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Rock weathering in engineering time

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Abstract

The paper attempts a comprehensive review of *in situ* weathering of rock used in civil engineering construction. It also presents some new data on weathered rock from Britain which have been used to develop a proposed tentative Rock Durability Indicator scheme. This is based on simple engineering tests to help assess the potential performance of the rock in service.

It is concluded that weathering in geological time can have significant influence, under certain circumstances, on the durability of aggregate or stone in-service. Durability is defined as the rock material's ability to resist degradation during its working life and is considered to be dependent on a number of parameters; viz. the original stage of weathering of the rock mass; the degree of imposed stressing during winning, production, placing and service; the climatic; topographical and hydrological environments in-service.

The production and construction procedures can have an important influence on the mechanical strength of the material. Physical weathering processes and imposed loading generally have the most significant effect on deterioration but chemical weathering could be of significance in-service, especially in hot, wet climates.

No one engineering test can be used as an absolute predictor of performance. Combinations of common mechanical and physical tests such as water absorption, specific gravity, point load strength, modified AIV and magnesium sulphate soundness can be used in various combinations to help assess potential durability. For a more complete evaluation, environmental factors such as the climate, topography and hydrological regimes need to be taken into account.

Introduction

Many definitions of the term 'weathering' have appeared in the abundant literature which covers this large and somewhat diverse subject (e.g. Merril 1897; Rieche 1950; Keller 1957; Loughnan 1969; Ollier 1984). Although all recognize the importance of the interaction of the hydrosphere and atmosphere on rock material, the time factor considered is usually on a geological scale. The purpose of this paper, however, is to emphasize and review those weathering and degrading forces which could act to reduce the material durability within an engineering time scale, i.e. tens of years. Within this time, the activities of man and his use or abuse of the geological materials cannot be easily isolated from naturally occurring weathering processes. For the purposes of this paper, weathering of construction materials within engineering time is defined as: 'the degradation or deterioration of naturally occurring construction materials under the direct influence of the atmosphere, hydrosphere and the activities of man, within an engineering time scale.'

Naturally occurring weathering processes

The ability of a rock material to weather or degrade is dependent primarily on a departure from the environment of its formation. It is evident that igneous and, say, high grade metamorphic rocks, by virtue of the high temperatures and/or pressures of their formation, will be most susceptible to mineral and other readjustments (i.e. weathering), at or near to the earth's surface. However, this does not exclude the sedimentary rocks from the naturally occurring weathering processes, for example the dissolution of limestones or the frost susceptibility of some sandstones. The two dominant processes of weathering include *physical weathering,* which results in the disaggregation of rocks without mineralogical change and *chemical weathering* resulting in the decomposition of the constituent minerals to stable or metastable secondary mineral products. Either of these two processes can dominate, though their occurrence in isolation is rare and most commonly one acts to enhance or accelerate the other; the dominant process being a function of both climate and local environment.

Physical weathering

Rieche (1950) defined physical weathering as 'any process which causes essentially *in situ* fragmenting or comminuting without contributory chemical change'. Physical weathering essentially breaks down rock material by application of a series of cyclical stresses, such as freeze–thaw, wetting–drying or heating–cooling, which lead to the eventual rupture of the rock material, usually along discontinuous surfaces and

TABLE 1. *Factors and processes important in weathering (based on Brunsden 1979) (* indicates those processes considered to be most applicable to an engineering timescale)*

Main controls			*Physical weathering*		*Response of material*	
Weathering environment Climate Atmospheric Hydrospheric Local factors e.g. topography drainage water table	The physical environment	→	Crystallization processes* Wetting and drying* Colloid processes (Organic processes) (Sheeting, unloading and spalling)* Insolation*	→	Disintegration Comminution Volume change Grain size change Surface area change Consolidation	
			Chemical weathering			
Lithosphere Lithology Parent rock Structure Climate Atmosphere	The chemical environment	→	Hydration Hydrolysis Solution* Oxidation* Reduction* Carbonation*	→	Unaffected minerals due to lack of time or weak agents Decomposition, recombination, and cation exchange reactions	→ Fig. 1
Hydrosphere Crystal structure			Chelation Fixation		Leaching Dissolved ions	

flaws within the material fabric. The processes of physical weathering and their relation to areas of climatic extremes have been recognized in previous work (e.g. Peltier 1950; Weinert 1964; Sanders & Fookes 1970). Table 1 presents a summary of those physical weathering processes considered to be most applicable within an engineering timescale.

Crystallization processes, such as freeze–thaw and salt weathering can be particularly deleterious to rock materials over even short periods of time. Salt weathering by hydration, crystallization and thermal expansion is essentially an arid and/or coastal phenomenon, although the application of de-icing salts to roads can in effect allow the process to occur anywhere they have been applied. The action of freezing and thawing of water within the microfabric of rocks can also be highly deleterious and may be found in any climate where the appropriate environmental and/or altitudinal conditions prevail. Sources of salts within engineering structures can be de-icing salts (usually sodium chloride), sulphates and chlorides within groundwater or salts carried by ocean spray or atmospheric dust. The effects of salt corrosion or salt fretting, particularly in low latitude areas such as the Middle East, is usually visible along the upper fringe of the capillary water transport front. Salt fretting results from a number of salt weathering processes (e.g. Winkler & Singer 1972) principally hydration pressure (e.g. Winkler & Wilhelm 1970), hygroscopic water retention (e.g. Vos & Tammes 1969) and expansion–contraction of salts due to changes in temperature and humidity (e.g. Peuhringer 1983). Crystallization processes, whether they are due to freezing of water or salt action, occurring in narrow, closed channels within the rock fabric can exert forces which may exceed, by several times, the tensile strength of the host material (typically in the range 10–20 MPa). Typical forces exerted due to crystallization pressures are given in Table 2.

Rock materials are poor conductors of heat and external surface heating by insolation can lead to the development of thermal gradients between the near surface and inner part of the material. Minerals possess different coefficients of thermal expansion and differential expansions within a polymineralic rock fabric can lead to the development of stresses along grain contacts which therefore can result in the development of microfractures and, ultimately, granular disintegration. Again the process is cyclical and occurs over short periods of time. Ravina & Zaslavsky (1974) suggest the process is greatly enhanced by the presence of condensed water at night.

TABLE 2. *Comparison of typical forces exerted by physical weathering processes with rock strength*

Physical weathering process	*Pressure applied (MPa)*
Freezing (max. at −20°C)[1]	200
Crystallization of salts[1]	2–20
Hydration of salts[1]	100
Clay expansion[2]	2

[1] After Ollier (1984).
[2] After Tucker & Poor (1978).

Fine-grained and cleaved rock materials can disintegrate readily by cracking and flaking when subjected to successive cycles of freeze–thaw or wetting and drying. Ollier (1984) suggests a mechanism of 'ordered-water' molecular pressure variations to explain this wetting and drying disintegration, whereby ordered water molecules could grow within the rock fabric and exert expansive forces on the host material. The absorption of moisture into the rock fabric, particularly within chemically weathered or hydrothermally altered rocks, has been reported as causing substantial volume changes in some materials. Cawsey & Mellon (1983) cite examples of linear expansions of 0.015–0.02% occurring in some basaltic materials when subject to wetting, and similar expansions have been reported by Nishioka & Harada (1958) for a range of rocks including sandstone, shale, limestone and granite.

Chemical weathering

Loughnan (1969) describes three simultaneous processes involved in chemical weathering as follows:

(1) The breakdown of the parent material structure with the concomitant release of the constituent elements as ions or molecules.
(2) The removal in solution of some of these released constituents.
(3) The reconstitution of the residue with components from the atmosphere to form new minerals, which are in a stable or metastable equilibrium with the environment.

These mechanisms of chemical decomposition have been summarized in Fig. 1 and the main controls on the chemical weathering process and the response of rock materials to it are shown in Table 1. Chemical weathering as a method of rock material decomposition has much greater potential where the climatic regime is hot and wet (Sanders & Fookes 1970) and is in operation over long periods of geological time.

Within an engineering timescale the most relevant chemical weathering processes are probably those of oxidation/reduction and solution. Pure limestones, limestone marbles, dolostones and crystalline marbles all dissolve in pure water without production of a residue. The solution rates of these materials depend on the temperature, the flow velocity and the pH of the solvent by which they are attacked, together with other factors such as the wind direction and surface angle to the horizon. The problem of dissolution of carbonate building stones is well documented (Winkler 1966, 1975, 1986) and its effects can be seen on many buildings and monuments constructed of carbonate and located within industrial and urban areas, where the presence of acid rain can greatly accelerate the process. The deterioration observed in St Pauls Cathedral is one of the best recorded examples and an excellent review of the weathering processes affecting dimension stone materials can be found in Winkler (1975).

Environmental factors controlling rock weathering

The natural weathering processes described are closely related to three important macro-environmental factors, the hydrosphere, the climate and the topographical situation.

The influence which the hydrosphere has on the weathering processes is evident from the vital role that water plays on the degradation processes outlined above. Using the hydrological divisions of Keller (1957), three zones of influence can be identified. These are the sub-aerial, sub-surface and sub-aqueous zones. Table 3 provides a summary of the main characteristics and processes affecting exposed rock materials within these zones.

The main climatic controls on rock weathering are related to the precipitation, evaporation and temperature variations within the local environment. The intensity, frequency and duration of precipitation events, along with season and diurnal temperature ranges are important elements in the determination of which physical and/or chemical weathering processes dominate within a given climatic regime. Peltier (1950) attempted to correlate the weathering activities favoured by some climates and inhibited in others by assessing the relationship between mean annual rainfall and temperature related to the dominant weathering type. Though the boundaries he proposed were basically hypothetical, the graphical relations can be useful, particularly for a preliminary estimate of weathering type expected when planning engineering structures in particular climatic regimes. Weinert (1964) attempted to correlate the effect that particular climatic factors have on the type of rock weathering in South Africa, by developing an index relationship between potential evaporation during the warmest month (Jan.), E_J, and the mean annual measured precipitation, P_a.

$$N = \frac{12E_J}{P_a}$$

He found that where N had a value >5, physical disintegration was the dominant process and where $N<5$, chemical decomposition was the dominant process. Table 4 summarizes some of Weinert's conclusions.

Ollier (1984) noted the important influence of topographical attitude of an area on the weathering processes. Slope angle, whether in a natural slope or engineering structure such as an embankment or cut

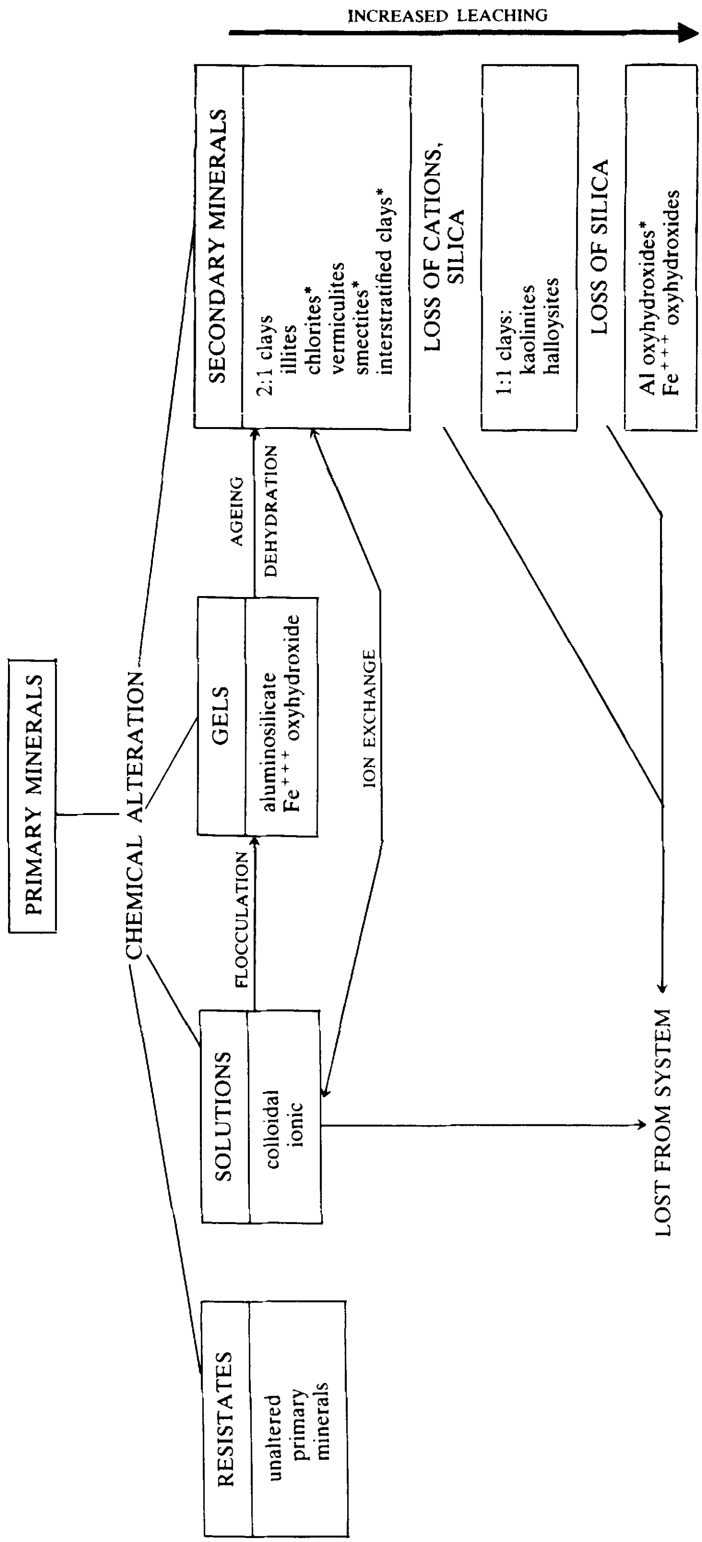

FIG. 1. Processes and products of chemical alteration (from Mellon 1985). * indicates those processes considered to be most applicable to an engineering timescale.

TABLE 3. *Some characteristics of the principal hydrological zones (after Keller 1957)*

Sub-aerial zone Surface	Evapotranspiration ↑	Rainfall pH 4–9 (Av. 5.7) Cations Na, K, Mg, Ca Anions Cl, SO_4 ↓ Wetting ↑	Pollutants CO_2, SO_2, H_2SO_4 ↓ Freeze–thaw	→ Runoff
Sub-surface zone	Percolation zone ↓	Drying Leaching ↓ Eluviation		→ Lateral through-flow
	Capillary zone ↕	Illuviation Variable oxidation–reduction		
	Fluctuating water table ↑	Migration of soluble ions away from the rock face		→
Sub-aqueous zone	Saturated zone ↓	Anaerobic conditions Possible stagnation		→ Water movement
	Water base			

TABLE 4. *Characteristics of Weinert's N values (based on Weinert 1964)*

N	*Dominant weathering processes*	*Observations*
1	Decomposition	Laterization
2	Decomposition	Kaolinite > montmorillonite
2–5	Decomposition	Clay depends on parent
>5	Disintegration	Physical breakdown dominant

slope, can have an important effect because as the angle increases weathered products can be easily removed, thus exposing new materials to the weathering environment. Relief and slope angle markedly influence of surface run-off, infiltration and through-flow which affect the materials. Orientation and shape of slopes will help determine the microclimate, rate of evaporation and soil temperature (Brunsden 1979).

Rate of rock and mineral weathering

Many attempts have been made to assess the rates at which different rock and mineral materials weather. Coleman (1981) divided these studies into two groups, 'controlled' and 'uncontrolled', depending on the method of observation and time control used in the study. Uncontrolled studies, such as the study of tombstones by Geikie (1880) and Rahn (1968), gave only a qualitative measurement of the degree and rate of weathering, as shown in Table 5, even though the time control used in this method was good, i.e. dated tombstones. Controlled study methods such as those presented in Table 6 can be divided into three groups, experimental, man-made structures and geological materials.

TABLE 5. *Classification of weathering of tombstones as used by Rahn (1968) for study of the rate of weathering of various rock types in the West Wilmington cemetery, Connecticut*

Class	*Description of tombstone weathering*
Unweathered	—
Slightly weathered	Faint rounding of corners or letters
Moderately weathered	Rough surface; letters legible
Badly weathered	Letters difficult to read
Very badly weathered	Letters almost indistinguishable
Extremely weathered	No letters remaining; scaling

TABLE 6. *Study methods and time controls in 'controlled' weathering rate studies*

Study method	*Time control*	*Example*
Experimental	Experimental time	Accelerated weathering experiments
Man-made structures	Engineering time	Tombstones, buildings, historical structures and monuments
Geological materials	Geological time	Weathering of geological deposits and materials

Most of the studies conducted in the past make use of the readily available dating on man-made structures, such as those described by Ollier (1984) and summarized in Table 7. These documented studies involve measuring the rates of surface lowering of structures affected by both physical and chemical weathering processes. Rates of weathering in these cases are assumed to be linear and are quoted as loss in millimetres per annum. Experimental studies can be used to simulate and artificially accelerate the processes of rock weathering. These studies are carried out over a wide range of conditions, as summarized in Table 8. A more detailed account of the various experimental techniques can be found in Cawsey & Mellon (1983). Most documented investigations involve feldspar weathering (e.g. Lagache 1965, 1976; Wollast 1967; Busenburg & Clemancy 1976; Holdren & Berner 1979), though more recently studies have included weathering of pyroxenes (Grandstaff 1977; Schott *et al.* 1981), olivines (Grandstaff 1978) and basalts (Mellon 1985).

Two main conclusions can be drawn from these studies depending on the mechanism of weathering proposed. Firstly, where a residual layer hypothesis is put forward, the proposed rates of weathering are suggested to decrease with time and the relationship has been described as parabolic; secondly, where a mechanism of surface reaction is suggested, linear rates of weathering are generally accepted. Coleman (1981) suggested that in addition to the lack of any real consensus for the mechanisms and rates of weathering in experimental studies, the extrapolation of laboratory results to the naturally variable weathering regime could also cause considerable difficulty. Physical and chemical weathering rates for naturally occurring, recent geological materials, such as volcanic ashes or basalts (dated using radiocarbon methods) have also been proposed (e.g. Ruxton 1968; Jackson & Keller 1970; Hay & Jones 1972). The results of these studies suggest decreasing rates of weathering with time; the generally accepted reason for this being the development of metastable protective residues such as rinds and rims as can be seen on some basalts (Coleman 1981).

Degradation processes in engineering time

The ability of a material to carry on its work within an engineering environment depends on a number of factors, collectively regarded as its durability. The durability, that is, its quality of lasting without perishing or wearing out (Minty & Monk 1966), depends on the material's resistance to natural or imposed weathering processes, or any other factor which can act to impair a long engineering life. Weinert (1968) considered the factors most important in the assessment of rock or aggregate material to be a knowledge of and the state of weathering at the time of selection; the expected engineering conditions; the mode of construction and any other potential future alteration which the material could undergo.

The reliability of engineering materials used within the construction industry are too often wrongly taken for granted as indicated by the large number of reported failures of engineering materials particularly over, say, the last 25 years or so. Table 9 summarizes some of the many reported case histories where in-service deterioration has been recorded within an engineering timescale. Two factors common to all the reported failures are immediately apparent from the table. Firstly, the aggregate or rock material used was generally of igneous (usually basic) origin, and secondly the cause of degradation was either the presence of secondary minerals due to alteration or weathering and/or the presence of active *in situ* weathering as described earlier. In addition it can be seen from the reports that in-service failures occur on a worldwide scale and are spread over various climatic regimes.

Any assessment of the potential durability of a material must take into account the selection processes, any imposed mechanical stressing and the environmental conditions to which the aggregate or rock material will be subjected in-service.

Selection processes

Numerous authors (e.g. Weinert 1964, 1968; Wylde 1976, 1977; Fookes 1980; Minty *et al.* 1980) have suggested that it is weathering in geological time which dictates the durability of crushed and uncrushed rock material in engineering time. In many parts of the world, particularly those areas which have escaped the scouring effects of glaciation, the engineering overburden usually consists at least in part of weathered rock or residual soil profiles. In the United Kingdom, some areas in south-west England and Northern Ireland provide preserved Tertiary age examples of these types of sequence, and in many quarries located in these areas the demarcation

TABLE 7. *Records of rates of surface lowering reported for various rock types (based on Ollier (1969) and Brunsden (1979))*

Rock type	*Surface studied*	*Period (years)*	*Remarks*	*Average* (mm^{a-1})	*Location*	*Reference*
	Ancient structures	4000	Fresh	0.0009	Aswan	Barton (1916)
Granite		5400	Flaking	0.0015	Giza	
	Glacial surface	10 000	—	0.00105	Narvik	Dahl (1967)
Slate	Tombstones	90	Engraving clear	—	Edinburgh	Geikie (1880)
Mica schist	Glacial surface	8	—	0.04–0.15	Karkevagge	Rapp (1960)
Marble	Tombstones	90	Crumbling	—	Edinburgh	Geikie (1880)
	Tombstones	500	—	0.051	Yorkshire	Goodchild (1890)
	Tombstones	300	—	0.085	Yorkshire	Goodchild (1890)
	Tombstones	250	—	0.102	Yorkshire	Goodchild (1890)
	Tombstones	240	—	0.106	Yorkshire	Goodchild (1890)
	Great Pyramid	1000	Hard grey	—	Giza	Emery (1960)
	Great Pyramid	1000	Soft grey	0.01–0.02	Giza	Emery (1960)
Limestone	Kammetz fortress	230	—	1.32	Ukraine	Akimtzev (1932)
	Bare surface	1000	—	0.009–0.0125	Austrain Alps	Bauer (1962)
	Covered surface	1000	Under acid soil	0.028	Austrian Alps	Bauer (1962)
	Jetty	16	Intertidal	0.5–1.0	Norfolk Island	Hodgkin (1964)
	Coastal notch		—	1.0	Point-Perm Australia	Ollier (1969)
	Inscriptions		—	0.5	La Jolla, California	Emery (1941)
	Inter-tidal notch	155	—	1.0	Puerto Rico	Kaye (1959)
Carb. limestone	Eratic block	12 000	—	0.025–0.042	N. England	Sweeting (1960)
Carb. limestone	Glacial striae	13	—	2.2–3.8	N. England	Sweeting (1960)
Carb. limestone	Runnels in glacial surface	13	—	11.5	N. England	Sweeting (1960)
Limestone	Great Pyramid	1000	Hard grey	Little	Giza	Emery (1960)
	Great Pyramid	1000	Soft grey	0.01–0.02	Giza	Emery (1960)
Kirkby Stephen limestone	Tombstones	500	—	0.051	Yorkshire	Goodchild (1890)
Tailbrig limestone	Tombstones	300	—	0.085	Yorkshire	Goodchild (1890)
Penrith limestone	Tombstones	250	—	0.102	Yorkshire	Goodchild (1890)
Askrigg limestone	Tombstones	240	—	0.106	Yorkshire	Goodchild (1890)
Algal limestone	Tombstones	<1	Microerosion meter	0.11	Aldabra	Trudgill (1976)
Limestone (poorly cemented)	Limestone pavement		—	0.003–6.3	Co. Clare	Trudgill (1976)
Limestone chert	Glacial surface	70	—	0.02–0.2	Spitzbergen	Rapp (1960)
Limey shale	Great Pyramid	1000	Rubble	0.2	Giza	Emery (1960)
Grey shale	Great Pyramid	1000	—	0.2	Giza	Emery (1960)
Sandstone	Tombstones	200	Little	—	Edinburgh	Geikie (1880)
Sandstone	Glacial surface	10 000	—	0.34–0.5	Spitzbergen	Rapp (1960)

between fresh and weathered rock is often ill-defined. The existence of weathered material in the quarry face therefore, can have a marked influence not only on the quality of rock produced and the extractive techniques employed but also on the overall cost of separating the good (sound) from the bad (unsound) rock. The failures reported in Table 9 can be taken to illustrate the consequences of lack of quality control and understanding of the earlier processes that had affected the material by the time it had reached the selection stage.

Imposed mechanical stressing

In addition to the geological processes of weathering which affect the rock mass, a series of mainly

TABLE 8. *Experimental conditions and methods of observation usually employed in accelerated weathering experiments (partly based on Coleman 1981)*

Drainage condition	*Water chemistry*	*Grain size*	*Temperature*	*Method of observation*
Percolation	Distilled	Variable	Variable	H^+ change
Immersion	Natural rainwater	(decrease in size increases rate of dissolution)	(usually low)	Measure released cations
Capillary rise	Sea-water			Mineral changes
	Stagnant CO_2-rich			

mechanical degradation processes can take place once the material is separated from the parent rock. These processes can take effect during the production, construction and in-service life of the aggregate or rock material. Figure 2 summarizes the processes involved and indicates the possible effect they may have on the physical, chemical and mechanical durability of the material produced or used in-service.

Production processes

The extraction and processing of rock can have significant effects on its physical and mechanical properties (e.g. Dibb *et al.* 1983; Hosking & Tubey 1969), particularly when reduced to aggregate. Shockwave propagation through the rock, generated by blasting, may lead to the development and/or enhancement of microfractures within the material. Though these microfractures can aid later crushing processes, within the larger aggregate size ranges and within riprap, for example, these flaws can be carried into the service life of the material. Crushing processes also have the potential to induce or enhance the development of intragranular, transgranular and grain contact flaws and weaknesses. Screening and washing processes are often set up to maximize removal of dust and soft materials from the good aggregate; these can add to degradation of the good rock by wetting and drying, abrasion and impact.

The stockpiling of aggregate materials can also add to the potential degradation of material early in its engineering life (Wylde 1976). Pressure loading of aggregate within the stockpile or exposure to subaerial weathering processes such as wetting and drying, freeze–thaw and solution, can be particularly important. Lees & Kennedy (1975) noted that some materials are particularly vulnerable to these processes due to their exposed state and increased surface area to volume ratio. For example, the deterioration of stockpiled tuffaceous aggregate recorded by Reed (1967) was found to be caused by the expansive hydration of the zeolitic minerals it contained. Weinert (1968) and Wylde (1976) suggest that the production of potentially harmful sulphuric acid may occur as a result of oxidation of sulphide minerals found in the matrix of many stockpiled igneous and sedimentary rocks.

Construction processes

The essentially mechanical degradation processes at work during construction are perhaps more aggressive than the production of subaerial weathering processes. Highway construction is a commonly cited situation, where loading, spreading and compaction subjects the aggregate materials to impact, abrasion and crushing, with the ultimate consequence being size reduction and particle stressing. Balch (1972), for example, reported the production of highly active (mobile) slurries in road pavements due to over-rolling and over-watering of chlorite and smectite rich basaltic aggregates in New Zealand.

In-service degradation

Rock and aggregate materials for use within certain engineering situations are usually selected for their inherent physio-mechanical properties which may be the most appropriate for a particular structure. These structures can be divided into two groups reflecting the degree of imposed loading to which the material will be subjected during its service life. These are: firstly the relatively static structures, where loading is constant, e.g. riprap slope protecting blocks, gabion stone, filter, drainage and most concrete aggregate materials; and secondly the relatively dynamic structures, where the materials suffer repeated and varied loading cycles, e.g. within bound and unbound

TABLE 9. *Summarized case histories reported for in-service deterioration of geological materials*

Engineering structure	*Material used*	*Material's original quality*	*Age when deteriorated*	*Location of structure*	*Cause of degradation*	*Reference*
Roads	Basalt	Altered	<5 years	NW USA	High percentage of secondary alteration minerals	Scott (1955)
Roads	Miocene basalt	Altered	3 months	Washington State	Presence of secondary minerals and production of plastic fines	Minor (1960)
Roads	Basalt			Idaho	Presence of secondary minerals and alteration products + change in particle size distribution	Day (1962)
Motorways	Indurated argillite	Partially weathered		Auckland, New Zealand	Production of moisture sensitive fines	Buckland (1967)
Runway	Basic igneous	Weathered	18 months	Mauritius	Presence of secondary minerals	
Road	Olivine basalt	Weathered		A511 Derby, UK	*In situ* weathering	Hosking & Tubey (1969)
Road	Olivine dolerite	Weathered		A30 Hampshire, UK	*In situ* weathering	
Riprap	Various	Fresh–weathered	Variable	California	Mostly physical weathering processes	Smith *et al.* (1970)
Concrete structures	Basalt	Altered		Victoria, Australia	Dimensional stability of aggregate reduced by presence of alteration products.	Cole & Lancuchi (1976)
Riprap	Granite	Chemically weathered		Waddel Bluffs, Santa Mateo	Secondary mineral expansion on exposure to moisture	Anon (1970)
Motorway hard shoulder (used as sidetrack)	Basalt	Altered	6 months	Victoria, Australia	Use of reject stockpile 30–50% containing 20% secondary minerals	Bethune (1971)
Roads	Basalt	Altered		Glenbrook, New Zealand	Action of moisture on alteration products Production of highly active plastic slurries	Balch (1972)
Roads	Dolerite	Weathered		S. Africa	Presence of secondary minerals	Weinert (1964, 1968)
Roads	Mostly basalts	Slightly to moderately weathered	Variable	Australia	Rock secondary mineralogy and texture. Geological history	Wylde (1976)
Roads	Volcanic breccia	Altered		New South Wales, Australia	Presence of expandable clays and permeability of rock fabric	Minty (1976)
Roads	Dolerite	Weathered	<1 year	SW England	Physical degradation of weakened aggregates	Cawsey & Massey (1984)
Roads	Basalt gravels	Altered	<5 years	Ethiopia	Physical degradation leading to increased cracking	Mellon (1985)

road pavement layers, rock breakwaters and railway ballast. Acting in parallel with imposed stresses are the natural forces of weathering. Table 10 summarizes the main degradation mechanisms to be expected on some dynamic and static engineering structures.

Chemical weathering of in-service materials has been dismissed by most authors as unlikely to occur within the timescale of most engineering structures. However, though as yet no conclusive published evidence for this has been found by the writers, it should not be completely dismissed as a possible

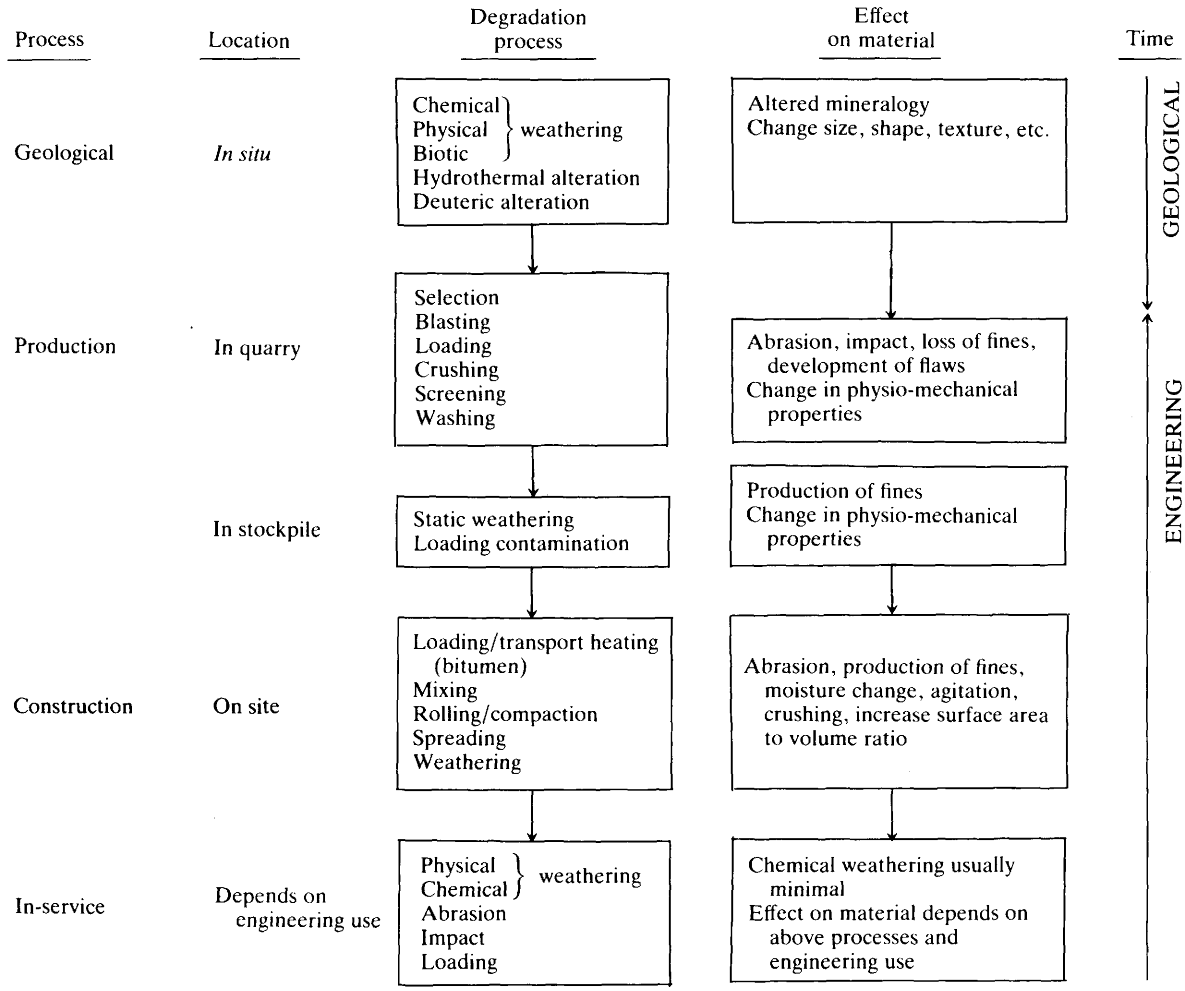

FIG. 2. Factors affecting the durability of rock and aggregate materials.

degrading mechanism, particularly when the effects of scale reduction are considered. Aggregate particles have high surface area to volume ratios, and consequently any potential chemical weathering processes available to the particle, could act to degrade it within a relatively short timescale, which could be engineering time. However, recent accelerated weathering experiments on aggregate size materials, such as those of Mellon (1985) in weathered basalts show no production of secondary minerals over timescales equivalent to engineering time.

The physical weathering processes and imposed mechanical stresses such as those presented in Table 10, are generally regarded as being most applicable within an engineering timescale. The mineralogy, particularly the type and distribution of secondary minerals is significant, and the presence of flaws (such as cracks and voids) greatly enhances the weakening of intergranular bonds between mineral grains and accentuates degradation processes such as those described by Lees & Kennedy (1975). In addition it creates access for weathering agents.

Hydrological regime

The position of the engineering structure, in relation to the hydrological zones (Table 3), is usually an important factor in dictating the durability of the materials within the structure: a good example would be a road. The presence of moisture within the fabric of a rock is especially significant as it acts to weaken the rock when under an imposed load. This is demonstrated by the simple example of reduction in uniaxial compressive strength of quartzitic sandstone with increased moisture content. Figure 3 shows the

TABLE 10. *Degrading mechanisms acting on rock/aggregate materials in particular engineering structures (from numerous sources)*

Engineering structure	*Type of structure*	*Main degradation mechanism* Abrasion	Impact	Crushing	Salt crystallization	Freeze–thaw	Polishing	Wetting–drying
Unbound road base	D			×		×		
Road wearing course	D	×	×	×	(×)	×	×	×
Riprap/cut slopes	S				(×)	×		×
Filter media	S	(×)				(×)		×
Railway ballast	S + D		×	×		×		×
Breakwater armour	S + D	×			×			×

×, important; (×), may be of importance; S, static; D, dynamic.

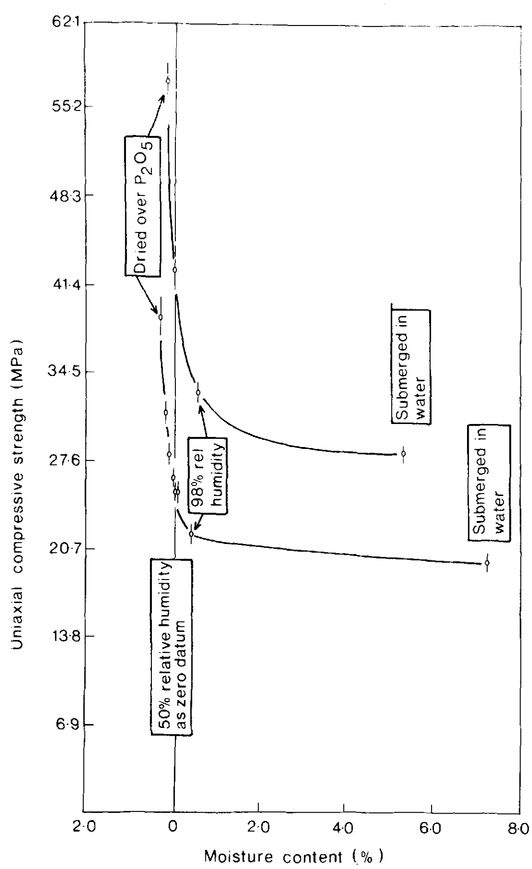

FIG. 3. Relationship between uniaxial compressive strength and moisture content for quartzitic sandstone (after Bell 1983).

reduction in strength of about 50% which occurs when the moisture content is increased to only 0.5%. The location of an engineering structure, such as a road, with respect to the water table will have a significant effect on the aggregate strength and ability to resist the imposed load. The quality and type of aggregate chosen is obviously important, especially where used in an unbound condition within the subsurface zone. Weathered rocks and other materials exhibiting high water absorption capabilities should be considered especially carefully therefore when locating structures low in the sub-surface zone.

Figure 4 shows the likely degradation processes acting on a highway pavement, one located within the subaerial zone and one located deep within the sub-surface zone. Both structures are subject to essentially the same subaerial weathering processes (e.g. wetting–drying, freeze–thaw, insolation, leaching) and imposed dynamic loading (impact, abrasion, crushing). However, the availability of water will strongly influence not only the strength of the aggregate but also the effectiveness of the subaerial weathering processes to which it will be subject. In practice Fig. 4a could be a highway constructed on an embankment whilst Fig. 4b could be a highway in cut. Though both structures can be constructed of essentially the same material, those used within the cut may prove to be the less durable due to the state of saturation and the increased aggressiveness of the subaerial weathering processes. The slope-protecting riprap and drainage materials are static structures and are subject only to the physical weathering processes, though increased degradation may be apparent down the slope. The vertical and lateral extent of the hydrological zones must therefore be considered an

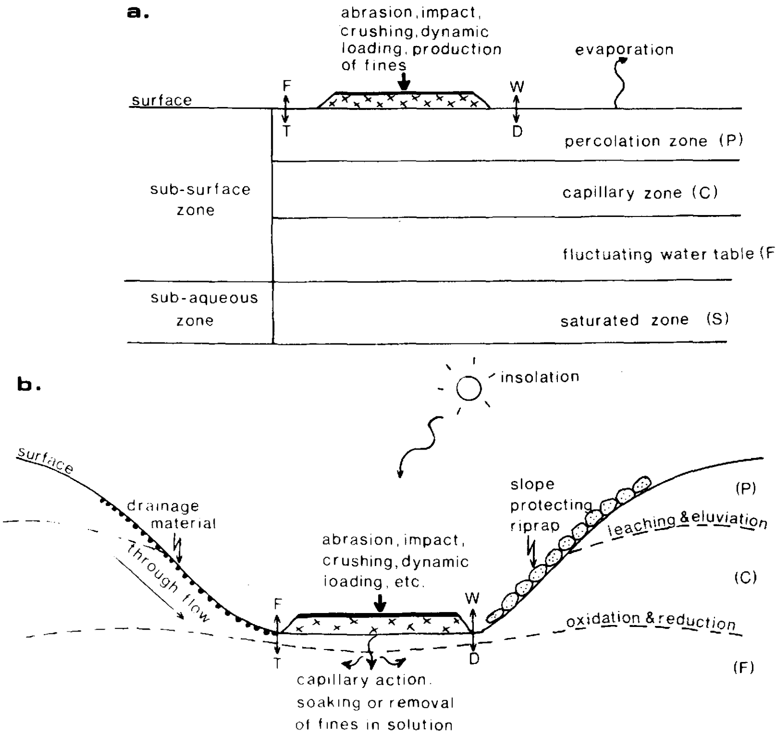

FIG. 4. Idealized possible degradation mechanisms operating in the principal hydrological zones. W = weathering; D = drying; F = freezing; T = thawing.

important component when determining the durability of a structure or the aggregate within it.

Topography and climate

The form of the hydrological regime and the effectiveness of the subaerial weathering processes, including their influence on the durability of rock will be directly related to the climate and topography of the area of interest. The climate and its influence on the subaerial weathering processes has already been discussed, though the importance cannot be overemphasized.

Some attempts have been made in the past to quantify the effects of climate on the durability of engineering materials. Weinert (1964), using his '*N*' variable, tried to correlate the effect of climate with the durability of variously weathered basalt used for road materials. The results of his study are shown in Fig. 5. However, the ability to predict the durability

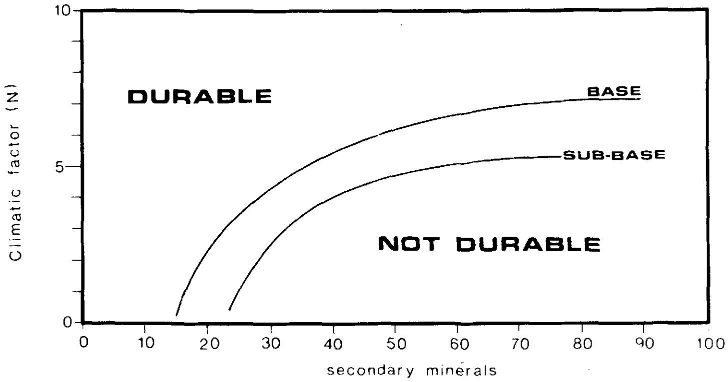

FIG. 5. Secondary mineral content, climatic factor (*N*) and potential performance of dolerite roadstone in South Africa (Weinert 1964, 1968).

was found to be applicable only to areas of very simple climatic regime. The natural variability of rainfall and temperature, on the long and short term scales, serves to emphasize the difficulty of trying to quantify such variable parameters especially within the relatively short span of engineering time.

The location of the engineering structure in relation to the topography and aspect is also of importance when assessing material durability. The degree to which freeze–thaw, wetting–drying, insolation and evaporation can be active is also dependent on whether the microclimate is exposed or sheltered. The higher the altitude the greater the effect of freezing on exposed structures in any one local area. The degree of wetting and drying effects will vary according to the aspect, the position of the structure and the local rainshadows.

Engineering tests and the assessment of rock durability

The variability of the factors which control the durability of an engineering material makes the prediction of in-service durability difficult and in many cases effectively impossible. Rock quality is perhaps the only variable which can be indicated with any degree of accuracy. Cox (1973) summarized the importance of rock and aggregate material testing as follows:

(1) To assess the quality, usefulness or otherwise of new sources of stone.
(2) To ascertain whether the type of stone from a given source is changing significantly.
(3) To compare samples from a given source to ascertain that quality remains relatively constant.
(4) To compare quality of stone from different sources.
(5) To ascertain that the characteristics of the stone satisfy specification requirements.

De Puy (1965) also noted the importance of testing to establish or predict the performance of material in-service. To this end a series of physical, mechanical and simulation tests, as indicated in Table 11, have been used in the preliminary estimation of material durability. In addition petrographic techniques, such as those described by Cole & Sandy (1980), Weinert (1968) and ASTM C-295, can be used to assess the rock and aggregate quality; alteration or weathering products (secondary minerals); flaws and other defects.

TABLE 11. *Commonly used test methods for the assessment of rock/aggregate durability*

Physical tests	*Mechanical tests*	*Simulation tests*	*Petrographic evaluation*
Specific gravity (apparent, oven-dried, saturated surface dry) (BS 812)	Point load strength (ISRM 1985)	Modified aggregate impact value (Hosking & Tubey, 1969)	Petrographic examination (ASTMC 295)
Water absorption (BS 812)	Schmidt rebound number (Duncan 1969)	Los Angeles abrasion (ASTM C535)	Clay mineral analysis (XRD, DTA, methylene blue absorption)
Unconfined compressive strength	Aggregate impact value (BS 812)	Washington degradation test (DMR T214)	
	Aggregate abrasion value (BS 812)	Wetting and drying	
	Aggregate crushing value (BS 812)	Magnesium sulphate soundness test (ASTM C88)	
	10% Fines (BS 812)	Freeze–thaw durability test (AASHTO T103-78)	
		Slake durability	

TABLE 12. *Main petrological features affecting engineering test results*

Aggregate petrography / engineering test	*Specific gravity*	*Mineralogy*	*Compactness*	*Porosity*	*Hardness*	*Texture*	*Shape*	*Moisture content*	*Anisotropy*	*SM content*	*Micro fractures*	*Cleavage*	*Grain size*
Water absorption			×	×						×	×		
Special gravity	×	×	×	×						×	×		
Compressive strength			×		×	×		×	×	×	×	×	
Tensile strength			×			×		×	×	×	×	×	
SHV		×	×	×	×			×			×		
Slake durability	×			×	×	×		×		×			
Washington degradation test	×	×	×	×			×		×				
Wetting–drying				×		×				×	×		
Freeze–thaw			×	×		×		×			×		
Sulphate soundness			×	×			×		×	×	×		
Rapid abrasion test	×		×		×	×	×	×			×		×
Los Angeles abrasion	×		×		×		×				×		×
AAV			×		×	×	×				×		×
ACV		×		×	×	×				×	×	×	
10% fines			×		×	×	×				×	×	×
PSV		×			×	×				×		×	×
Aggregate shrinkage		×		×				×		×			
Sonic velocity			×	×				×			×		
M.AIV	×		×	×	×	×	×	×		×	×		
Ultrasonic cavitation			×		×	×				×	×	×	

× = significant to test result.

An understanding of the properties of the material on which a given engineering test depends is important so that overlap in properties measured can be minimized and a set of tests can be devised which covers the full range of rock and fabric properties. Table 12 presents an assessment of some of the rock properties influencing common engineering test results. This allows a quick assessment to be made of the ability of the test to quantify the important petrographic properties affecting the ability of the material to resist the imposed forces indicated in Table 10.

Physical tests

Specific gravity and water absorption tests have been found to be useful indicators of material quality (e.g. Minty & Monk 1966; Smith *et al.* 1970; Baynes *et al.* 1978). The water absorption test in particular may be useful in assessing the degree of hydraulic conductivity of a rock due to the presence of interconnecting networks of secondary minerals and microfractures, which are especially common where rock material is weathered.

Mechanical tests

Point load strength (ISRM 1985) and Schmidt hammer rebound tests, though not durability tests, have been found to perform well in the detection of weathered and altered rocks (De Puy 1965) due to the strength reduction caused by the presence of weak or soft secondary minerals, microcracks and flaws and increased water absorption capacity. Tensile strength is a useful parameter in determining sensitivity of a rock to degradation by crystallization processes.

Aggregate impact and crushing tests (BS 812) can be used to assess the durability of materials subjected to processing, construction and in-service dynamic processes. However, where weak or potentially unsound materials are tested, the consequent high percentage of fines produced may lead to compaction and improve the final test result (Dhir *et al.* 1971). The 10% fines crushing test (BS 812) has largely replaced the aggregate crushing test, and failure in this test is caused by flexural stressing at the ends of rock prisms, a mechanism more comparable to the degradation process described by Lees & Kennedy (1975). However, as with most of the mechanical tests, the material is tested in a dry condition, which may not reflect the environment under which the material will be required to serve, and thus a misleading assessment of material strength and durability may be given.

Simulation tests

Simulation tests should reflect as closely as possible, within a laboratory environment, the type of physical, chemical and mechanical degradation processes that the material will suffer during its engineering use. These tests (Table 11) have been used with varying degrees of success in the past (e.g. De Puy 1965; Smith *et al.* 1970; Anon 1970).

Abrasion tests, such as those shown in Table 11, measure the dry resistance of aggregate to abrasion and can be used for the assessment of abrasion loss during handling and whilst in-service. The Los Angeles test, however, has been criticized as a simulation test for a number of reasons. De Puy (1965) noted that the test subjected the aggregate to significant impact, as well as abrasion; a point used to explain its lack of correlation with the other abrasion tests. Hudec (1978) criticized the test for not simulating the actual type of deterioration to which an aggregate is subject in-service, and Smith *et al.* (1970) commented that the test was only useful in the prediction of durability when used in combination with other test results (a point generally valid for all the engineering tests used in durability evaluation).

Hosking & Tubey (1969) developed a modified version of the BS 812 impact test, to make it more applicable to testing of weak or potentially unsound aggregates. This test method has overcome the incipient difficulties of the BS 812 impact test and recent work (e.g. Gourley 1986) has found the test particularly useful in discriminating variously weathered aggregate materials, particularly in the difficult boundaries of grade Ib–II and II–III (weathering grades after Anon 1977). The nature of the test is such that it simulates dynamic loading of aggregate in a saturated state, as could occur on the road material shown in Fig. 4b.

Tests have been developed to simulate crystallization processes, such as the freeze–thaw durability and sulphate soundness tests. The freeze–thaw test measures the resistance of a material to the cycle of crystallization pressures set up during the freezing water. The test is most applicable to material with large pores and weathered absorptive materials, though in some cases absorptive materials such as poorly cemented sandstones with large pores may pass even the best specifications. Another problem with the test is the time required to carry it out. This reduces its potential usefulness as a quality control test, a criticism which can also be exacted on the ASTM C-88 sulphate soundness test.

The sulphate soundness test, however, has been modified to a 5-day cycle by Hosking & Tubey (1969), though a major problem with its reproducibility still exists. The reproducibility problem is accentuated in the more aggressive sodium sulphate test and is attributed to the ability of the sodium sulphate to crystallize in two distinct crystal forms. Hosking & Tubey (1969) and Gourley (1986) have found the magnesium sulphate soundness test useful in distinguishing sound and unsound aggregates as it also gives an indication of water adsorption capability, tensile strength and resistance to freeze–thaw. However, the test result is dependent on the particle shape and size tested, as noted by Minty & Monk (1966), as the soundness loss increases with particle angularity and size of the aggregate tested. The test also has the drawback that it cannot be used easily with carbonate rocks due to the chemical reaction which occurs between the carbonate and sulphate in the solution (Gandhi & Lytton 1984).

Petrographic techniques

As seen in Table 9, many of the reported failures of geological materials in-service are either caused or accentuated by the presence of incipient secondary minerals, microcracks and voids within the rock fabric. These observations have led to the development of quantitative petrographic techniques to characterize unsound fabric features in the rock. Since the pioneering work of Lord (1916), the prediction of aggregate quality using petrographic methods has greatly increased (e.g. Scott 1955; Day 1962; Weinert 1968; Cole & Sandy 1980). The proportion of secondary minerals and presence of other potentially unsound fabric features forms the basis of these petrographic techniques. A summary of some of the indices proposed is presented in Table 13. These indices have proved useful laboratory guides to estimating the degree of unsoundness and the likely engineering properties. They cannot, however, be used as a replacement for engineering testing and are best used in conjunction with or as controls for such tests.

The 'percentage secondary mineral' index of Weinert (1964) was related to his climatic factor '*N*'. Weinert went on to develop the relationship and proposed a 'soundness line' which enabled the prediction of material durability, taking into account secondary mineral content and the climate of the location as illustrated in Fig. 5. The index proposed by Mendes *et al.* (1966) was complicated by the use of weighted coefficients measuring the effects of mineralogy and fracture on the mechanical properties of the

TABLE 13. *Some of the proposed petrographic indices for assessment of unsound materials*

Petrological index	*Variables*	*Reference*
$X_d = \frac{N_q - N_{q0}}{1 - N_{q0}}$	N_q–Weight ratio quartz/feldspar in soil N_{q0}–Weight ratio quartz/feldspar in rock	Lumb (1962)
$K = \frac{\sum_{i=1}^{n} P_i \cdot X_i}{\sum_{i=1}^{m} P_j \cdot Y_j}$	n values of X_i–96 Sound minerals n values of Y_i–96 Unsound minerals P_i and P_j–Weighted coefficient measuring effect of mineral or fracture in rock	Mendes *et al.* (1966)
$IP = \frac{\text{\% Sound constituents}}{\text{\% Unsound constituents}}$	IP–Micropetrographic index Sound–Primary minerals Unsound–Secondary minerals + voids + cracks	Irfan & Dearman (1978)
$R_{sm} = \sum [(P, M)]TR$	R_{sm}–Secondary mineral rating P–Percentage secondary minerals M–Stability rating for mineral TR–Textural rating	Cole & Sandy (1980)
$SMC = \frac{S}{M} \times 100$	S–Secondary mineral content, voids, microfractures M–Total mineral content (primary and secondary) SMC–Secondary mineral content	County Roads Board (test method 3730) (1982)

rock and it was this index which formed the basis of the simple micropetrographic index of Irfan & Dearman (1978).

The secondary mineral rating proposed by Cole & Sandy (1980) was based on the textural distribution as well as the percentage and stability of the secondary minerals. This index was found to give a more reasonable assessment of material performance and showed a good correlation with the Washington Degradation factor (ARRB T-214) and Methylene Blue dye absorption tests. Limits which have been proposed for some of the indices are given in Table 14. Realistic limits, however, would depend on other factors involved within the durability determination, imposed loading, climate, topography, etc. Hosking & Tubey (1969) note the difficulty experienced in designating some troublesome aggregates in the borderline region (30–33% of secondary minerals), as in some cases they performed satisfactorily and in others they caused failure. The exclusion of the other factors influencing the durability may well explain this phenomenon.

TABLE 14. *Proposed limits for acceptable secondary mineral content in roadstones from previous studies*

Author/source	*Rock type*	*Limits*	*Comments*
Scott (1955) (Oregon)	Basalt	<20% 20–35% >35%	Little adverse effect Borderline Failure almost certain
Weinert (1968) (S. Africa)	Dolerite	<15% 15–30% >30%	Fresh Decomposed Badly decomposed
Cole & Sandy (1980) (Australia)	Basalt	$R_{sm} < 140$ $R_{sm} > 140$	Durable Potentially unsound

A petrographic technique to assess road material durability has been developed and used with some success in Australia. This technique by Wylde (1980, 1982) assesses the degradation of crushed basalt road bases by monitoring changes in aggregate particles using a Textural Factor formula:

$$TF = \frac{1N_1 + 2N_2 + 3N_3 + 4N_4 + 5N_5}{N}$$

A numerical scale of 1 to 5 is used; 1 representing continuously graded fines, and 5 poorly graded fines. In the formula, N is the total number of points with visible fines and $1N_1$ the number of points (by point counting) showing a scale factor of fines with a distribution of 1, and so on up to $5N_5$. A consistent relationship was observed between TF and pavement conditions both in roads in-service and in full scale test track studies. This method has proved very useful in studies of road deterioration where the rearrangement of fines due to repeated loading decreases the stability of the road.

Correlations between engineering tests

The use of petrographic techniques as rock quality indicators in the assessment of durability has at least one major drawback, in the time required to obtain the test result. Their usefulness for durability assessment cannot be ignored, however, though it may be limited to assessing the ability of other engineering tests to detect unsoundness in materials or to check other test results that suggest unsoundness.

As seen in Table 12, there is some overlap in the petrographic properties measured by using various engineering tests. Where the overlap is dependent on rock properties occurring between two tests, at least some degree of correlation between the test results for the same rock may be expected. One of the main aims of cross correlation studies has been to identify any quick and simple test methods which can be used as substitutes for more cumbersome, complex or time-consuming tests. The potentially best correlations occur between tests measuring similar rock properties, and a rough guide to the expected degree of correlation can be obtained from Table 12. Where little correlation exists between a pair of tests results, it cannot simply be assumed that different rock properties are measured; other factors such as textural differences, particle size and shape, standardization of test methods or saturation can also decrease the correlation coefficient. In most studies of engineering test correlation there has been little or no standardization of sample size, shape or degree of saturation, and in addition the tests do not strictly apply to the same sample (Minty *et al.* 1980). However, despite these disturbing aspects, much work has been published on the correlation of various engineering tests, using a range of variously weathered or otherwise altered rocks as a database (e.g. Minty *et al.* 1980; Ghosh 1980; Ramana & Gogte 1982; Lumb 1983; Turk & Dearman 1985; Martin 1986).

A detailed study carried out by the Department of Main Roads (DMR) in Australia forms a very good example of this type of correlation study. The results shown in Table 15 were based on data collection of strength and durability testing of variously weathered aggregate materials used in road construction over ten years. Good correlations were reported between aggregate crushing values and 10% fines (dry), and Los Angeles abrasion and aggregate crushing value. The relatively low correlations reported for the other test pairs may reflect the presence of some of the disturbing aspects already noted, or that other regression functions may be more applicable to the results, or equally, that the test pairs are dependent on different rock properties.

Table 16 gives details of some recent work on the correlation of engineering tests, by the writers on water absorption, specific gravity, Washington Degradation test, magnesium sulphate soundness, modified aggregate impact value and point load strength index (IRSM 1985). Test pairs were correlated using two

TABLE 15. *Correlation of aggregate strength and durability tests for curves of best fit (Minty* et al. *1980)*

Property	*Relationship*	*Source*	*Number of samples*	*Coefficient of correlation*	*Function*
Strength	LA vs ACV	DMR[1]	203	0.74	Linear
		DMR + others	327	0.87	Linear
	LA vs 10% dry	DMR	249	0.71	Linear
	LA vs 10% wet	DMR	249	0.71	Linear
	LA vs 10% variation	DMR	249	0.24	Linear
	ACV vs 10% dry	DMR	78	0.91	Linear
		DMR + others	109	0.88	Linear
	ACV vs 10% wet	DMR	78	0.80	Linear
	ACV vs 10% variation	DMR	78	0.24	Linear
Durability	10% variation vs soundness	DMR	172	0.67	Linear
	10% wet vs soundness	DMR	173	0.44	Linear
	10% wet vs WD[2]	DMR	38	0.23	Linear
	10% variation vs WD	DMR	38	0.38	Linear
	Soundness vs WD	DMR	53	0.53	Linear
		DMR + others	69	0.48	Linear

[1] DMR, Department of Main Roads, Australia.
[2] WD, Washington degradation.

TABLE 16. *Two variable linear correlations and regressions for some British granites and dolerites*

Rock type	*Linear correlation equation*	*Correlation coefficient*	*Other best-fit function*	*Source*
Dolerite	$SST = 107.1 - 12.5(I_{s(50)})$	−0.93		Gourley (1986)
Granite	$SST = 15.9 - 1.56(I_{s(50)})$	−0.50		
Dolerite	SST = 17.8 + 0.15(M.AIV)	0.26		Tooth (1980) Miglio (1981) Gourley (1986)
Granite	SST = −0.7 + 0.15(M.AIV)	0.97		
Dolerite	SST = −3.49 + 9.79(WA)	0.59	Power	
Granite	SST = −0.7 + 5.23(WA)	0.91		
Dolerite	M.AIV = 2.14 + 8.17(WA)	0.59	Power	
Granite	M.AIV = 2.05 + 32.6(WA)	0.91		
Dolerite	WDF = 98.8 − 3.49(WA)	−0.49		Gourley (1986)
Granite	WDF = 105.9 − 8.57(WA)	−0.92		
Dolerite	$WDF = 83.1 + 1.6(I_p)$	0.85		
Granite	$WDF = 52.2 + 7.7(I_p)$	0.64		
Dolerite	WDF = 97.9 − 0.16(M.AIV)	−0.96		
Granite	WDF = 95.1 − 0.2(M.AIV)	−0.88		
Dolerite	$I_p = -0.55 + 1.07(I_{s(50)})$	0.79		
Granite	$I_p = 1.51 + 0.36(I_{s(50)})$	0.79		

SST = magnesium sulphate soundness; $I_{s(50)}$ = point load index; WA = water absorption; WDF = Washington degradation factor; M.AIV = modified aggregate impact value.

variable linear correlations, but in the case of modified aggregate impact value and magnesium sulphate soundness correlated with water absorption, a power function was found to give a slightly better correlation coefficient. The test results were obtained from variously weathered granites and dolerites from south-west England and the Midland Valley of Scotland.

Rock durability indicators

From the foregoing it should be clear that no engineering or petrographic test method can be considered an absolute indicator of rock or aggregate quality. An assessment of material durability in-service cannot be given unless all factors affecting the durability are considered, including rock quality, hydrological regime, climate, topography, the type of structure and imposed forces (dynamic or static).

Visual assessment of the performance of in-service structures within particular environmental conditions can give a most useful estimate of the potential performance of new structures built from similar materials. For example Smith *et al.* (1970) attempted an assessment of slope-protecting riprap material in California and investigated the correlation between simple engineering tests and visual assessment. By this method they were able to determine which engineering tests gave the best indication of durability in-service. However, they were concerned with the length of time required between the collection of samples and receiving the test result back from the laboratory (up to 1 month). Their study, therefore, was limited to quick and simple engineering tests which could be carried out on site or in the site laboratory. A summary of the test methods and results of their study is shown in Table 17. They concluded that the best correlation between visual assessment of field performance and original test results was gained for the water absorption and durability index (a wet abrasion test) results. They went on to propose the combination of these test results in the form of a durability absorption ratio (DAR)

$$DAR = \frac{\text{Durability index}}{1 + \text{percentage water absorption}}$$

This had two main advantages: firstly, it was quick, and secondly it allowed a material weak in one property to be compensated for by strength in another and a test method discriminating against one material could be compensated by use of a test favouring that material. The success of the DAR in predicting rock performance is illustrated by its current use as a specification for quality control of riprap material in California.

Within the construction industry the quick, correct assessment of the potential durability of rock and aggregate is of great importance to quarry managers, contractors, consulting and local authority engineers

TABLE 17. *Correlation of various methods of evaluating the quality of rock slope protection material* (*Smith* et al. *1970*)

Test method	*Specification*	*Number of samples*	*Correlation (%)*
Apparent specific gravity	25 minimum	65	86[2]
Absorption	2% maximum	65	91[2]
Los Angeles rattler	45% maximum loss	65	83[2]
Sodium sulphate soundness	5% maximum loss	65	77[2]
1974 standard specification		65	71[2]
Durability index	52 minimum	264	94[3]
Rapid abrasion	24% maximum loss	112	88[3]
Durability absorption rate[1]	>23 acceptable <10 unacceptable 10–23 acceptable if durability index > 51	261	97[3]
Usual evaluation		65	94[2]

[1] Durability absorption ratio = Durability index (percentage absorption + 1).
[2] Correlation with field performance only.
[3] Correlation with field performance or visual evaluation.

and others who make predictions, and evaluate structures and materials already in-service. Any change in the quality or potential durability during the processing and placing of materials (as indicated in Fig. 2) should be investigated and reported quickly so the situation can be rectified and time and money can be saved at an early stage. To this end a series of durability indicators, using a combination of simple engineering tests, is tentatively proposed here. The indicators proposed are applicable to either rock or aggregate materials in a dynamic or static engineering environment and may be used in the assessment of the potential durability at any stage in the life of the structure (Fig. 2). The Rock Durability Indicators have been given the notation RDI, with subscript 's' or 'd' indicating the static or dynamic case, respectively. The indicators were developed from a reasonably comprehensive set of engineering tests on British weathered dolerites and granites.

Static rock durability indicator

The static rock durability indicator RDI_s requires four engineering tests combined as follows:

$$RDI_s = \frac{Is(50)^* - 0.1(SST + 5WA)}{SG_{ssd}}$$

where $Is(50)^*$ = average dry and saturated point-load index (IRSM 1985); SST = magnesium sulphate soundness test (Hosking & Tubey 1969); WA = water absorption (BS 812); SG_{ssd} = specific gravity saturated and surface dried (BS 812).

The water absorption test result is multiplied by an arbitrary factor of 5 to bring the magnitudes of the variables into equivalent terms, and to emphasize its importance in assessing the durability of rock (Smith *et al.* 1970). The point load strength is used to give an assessment of the static strength of the material, and is especially useful where material is not subject to dynamic loading, as it would be in, say, foundations of structures, cut slope faces, dam or highway embankments. The magnesium sulphate soundness test is included to assess the ability of the material to resist some of the cyclic physical weathering processes, such as salt crystallization, heating and cooling, and possibly freeze–thaw.

Table 18 gives a tentative estimation of the potential durabilities of rock and aggregate materials based on the static rock quality indicators, using the engineering weathering grades in Anon (1977) as the boundary controls. Tables 19 and 20 show some results for static durability indicators (RDI_s) carried out on granites and dolerites from south-west England.

As the RDI_s contains the magnesium sulphate soundness test, the time required to carry out this test severely limits the use of the RDI_s when quick assessment of material is required. It is, therefore, proposed to use the regression equation for magnesium sulphate soundness and water absorption, given in Table 16 and to substitute this in the RDI_s equation. By this substitution the RDI_s for dolerite

TABLE 18. *Tentative estimation of indicated potential durability—static case*

RDI_s	*Potential durability*
>2.5	Excellent
2.5 to −1	Good
−1 to −3	Fair
< −3	Poor

TABLE 19. *Rock durability indicators for some weathered granites, south-west England*

Sample number	WG	$SG_{(SSD)}$	WA	$I_{s(50)(ads)}$	SST	$SST_{(WA)}$	M.AIV	RDI_s	Pd	RDI_{sq}	Pd	RDI_d	Pd
H1.E	Ib	2.64	0.33	9.07	0.4	1.1	7.2	3.36	E	3.33	E	0.34	E
H2.E	Ib	2.63	0.37	10.55	0.3	1.4	5.7	3.93	E	3.89	E	0.29	E
H3.E	II	2.57	1.53	6.43	0.2	7.4	9.2	2.20	G	1.92	G	0.65	G
H4.E	Ib	2.62	0.54	12.05	0.5	2.2	7.7	4.48	E	4.41	E	0.39	E
H5.E	II	2.53	2.51	2.73	10.2	12.4	38.9	0.18	G	0.09	G	2.03	F
H6.E	II	2.60	1.89	1.02	3.4	9.2	22.7	−0.10	G	−0.32	G	1.23	G
H7.E	III–IV	2.31	9.65	0.1[1]	46.6	49.4	321.6	−4.06	P	−4.19	P	16.01	P
H2.W	III	2.39	6.91	0.1[1]	20.7	35.2	172.4	−2.27	F	−2.88	F	8.66	P
H3.W	II	2.56	2.72	5.45	13.9	13.6	36.6	1.05	G	−1.07	G	1.96	G
H4.W	III–IV	2.35	8.79	0.1[1]	64.9	44.7	402.3	−4.59	P	−3.75	P	18.98	P
H5.W	II	2.51	3.64	5.06	6.9	18.3	24.1	1.02	G	0.56	G	1.68	G
H6.W	II	2.59	2.32	3.38	13.2	11.5	31.5	0.35	G	0.42	G	1.66	G
H7.W	Ib	2.64	0.45	12.7	0.3	1.8	5.4	4.71	E	4.66	E	0.29	E

Abbreviations: WG = weathering grade; SG_{ssd} = specific gravity (saturated and surface dry); $I_{s(50)(ADS)}$ = point load index, calculated from $0.5[I_{s(DRY)} + I_{s(SAT)}]$; W.A = percentage water absorption; M.AIV = modified aggregate impact value; SST = $MgSO_4$ soundness value; $SST_{(WA)}$ = derived $MgSO_4$ soundness value from regression equation; RDI_s = static rock durability indicator; RDI_{sq} = quick static rock durability indicator; RDI_d = dynamic rock durability indicator; Pd = potential durability.

[1] Material broke between plates prior to loading.

becomes:

$$RDI_{sq} = \frac{Is(50)^* - 0.1[14.79(WA) + 3.49]}{SG_{ssd}}$$

and for granite, it becomes:

$$RDI_{sq} = \frac{Is(50)^* - 0.1[10.23(WA) - 0.7]}{SG_{ssd}}$$

The notation 'q' indicates the quick static durability indicator and by this method the inherent properties of the sulphate soundness test are still taken into consideration and the long time between sampling and obtaining the test result is reduced, providing a suitable regression equation has already been developed. This method was applied to the rocks in this study and the results of the quick rock durability indicators are also given in Tables 19 and 20. A separate correlation is necessary for each rock type and this may be developed by comprehensive testing at an early stage in the history of the particular quarry.

Dynamic rock durability indicator

Where the rock or aggregate is subject to degradation by dynamic loading processes, a dynamic engineering test must be included in the rock durability indicator. The modified aggregate impact value of Hosking & Tubey (1969) was found to be most appropriate in this case. Reference to Table 12 shows that the test result takes into consideration a large number of petrographic properties as well as simulating the effect of repeated loading in a weakened, saturated condition.

TABLE 20. *Rock durability indicators for some weathered dolerites, south-west England*

Sample number	WG	$SG_{(SSD)}$	WA	$I_{s(50)(ADS)}$	SST	$SST_{(WA)}$	M.AIV	RDI_s	Pd	RDI_{sq}	Pd	RDI_d	Pd
Tr.1a	Ib	2.92	0.53	5.82	0.7	1.7	3.22	1.88	G	1.60	G	0.20	E
Tr.1b	Ib	2.92	0.46	8.47	1.5	1.0	6.9	2.77	E	2.55	E	0.31	E
Tr.2	Ib	2.72	0.77	7.82	0.6	4.0	5.2	2.71	E	2.32	G	0.33	E
Tr.3	II	2.65	1.95	7.48	3.8	15.6	8.1	2.31	G	1.60	G	0.67	G
Tr.5	Ib	2.83	0.47	9.0	3.9	1.1	9.3	2.96	E	2.81	E	0.41	E
Tr.6	II	2.65	1.91	1.97	8.7	15.2	22.3	0.05	G	−0.87	G	1.20	G
Tr.7	III	2.51	6.60	0.17	89.6	61.1	74.7	−4.82	P	−3.96	P	4.29	P
Tr.8	IV	2.36	11.88	0.13	100.	112.	141.1	−6.70	P	−7.54	P	8.49	P
Tr.15	Ib	2.85	0.61	8.33	1.8	2.5	8.1	2.75	E	2.48	G	0.39	E
Tr.19	II	2.64	3.97	3.06	6.4	35.4	nd	0.16	G	−1.20	F	—	—

For abbreviations, see Table 19.

TABLE 21. *Tentative estimation of indicated potential durability—dynamic case*

RDI_d	*Potential durability*
<0.5	Excellent
0.5–2.0	Good
2.0–4.0	Fair
>4.0	Poor

The test shows a high degree of correlation with many of the mechanical test methods and it is assumed that the modified aggregate impact value will reflect most of the mechanical weaknesses appropriate to a material being used in a dynamic situation (including the degrading forces acting during construction and production). The dynamic durability indicator tentatively proposed is:

$$RDI_d = \frac{0.1[M.AIV + 5(WA)]}{SG_{ssd}}$$

where M.AIV is the modified aggregate impact value of Hosking & Tubey (1969).

The tentative limits proposed for potential durability in the dynamic situation are shown in Table 21. The limits were again determined by tests on variously weathered materials. Tables 19 and 20 show the results for RDI_d carried out on weathered granites and dolerites from south-west England.

The potential for the use of the simple indexes in the assessment of rock quality and potential durability is indicated by the test results for various weathered rock materials given in Tables 19 and 20. By a combination of the engineering tests in this way the important petrographic properties, together with some simulation of the imposed stresses, can be given, and therefore an indication of potential durability in the particular engineering environment obtained.

Suggested further development

The rock durability indicators proposed can be considered as measuring only two of the five parameters which make up a full assessment of potential durability. In the future it is hoped to weight the RDIs so that some assessment of topography, hydrological regime and climate can be included within the index to take into consideration the expected site environmental conditions. The tentative nature of the RDI_s and RDI_d was emphasized earlier and there is an obvious need to accumulate a large data base of various test methods and results on a much wider range of rock and aggregate materials. This would allow improved and more reliable statistical regressions to be developed, and the inclusion by substitution of more complicated test methods. The RDIs proposed contain an in-built bias towards the effect of water on the durability of the material. This reduces their applicability when the materials are used in a tightly bound or waterproofed condition or within drier climatic regimes where the effect of water may be minimal.

Ultimately the most useful area of development would be the assessment of change in RDI with time, so that an estimate of the rate of degradation of a particular material with time could be given. Figure 6 gives a conceptual view of how various materials of different original weathering grade could degrade in engineering time and Fig. 7 shows how the RDIs could be developed, for example by testing of existing

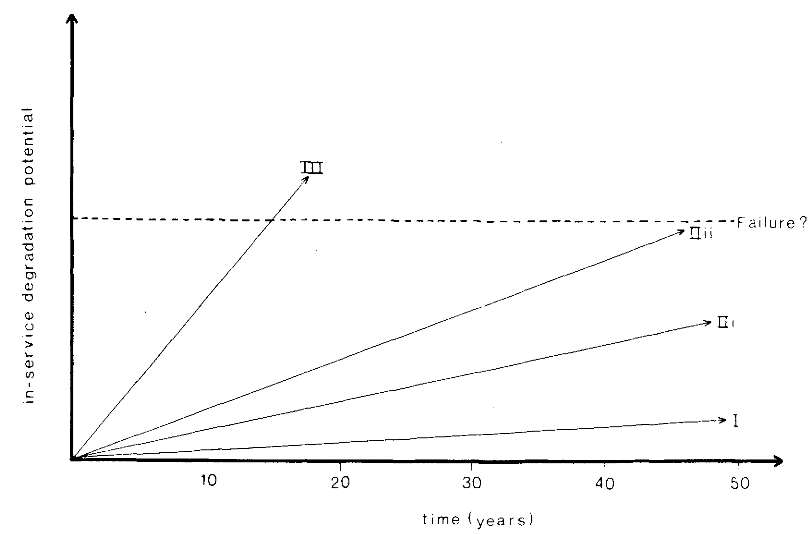

FIG. 6. Conceptual view of the in-service degradation of weathered materials.

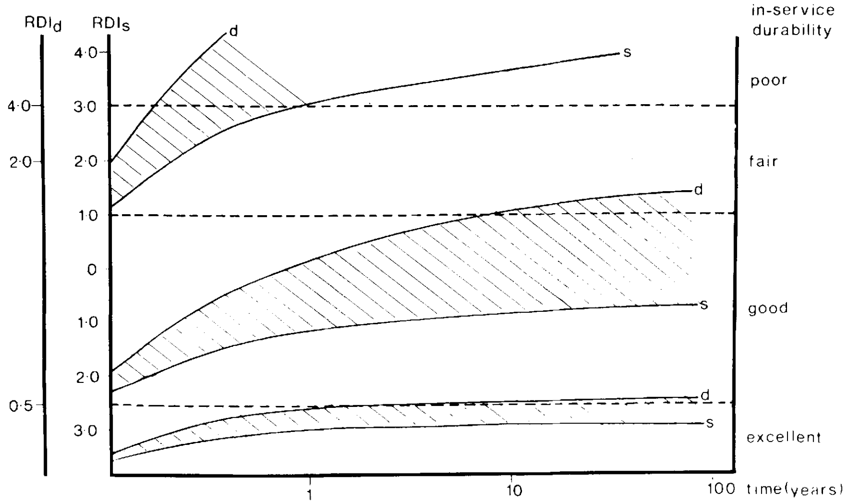

FIG. 7. Conceptual view of reduction in durability of various weathered/altered aggregates with time, monitored using static and dynamic rock durability indicators.

structures within various topographic, climatic and hydrological regimes. This could be used for prediction of the desirability of engineering materials under similar circumstances.

Conclusions and summary

(1) Weathering of rock mass material in geological time can have a direct and important influence on the durability of aggregate or construction stone in engineering time.
(2) Careful monitoring of materials produced and their assessment during construction is required to prevent use of unsound material. Selective quarrying may be necessary, for example.
(3) Production processes and construction procedures can have an important influence on the mechanical strength of engineering materials.
(4) Durability, i.e. the rock's ability to resist degradation during its working life, is dependent on a number of important parameters: original stage of weathering of rock mass, degree of imposed stressing during winning, production, placing and service, the climatic, topographic and hydrological environments in-service.
(5) Physical weathering processes and imposed loading generally have the most aggressive effect on engineering materials in engineering time.
(6) Chemical weathering should not be ignored as a possible mode of degradation of materials in-service, particularly where materials are used in hot wet climatic regimes.
(7) No one engineering test can be used as an absolute predictor of potential durability.
(8) Combinations of engineering tests, such as water absorption, specific gravity, point load strength, modified AIV, and magnesium sulphate soundness, can be used as rock durability indicators.
(9) A rock durability indicator (RDI) has been tentatively proposed which has the potential for a quick and easy method of quality control during quarrying, processing and on-site activities.
(10) Static RDI may be of use in the in-service assessment of cut slope degradation, riprap, concrete aggregates, foundation and embankment materials, stockpiled aggregates etc.
(11) Dynamic RDI may be of use in assessing aggregate degradation whilst in motion and where the material is subject to dynamic loading in service, e.g. road aggregates.
(12) Correlation of engineering tests may prove useful for replacement of more complex and time-consuming tests.
(13) For complete assessment of potential durability, environmental factors such as climate, topography and the hydrological regime need to be taken into consideration.
(14) Further work on the lines indicated in the paper is in progress and the work presented to date is preliminary.

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