* Particles larger than 2 mm in diameter or in largest dimension. Particles easily visible to the naked eye. The size corresponds to the gravel-sand boundary in the soil classification
Part-calcareous Non-calcareous material (e.g. quartz or clay matter) is present in substantial amounts but some of the rock reacts with dilute HCl. In this event place (*P*) after the Group Number	For non-calcareous rocks, use dark only for black or dark grey materials For calcareous rocks, use dark for materials of a "muddy" composition	*Medium-grained (b)* Particles between 0.1 mm and 2 mm and visible to the naked eye
Calcareous Calcium carbonate is the main constituent. The sample reacts with dilute HCl (i.e. effervesces). Place (*C*) after the Group Number	After Group Number and composition letter place: 1 for *light* rocks; 2 for *dark* rocks	*Fine-grained (c)* Particles less than 0.1 mm and invisible to the naked eye
		It can be useful also to note whether the rock is *Equigranular (x)* Grains of the same size approximately throughout; or *Inequigranular (y)* A range of grain sizes throughout the rock

discontinuity systems, for which the RQD logging system may not provide an infallible guide. They suggest that these characteristics, which are critical in the first 10 feet of rock below the loaded surface, could at least be inspected by borehole camera.

Characterization of Rocks for Rock Mechanics in British Practice

The selected group of seminal papers reviewed in the last section had a continuing influence on British developments in rock material classification and the search for index properties that would act as a guide to other rock properties. There is, once again, a clear distinction between the classification of rock material and the *in situ* rock mass.

Rock Material Classification

Duncan (1966) sought a quantitative system of rock material classification which could be backed up by simple field tests and non-destructive laboratory tests. He adopted for his purpose textural features long used in petrographical descriptions of rocks (p. 6), added a simple estimate of composition, and demonstrated that, as naturally occurring materials, rocks fall into six groups (Table 10) on the basis of texture and structure.

The field tests are simple and require only a knife, a hand lens and dilute hydrochloric acid. For a full description of any rock material, one term is selected from each of the columns in Table 10. The group number is governed by the diagnostic features listed in the texture column except in the case of Group VI where fracture-foliated is the diagnostic feature. A rock description applicable to granite would be "crystalline, homogeneous, non-calcareous, light coloured, coarse-grained rock"; it would belong to Group I(N) and could be more completely coded as IhNlay.

The system of field identification and classification is qualitative and should be augmented by quantitative assessments which also permit more precise description of rocks.

Rock variables are:

(i) nature of the mineral grains;

(ii) nature and extent of voids, and

(iii) nature of the bond between mineral grains.

Petrographic methods are available for the determination of the nature of the mineral grains, and instrumental techniques such as X-ray diffraction and differential thermal analysis are available for the identification of fine-grained minerals and mineral mixtures. Voids and bonds between grains may be determined by simple physical tests which may be considered as *index tests*, with the quantitative results of the tests, carried out under standardized conditions, providing an *index property*. Determinations involved are:

(a) saturation moisture content;

(b) dry bulk density, and

(c) saturation swelling coefficient.

Both (a) and (b) are standard tests (Anon., 1967) and from them the total connected porosity may be determined. Measurement of mineral grain specific gravity would permit assessment of the total porosity of the sample.

The saturation swelling coefficient is determined on a sawn length of drill core, or a specially prepared cube, half immersed in water. Change in the original length of the sample, L, is recorded until expansion ceases or the sample fails. The swelling coefficient is dL/L. Compact rock types (Table 10) swell, and this test, which may be carried out in a standard oedometer, is a useful means of distinguishing rocks of this textural group.

Duncan has shown that variations in saturation moisture content and dry bulk density are related to textural variations (fig. 4).

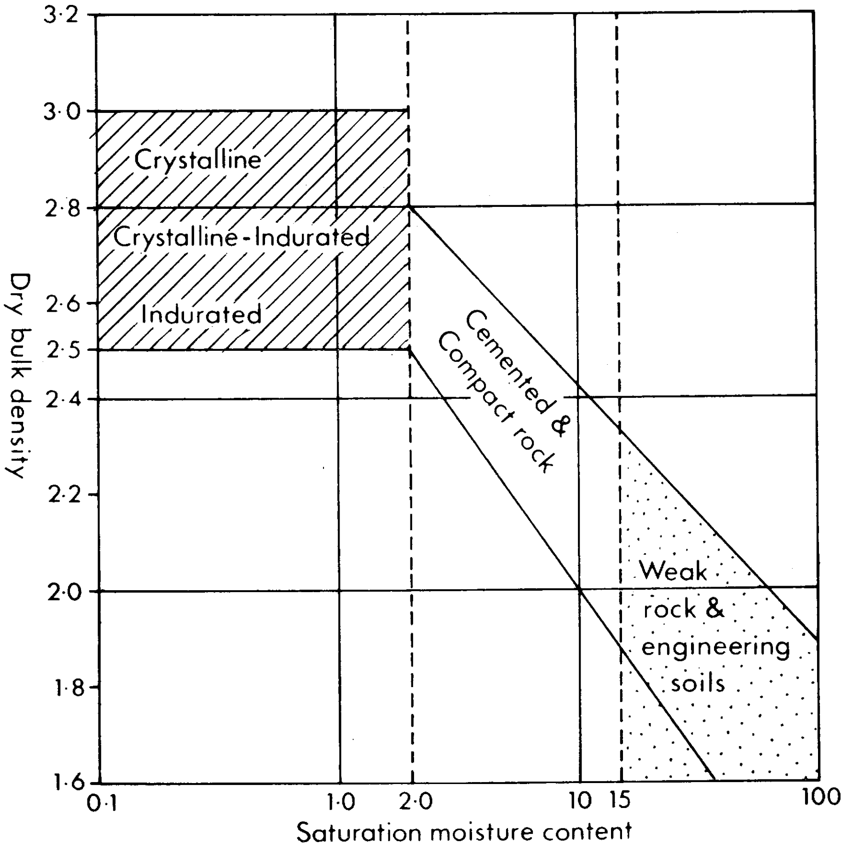


FIG. 4. — *Rock classification: the general relationship between rock texture, dry bulk density and saturation moisture content (after Duncan, 1969, fig. 26a).*

In some ways Duncan's work took a backward step. Whilst accepting the need for a certain amount of geological expertise in assigning rocks to their respective textural groups, he was unwilling to take the additional step of identifying broad mineral groups. A knowledge of the mineralogy together with textural features would have led directly to the selection of an appropriate rock name, with the attendant advantages enumerated by Deere (1963) and Coates and Parsons (1966). He did, however, refer standard geological rock types to his rock material groups and related the index properties of each group to ranges of unconfined compressive strength and the modulus of elasticity.

Rock Mass Classification

One of the main uses of rock characterization and classification lies in the field of engineering geological mapping. The basis of all geological mapping is the recognition of acceptably homogeneous units and the delimitation of these units on a map or cross-section as appropriate. Mapping units will be defined in terms of rock grade or rock quality, determined in rock mechanics by either *in situ* or laboratory determination of design parameters. Such determinations are expensive to carry out and in consequence the number of tests tends to be small. An important aim in rock mechanics research is, as has already been shown, the development of simple and cheap index tests to provide a much greater coverage of index property values which are directly correlatable with the restricted and expensive design parameters determined both *in situ* and in the laboratory.

It will be shown later that engineering geological characterization, supplemented where necessary by selected index tests, provides an even better method of predicting the distribution of design parameters. But before this, research on rock mechanics index tests and descriptions will be reviewed.

Franklin (1970), Cottiss *et al.* (1971), Franklin *et al.* (1970, 1971) have discussed recent developments in the field of engineering geological mapping and core logging in the United Kingdom from the restricted viewpoint of rock mechanics.

Franklin (1970) has approached mapping from the point of view of providing a map of rock quality variation for the use of the engineer. Assessment of rock quality may be visual and based on criteria such as those set out in Table 10. Although simple consistency tests have long been used in soil mechanics, Franklin asserts that hammer and penknife tests, although simple and relevant, are not an effective means of discriminating one rock from another. He considers that classification tests require:

1. Rapid techniques; these are necessary due to the large number of samples that must be observed for adequate mapping. For this reason, also since many rocks are too broken or soft to machine, specimen preparation should be minimized.

2. Simple techniques; these should allow classification by non-experts. Observations requiring special skills or subjective judgements will usually also call for these skills when interpreting the results.

3. Robust, portable apparatus; this is required to allow classification in the field. Transport of large numbers of specimens to the laboratory should be avoided to save time. In addition samples deteriorate in transit and should not be examined out of context.

4. Relevance to rock properties; natural rock characteristics determine the scope of tests and observations required. A test appropriate for one class of rocks may be irrelevant if applied to another.

5. Relevance to engineering problems; a test should be useful and not just of interest. However an important property such as strength may often be estimated by observing another property such as porosity, which itself may at first glance appear irrelevant to the problem.

6. Power of discrimination; many of the simpler tests have an inherently large error of measurement compared with the full range of properties to be observed, and so record similar values when applied to different samples.

Franklin, and others, strongly emphasize the need for simplicity in test procedure combined with ability to produce a large number of results for statistical evaluation. The attributes for a basic classification are brokenness, strength, durability, mineralogy, and texture.

(i) BROKENNESS

Even the simplest classification of rock for engineering purposes must take account of the discontinuous nature of the rock mass. A *fracture index*, defined as the average linear size of blocks comprising the rock mass, is suggested as a measure of brokenness. The definition emphasizes the three-dimensional nature of this rock property, which may be visualized as a "grain-size." Fracture index may be estimated from the average size of lumps in a scree, in a heap of blasted rock, in a tip of excavated material, or from the average spacing of fractures in a core or in an outcrop. The index may be compared with "Rock Quality Designation" (page 22) which is also a measure of fracture spacing, or with "Velocity Ratio" which reflects not only spacing but openness and degree of infilling of fractures.

(ii) STRENGTH

Once the size of a typical unit rock block has been determined, its intact strength must be defined. This is usually achieved by the uniaxial unconfined compression test, but the test requires careful specimen preparation and as such is restricted to those samples which can be machined to the requisite shape.

It is suggested that the most satisfactory alternative is a version of either the line-load or the point-load indirect tensile strength test (Protodyakonov, 1960; Hobbs, 1963; Hiramatsu and Oka, 1966) of which three seem particularly relevant as they require a minimum of sample preparation. These are the diametral long core (fig. 5*a*), the axial point load on core discs (fig. 5*b*), and the test on irregular lumps (fig. 5*c*).

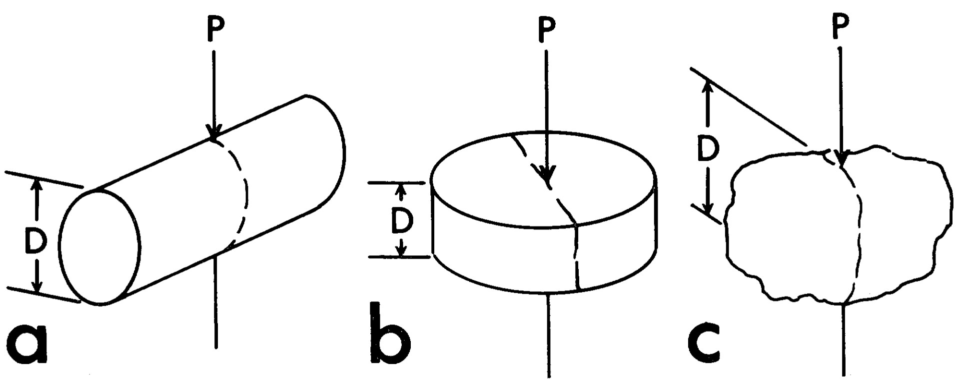


FIG. 5. — *Typical point-load strength tests (after Broch and Franklin, 1972, fig. 1). (a) diametral long core; (b) axial point load on core discs; (c) irregular lumps.*

If, however, drill core is readily available, the Brazilian test may be performed on roughly sawn discs with a thickness/diameter ratio of less than one. The

Brazilian strength, approximating to the direct tensile strength of the rock, is calculated from the equation:

$$\text{Brazilian strength} = \frac{2F}{\pi DT}$$

where F is the load at failure applied across the diameter of the disc (fig. 6); D and T are respectively the diameter and thickness of the disc.

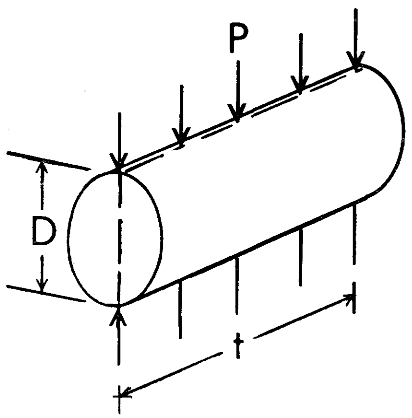


FIG. 6. — *The Brazilian line-load strength test.*

The vertical concentrated applied load induces a horizontal tensile stress and failure occurs on a plane or planes parallel to the direction of applied load. The maximum tensile stress, occurring at the centre of the specimen, may be related to the applied load P, the distance between the platens D, and the length of line loading t, by an expression of the form:

$$\sigma_t = kP/Dt \quad \text{for line-load tests}$$

or

$$\sigma_t = kP/D^2 \quad \text{for point-load tests}$$

when k is a constant with approximate values ranging from 0.5-1.0 depending on the geometry of the specimen.

Although specimens must still be machined the quality of machining is not so critical as in the uniaxial compressive test where the machined ends of the specimens are loaded.

Particular advantages are associated with point load testing of irregular lumps now that the size dependency of the test result has been recognized. Apparatus has been designed (fig. 7) that is robust, light and portable since only small forces are required to fracture the specimens. The test has been described and evaluated in detail by Broch and Franklin (1972). Point load tests on irregular lumps have been used to study weathering (Fookes *et al.*, 1971) because core was not available, and the more highly weathered rocks, which could be crumbled between the fingers, would have presented insurmountable problems in the preparation of regular-shaped samples for conventional compressive strength testing.

Results from the irregular lump tests are more scattered than those for point load tests on core. As the test is quickly carried out, scatter can be compensated

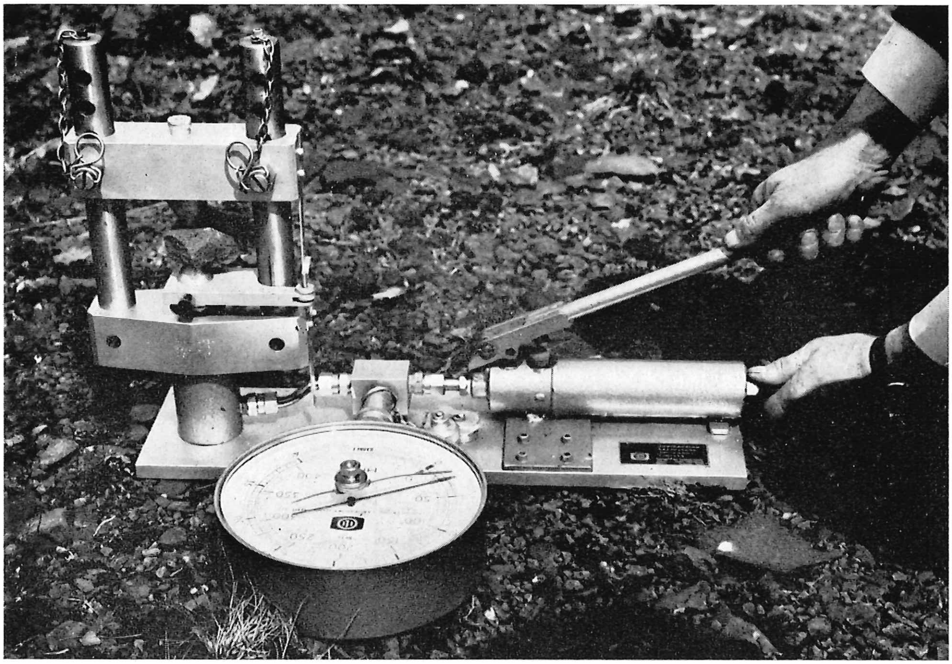


FIG. 7. — *The portable point-load tester being used to test an irregular lump.*

to some extent by testing a large number of lumps and taking the median value as an index.

The Diametral Point-load Test

In the diametral point-load test, the failure load P is independent of the length of the core provided that the distance L is sufficiently large (fig. 8); if this condition is satisfied the end faces of the specimen need not be machined flat.

Broch and Franklin (1972) determined the minimum value of L that could be used, since rock core is usually available in limited lengths and several tests on the same piece of core are usually needed. Experiments were carried out on 38 mm diameter core taken from sandstone and dolerite, chosen for their apparent homogeneity and contrasting strength and geological character. The results are shown in fig. 9. The shortest length of specimen that could be tested with consistent results had an overall length 2L equal to the core diameter.

It is well known that specimen size affects the result in unconfined compression testing, and the same effect applies to the point-load test. In the diametral point-load test the size effect is due to the diameter of the specimen, since the strength index is independent of specimen length provided that certain conditions (fig. 9) are fulfilled. Size effect was investigated using cores of different diameters from each of five contrasted rock types selected for their isotropic nature. Strength of specimens was found to decrease with increasing core diameter (fig. 10), and strength changed more rapidly at smaller diameters. Results from one sample of

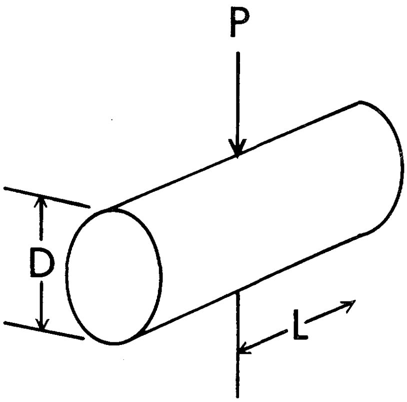


FIG. 8. — *Critical specimen dimensions for the diametral point-load test.*

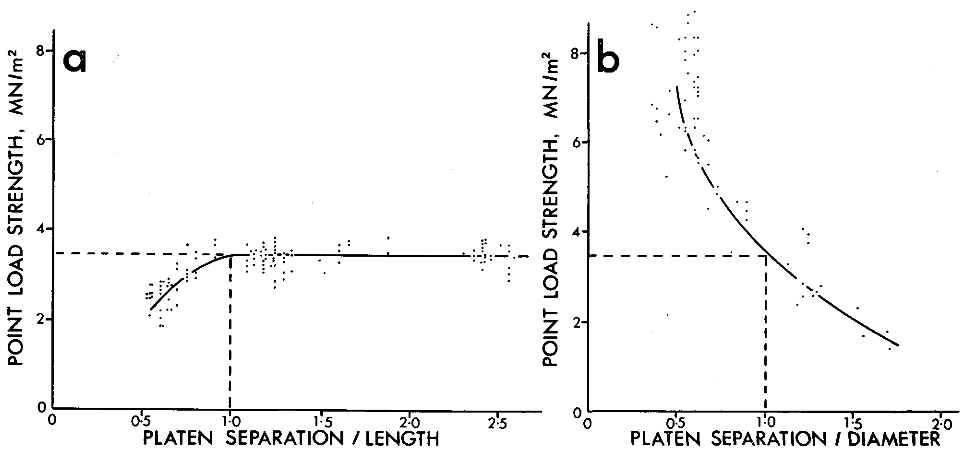


FIG. 9. — *Size and shape effects in the point-load test; (a) the diametral point-load test; (b) the axial point-load test (after Franklin* et al., *1970, fig. 4).*

Pennant sandstone (Sample No. 219, fig. 10) were anomalous, but the other results produced a family of similar curves over a range of strengths. These have been used to produce the size-correction curves in fig. 11. Broch and Franklin propose that the strength index, I_S, obtained on any available core should be corrected to a value $I_{S.50}$ at a "reference diameter" of 50 mm. Curves have not been plotted for core diameters of less than 25 mm because below this diameter the size correction becomes both variable and large. Tests on samples less than 25 mm diameter are not recommended.

Using the size correction chart (fig. 11) the error is unlikely to exceed 15 per cent, and in most cases should be much smaller.

The Axial Point-load Test

Experimentally determined test values on specimens machined from two different rock types, sandstone and dolerite, show that this test (fig. 5*b*) suffers from

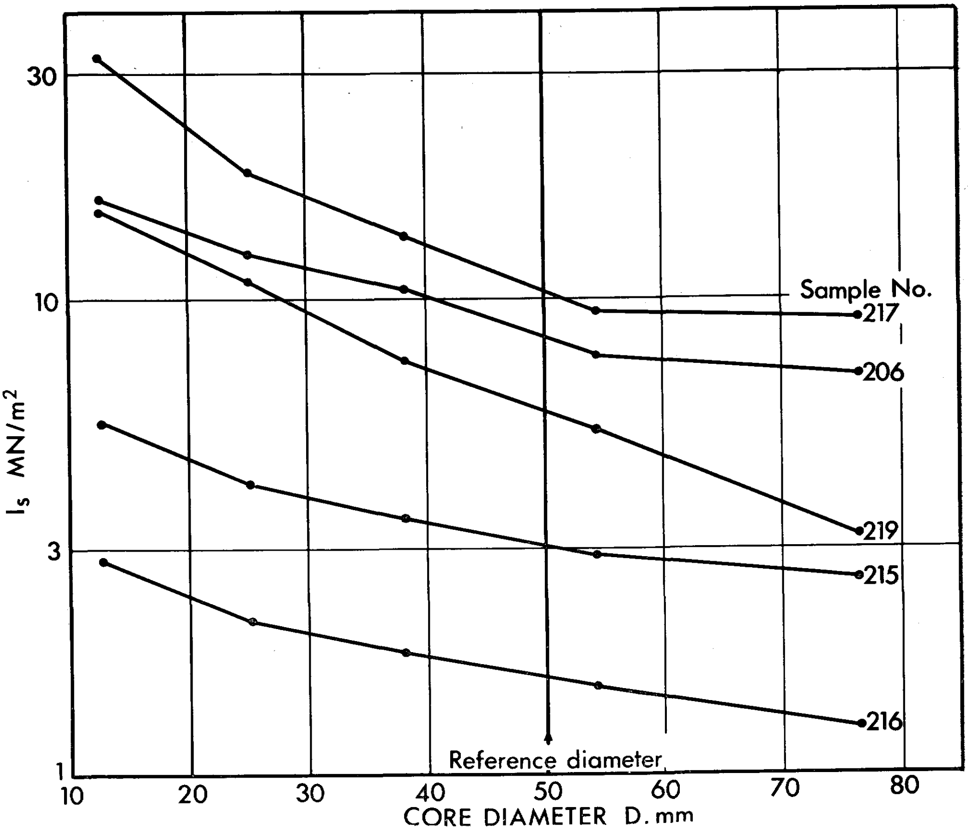


FIG. 10. — *Size effect in the diametral point-load test (after Broch and Franklin, 1972, fig. 9).*

shape effects. Accordingly, it is recommended that specimens should be used that have a length/diameter ratio of 1.1 ± 0.05. If these conditions are fulfilled, the results obtained from axial testing are identical to those of a diametrical test on the same material, with a maximum discrepancy of 10 per cent.

The diametral test is more reliable for strength classification because it suffers less from shape effects, and the axial test should only be used in the determination of strength anisotropy.

The Irregular Lump Point-load Test

The irregular lump test is less accurate than the diametral point-load test, but with careful specimen selection the scatter of results can be kept to a minimum. Shape requirements can be deduced from the results of tests on cylinders and rectangular prisms (Broch and Franklin, 1972, fig. 11). A shape factor, defined as the ratio of distance between loaded points to the smallest specimen dimension in a perpendicular direction, of between 1.0 and 1.4 is recommended. A shape factor of 1.0 should be used for testing well-rounded specimens, whereas for

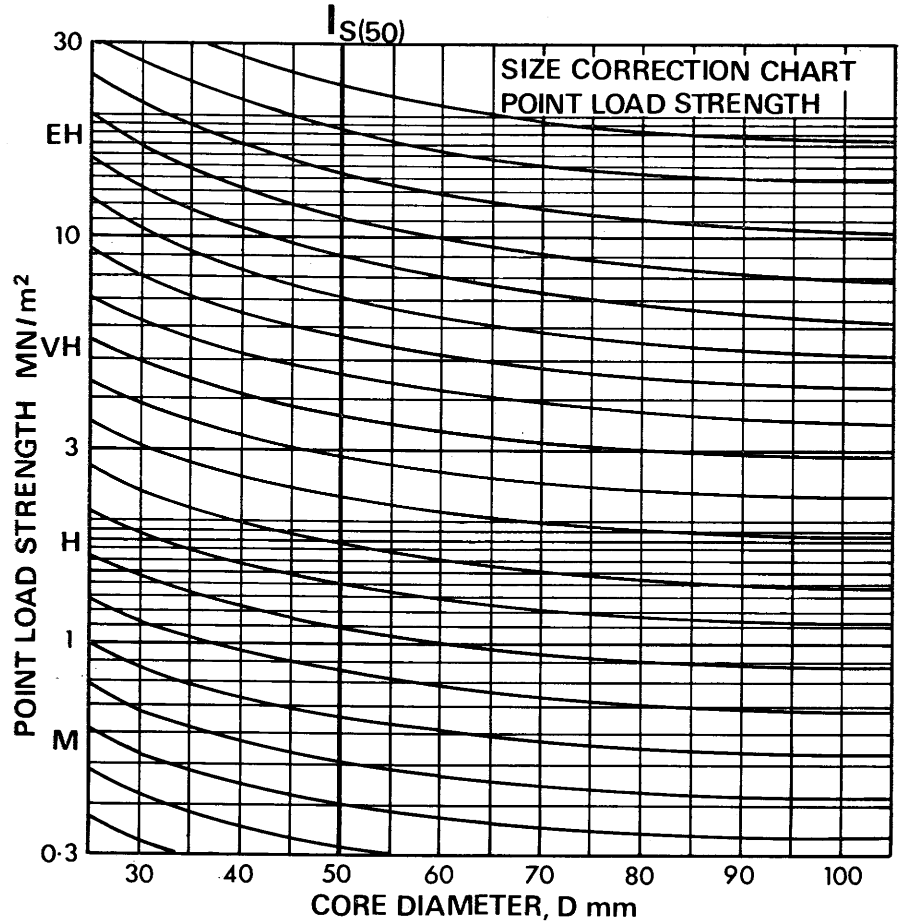


FIG. 11. — *Size correction chart for point-load strength testing (after Broch and Franklin, 1972, fig. 25).*

prismatic specimens the ratio should be nearer to 1.4. The thickness of the lumps should be close to 50 mm, when the size correction chart (fig. 11) can be used without too much extrapolation. Accuracy can be improved to some extent by testing a large number of samples (15-25 is recommended), but the latitude allowed in the shape of test specimens probably results in a ± 15 per cent variation in the results. Within these limits, the results of the irregular lump point-load test correspond to those that would have been achieved by diametral testing.

Computation of Test Results

Individual test results are each normalized to 50 mm diameter and the median value determined by systematically deleting the highest and lowest values until only two values remain; the average of these is taken as the median value, the point-load strength index. The median value is preferred to the mean because it requires little computation and is less sensitive to extreme results. A nomogram (fig. 12) and the size correction chart (fig. 11) can be used to calculate the strength index.

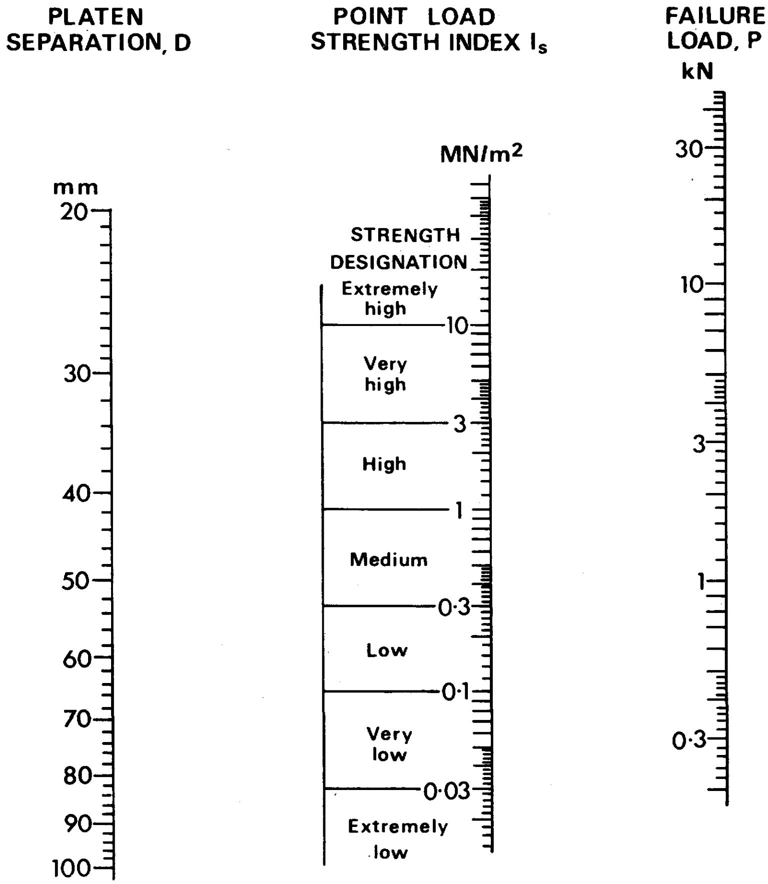


FIG. 12. — *Nomogram for computing point load strength index, and Franklin's strength classification (based on Broch and Franklin, 1972, fig. 24).*

(iii) DURABILITY

Rock likely to degrade while forming part of an engineering structure must be characterized as to its durability, since subsequent degradation in place may render the original measurements of fracture spacing and strength meaningless. Durability is defined *in this context* as the resistance of rock to weakening and disintegration when subjected to short term weathering processes (Fookes *et al.*, 1971).

There are standard freezing-and-thawing, and salt crystallization tests, which are considered later. A test has been developed (Franklin and Chandra, 1972) to assess the *slake durability*, the resistance to wetting and drying, of a rock sample. Particularly applicable to mudrocks, and to rocks which have weathered to a certain extent to produce clay and other secondary minerals, the test provides a rapid, quantitative assessment of the mechanical character of the rock. However, a major disadvantage is that the test has to be conducted under laboratory conditions.

The slake durability test has been standardized. In the test the sample consists of ten representative rock lumps, each weighing between 40-60 g. The sample, with corners rounded off, is placed in a standard test drum, oven dried and weighed. A lid is placed on the drum, which is then half immersed in a water tank (fig. 13) and rotated for ten minutes at 20 rpm. The body of the drum is made of sieve mesh of standard size (2 mm) and during slaking a proportion of the disintegration products passes through the mesh into the tank. The speed of the drum is such as to stir the sample without appreciable mechanical attrition.

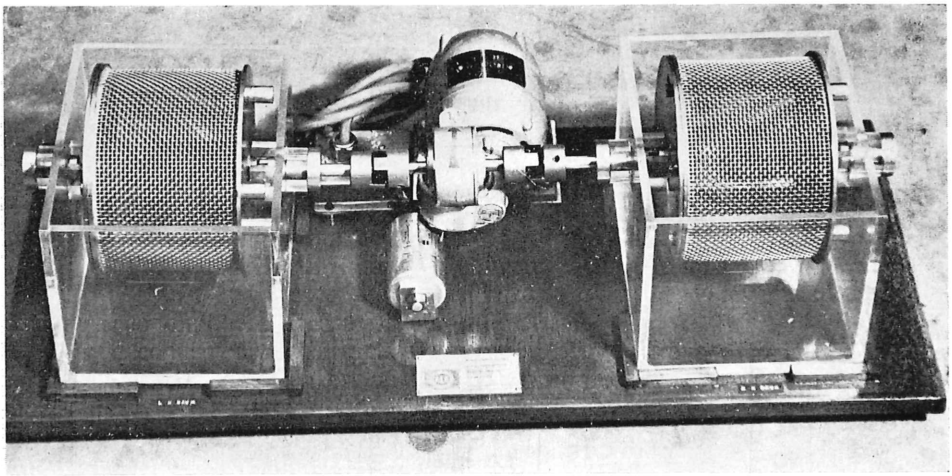


FIG. 13. — *The slake durability test apparatus.*

After slaking, the drum with the retained material is again dried and weighed. Knowing the weight of the empty drum, a slake-durability index I_d can be calculated as the percentage ratio of retained dry weight to that of the sample before slaking. The index can vary from 0 % when the sample completely disintegrates to 100 % where no change takes place.

For samples with an index from 0 to 10 per cent the result is reported as the first cycle index I_{d1} ; for higher indices the test is repeated under the same conditions and the result reported as the second cycle slake durability index I_{d2} . Indices determined after several cycles may be useful in evaluating rocks of high durability. The immersion fluid may also be varied.

(iv) Petrographical Aspects

The materials confronting the engineer in rock mechanics studies are naturally occurring rocks, and so some attention has to be paid to simplified petrographical classifications of rocks. It is evident (p. 5) that rocks can be classified on the bases of chemical composition, reflected in mineralogical constitution, and texture. Mineralogy and texture have both been considered by Franklin (1970) as essential classification properties.

Mineralogy

Only five categories of mineral assemblage, it is suggested, occur with sufficient abundance to justify detailed consideration by the engineer. These may be listed as follows:

1. Quartzofeldspathic (e.g. acid igneous rocks, quartz and arkose sandstones, gneisses and granulites). Usually strong and brittle. Important indices—porosity, quartz/feldspar ratio and feldspar freshness.

2. Lithic/basic (e.g. basic igneous rocks, lithic and greywacke sandstones, amphibolites). Usually strong and brittle. Important indices—porosity texture, quartz content, freshness of dark minerals.

3. Pelitic (clay) (e.g. mudstones, slates, phyllites). Often viscous plastic and weak. Important indices—durability, quartz and clay content, porosity and density.

4. Pelitic (mica) (e.g. schists). Often fissile and weak. Important indices—fissility, mica and quartz content, porosity.

5. Saline/carbonate (e.g. limestones, marbles, dolomites, salt-rocks). Sometimes viscous, often plastic and weak. Important indices—porosity, texture, mineral type.

This is basically a petrographic classification determined by the presence or absence of the characteristic minerals:

1. Quartz;
2. Dark grains;
3. Fresh feldspars;
4. Salts and carbonates;
5. Altered minerals;
6. Micas and platy minerals;
7. Clay minerals;
8. Pores and cracks.

The minerals are said to be listed in approximate order of mechanical quality. Each "mineral" is easy to indentify and Franklin points out that as there is gradation from one rock category to another, it might be more useful in classification to identify and determine the abundance or lack of the major mineralogical varieties, each of which have characteristic mechanical properties.

Texture

The only textural parameter commonly used in engineering descriptions of intact rock is grain size, but the value of this property as an index to mechanical behaviour may be questioned. Sorting, crystallinity, preferred orientation and porosity are probably of greater mechanical importance and may be taken into account by noting the proportions of four textural constituents. These constituents, namely coarse fragmental (detrital or clastic) material, coarse crystalline material, muddy or microcrystalline matrix and pore space, should each be represented by a volumetric percentage and a size value. In addition, if it can be observed an indication should be given of whether a matrix is crystalline or fragmental. If the four constituents are represented by the symbols *F*, *X*, *M*, *P* then a code for rock texture can be constructed. Size also requires coding, and may be expressed as x where the actual size is 2^x microns (the International Society of Soil Science system). Hence a 2 % 3*P*, 18 % 11*X*, 80 % 3*M* rock has 2 % size 3 pores and 18 % coarse crystalline (porphyritic crystals) in a size 3 crystalline matrix.

Franklin avers that there seems every reason to use, contrary to present practice, a common grain size scale for all rock types and constituents. There is much to be said for a uniform approach, but a system that demands mental arithmetic before it can be applied is hardly likely to find general approval for field use.

Other textural characteristics should be taken into account, including coherence, fissility and friability of the rock as selected examples.

The index tests proposed by Franklin for the estimation of strength, and by Broch for the determination of slake durability, provide index properties for rock material. They are in a similar category to the tests for the determination of porosity and bulk density proposed by Duncan (1966), which, if anything provide a better index of rock material quality.

Standard tests for the classification and characterization of rock have been listed (Cottiss *et al.*, 1971) by the International Society of Rock Mechanics as:

Category 1. Classification and characterization

A. Intact rock material

(1) Density, water content, porosity, absorption
(2) Strength and deformability modulus in uniaxial compression; point load strength
(3) Hardness abrasion, attrition and drillability (Schmidt hardness, Shore scleroscope, identation, Los Angeles test, Deval test, etc.)
(4) Swelling, and slake-durability
(5) Sound velocity; pulse and resonance (Lab)
(6) Permeability (Lab)
(7) Micro-petrographic description for engineering purposes (emphasis on mechanically important features)
(8) Anisotropy indexes

B. *In situ* mass

(1) Joint systems; orientation, spacing, openness, roughness, geometry, filling and alteration
(2) Core recovery, rock quality designation and fracture spacing
(3) Seismic tests for mapping and for rock quality index purposes
(4) Geophysical logging of boreholes

Category 2. Engineering design tests

A. Laboratory tests

(1) Determination of strength envelope and elastic properties (triaxial, biaxial, uniaxial compression and tensile tests; direct shear tests)
(2) Strength of joints and planes of weakness
(3) Time dependent and plastic properties

B. *In situ* tests

(1) Deformability tests
(2) Direct shear tests (intact material, joints, rock-concrete interface)
(3) Field permeability, piezometric levels and ground-water flow
(4) Stress measurements
(5) Rock movement monitoring; rock noise monitoring; blast and ground-motions monitoring
(6) Uniaxial, biaxial and triaxial compressive strength.

The two categories clearly differentiate the rock mechanics approach to rock classification and characterization from the engineering-geological approach described in the succeeding sections. A great deal of this type of testing has been done in the United Kingdom, and in many cases the results refer to geologically described rock types (Meigh, 1968; Meigh and Early, 1957; Meigh and Greenland, 1965).

Classification and Characterization of Rocks for Engineering-Geological Purposes

Introduction

Engineering-geological classifications of rocks are designed to be used in engineering-geological mapping, in the logging of rock cores, for the recording of conditions in engineering excavations, and for the description of natural engineering materials. A particular aim in all of these fields is the recognition and delimitation of units on the map or in the bore core that for all practical purposes may be considered to be homogeneous in their engineering-geological properties.

An Historical Review of Rock Characterization in British Practice

The pioneer approach. — Geological conditions in the cut-off trenches and foundations of dams have been recorded for many years in the United Kingdom (Sandeman, 1901; Lapworth, 1911) and the same attention has been given, for example, to tunnels (Peach, 1929). It is interesting to recall these early applications of geology to engineering, and to see how the problems of describing rock conditions were tackled. One example will suffice; under construction in 1942, the geology of the Fernworthy dam site (fig. 14) was not described until some years later (Kennard and Lee, 1947). Under the southern part of the dam, the granite is described as hard, fine-grained pinkish-grey granite with tight beds (horizontal joints) and joints. The deepest part of the excavation marks the position of a 10 ft

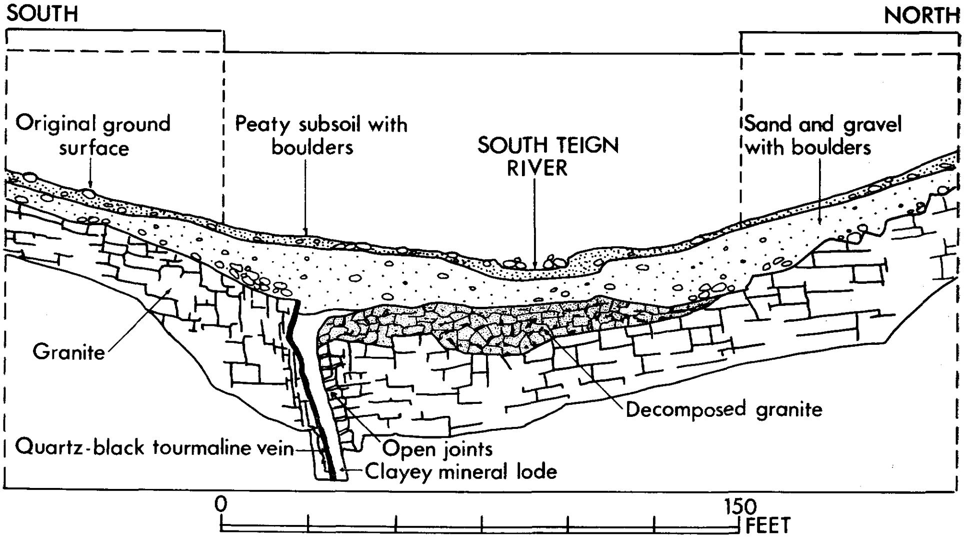


FIG. 14. — *Geological conditions at the Fernworthy dam site, Devon, England (Kennard and Lee, 1947, plate II).*

wide vertical mineral vein faced on the north side by very hard, unbroken, quartz-black tourmaline vein. The vein itself is soft clayey material, containing micaceous iron and copper deposits, varying from dark red and flesh tints to brown, orange and yellow. Granite on the north side of the vein is broken, partly decomposed and open-jointed. At the north end of the excavation granite with large feldspars, with fractured and disturbed horizontal joints and vertical joints open and in many cases filled with clay, is crossed by a vertical seam trending just off the centre-line of the dam. Comprising various layers varying in colour from reddish-brown to putty, the vertical seam could be removed with a pick, but was dense and water-tight. After exposure the surface of the granite in the seam disintegrated and became loose and gritty.

On the construction record (fig. 14) the limits of homogeneous units are given, and in the description of the engineering works Kennard and Lee clearly relate the ground conditions in the excavation to the geological conditions, and recount the engineering solution to the difficulties encountered, for example, with the clayey mineral lode.

Note how close the descriptions of the various types of granite are to the modern concept of rock description (p. 14); hardness, grain size, colour, discontinuities with degree of opening and nature of infilling material, degree of decomposition, and weatherability are all mentioned in one or other of the descriptions. All that is lacking is the orderly approach to the description of every rock type using semiquantitative or quantitative descriptive terms.

British Standard Code of Practice CP 2001, Site Investigations. — Published in 1957 as a revision of Civil Engineering Code of Practice No. 1 (1950), the code marks, to a great extent, the significant change from geology for engineering to engineering geology in the modern sense. It deals with the classification of rocks "met in site exploration... to provide an accepted, concise, and reasonably systematic method of designating the various types of materials encountered in order to enable useful conclusions to be drawn from a knowledge of the type of material. Without the use of such a classification, published information or recommendations on design and construction based on the type of material are likely to be misleading, and it is difficult to apply experience gained to the design of the other works. For practical purposes, ... the term "rock" refers to the hard, rigid and strongly cemented deposits." (*ibid.*, p. 14-15).

"The geological classification of rocks is very complex and is unnecessarily detailed for many engineering applications. For some purposes it is sufficient to know whether or not explosives will be needed for excavation. In site exploration, however, it is desirable to obtain a more detailed description of the rocks and to employ a simple classification having a sound geological basis" (*ibid.*, p. 16). A simple classification was given, reproduced here as Table 11, with broad groups which should be recognizable by visual inspection of hand specimens. Appendices to the code provide definitions of large numbers of rock types as a means of identification, and indicate broadly the inferences to be drawn. In a very significant paragraph reference is made to the fact that the rock types in Table 11 "may exist either in a sound condition, or may be fissured or jointed in such a way as to influence their engineering behaviour. Thinly-bedded limestones and chalk may be excavated without the use of explosives, but for most other rock types, except under certain states of weathering and decomposition, blasting is necessary" (*ibid.*, p. 16).

TABLE 11. — *Classification of rocks* (ANON., 1957)

Group	Rock type
Sedimentary	Sandstones (including conglomerates): Siliceous, Calcareous, Ferruginous, Argillaceous Some hard shales and tuffs Limestone: Massively bedded (including chalk), Thinly bedded
Metamorphic	Some hard shales Slates Schists Gneisses
Igneous	Granite Dolerite Basalt

By that time quantification of rock properties had lagged behind that of soils for which there were tests to permit the type of soil to be more accurately defined, as well as tests to determine the essential characteristics governing design, account only being taken of the unconfined compressive strength. But there was just a hint of future developments in the suggestion that it might be necessary to carry out tests with bedding planes at different angles to the loading axis; and that for soft rocks high pressure triaxial tests might be useful in the estimation of bearing capacity. The need to quantify rock properties for design purposes led to the development of rock mechanics.

The Engineering-Geological Characterization of Rock

Direct quantitative determinations of rock mass properties *in situ* for example deformation modulus, can only be made by expensive field loading and shearing tests. Valuable qualitative assessments can be made, however, in surface or underground excavations using the techniques of engineering geological description to characterize and grade the rock material. If the two techniques are combined, then relatively inexpensive semi-quantitative estimates of rock mass properties can be extended to larger areas or volumes of *in situ* rock.

The engineering geological approach, which has very high powers of discrimination, is based on detailed description of both the rock material and the rock mass. Recommended techniques for the description of rock cores are given in a report on the logging of rock cores for engineering purposes by a working party of the Engineering Group of the Geological Society of London (Anon., 1970). A slightly modified system has been recommended for rock description in engineering geological mapping (Anon., 1972). In emphasizing the present condition of the rock mass, both reports highlight the importance of understanding the geological history of the rock mass as a prerequisite of engineering-geological classification and characterization of rock. Classification must acknowledge the significance of geological processes and therefore must have a strong genetic basis.

The Genetic Basis of Rock Classification

Geological processes influencing the condition of rock masses fall into two contrasted groups. The first group is essentially of internal origin and includes the processes of igneous and metamorphic activity and earth movements Processes of external origin, forming the second group, act at or near the surface, and surficial materials are deposited as sediments. Sediments may be precipitated as crystalline rocks, but most sediments are subsequently lithified by diagenetic processes which link the two fields of external and internal processes.

Rocks acquire the characteristics of mineralogy and texture, bases of petrographical nomenclature and classification, mainly as a result of internal genetic processes. On the other hand, they are modified mainly by external processes to acquire those additional features which are highly significant in engineering geological description and classification.

The cyclic nature of geological processes, in which equilibrium is never achieved for long, emphasizes the importance of change. Therefore, in engineering-geological characterization of rock it is necessary to take into account not only the present state of the rock mass, but also the possibility of changes in the rock mass being brought about by engineering activities. A rock newly exposed may, for example, weather, slake, swell, and these characteristics should, if possible, be taken into account.

The Practical Bases of Rock Characterization

The classifications of rocks used by geologists, even in the simplified versions given earlier (p. 4), are too elaborate for engineering purposes, and rock properties in engineering terms are generally not included in, and frequently cannot be inferred from, the usual geological description. It has been recommended that for mapping practice (Anon., 1972), and the method is of general engineering-geological application, that a simple geological rock name should be elaborated by adding qualifying terms.

Classification of rock for the present purpose has thus to be approached first from the point of view of a simplified geological classification of rock as a material. This would take care of the geological context of the rock by placing it in one of the main genetic categories, namely igneous, sedimentary or metamorphic. Secondly, terms must be selected to describe significant attributes of both the rock material and the rock mass, and also to indicate the main engineering properties.

A Geological Rock Classification for Engineering Purposes

Only in a thin section can an igneous, sedimentary or metamorphic rock be fully described, interpreted and accurately classified. But a good approximation can be made using a binocular microscope or a hand lens to examine a weathered or fractured surface of the rock; a few simple tests may significantly aid identification.

It is not possible to avoid the use entirely of technical mineralogical and geological terms, but although these are kept to a minimum, they do provide a most convenient descriptive shorthand.

The attributes on which the primary divisions into the main genetic classes may be made are:

(a) Igneous. Such rocks are massive, with a homogeneous structure over wide areas, and display a lack of layering, foliation, cleavage or similar features.

(b) Sedimentary. These are bedded rocks.

(c) Metamorphic. Rocks with a foliated or schistose texture; obviously altered igneous, sedimentary and foliated rocks may occur at the margins of igneous rocks.

This is perhaps the most difficult step in classification which is made easier if the general associations and interrelationships of the rock groups are understood. Once this subdivision has been made, however, further subdivision within each main category is based primarily on the well defined attributes of grain-size and mineralogy. Appeal to other textural features (p. 6) may be needed as indicated in the diagnostic tables.

Grain size. — It is recommended that the grain size classification used for soils should be adopted for all rock groups. The terms recommended are:

For practical purposes the lower limit of unaided vision is 0.06 mm; grains

Equivalent soil grade	Term	Size of component particles
Boulders and cobbles	Very coarse-grained	> 60 mm
Gravel	Coarse-grained	2-60 mm
Sand	Medium-grained	0.06-2 mm
Silt	Fine-grained	0.002-0.06 mm
Clay	Very fine-grained	< 0.002 mm

larger than 0.01 mm are visible using a × 10 hand lens. Some igneous rocks may be partly or entirely glassy.

Mineralogy. — In those rocks which are medium or coarse-grained, diagnosis largely depends upon:

(i) ability to recognize quartz;

(ii) discrimination of hard and soft light-coloured minerals;

(iii) for the soft, light-coloured minerals, determination of carbonate.

For all rock types, determination of colour index, the relative proportions of light and dark coloured minerals may be a useful diagnostic feature.

Recommended Classification and Aid to Identification

A geological rock classification for engineering purposes is set out in Table 12. The table may also be used as an aid to identification.

Rock Description for Engineering Geological Purposes

The following scheme of description is slightly modified from that given in the Working Party Report on Engineering Geological Mapping (Anon., 1972). It is recommended that *prefixes* to a particular rock name should be used for selected descriptive terms of the rock in hand specimen as a material and in the mass, and *suffixes* should be used to indicate the main engineering properties, as follows:

Prefixes

(i) Colour

(ii) Grain size

(iii) Texture and structure

(iv) Discontinuities within the mass

(v) Weathered state

- (a) Physical disintegration
- (b) Chemical decomposition
- (c) Solution

(vi) Alteration state

(vii) Minor lithological characteristics

(viii) ROCK NAME

Suffixes

(ix) Estimated mechanical strength of the rock material

(x) Estimated mass permeability

(xi) Other terms indicating special engineering characteristics.

Adequate description of a rock mass may require additional information including the dip and strike or attitude of structures and discontinuities, the character of bedding planes and other discontinuities, the variability of structures and discontinuities, the details of the weathering profile, and the variety and association of rock types. Description may often have to be supplemented by pictorial representation wherever there is variation within the rock mass in an exposure, in an excavation, or over the extent of a plan or map.

Examples of the use of the descriptive scheme for rocks are:

Dark olive brown, fine to medium-grained, massive, moderately widely jointed with majority of joints open to 10 mm, slightly weathered by chemical decomposition, contact metamorphosed, DOLERITE, strong, impermeable except along open joints.

Dark grey, fine-grained, medium to thickly bedded and thinly laminated (within beds), with moderately to widely spaced bedding discontinuities and widely spaced joints, fresh, SHALE, strong, effectively impermeable, brittle.

Light pinkish grey, coarse to very coarse-grained, massive, moderately widely spaced joints with occasional vertical joints open 5 mm, slightly to moderately weathered by chemical decomposition, porphyritic biotite GRANITE, very strong, slightly permeable.

(i) COLOUR

Rock colour is a property that is easy to appreciate but difficult to quantify. Although not always of great value as an index of mechanical properties, its significance should not be underrated. Rock colour may be expressed quantitatively in terms of three parameters, the *hue* which is a basic colour or a mixture of basic colours, the *chroma* or brilliance or intensity of colour and the *value* or the lightness of colour. A Rock Colour Chart using this system has been published by the Geological Society of America (1963) and is based on Munsell (1941). Use of this chart is strongly recommended as a standard for rock colour nomenclature.

A simple subjective scheme would involve choice of a colour from Column 3 in the table below, supplemented if necessary by a term from Column 2 and/or Column 1:

1	2	3
light	pinkish	pink
dark	reddish	red
	yellowish	yellow
	brownish	brown
	olive	olive
	greenish	green
	bluish	blue
		white
	greyish	grey
		black

TABLE 12. — *Classification and aid to identification*

GENETIC GROUP			SEDIMENTARY						
Structure			BEDDED						
Texture			Detrital grains						
Composition			Grains are of rock, quartz, feldspar and clay minerals		50 % grains are of carbonate		50 % grains are of fine-grained igneous rock		Chemical-organic rocks
GRAIN SIZE (mm)		Very coarse-grained	RUDACEOUS	Grains are of rock fragments Rounded grains: CONGLOMERATE Angular grains: BRECCIA	LIMESTONE	CALCIRUDITE	PYROCLASTIC ROCKS	Rounded grains : AGGLOMERATE Angular grains : VOLCANIC BRECCIA	SALINE ROCKS Halite Anhydrite Gypsum
	60	Coarse-grained							
	2	Medium-grained	ARENACEOUS	SANDSTONE Grains are mainly mineral fragments *Quartz sandstone:* 95 % quartz, voids empty or cemented *Arkose:* 75 % quartz, up to 25 % feldspar; voids empty or cemented *Greywacke:* 75 % quartz, 15 % fine detrital matrix ; rock and feldspar fragments		CALCARENITE		TUFF specify grainsize	CHERT
	0.06	Fine-grained	ARGILLACEOUS or LUTACEOUS	MUDSTONE SHALE is fissile mudstone SILTSTONE, 50 % fine-grained particles CLAYSTONE, 50 % very fine-grained particles		Crystalline Limestone			FLINT
	0.002	Very fine-grained				CALCILUTITE			COAL

0.06 mm is the limit of unaided vision.

Discrimination:

(i) Character of rock fragments.
(ii) Presence or absence of quartz, feldspar, carbonate, clay minerals, saline minerals.
(iii) Grain size.

Distinctive features:

(i) Crystalline texture present in crystalline limestone, saline rocks, individual grains cannot be separated.
(ii) Cryptocrystalline texture present in chert, flint; individual grains cannot be separated.
(iii) May be composed of angular to rounded rock or mineral fragments, which may be cemented together. Pore spaces may be partly or completely filled with cement or finer grained detrital material.
(iv) Weakly cemented types are friable.
(v) Argillaceous rocks yield fine rock flour when scratched with knife.
(vi) Saline rocks; light-coloured, soft, cleaved minerals.

of rocks for engineering-geological purposes

METAMORPHIC		IGNEOUS			GENETIC GROUP	
FOLIATED		MASSIVE			Structure	
Crystalline and cryptocrystalline					Texture	
Quartz, feldspars, micas acicular dark minerals		Light-coloured minerals are quartz, feldspar, mica and feldspar-like minerals			Composition	
GNEISS Alternate bands of granular and flaky minerals	HORNFELS GRANULITE Crystalline Limestone QUARTZITE	PEGMATITE Granite pegmatite etc.			Very coarse-grained	GRAIN SIZE (mm)
		GRANITE	Diorite	GABBRO	Coarse-grained	60
SCHIST		MICRO-GRANITE	Micro-diorite	MICRO-GABBRO	Medium-grained	2
		RHYOLITE	Andesite	BASALT	Fine-grained	0.06
SLATE					Very fine-grained	0.002
		Obsidian and Pitchstone		Tachylyte	GLASSY	
		0	20	40	100 Colour-index	
		Quartz 50-10 % of light-coloured minerals	Quartz 10-0 % of light-coloured minerals			

Discrimination:

(i) Grain si e.
(ii) Alternate light and dark bands in gneiss.

Distinctive features:

(i) Foliation.
(ii) Crystalline texture in hornfels, quartzite and in granular bands in gneiss.

Other features:

(i) Field occurrence of hornfels adjacent to igneous bodies.
(ii) May be bedded or have the appearance of bedded rocks.

Discrimination:

(i) Presence or absence of quartz.
(ii) Colour index (% dark coloured minerals).
(iii) Grain size.

Distinctive features:

(i) Crystalline texture.
(ii) Glass may be present.
(iii) Porphyritic crystals may be present.

Other features:

(i) Identification of porphyritic crystals in fine-grained types may be used as a guide to identification.
(ii) Light-coloured minerals are cleaved and hard, except for mica, soft, one good cleavage and quartz, hard, glassy fracture.

A colour index (Table 12) may be of use in rock identification.

(ii) Grain Size

Many common rock names have inherent grain size implications; some exceptions are to be noted in Table 12. It is felt that an indication of grain size irrespective of rock name would be particularly appropriate for field determinations and also of use in the laboratory. An observer may not be able to name a rock sample; alternatively a given name may on subsequent examination, prove to be incorrect.

The actual size of mineral grains may also be given, for example *coarse-grained, 4 mm*, if say greater precision is needed in the use of the term *porphyritic*, or as a means of distinguishing two rocks of the same type.

(iii) Texture and Structure

The texture of a rock (p. 6) refers to individual grains and the arrangement of grains, referred to as the rock fabric, which may show a preferred orientation. Structure is concerned with the larger-scale interrelationship of textural features. Common terms should be used where possible; a separate term may not be necessary if it is implicit in the rock name (viii) or is more appropriately referred to as a minor lithological characteristic (vii).

Terms frequently used include sheared, cleaved, foliated, lineated, massive, flow-banded, veined, porphyritic, homogeneous. Sedimentary rocks occur in beds which may be regular, laminated, cross-laminated, graded or show slump-structure; bedding planes may be ripple-marked, sun-cracked or sole-marked.

Descriptive terms should be used for the spacing of planar structures including bedding and lamination in sedimentary rocks, foliation in metamorphic rocks and flow-banding in igneous rocks.

The following scale should be used:

Term	Spacing
Very thickly bedded	> 2 m
Thickly bedded	600 mm-2 m
Medium bedded	200 mm-600 mm
Thinly bedded	60 mm-200 mm
Very thinly bedded	20 mm-60 mm
Laminated (Sedimentary) Closely (Metamorphic and igneous)	6 mm-20 mm
Thinly Laminated (Sedimentary) Very closely (Metamorphic and igneous)	< 6 mm

For igneous and metamorphic rocks, structures such as foliation and flow-banding may be described by the adoption of the bedding-plane spacing scale given above, for example *medium-foliated gneiss.* It is suggested that the terms *closely* and *very closely*, for example very closely foliated, or closely flow-banded, should be applied to spacings which in sedimentary rocks would be described as laminated or thinly-laminated.

(iv) Discontinuities within the Mass

Discontinuities are open fractures, or potentially openable features in rock and include bedding, lamination, foliation, joints, fissures, faults, cleavages and irregular shattering. Discontinuities separate the solid blocks of the rock mass and have appreciably lower strength than the rock material.

Apart from bedding and similar structural features, rocks are jointed and fissured in well defined directions and tend to occur in sub-parallel groups forming joint sets. Several joint sets forming a regular pattern are referred to as a joint system. A joint system present over large areas forms a regional jointing pattern.

It is essential to record the details of all discontinuities and an indication should be given of their genetic type, orientation, continuity, spacing; whether the discontinuities are open or tight, healed, cemented or infilled, integral or incipient. The nature of surface asperities, whether the walls of the discontinuities are slickensided, plane, curved, irregular, smooth, rough (Fookes and Denness, 1969; Piteau, 1970) should be recorded. Large discontinuities should be individually described.

The following descriptive schemes are recommended:

(a) *Spacing of discontinuities*

Term	Spacing
Very widely spaced	> 2 mm
Widely spaced	600 mm-2 m
Moderately widely spaced	200 mm-600 mm
Closely spaced	860 mm-200 mm
Very closely spaced	20 mm-60 mm
Extremely closely spaced	< 20 mm

(b) *Continuity*

Continuity in both dip and strike directions may be quantified with respect to the spacing of the discontinuity set:

Term	Dip/strike length as a multiple of discontinuity spacing
Minor discontinuity	1
Major discontinuity	10
Master discontinuity	100

Where greater precision is needed the lengths of discontinuity traces may be measured.

(c) *Surface asperities*

Piteau (1970) recognizes two orders of discontinuity surface asperities. Major asperities appear as a *waviness* of the surface and are of such dimensions that they are unlikely to shear off during deformation of the rock mass. Minor asperities, *roughness*, are sufficiently small to shear through. Waviness is considered to modify the apparent angle of dip of the discontinuity but not its frictional properties; increased roughness, on the other hand, increases the frictional properties.

Five categories of roughness may be recognized.

Category	Degree of roughness	Sandpaper grade
1	Slickensided surfaces	< 00
2	Smooth	00-01
3	Slightly rough, defined ridges	01-02
4	Rough small steps	02-03
5	Very rough	03-04

The subdivisions (after Piteau, 1970) are completely arbitrary, and Fookes and Denness (1969) suggested the use of different grades of cabinet makers' *sandpaper* as a familiar standard roughness model for quantitative recording of surface roughness.

A conservative estimate of waviness-angle may be made by measuring the amplitude a and the wavelength l of the waves. The tangent of the waviness angle is $a/\frac{1}{2}l$. The direction of the normal to the wave crests should be recorded.

The spacing divisions are those adopted for bedding planes spacing and the descriptive terms may be used in the following way: *with very widely spaced joints.* Three-dimensional shapes of discontinuity bounded masses may be described using such terms as blocky, tabular, columnar, (Pettijohn, 1957, fig. 25; Burton, 1965) which should be defined.

Openness of discontinuities may be quantified if necessary, as may the properties of the material infilling open discontinuities.

(v) WEATHERED STATE

The degree of weathering will generally be visible only in recently formed natural exposures or in cuts, pits, trenches, tunnels and cored boreholes (Fookes, Dearman and Franklin, 1971). It is recommended that the following descriptive terms and grades (Dearman, 1974) should be used (p. 51).

(vi) ALTERATION STATE

Common terms should be used where possible, e.g. *kaolinized, mineralized.* The same terms and grades recommended for weathering can be used, using the prefix A; thus A IV is *highly altered.*

PHYSICAL DISINTEGRATION

Term	Grade symbol	Diagnostic features
Fresh	W I	100 per cent rock; discontinuities closed
Slightly disintegrated	M II	100 per cent rock; discontinuities open and spaced at more than 60 mm
Moderately disintegrated	M III	Up to 50 per cent of the rock is disintegrated by open discontinuities, or by spheroidal scaling spaced at 60 mm or less, and/or by granular disintegration. The structure of the rock is preserved
Highly disintegrated	M IV	More than 50 per cent and less than 100 per cent of the rock is disintegrated by open discontinuities, or spheroidal scaling spaced at 60 mm or less, and/or by granular disintegration. The structure of the rock is preserved
Completely disintegrated	M V	The rock is changed to a soil by granular disintegration and/or grain fracture. The structure of the rock is (mainly) preserved
Residual soil	M VI	The rock is changed to a soil by granular disintegration and/or grain fracture. The structure of the rock is destroyed and the soil is a residuum of minerals unaltered from the original rock
Discontinuity spacing should be recorded in semiquantitative terms		

CHEMICAL DECOMPOSITION

Term	Grade symbol	Diagnostic features
Fresh	W I	100 per cent rock; no discolouration, decomposition, or other change
Slightly decomposed	C II	100 per cent rock; discontinuity surfaces discoloured; the rock material may be discoloured
Moderately decomposed	C III	Soil resulting from decomposition of the rock forms up to 50 per cent of the mass
Highly decomposed	C IV	Soil resulting from decomposition of the rock forms between 50 and 100 per cent of the mass
Completely decomposed	C V	The rock is changed to a soil in which the original rock texture is (mainly) preserved
Residual soil	C VI	The rock is completely changed to a soil in which the original rock texture has been completely destroyed
Core stones and lithorelics should be referred to as boulders, cobbles, or gravel, or their size stated		

SOLUTION

Term	Grade symbol	Diagnostic features
Fresh	W I	100 per cent rock; discontinuities closed
Slightly dissolved	S II	100 per cent rock; discontinuity surfaces open. Very slight solution etching of discontinuity surfaces may be present
Moderately dissolved	S III	Up to 50 per cent of the rock has been removed by solution. A small residuum may be present in the voids. The structure of the rock is preserved
Highly dissolved	S IV	More than 50 per cent of the rock has been removed by solution. A small residuum may be present in the voids
S V and S VI cannot occur. The grades can be applied to interbedded soluble and insoluble rocks. Void size should be recorded		

(vii) Minor Lithological Characteristics

Common terms should be used where possible, e.g. clayey, marly, silty, sandy, calcareous, siliceous, ferruginous, shaly, clastic, bioclastic, metamorphosed. If there is any possibility of ambiguity the terms should be defined and where possible quantified. Mineral names may be used to qualify the rock name, e.g. biotite GRANITE.

(viii) Rock Name

Rock names should be technically correct and simple enough for general and field use; where there is a need for greater precision application of appropriate terms for minor lithological characteristics (vii) may suffice. Alternatively a petrographically correct name may be given supported by an indication of the class of the rock and its closest associate in a simple classificatory scheme.

Recommended rock names for the common sedimentary, igneous and metamorphic rocks are given in Table 12.

(ix) Estimated Mechanical Strength of the Rock Material

Field determination of uniaxial compressive strength requires the use of carefully prepared rock cores in a well equipped laboratory.

A scale of strength, based on uniaxial compressive tests, is recommended as follows:

Term	Compressive strength MN/m^2 (1 MN/m^2 = 145 lb/in^2)
Extremely strong	> 200
Very strong	100-200
Strong	50-100
Moderately strong	12.5-50
Moderately weak	5-12.5
Weak	1.25-5
Very weak	< 1.25

Any rock with a uniaxial compressive strength significantly less than 1.25 MN/m^2 should be described and tested as a soil.

Field estimations of rock strength may be made with a minimum of sample preparation on irregularly shaped specimens using the point load test. A portable testing machine has been developed by Franklin *et al.* (1970) and such tests can be supplemented by using the Schmidt concrete hammer. D'Andrea *et al.* (1965) have related point load strength to uniaxial compressive strength and the conversion to the equivalent approximate uniaxial compressive strength may be based on their work or on independent laboratory correlations. The uniaxial compressive strength is approximately sixteen times as great as the point load tensile strength, and a comparable scale of strength would be as follows:

Term	Point load strength kN/m^2 (kN/m^2 = 145 × 10^{-3} /in^2)
Extremely strong	> 12 000
Very strong	6 000-12 000
Strong	3 000-6 000
Moderately strong	750-3 000
Moderately weak	300-750
Weak	75-300
Very weak	< 75

Any rock with a point load strength significantly less than 75 kN/m^2 should be described and tested as a soil.

A more subjective series of field tests for hardness, extending estimations of consistency of soils (Anon., 1957) and providing the basis for estimation of cohesion and strength extending from very soft to very hard rock is set out in Table 13.

(x) Estimate of Mass Permeability

This is a field judgement of the likely magnitude of the permeability value k expressed in m/s units for a mapped lithological suite, lithological complex, litho-

Table 13. — *Field estimation of hardness* (modified from Piteau, 1970 and Anon., 1957)

					Compressive Strength kN/m^2	
Soil	S	1	Very soft	Cut with a knife	< 36	Exsudes between fingers when squeezed
Soil	S	2	Soft	Cut with a knife	36-72	Easily moulded with fingers
Soil	S	3	Firm	Cut with a knife	72-144	Moulded only by strong pressure of fingers
Soil	S	4	Stiff	Cut with a knife	144-288	Cannot be moulded with fingers. Requires hand picking for excavation
Soil	S	5 5	Hard (soil) Very weak (rock)	Cut with a knife	> 288 MN/m^2 < 1.25	Brittle or very tough difficult to move with hand pick requires pneumatic spade for excavation
Rock	R	1 1	Weak Moderately weak	Cut with a knife	1.25-5 5-12.5	*Very soft rock.* Material crumbles under firm blows with sharp end of geological pick. Too hard to cut by hand into a triaxial sample
Rock	R	2	Moderately strong		12.5-50	*Soft rock.* 5 mm indentations with sharp end of pick
Rock	R	3	Strong		50-100	*Hard rock.* Hand-held specimen can be broken with single blow of geological hammer
Rock	R	4	Very strong		100-200	*Very hard rock.* More than one blow required
Rock	R	5	Extremely strong		> 200	*Very very hard rock.* Many blows to break

logical type or engineering geological type. It should take into account both the intergranular and the discontinuity components of flow. Ranges of k values are more realistic than single values. Davis (in de Wiest, 1969) quotes k values for a wide range of natural materials, and the following descriptive scheme (cf. Terzaghi and Peck, 1967, table 11.1) provides generalized values for rock with discontinuities:

Rock mass description	Permeability value ([a])	
	Term	k in m/s units
Very closely to extremely closely spaced joints	Highly permeable	10^{-2}-1
Closely to moderately widely spaced joints	Moderately permeable	10^{-5}-10^{-2}
Widely to very widely spaced joints	Slightly permeable	10^{-9}-10^{-5}
Unjointed, solid	Effectively impermeable	10^{-9}

(*a*) It is recognized that this type of estimation is difficult in the field, and hence the scale has deliberately been left coarse; for detailed subdivision based on laboratory and other determinations see Janbu (1970).

It is assumed that the discontinuities allow passage of water.

(xi) Other Terms indicating Special Engineering Characteristics

Common descriptive terms should be used where possible, e.g. non-swelling, swelling, non-slaking, slakes slowly on exposure, slakes readily on exposure, crumbles in the fingers. They should be quantified where possible and defined if there is any possibility of ambiguity. For example, slaking is used here in the accepted engineering sense of physical disintegration.

Estimates may be made of deformation moduli, and if these, and strength and permeability determinations, are quantified by field and laboratory tests, the complete engineering-geological description becomes a true rock mechanics assesment of the rock mass.

Applications of the Proposed Engineering Characterization of Rock

Early versions (Anon., 1970, 1972) of the proposed method for the description of rock have been applied to core logging during site investigation and to the mapping of natural rock faces and rock excavations during construction (Anon., 1972, fig. 13.1.9). However, no complete examples have yet been published, although papers are known to be in course of preparation. What can be done at the present time is to illustrate the engineering geological approach to rock characterization by showing examples of the application of early versions of the classification scheme to civil engineering projects. Modified versions may also have been used for simplicity, or to meet the requirements of a particular site or recording for a particular purpose. These too will be illustrated.

Applications to Engineering Practice

(a) *The Latiyan and Roseires Dams*

For the Latiyan dam near Tehran, Persia, Knill and Jones (1965) were able to establish seven grades of rock condition in the Devonian sandstones and quartzitic sandstones exposed in the foundation excavations. The grading classification was based on the assessment of a variety of geological characteristics, which may be summarized as:

(i) State of weathering and loss of cohesion;
(ii) Relative compactness of the rock mass;
(iii) Intensity and orientation of the various sets of fractures, namely bedding-planes, joints and faults;
(iv) Relative cleanness of fractures and the rock mass as a whole, and
(v) Relative abundance of shale layers.

These characteristics, considered together, controlled the engineering behaviour of the rock. The established grades of rock condition were:

Grade I. Sound massive rock with no weak seams and widely spaced joints.

Grade II. Bedded, relatively solid rock, with some shale layers.

Grade III. Thinly bedded or flaggy rock, with some shale layers.

Grade IV. Blocky, seamy rock with frequent intercalations of shale and clay-silt. Some open joints are present.

Grade V. Broken faulted rock or weathered rock mixed with shales and/or clay-shales, found generally in a loose condition.

Additional grades were applied to Tertiary Green Beds, which were consistently in a poorer condition than the Devonian sandstones:

Grade VI. Thinly bedded rock with thin clay-shale seams.

Grade VII. Friable clay shales.

Distribution of rock grades and the rock structure in the left bank are shown in figure 15. Knill and Jones point out that Grade IV rock appears to represent Grade II rock in a more weathered and fractured state.

Because of the form of the excavations it was possible to predict the distribution of rock grades in depth (fig. 15).

The approach adopted by Knill and Jones has been one of broad rock-mass characterization. It is without doubt a successful attempt at establishing homogeneous, mappable units which could be correlated generally with the results of *in situ* and laboratory design tests (Lane, 1964). In other words, the engineering-geological approach to broad rock characterization is correlatable, in this case, with the rock mechanics parameters as summarized in Table 14.

TABLE 14. — *Correlation of rock grade and the results of* in situ *jacking and seismic tests, Latiyan Dam, Iran* (from KNILL and JONES, 1965)

Rock grade	E_1 kg/cm²	E_2 kg/cm²	V_f m/sec	V_f/V_l
I	60 000	150 000	3 800	0.72
II	45 000	100 000	3 400	0.69
III	15 000	40 000	2 600	0.59
IV	18 000	20 000	2 000	0.50
V	8 000	20 000	2 500	0.74

E_1 : *in situ* secant modulus of deformation. E_2 : *in situ* modulus of elasticity (third loading cycle). V_f : seismic velocity in saturated rock in the field. V_l : saturated laboratory sonic velocity. V_f/V_l : fracture index.

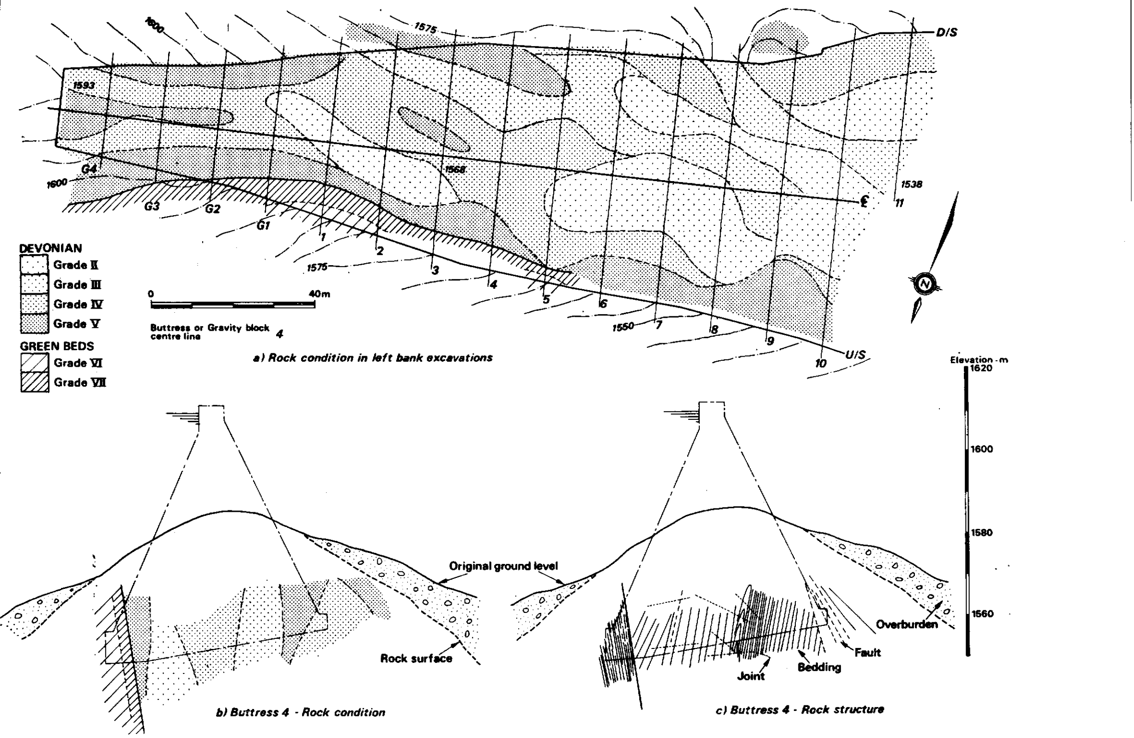


FIG. 15. — *Characterisation of* in situ *rock in the foundations of the left bank of the Latiyan dam. (a) map of rock condition; (b) section through Buttress 4 illustrating the distribution of the grades of rock condition; (c) section through Buttress 4 illustrating the rock structure (after Knill and Jones, 1965, fig. 19).*

At the Roseires dam on the Blue Nile south-south-east of Khartoum, probably the most important event from the engineering viewpoint has been the weathering of three types of near surface rock. The complex geological conditions are illustrated in figure 16, and because of this complexity a simple means was devised of describing the rock for engineering purposes.

Gneisses are the most severely weathered rocks at the dam site, and it was possible to recognize five broad classes of gneiss on this basis. Two other rock types at Roseires are the early and late granites, and all three rock types have responded differently to weathering. Variable response appears to have resulted from textural differences between the rock types. Crystals in the gneisses have smooth grain-boundaries with no interlocking: a weak fabric which has permitted ready disintegration of the rock. On the other hand, the highly sutured grain-boundaries of the late granites provided a strong resistant fabric; the early granites have an intermediate fabric and consequently they show some disintegration.

The classification of weathered gneiss was extended to cover the other rock types and four separate grades of rock condition, grouping together rocks of different type but with similar engineering properties, were established:

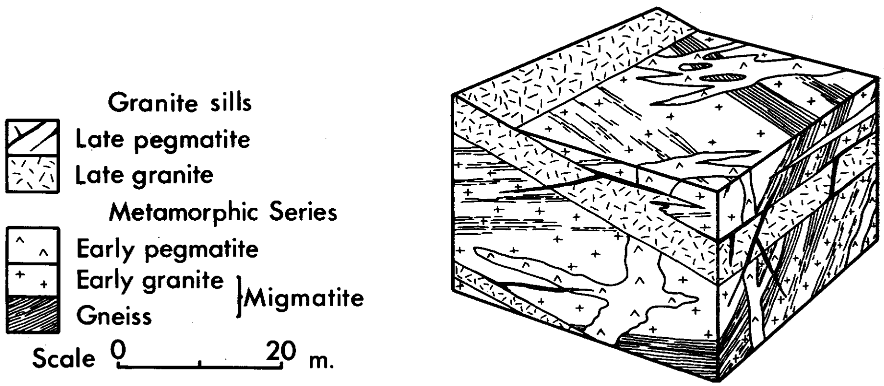


FIG. 16. — *Block diagram illustrating the geological relations in the bedrock at Roseires (Knill and Jones, 1965, fig. 10).*

Grade	Description	Recovery %	Engineering properties
I	Fresh	> 90	Satisfactory foundation material. Requires less explosive for excavation than Grades II and III
II	Slightly weathered	70-100	Permeability < 1 Lugeon
III	Moderately or highly weathered	15-70	Not suitable for concrete dam foundation. Requires blasting; slopes stable up to 10 m. Permeability 2 Lugeons
IV	Completely weathered	< 15	Not suitable for concrete dam foundation. Disintegrates in contact with water; cut slopes disintegrate to 25-40° angles. Readily excavated mechanically; can be dug by hand. Very permeable

(b) *The Site for a Large Proton Accelerator at Mundford, Norfolk, England*

The deformation properties of a large site on Middle Chalk had to be assessed to find out whether it would meet the very exacting settlement requirements for the construction of the proposed CERN 300 GeV proton synchrotron (Ward *et al.*, 1968; Ward and Burland, 1968; Burland and Lord, 1969).

The site is about 9 × 5 km, underlain by very poorly exposed, gently dipping chalk. After four 75 mm diameter boreholes had been sunk, it became evident that the cores would not give either the required detailed information on the structure and stratigraphy of the Thetford chalk, or reliable measurements of compressive strength and Young's modulus. Accordingly, the traditional method of site investigation based on testing cores was dropped. Instead over 80 holes 0.76 m diameter were drilled by mobile auger. These permitted detailed visual

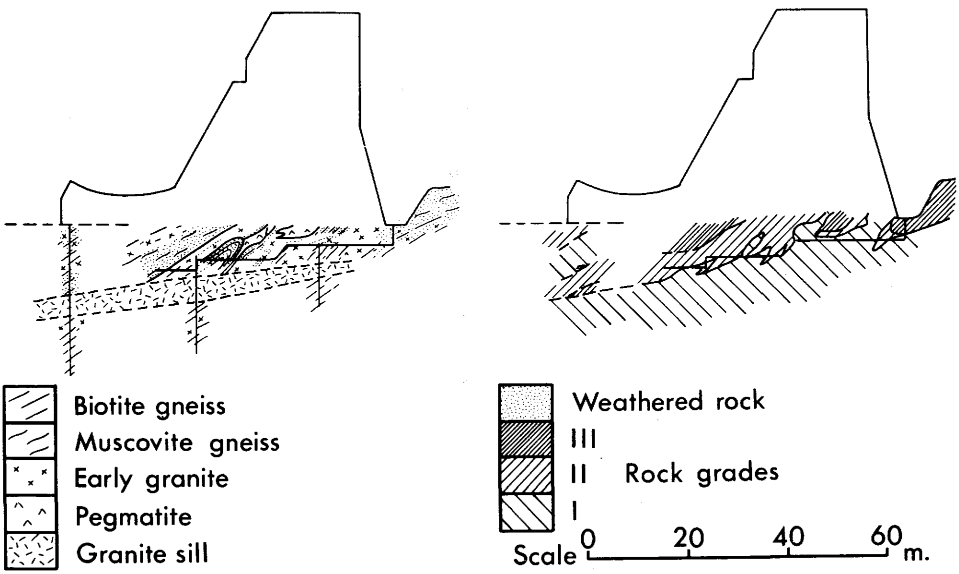


FIG. 17. — *Geology and variation in rock condition below Buttress 27, Roseires dam (Knill and Jones, 1965, fig. 14).*

inspection to be made down to the water table. Particular attention was given to those features of the rock structure which seemed likely to influence the stiffness of the ground, and in this way it was thought that some visual engineering classification of the chalk could be established. *In situ* chalk was classified into five "grades" which were likely to be related broadly to its deformation properties in the mass. The grades were:

Grade V. Structureless, deeply weathered CHALK, remoulded, containing angular blocks of fresh and partially-weathered CHALK.

Grade IV. Friable to rubbly bedded, closely jointed (10-60 mm), with joints open up to 20 mm and infilled with weathered debris and small unweathered chalk fragments, fresh or partially-weathered CHALK.

Grade III. Rubbly to blocky, jointed (60-200 mm), with joints open 3 mm with staining and fragmentary infilling, fresh CHALK, medium to hard.

Grade II. Widely jointed (>200 mm), with closed joints, fresh CHALK, medium hard, fractures irregularly when dug.

Grade I. Widely jointed (>200 mm), with closed joints, fresh CHALK, hard, brittle.

The original descriptions have been recast as far as possible into the proposed descriptive system. Grades IV and V are largely the result of weathering and periglacial activity (Higginbottom and Fookes, 1970) and are independent of lithology (fig. 18). Grades I and II are completely unweathered, the differences between them being a reflection of lithological differences in the chalk. Grade III usually occurs above I and II, but was occasionally noted adjacent to joints in otherwise intact chalk.

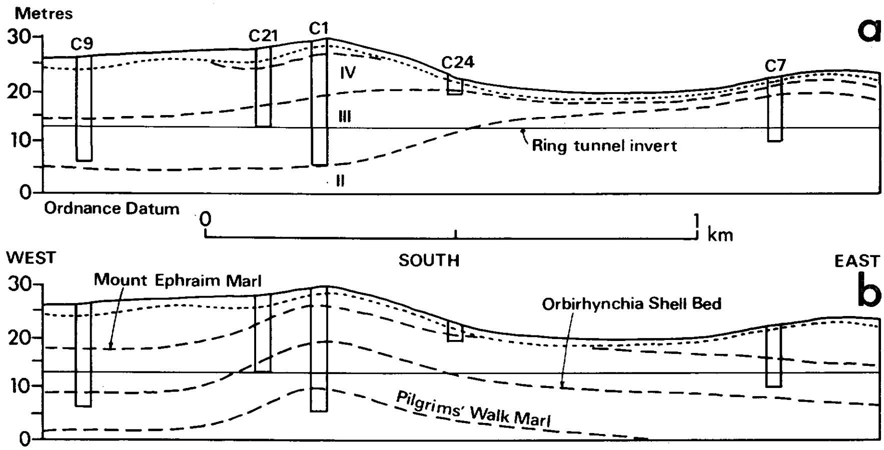


FIG. 18. — *Sections showing the relationship between (a) the engineering-geological grade and (b) the geology of the chalk at Mundford (after Ward* et al., *1968, fig. 5).*

The descriptive grades were then quantified at one location in terms of load/deformation characteristics, by a full-scale field loading test using a tank of water 18.3 m diameter. At two other points on the site, sets of 0.86 m diameter plate loading tests were carried out at various depths at the bottoms of auger holes. This combination of methods enabled the deformation characteristics of the whole site to be built up from the visual grading of the chalk in the remaining boreholes.

Wakeling (1970) showed that at the same site the visual grades could be correlated with Standard Penetration Tests results, and gave reasonably good agreement at other chalk sites. He gave a description of the lowest quality Grade IV chalk recognized from the S.P.T. test.

(c) *Batang Padang Hydro-Electric Scheme, Malaysia*

The geological process that exercised the greatest influence at Batang Padang is that of chemical weathering. This extends from the surface commonly to a depth of 100 ft. The maximum depth of weathering is 1 000 ft. Thus the delimitation of the weathered mantle and the definition of the engineering properties of weathered granite was the most important aspect of the geological investigation.

Newbery (1970, table 1), adapting the chemical weathering classification used on the Snowy Mountain Scheme (Moye, 1955), established six grades of chemical weathering and summarized their field description, identification and engineering properties. At this site the use of grade numbers proved most successful in the characterization of weathered granite, assuring consistent assessment of differing degrees of weathering in cores, outcrops and excavations by both engineers and geologists alike.

(d) *The Calton Hill Project, Edinburgh*

Cottiss *et al.* (1971) applied their system of rock classification to a number of road schemes, of which perhaps the most interesting was the Edinburgh project.

A major link road was to be constructed mainly in cutting with twin tunnels through Calton Hill. Bedrock in the area is quite variable; at Calton Hill basalts and welded basaltic tuffs crop out and other parts of the area are underlain by a variety of sandstones and siltstones. Most of the site is overlain by glacial and fluvioglacial material, fill, and recent river, lake and beach deposits up to 50 ft thick. Investigation of rock condition therefore depended on core samples from some 400 boreholes ranging in depth from 20 to 150 feet.

The variety of geotechnical problems and rock types suggested that rather than sophisticated testing at one or two sites a broader coverage should be attempted by using mapping combined with classification testing. Three aspects of the mechanical character of the rock were measured: brokenness, hardness and durability. Tests carried out included slaking; porosity, density and specific gravity determination; sound velocity; Schmidt rebound hardness; Brazilian strength; and uniaxial compressive strength. A simple petrographic examination was made to determine grain size, fabric and mineralogy. In order to simplify the data for engineering application a *rocky quality* score was computed by combining the assessed results of the tests by means of a standard formula.

On the basis of test results the whole site was divided into five zones corresponding to percentage composition of five main rock types, each rock type being characterized by the classification tests. Conditions in Zone 2 along the line of the Calton Hill tunnels are shown in fig. 19. The mechanical character of the rocks was determined as:

		Basalt	Welded tuff
Zone 2	Brokenness	Occasional	Infrequent
	Hardness	Very hard	Weak
	Durability	Durable	Durable
	Composition		
	Length cored (m)	275 (88 %)	37 (12 %)
	Samples tested	65 (96 %)	3 (4 %)

Sections along the line of the tunnels show the distribution of joint frequency (fig. 19*a*), and the rock quality scores (fig. 19*b*), as determined from the borehole records and tests on core. The sections and the plan (Cottiss *et al.*, 1971, fig. 4) provide an example of the use of a multivariate approach to rock characterization in geotechnical mapping carried out at the site investigation stage of an engineering project (Dearman and Fookes, 1974).

(e) *Site Investigation for a Highway in Fiji*

A zone notation was developed for the classification of deep residual soils developed by chemical and physical weathering of bedrock under wet tropical conditions (Lovegrove and Fookes, 1972). On material obtained by hand augering, six distinct zones were distinguished on the basis of texture, colour and consistency.

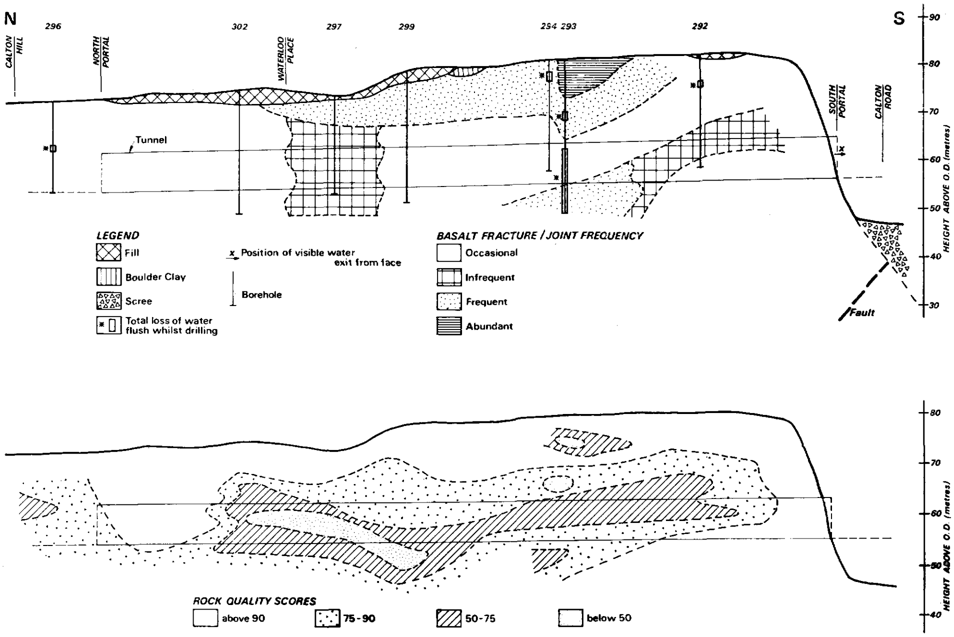


FIG. 19. — *Sections along the tunnel centre-line, Calton Hill, Edinburgh project. Above, (a) superficial soils and rock fracture frequency, and below, (b) distribution of rock quality scores.*

Weathered material was also observed *in situ* in trial pits and logged for colour, texture, weathering zone, discontinuities and during the initial stages the undrained shear strength was estimated using a hand shear vane and pocket penetrometer. Much later, in the design stage it was realised that determination of the undrained shear strength from simple *in situ* tests might have greatly assisted as an index test in the definition of the different zones of residual soil in the earthworks specification for the construction contract.

The zonal scheme was a modification of the Fookes and Horswill (1969) weathering classification adopted by the Working Party on engineering geological mapping (Anon., 1972).

The site investigation was to a large extend designed on the assumption that the physical and geotechnical properties of similar zones derived from the same parent bedrock were alike throughout the region in which the bedrock type was present.

(f) *The Clevedon Rock Cut, M 5 Motorway*

The route of the M 5 Motorway passes to the west of the City of Bristol, crosses the river Avon, and gradually ascends the 300-400 ft (109-182 m) high Carboniferous Limestone hills of the Tickenham Ridge (Eyre, 1973). Climbing the hillside the road is in cutting with a maximum face of 100 ft (30-48 m).

Structurally the situation is complex with gently dipping massive Carboniferous Limestone thrust over folded and contorted Coal Measures. At a late stage in construction, and after the disturbed Coal Measures below the thrust had been protected by a reinforced concrete wall, a systematic record was made of the completely exposed limestone face. In order to carry out an engineering geological survey, photographs (fig. 20*a*) were taken at 50 ft (15 m) centres. Ropes were hung down the face at the end of each 50 ft panel so that features of the rock face could be identified and located with reasonable accuracy on the photographs. These ropes were marked at 10 ft (3 m) intervals related to Ordnance Datum so that a grid could be drawn over the photographs to reference various features. Geological data and the location of rock bolts and various other types of treatment were then transferred to plans produced as overlays to the photographs (fig. 20*b*). Significant features were directly recorded on the overlays in the field.

Figure 21 shows a typical completed length of the mapped face with details of the geological information and stabilization works recorded. A rock quality classification of four grades was developed and applied to the mapping of the rock face. The main part of the face (figs. 21 and 22) is in unweathered Grade I limestone characteristically present in blocks greater than 500 mm diameter. Grades II and III represent the transition upwards to the surface through more and more closely jointed rock to the thin pedological soil but these grades may occur conspicuously within the main mass of Grade I material. As in fact does Grade IV which represents decalcified zones in and around solution pockets. The occurrence of each grade is related to weatherability and stability of the face, and rock treatment has been determined by rock quality. For example, rock bolting and dentistry of solution fissures is confined to Grade I limestone; masonry walling or facing to areas of Grade IV (fig. 22).

This is a good example of the application of rock characterization to engineering geology; at the present time, however, it is likely that classification would have been applied to the cores provided by the site investigation and, hence, rock characterization would have had a point to play at the design stage of the rock slopes forming the cutting wall. The present mapped record is for maintenance purposes, an equally important function of engineering geological mapping.

The classification scheme for the limestone in the Clevedon cutting was specially developed for one specific purpose but was devised on two general principles. These are the degree of physical disintegration implicit in joint spacing determinations; and degree of solution weathering with or without the formation of an insoluble residuum. Joint spacing links these two distinct aspects of weathering as estimation of the percentage of rock removed by solution can only be related to the spacing of the joint or bedding set affected by solution (Dearman, 1974, Table VI).

Applications to Engineering-Geological Research

Just one example will be given and this is related to research into the engineering properties of weathered rock (Fookes *et al.*, 1971; Dearman and Fookes, 1972). The work described was an orientation study for research now in progress.

Granite and a variety of rocks including dolerite and sedimentary rocks within and beyond the aureole of the Dartmoor granite were classified in terms of weathering grade using the established field criteria (Fookes and Horswill, 1969) subsequently adopted for mapping purposes (Anon., 1972). In addition, each rock

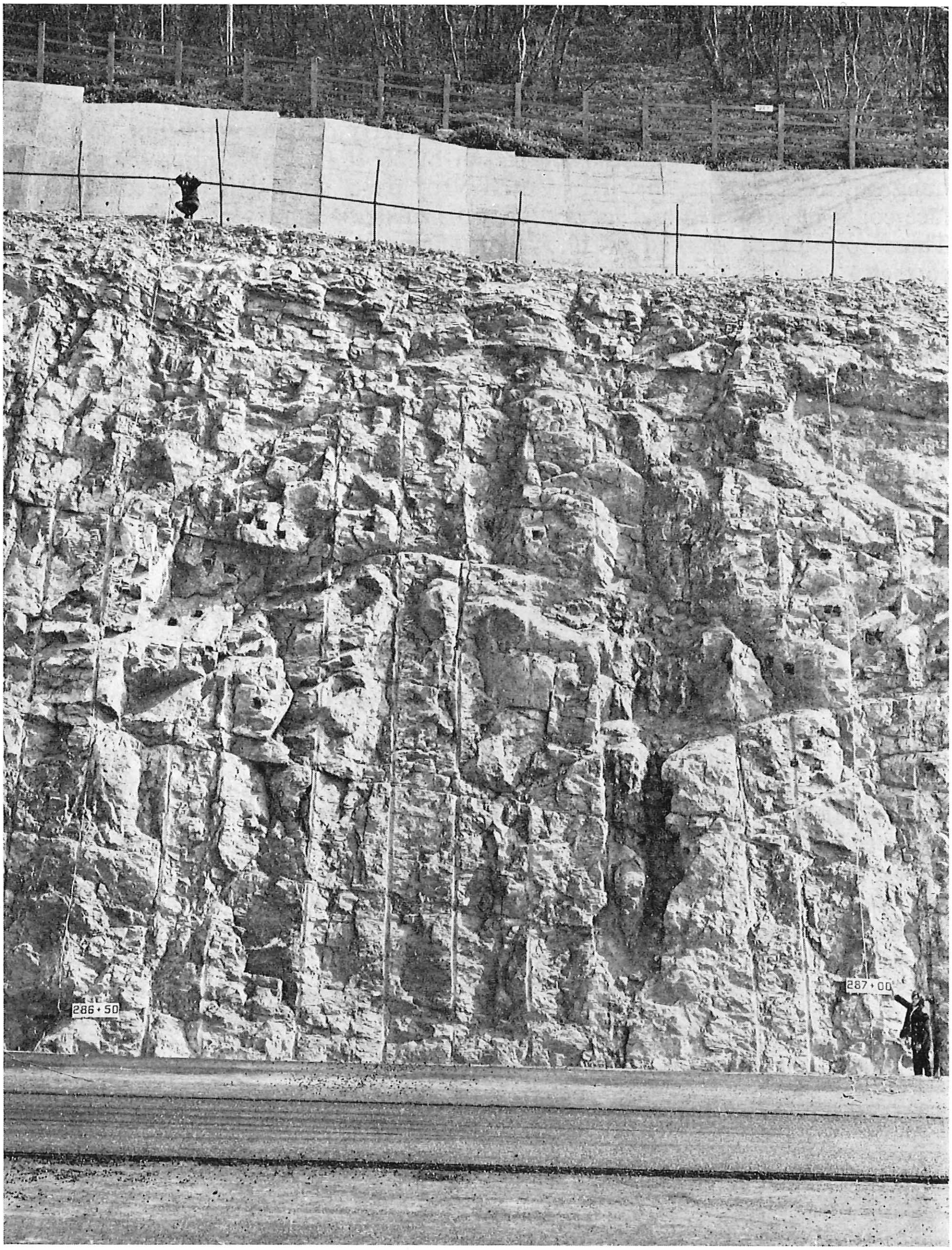


FIG. 20*a*. — *The Clevedon rock cut, M 5 motorway. Photograph of the limestone rock faces between chainage 286.50-287.00 showing bedding and jointing, discontinuity bounded blocks requiring rock-bolting, and the masonry infilling of solution cavities.*

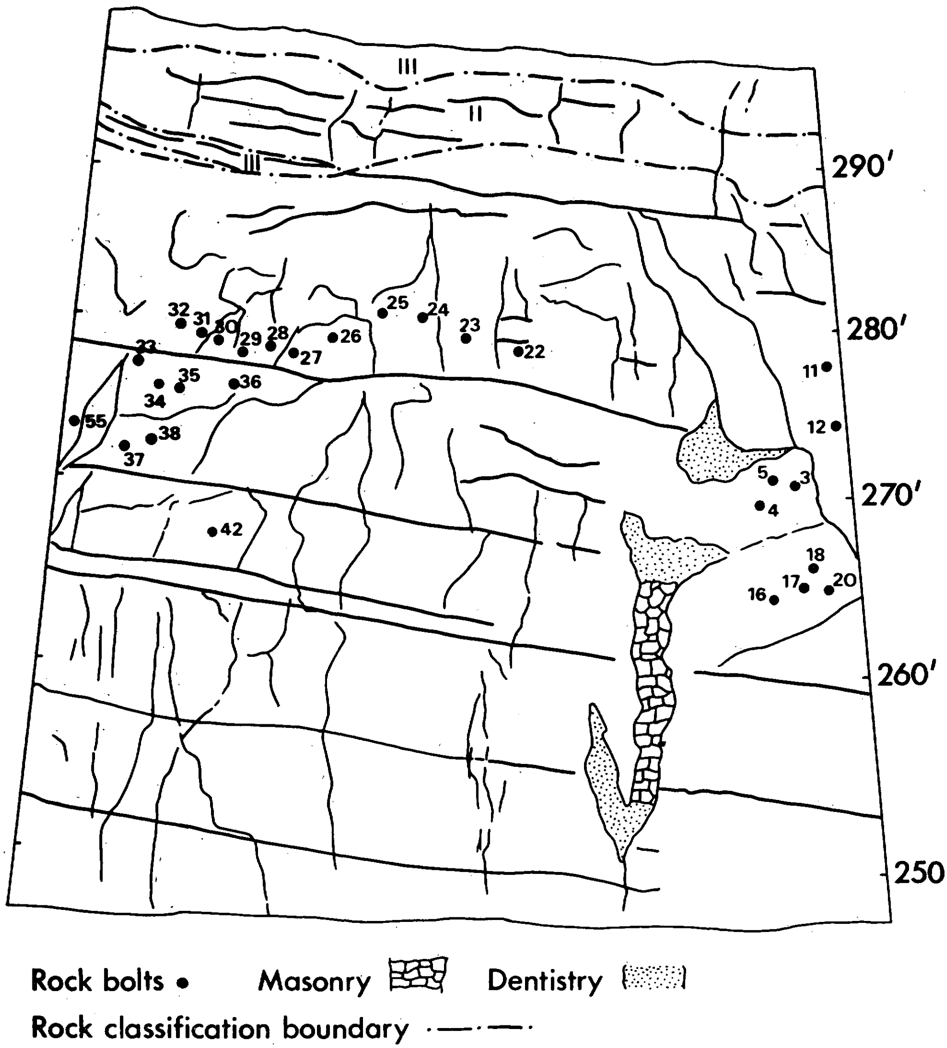


FIG. 20*b*. — *The Clevedon rock cut, M 5 motorway. Record drawing, showing rock grade distribution, of the area shown in the photograph.*

type was named petrographically and the following observations were made: colour, grain size, discontinuity spacing, alteration state, minor lithological characteristics. Field determination of point-load strength and in some cases Schmidt hammer value, and the laboratory determination of porosity completed the characterization of each rock type.

Franklin *et al.* (1971, fig. 7) had shown that rock quality could be classified in terms of fracture spacing and strength, and that the resultant diagram could be subdivided in terms of likely ease of excavation (fig. 24). The results for the Dartmoor rocks are shown in figure 23 from which it is apparent that there is a strong linear trend in the relationship between fracture spacing and strength (Cratchley, 1971).

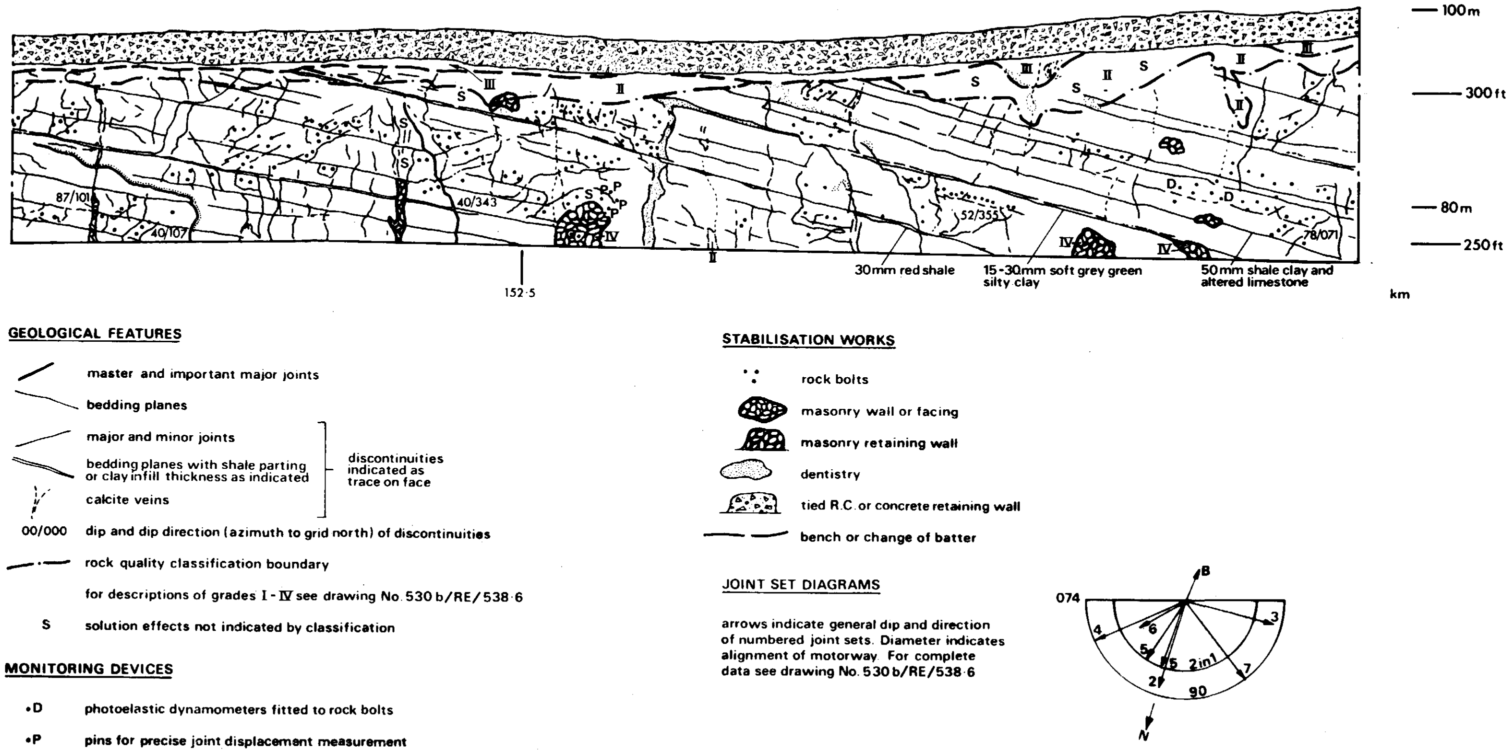


FIG. 21. — *The Clevedon rock cut, M 5 motorway. Part of the record drawing of the whole face produced for maintenance purposes.*

Chainage 286+00 – 290+00 ft	
CUT SLOPE	2 in 1
CUT ORIENTATION	approx. 75°
FACE APPEARANCE	good – average – ragged – average – ragged
MAJOR GEOL. FEATURES	grey to blue-grey fine grained crinoidal limestone (CARBONIFEROUS BLACK ROCK LIMESTONE) patchily dolomitised
MINOR GEOLOGICAL FEATURES	solution along most vertical joints as indicated. Dolomitisation associated with calcite veins and localised decalcification to yellow and brown clayey silt (grade IV)
BEDDING	regular medium becoming thick bedded upwards – 26·33/179-195 – occasional interbedded red silty clay (mylonite) or thin bedded shaley partings as indicated
JOINTS – DOMINANT	(5) 32-58/333-029 major/minor very well developed (6) 42-48/041-061 major/minor poorly developed (3) 75W-85E/261-273 (81-93) (master) major/minor very well developed
JOINTS – SUBORDINATE	(2) 68-V/349-027 master locally very well developed (7) 75N-80S/308-323 (128-143) major/minor not well developed (4) 80N-80S/039-049 (219-229) major/minor not well developed
AREAS OF WEATHERING	grade III very thin below natural ground surface but deepened in association with decalcified zones grade II generally not very deep with respect to height of face but deepened locally in association with decalcified zones and zones affected by solution
STABILITY OF ROCK STRUCTURE	potential plane failures on (5) very common and marginally possible on (6) assymetric wedge failure on (5) and (3) very common possible wedges on (6) and (3) relatively rapid ravelling in grade III and frost action in grade II likely
STABILISATION WORKS	tied R.C. wall and bench in weathered horizons very extensive bolting of potential plane and wedge failures as indicated dental work in open vertical fissures in solution cavities and along weathered shaley bedding planes
MONITORING	P (near 287+50); D (near 289+40)

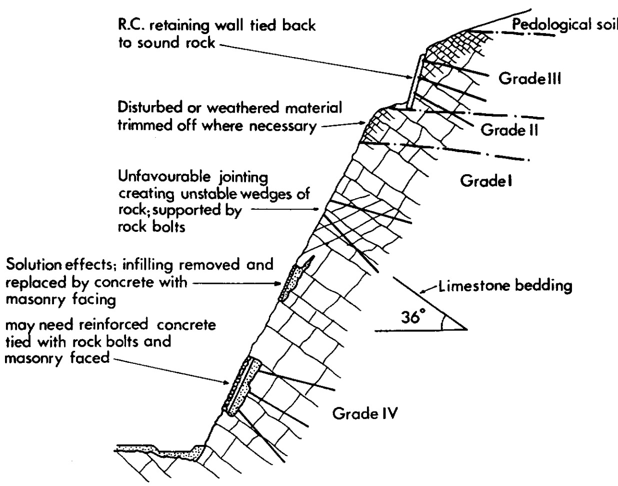


FIG. 22. — *The Clevedon rock cut, M 5 motorway. Composite cross-section showing types of treatment (revetting) on the main rock faces, related to rock grade (after Eyre, 1973, fig. 3).*

Individual quarry faces were mapped in terms of geology, weathering grade, fracture spacing, point load strength. Using the criteria in fig. 24, an engineering appraisal in terms of likely excavation conditions was given for different quarry faces illustrating the varying influence of lithology, structure and topography on the development of weathering patterns.

A modified version of one of the appraisals (Fookes *et al.*, 1971, fig. 18 and plate 5), incorporating recent modifications to the weathering classification originally used (Dearman, 1974) and adopted for the method of engineering-geological description of rock given in this paper (p. 44), is given in fig. 25.

DISCUSSION AND CONCLUSIONS

Approach in the fields of geology, rock mechanics and engineering geology to the question of rock classification and characterization differs markedly because of differing requirements in the three disciplines.

(a) *The Geological Approach*

The scientific study of rocks is related to all aspects of their genesis, to their genetic interrelationships, and to their accurate description and classification as geological materials comprising the three genetic groups, the igneous, the sedimentary and the metamorphic rocks.

Bases of classification are chemical, mineralogical and textural.

Simplified classifications are presented for each genetic group, chiefly based on mineralogical and textural features. It is noted that there is no system of grain size classification applicable to all rock groups.

Limitations of the geological classifications of rocks for engineering use are: (i) inability to predict engineering properties from unqualified geological names, and (ii) the geological name refers to fresh rock material and properties of the rock mass are largely ignored.

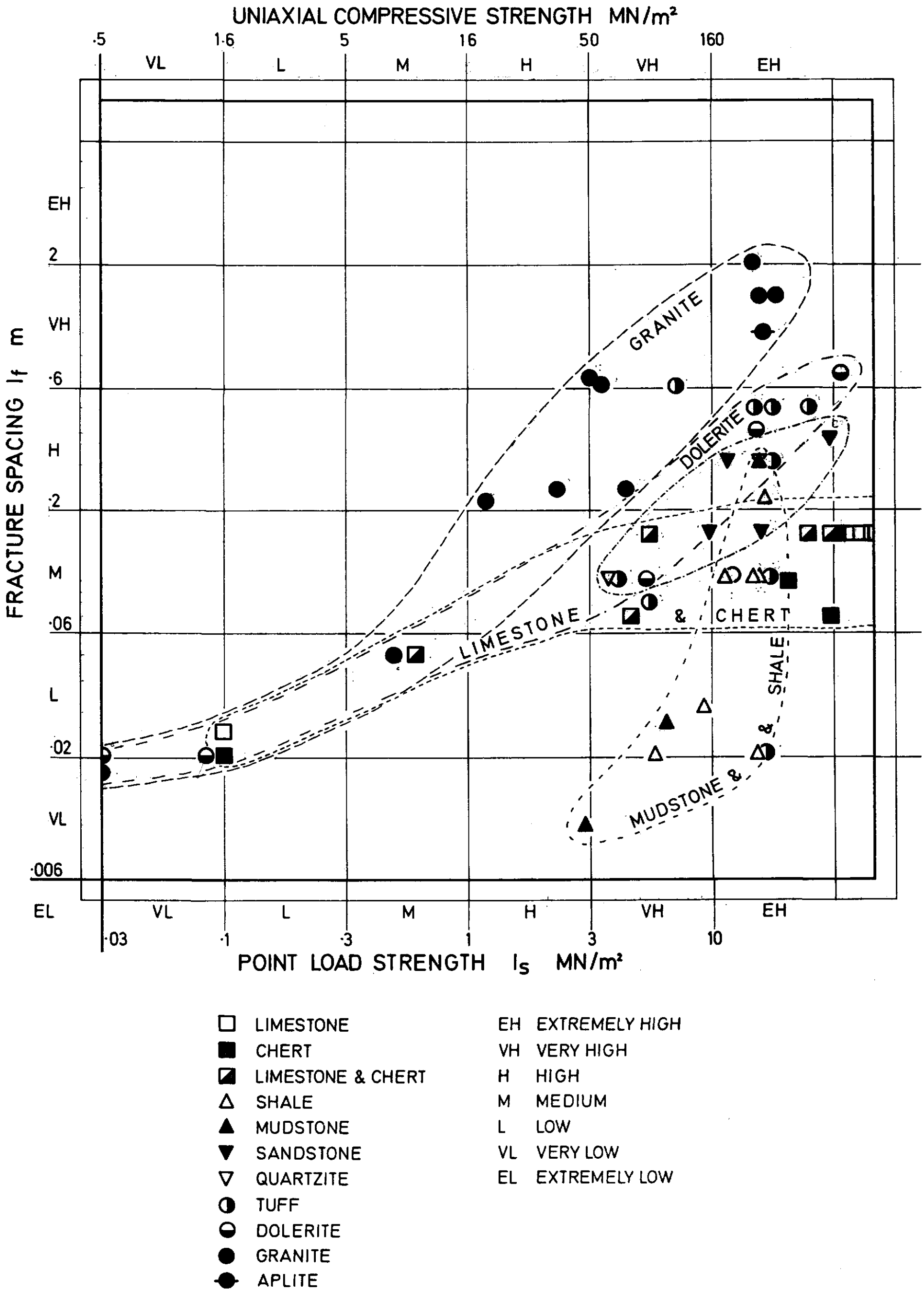


FIG. 23. — *Classification diagram for Dartmoor rocks of varying weathering grades showing the relationship between fracture spacing and point-load strength (from Fookes* et al., *1971, fig. 8).*

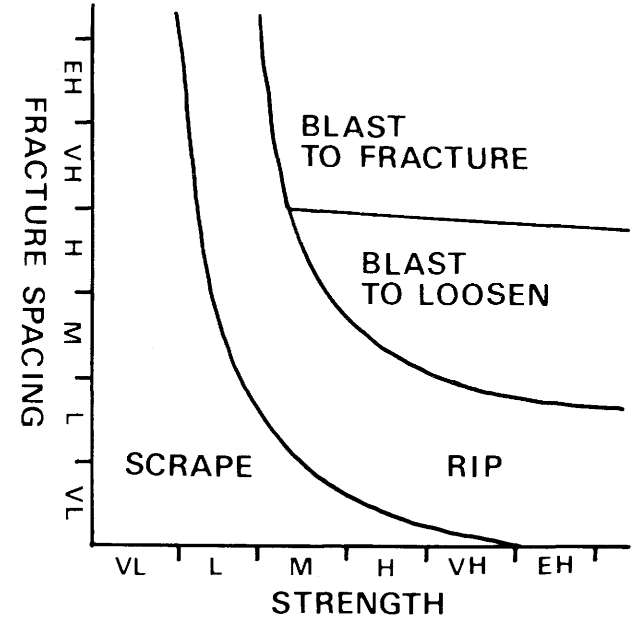


FIG. 24. — *Subdivision of the classification diagram shown in figure 23 in terms of likely ease of excavation, based on the author's practical experience of the Dartmoor rocks.*

(b) *The Rock Mechanics Approach*

The provision of design data relating both to the rock material and the *in situ* rock mass forms the basis for rock mechanics classification and characterization of rock. An early tendency to ignore geology has now largely changed and the value of a simple geological name is now accepted.

In the description of rock material emphasis is placed on texture and simple descriptive terms for colour and grain size. Mineralogy is either ignored or very simple.

Accepted means of classification and characterization are based on the experimental determination of physical and mechanical properties. There is a contrast between index properties determined by inexpensive, simple index tests applied to rock material and rock mass, and the more expensive and elaborate design tests.

The philosophy behind the index test: design test approach lies in the possibility of correlation of the results of both types of test, whereby index testing over large areas can be used to extend the application of the few results of design tests that are usually available.

Index tests applied to rock samples, giving an estimation of rock material properties, include determination of porosity, bulk density, strength and for some samples slake durability.

Of several available strength tests Schmidt hammer value on prepared samples is correlatable with uniaxial compressive strength and deformation modulus. One suggested classification is based on unconfined compressive strength, modulus of elasticity and a modulus ratio. For field use, portable apparatus has been designed for point-load strength determinations on either core lengths or irregular lumps.

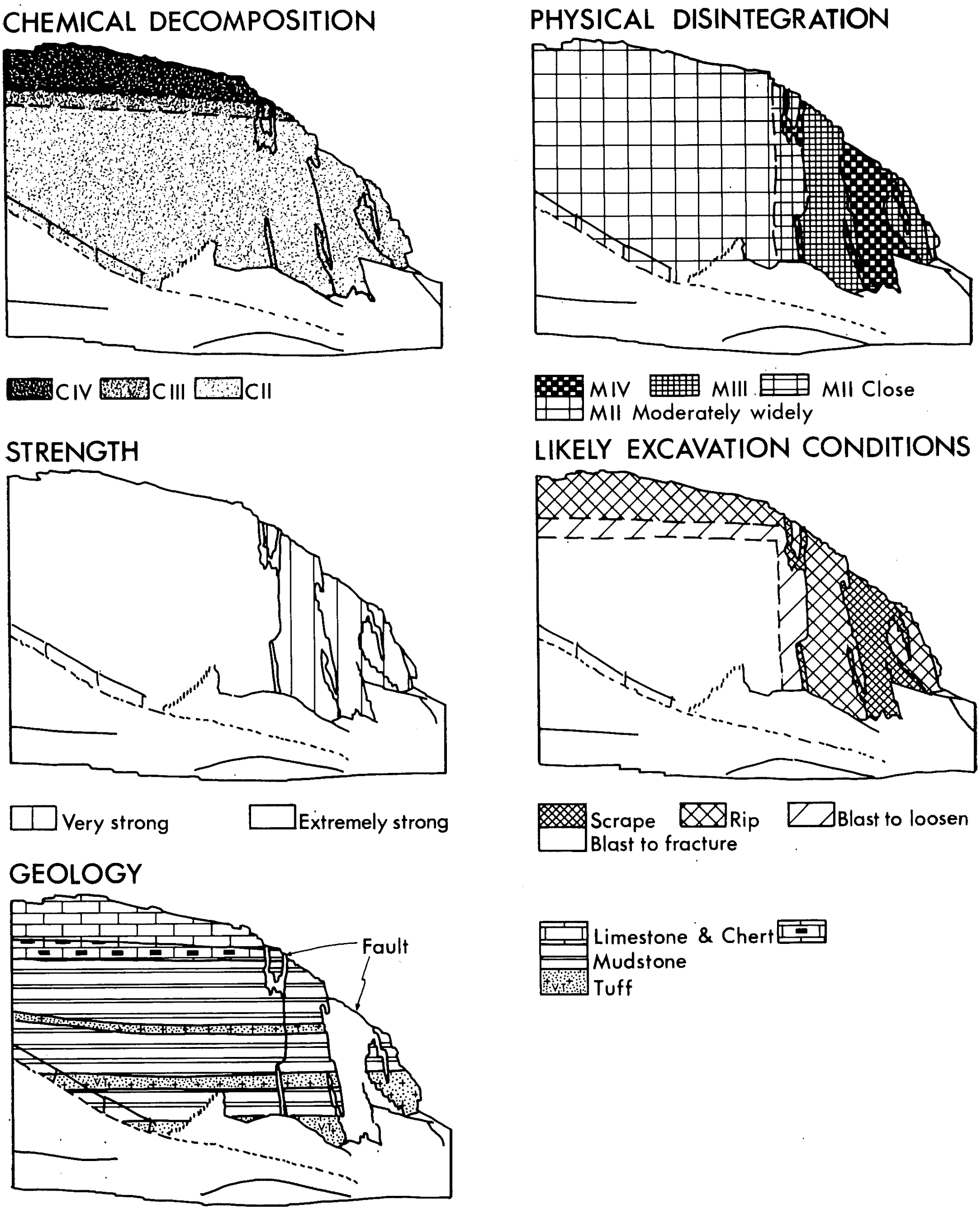


FIG. 25. — *Weathering stages and engineering geological appraisal of a quarry face (Dearman, 1974, fig. 7). Strength values based on Anon., 1972.*

Tests results are correlatable with unconfined compressive strength, and the conditions of the test and computation of results have been standardized.

Index tests applied to *in situ* rock include the determination of discontinuity spacing by direct measurement. Indirect assessment of a "fracture index," as an index property of *in situ* rock, may be made by comparing the properties of rock material and *in situ* rock by geophysical means.

(c) *The Engineering-Geological Approach*

This approach highlights the importance of understanding the geological history of the rock mass as a prerequisite of engineering-geological classification and characterization of rock.

The classifications of rocks made by geologists, even in their simplified versions presented here, are too elaborate for engineering purposes. Rock properties in engineering terms are generally not included in, and frequently cannot be inferred from, the usual geological description.

Classification of rock for the present purpose has been approached first from the point of view of a simple geological classification of rock as a material. A classification has been given, which can also be used as an aid to identification. This provides the essential rock name around which a fuller engineering-geological description can be built.

A system is given whereby significant attributes of both rock material and rock mass are used to elaborate the rock name, so as to provide an indication of the main engineering properties. It is recommended that *prefixes* to a particular rock name should be used for selected, quantifiable, descriptive terms of the rock in the hand specimen and in the mass, and *suffixes* should be used to indicate the main engineering properties.

The engineering-geological method of description adopted provides a basis for the classification of rocks designed to be used in engineering-geological mapping, in the logging of rock cores, for the recording of conditions in engineering excavations, and for the description of natural engineering materials. A particular aim in all these fields is the recognition and delimitation of units on the map or in the bore core that for all practical purposes may be considered to be homogeneous in their engineering-geological properties.

Engineering-geological homogeneity is likely to be related to homogeneity in distribution of engineering properties.

It is considered that the engineering-geological approach has higher powers of discrimination than the rock mechanics approach to rock mass characterization, and as such is to be preferred. Associated interpretation of geological conditions in engineering-geological terms is an added advantage.

Examples of the practical application of engineering-geological classification and characterization of rock for engineering purposes are given, but there are, as yet, no published accounts of the application of the preferred method except in the field of research.

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