Index properties of weathered rocks: inter-relationships and applicability

A. S. Gupta · K. Seshagiri Rao

Abstract The paper describes the change in physical and strength properties due to weathering of three crystalline rocks – granite, basalt and quartzite. It draws attention to the relationship between unconfined compressive strength and other measurements such as the point load index, the Brazilian tensile strength and the Schmidt hammer rebound number. The strength recorded is negatively related to the porosity which is considered an important indicator of the weathering state.

Résumé L'article décrit les variations des propriétés physiques et mécaniques de trois roches: un granite, un basalte et un quartzite, en fonction de leur degré d'altération météorique. Il attire l'attention sur les relations entre la résistance à la compression simple et d'autres résultats de mesure, tels que l'indice de résistance entre pointes, la résistance à la traction brésilienne et la valeur de rebond au marteau de Schmidt. La résistance mesurée est négativement corrélée à la porosité qui est considérée comme un important indicateur de l'état d'altération.

Key words Weathering · UCS strength · Point load strength · Density · Porosity · India

Introduction

Weathering, an inevitable process of nature, gradually alters a rock from its original hard state to a soil material and as a consequence, changes its engineering behaviour. Most rocks encountered are weathered to some extent and it is universally recognised that this process will have affected many of the engineering properties. Although a progressive deterioration of strength is generally found, to date no attempt has been made to compare the index properties of different rocks in different weathering conditions.

This paper reports a field and laboratory study of the index properties of three crystalline rocks at different stages of weathering and considers the implications of the findings when using the common index tests to characterise weathered rock material.

Previous work

Weathering of crystalline material usually results in the creation of voids, due to the preferential dissolution of certain mineral phases. As the weathering process continues and particular minerals are leached out, the original structure of the rock is changed and the material consists of altered grains with increasing numbers of macro and micro fractures. At the advanced stage of weathering, the remnant bonds collapse, resulting in the formation of a residual soil (Bjerrum 1967; Chandler 1967).

In general, rock loses its strength and becomes more plastic and permeable with weathering, although the extent of this will depend on the nature of the rock, the presence and types of weathering product and the stage of weathering (Anon 1970, 1977, 1995). The degree of weathering may be reflected by changes in index properties, such as density, void ratio, clay content and seismic wave velocity. A number of workers have noted an increase in void index, saturated moisture content and porosity with advancing weathering (e.g. Hamrol 1961, Duncan and Dunne 1967, Onodera et al. 1974). The latter authors recorded an increase in porosity of as much as 15% in granites at advanced stages of weathering, due to the formation of microcracks.

Detailed studies of the variation of such index properties as density, specific gravity of grains, porosity, void ratio

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and saturated moisture content during the weathering of granite have been carried out by Irfan and Dearman (1978a), Baynes et al. (1978), Dearman and Irfan (1978), Lumb (1983), Raj (1985), Irfan and Powell (1985) and Shequin et al. (1994). Similar observations have been made for basalt (Saito 1981), dolerite (Kilic 1995), andesite (Pasamehmetoglu et al. 1981, Turk et al. 1994), gneiss (Dobereiner and Porto 1993) and quartzite phyllite and schist (Komoo and Yakub 1990). A substantial increase in the porosity of khondalite due to leaching of garnet has also been reported by Raymahashay and Sharma (1993).

The influence of weathering on mudrocks has been studied by Taylor and Spears (1970), Chandler (1972), Russell and Parker (1979), Cripps and Taylor (1981), Hawkins and Pinches (1992) and Jevremovic (1994) while the index properties of common sedimentary rocks such as shale, sandstone, limestone and dolomite have been studied by Beavis et al. (1982), Beavis (1985), Leung and Radhakrishnan (1990). Beavis et al. (1982) stated that in pelitic rocks, fabric changes are not so apparent but solution and fracturing have resulted in increased porosity and as a consequence, a reduction in strength.

Point load strength index

The point load strength index (Is) provides a useful estimation of strength, particularly the unconfined compressive strength (UCS) of intact rocks and for rock classification (Broch and Franklin 1972). An index:strength ratio (UCS/Is) has been suggested by Broch and Franklin (1972), Bieniawski (1975) and ISRM (1985) who propose conversion factors (*K*) ranging from 20 to 25 for intact rocks.

Fookes et al. (1971) used the point load index for assessing the strength of weathered rocks in the field and to grade rocks in terms of their excavatability and suitability for road aggregate. They noted exceptionally high Is values of 17 MPa for granite and 55 MPa for limestone. These were attributed to the irregularity of the sample shape and the fact that no correction for shape and size had been made in the assessment (Dearman and Irfan 1978). Pettifer and Fookes (1994) have extended this into a consideration of the excavability of rocks using many examples from Britain, South Africa, Hong Kong and Turkey. Dearman and Irfan (1978) used a conversion factor of 25 to classify weathered rock and noted a very high coefficient of correlation ($r=0.98$) even for "coreable weakly cemented soil" where the Is ranged from 0.1 to 0.3 MPa.

Lumb (1983) also suggested weathered rocks could be graded in terms of excavatability (rippability) on the basis of the point load strength index, using an Is value of 2.5 MPa as the threshold of rippability. He recorded conversion factors ranging between 10 and 24 for granite and other volcanic rocks. Irfan and Powell (1985) proposed the UCS/Is ratios range from 12.5 to 25, suggesting that an incorrect compression testing procedure may be the reason for the variation in the conversion factor. Leung and Radhakrishnan (1990) considered a conversion factor of 6.12 to be appropriate for the weathered sedimentary rocks of Singapore when the Is value is >8 MPa while Ghosh and Srivastava (1991) reported 16 was applicable for Himalayan granitic rocks.

Table 1 shows the values of Is for a number of rocks at different stages of weathering. There is little in the literature to explain the variation in the conversion factor even for a single rock type in its unweathered state. Chau and Wong (1996) suggested that the conversion factor *K* depends on both the stress concentration factors [Poisson's ratio (ν), the length of the specimen and the shape of the specimen] and the compressive to tensile strength ratio. However, the applicability of this is questionable as it involves the determination of Poisson's ratio and tensile strength, which is likely to be more difficult than the determination of compressive strength.

Tensile strength

There is very little information available on the effect of weathering on tensile strength (σ_t). Most rocks have a low tensile strength and in their weathered state this decreases dramatically (Pasamehmetoglu et al. 1981; Turk et al.

Table 1
Point load index (I_s) for different rocks in their fresh and weathered state

Rock	Source	Weathering grade				
		I	II	III	IV	V
Shale (calc.)	Beavis et al. (1982)	2.82	1.68	1.13	1.23	0.82
Shale (dol.)	Beavis et al. (1982)	3.98	2.42	2.33	1.20	–
Agglomerate	Turk et al. (1994)	6.08	3.14	0.98	0.39	–
Andesite	Turk et al. (1994)	5.40	3.04	2.60	0.64	–
Andesite	Pasamehmetoglu et al. (1981)	13.40	4.12	2.50	0.20	–
Granodiorite	Irfan and Powell (1985)	11.00	9.00	7.00	6.00	0.60
Granite	Irfan and Dearman (1978a)	10.00	5.20	1.70	0.30	–
Granite	Dearman and Irfan (1978)	7.10	4.10	2.70	2.00	1.10
Granite	Dearman and Irfan (1978)	9.00	7.20	4.70	3.00	–

1994). From a detailed study of the tensile strength of clastic sedimentary rocks, Beavis (1985) noted a reduction of up to 75% in the tensile strength of a fresh claystone compared with that in its slightly weathered state and attributes this to the development of microfractures. It has been noted that the effect of weathering is not always as great for tensile strength as it is for compressive strength. However, the reverse would be expected in crystalline and igneous rocks in which microfractures are more important.

Present investigation

Three rocks were studied: the granite of Malanjkhand (MP), the basalt of Nagpur (Maharashtra) and quartzite of Delhi (India).

Malanjkhand granite

This country rock of Precambrian age is part of the 1500 km^2 of granitic terrain around the area of Malanjkhand in the states of Madhya Pradesh and eastern Maharashtra (Fig. 1). The area has dyke intrusions and mineralisation is associated with quartz veins and quartz monzonites.

The granites are generally medium to coarse grained and porphyritic, varying in colour from light grey to buff and pink. The main minerals are quartz, alkali feldspar, oligoclase and various types of perthites while secondary minerals such as biotite, chlorite, epidote and amphiboles also occur in various proportions as well as apatite, sphene, zircon and limonite (Sikka 1989). Perthititc intergrowth was observed in some alkali feldspars.

Under the present climatic conditions the granite weathers easily (Sikka 1989), notably in the hill areas. Although the rock is heavily weathered at a few metres below the ground surface, weathering may extend to a depth of some 90 m.

Samples were taken from the hanging and footwalls of a quarry where copper deposits were mined. A number of benches had been cut into the vertical slopes, from the crest of the pit (RL 590) to its base (RL 484). A depth of 100 m was available for the profile study.

Nagpur basalt

The basalt exposed at Nagpur is from the lower of the three stratigraphic units of the Deccan Trap of Upper Cretaceous to Lower Eocene age (Alexander 1978). The area of study lies in the western part of Nagpur city (Fig. 1). The basalt is present in the whole area, often overlain by Quaternary alluvium and black cotton soil. At some places, the Lametas (Upper Cretaceous) and Gondwana rocks are visible, but they were not exposed where the three profiles were taken: in the road aggregate quarries at Lava and Khondali and a deep foundation excavation site at Savarkar Nagar.

The Nagpur basalt is strong, compact and melanocratic. The crystals are not visible to the naked eye but under the microscope plagioclases, pyroxenes and glass are seen to be the major constituents with some labradorite which shows a subophitic texture with augite. Deshmukh (1984) observed the plagioclase and pyroxene to be considerably weathered and oxidized. Chlorite and altered magnetite were also reported, together with other subsidiary minerals.

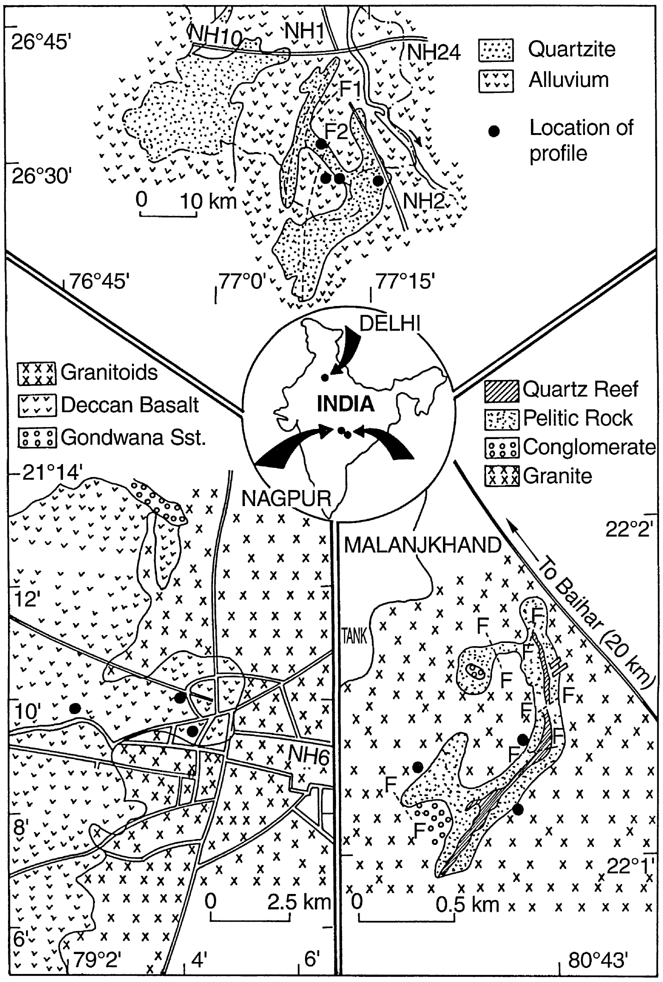

Fig. 1
Location maps of the studied area

Delhi quartzite

The quartzites of Delhi were taken from exposures at south Delhi and the Delhi-Harayana border (Fig. 1). Five profiles were selected from different sites where the full development of weathering could be seen within the rocks.

The quartzites are of the Alwar series of the Delhi system, of Precambrian age (circa 2 billion years). They are of sedimentary origin and have been subjected to various degrees of metamorphism (Krishnan 1982). Lying unconformably over the older gneisses, the rocks of the Delhi System are overlain by the Vindhyans. The base of the quartzite is not exposed and the rock is intruded by pegmatites (713–915 million years – Tyagi 1980). In many places the quartzites are covered by recent alluvium.

The rock is light to dark grey in colour and predominantly quartz (85–95%) with some secondary minerals including muscovite, biotite, feldspars and opaques. The quartzite was highly weathered at the surface but little effect could be seen at the bottom of the profile. The extent of the weathering was marked by a variable degree of staining and colour changes from pale yellow to dark brown at joints and exposed surfaces. In some places, pits up to 7 mm in size were noted on joint surfaces, probably due to the differential solution of the constituents.

Material identification

The stages of weathering are sequential and degradational, each characterised by such features as discoloration, staining, mineral alteration and textural changes. The strength is also reduced, affecting the competence of the rock. In the present study the relative strength was assessed qualitatively by geological pick, knife and nail and quantitatively using the Schmidt hammer. It was noted that while some characteristics vary continuously throughout the stages of weathering, others are limited to certain grades (Lee and de Freitas 1988).

Five recognition factors have been used to classify the important changes in visual characteristics throughout a weathering spectrum: discoloration and staining, texture and fabric, disintegration, decomposition and relative strength (Gupta 1997). Based on these recognition factors, the weathered materials were characterised into six grades on the basis of the terms and symbols suggested by IAEG 1981, ISRM 1981a. Table 2 shows the symbols used in this paper for the various weathering grades. For convenience, when referring to the weathering of different rocks, the symbol is pre-fixed by the initial letter of the rock name, eg QW_2 indicates moderately weathered quartzite.

Recognition of weathered rock mass

The distribution pattern of the different stages of weathered rock material within the weathering profile is distinctive and allows several morphological zones to be identified. Some of the existing empirical procedures developed by the Geological Society of London (Anon 1970, 1977, 1995), IAEG (1981), ISRM (1978, 1981a), Hencher and Martin (1982) and Martin and Hencher (1986) have been employed with few modifications.

The weathering zones were studied by observing the original structures, as much can be learned of the degree of rock mass weathering by the condition at and along joints. The intensity of fracturing also reflects the physical weathering within the mass, hence the number of fractures per unit length of spacing was measured together with joint frequency and width or openness of the joints. Where this was problematic, eg across the relic joints in highly fractured zones or for joints having varying widths, an average value was taken based on the observable thickness of the joints.

Although in general unweathered or less weathered rock materials predominate in the lower part of the weathering profile and more weathered rocks in the upper part, this is not always the case. Hencher and Martin (1982) suggest that when morphological zones are to be considered to represent different stages of the weathering of the rock mass, each zone must have distinctive and uniform engineering properties. Again difficulties were found in delineating the weathering zone where the distribution of weathering was heterogeneous. This was resolved by dividing the exposure into small units (sub-zones) and classifying each separately. Although Knill (1993) considered that the earlier classifications (eg Ruxton and Berry 1957) have overemphasised the role of corestones, the zones containing corestones were fully described in terms of their matrix and fragments (Dearman 1974).

The joint characteristics were studied in detail following the method proposed by ISRM (1978, 1981a). Joints were mapped using a scan line survey to determine an RMR value (Bieniawski 1974). A typical example of the gradational weathering profile developed over the granite at Malanjkhand copper ore mines is illustrated schematically in Fig. 2. This shows the distribution of fractures and the weathering state in delineated zones of the rock mass. The observations of the features recorded are described briefly in Table 3 which also gives the assigned weathering grades.

Table 2
Terms and symbols for weathering grades used in this paper

Weathering grade term	Symbol
Residual soil	W_5
Completely weathered	W_4
Highly weathered	W_3
Moderately weathered	W_2
Slightly weathered	W_1
Fresh rock	W_0

Laboratory investigation

Having collected the samples from the field, selection for further examination was made using the results of a Schmidt hammer test on a saw cut surface. Care was necessary in order to ensure the samples were of a specific size and shape, particularly with the more highly weathered specimens. As coring was sometimes difficult, cube and prismatic samples were prepared for the more highly weathered materials. Further spalling of grains/fragments from the freshly cut surfaces was prevented by the application of a thin layer of plaster of Paris. This layer was subsequently

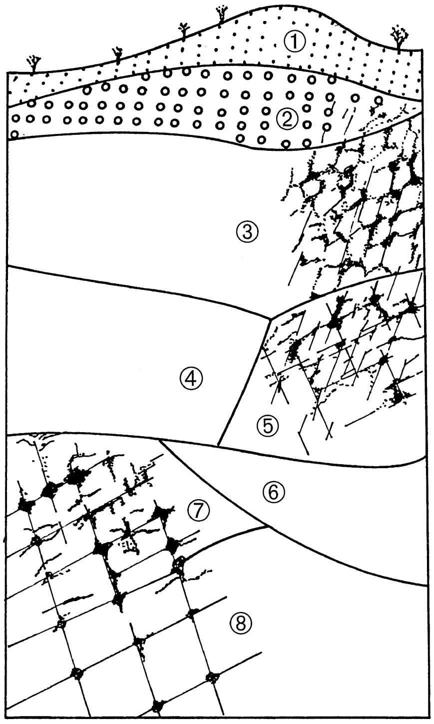

Fig. 2
Different zones of a weathered granitic profile observed at Malanjkhand Copper Mine. Zones are marked in numbers (1–8) – see Table 3

removed by dry grinding and only the well prepared specimens were selected for the laboratory testing.

Non-destructive tests were conducted to determine the physical index properties, after which destructive testing was undertaken. The point load strength, Brazilian and line load tests were carried out to determine the strength properties. Unconfined compressive strength was determined for each grade and the axial and diametrical strain measured under a constant rate of loading. Normally, three to six tests were undertaken for each sample following the method suggested by ISRM (1981b).

Each of the rocks tested was studied microscopically. Weathering features were noted and the proportion of altered to unaltered minerals recorded. Where appropriate, X-ray diffraction and SEM studies were carried out to assess the effects of weathering on the contained minerals.

Results and discussion

Physical properties

Physical properties, such as specific gravity, dry and saturated densities, moisture content, void ratio, absolute and effective porosities, quick absorption index and dry and saturated sonic wave velocities were evaluated. Generally, for each physical index the value quoted is the mean from 10 to 25 test specimens. The minimum and maximum values together with the mean values for the selected weathering grades are given in Tables 4, 5 and 6 for granite, quartzite and basalt, respectively. The results of absolute and effective porosity, void ratio and saturated moisture content are also summarised in the tables.

The porosity increases with the weathering sequence for all the rocks. In quartzitic rocks, the absolute and effective porosities are increased from circa 0.1% (fresh) to circa 17% and circa 11%, respectively. Basalt showed the highest increase in porosity with weathering, from circa 0.66% in

Table 3
Different weathering zones over a typical profile of granite

Zone	Decription	Class
1	Structureless layer of soil of variable thickness. Various shades of dark to light reddish brown show different horizons of vegetation, leaching and accumulation. Rock fabrics are absent	Residual soil
2	The zone contains predominantly decomposed rocks; most of the materials are W_4 (70%); floating rounded regoliths can be seen; original rock fabric preserved; relict joints are visible; the weathering is heterogeneous with very little development of corestones	Completely weathered
3	The zone is more than 70% highly weathered material (W_3 grade). Rectangular blocks are separated by thin seams of decomposed and friable materials	Highly weathered
4	This zone has suffered little decomposition; friable materials are limited to narrow seams of joints	Moderately weathered
5	Moderately weathered material represents the exposed part of the zone; some joints are clearly visible with aperture widths of 5–10 mm; joint surfaces are highly weathered; the joint no./m ranges from 2 to 4	Moderately weathered
6	Joints are rough with aperture widths of 1–3 mm; some joints are filled with highly weathered materials; very thin layer of weathered material can seen at the margin of a few blocks	Slightly weathered
7	The features are similar to those in zone 6, with almost no sign of corestone development	Slightly weathered
8	Large blocks are present in this zone with slight staining joint at surface; few discontinuities, randomly spaced and oriented	Slightly weathered

Table 4
Physical index properties of fresh and weathered granite

Physical index properties	GW_0				GW_1				GW_2				GW_4			
	Min	Max	No	Av	Min	Max	No	Av	Min	Max	No	Av	Min	Max	No	Av
Sp. gravity (G)	2.77	2.79	5	2.78	2.72	2.78	6	2.74	2.59	2.62	5	2.61	2.58	2.62	5	2.61
Dry density ($_d$) (g/cc)	2.64	2.79	15	2.75	2.65	2.76	18	2.69	1.82	2.90	14	2.54	1.88	2.08	15	1.97
Sat. density ($_s$) (g/cc)	2.65	2.79	15	2.75	2.66	2.78	18	2.71	1.84	2.95	14	2.58	2.13	2.29	15	2.19
Sat. moisture content (%)	0.01	0.07	15	0.03	0.48	0.70	18	0.58	0.94	2.14	14	1.37	8.67	13.39	15	11.10
Void ratio (e)	0.002	0.01	18	0.01	0.013	0.036	18	0.02	0.075	0.099	14	0.09	0.25	0.38	15	0.32
Porosity (absolute; η_a) (%)	0.02	0.95	15	0.61	1.32	3.49	18	2.09	7.01	9.05	14	7.89	20.30	28.05	15	24.41
Porosity (effective; η_e) (%)	0.05	0.10	15	0.09	1.30	2.51	18	1.46	2.98	4.10	14	3.28	20.12	24.36	15	21.92
Quick absorption index (%)	0.003	0.03	15	0.01	0.40	0.65	18	0.51	0.80	1.76	14	1.16	6.09	11.00	15	9.03
US wave velocity (dry) (m/s)	5854	6096	15	5983	3307	4088	18	3691	1124	2280	14	1449	131	199	10	178
US wave velocity (sat.) (m/s)	5860	6137	15	5986	4243	4557	18	4437								

Table 5
Physical index properties of fresh and weathered quartzite

Physical index properties	QW_0				QW_1				QW_2				QW_3				QW_4			
	Min	Max	No	Av	Min	Max	No	Av	Min	Max	No	Av	Min	Max	No	Av	Min	Max	No	Av
Sp. gravity (G)	2.68	2.68	5	2.68	2.65	2.63	5	2.64	2.66	2.65	5	2.65	2.66	2.66	5	2.66	2.66	2.67	5	2.67
Dry density ($_d$) (g/cc)	2.68	2.68	11	2.68	2.58	2.61	16	2.59	2.48	2.52	16	2.50	2.36	2.47	26	2.42	2.06	2.31	15	2.20
Sat. density ($_s$) (g/cc)	2.68	2.68	11	2.68	2.58	2.62	16	2.60	2.53	2.56	16	2.54	2.42	2.52	26	2.47	2.15	2.79	15	2.31
Sat. moisture content (%)	0.02	0.03	11	0.02	0.20	0.35	16	0.25	1.28	2.64	16	1.62	1.54	2.55	26	2.02	3.57	6.34	15	4.89
Void ratio (e)	0.0006	0.002	11	0.001	0.01	0.02	16	0.02	0.05	0.07	16	0.06	0.075	0.127	26	0.10	0.16	0.29	15	0.21
Porosity (absolute; η_a) (%)	0.06	0.20	11	0.11	1.14	2.35	16	1.97	4.72	6.40	16	5.54	6.96	11.27	26	9.16	13.5	23.0	15	17.4
Porosity (effective; η_e) (%)	0.05	0.10	11	0.07	0.54	0.91	16	0.65	3.81	5.90	16	4.06	3.10	6.21	26	4.89	8.43	15.4	15	10.8
Quick absorption index (%)	0.007	0.02	11	0.02	0.12	0.60	16	0.2	1.02	1.57	16	1.32	1.51	1.85	26	1.71	3.54	4.95	15	4.39
US wave velocity (dry) (m/s)	5753	5930	11	5800	5153	5514	16	5410	1433	2111	15	1703	845	1225	26	1012	916	1518	15	1357
US wave velocity (sat) (m/s)	5753	5930	11	5800	5231	5597	16	5482	1592	2187	15	1829	–	–	26	–	–	–	15	–

fresh rock to circa 30% for BW_4. In these samples there was little difference between absolute and effective porosities indicating that voids and microfractures are only poorly interconnected. However, for BW_3 there was a significant difference between the absolute and effective porosity. In the case of completely weathered granites the porosities increased many times with the absolute porosity approximately 24% and the effective porosity 22% compared with 0.1 and 0.5%, respectively, for fresh granite. These observations correspond to those recorded by other researchers including Irfan and Dearman (1978a), Baynes et al. (1978), Saito (1981), Komoo and Yakub (1990) and Dobereiner and Porto (1993). Similar trends have been observed for the saturated moisture content, void ratio and quick absorption index.

Ultrasonic velocity

The maximum compressional wave velocity (V_p) measured in fresh rocks ranged between 5,800 and 6,000 m/s. The velocities for the various weathering grades for each rock are given in Tables 4 to 6. In each case the ultrasonic velocity decreased with increased weathering grade. Compared with fresh granite, GW_4 shows a 97% reduction in velocity. Unfortunately, it was not possible to test the basalt samples over the full of range of weathering.

In saturated conditions the ultrasonic velocity showed a general decrease with increased weathering which was considered to result from the development of micro-fissures and loosely bonded clay minerals.

Table 6
Physical index properties of fresh and weathered basalt

Physical index properties	BW_0				BW_1				BW_3				BW_4			
	Min	Max	No	Av	Min	Max	No	Av	Min	Max	No	Av	Min	Max	No	Av
Sp. gravity (G)	2.98	3.30	5	2.98	2.88	2.92	5	2.89	2.80	2.89	6	2.85	2.59	2.68	5	2.61
Dry density ($_d$) (g/cc)	2.90	2.98	18	2.96	2.66	2.77	14	2.74	2.35	2.54	12	2.47	1.73	1.88	15	1.82
Sat. density ($_s$) (g/cc)	2.91	2.98	18	2.96	2.73	2.81	14	2.79	2.44	2.64	12	2.56	2.02	2.20	15	2.12
Sat. moisture content (%)	0.14	0.29	18	0.22	1.12	2.74	14	1.82	2.46	5.53	12	3.86	15.37	17.25	15	16.19
Void ratio (e)	0.001	0.002	18	0.001	0.04	0.08	14	0.06	0.12	0.21	12	0.16	0.39	0.51	15	0.43
Porosity (absolute; η_a) (%)	0.11	2.70	18	0.66	4.12	7.99	14	5.24	10.92	17.51	12	13.54	27.89	33.85	15	30.13
Porosity (effective; η_e) (%)	0.18	1.56	18	0.64	3.10	7.48	14	4.97	6.19	13.45	12	9.50	28.32	32.14	15	29.52
Quick absorption index (%)	0.060	0.124	18	0.09	0.050	1.81	14	0.72	1.11	3.61	12	2.47	13.27	14.48	15	13.82
US wave velocity (dry) (m/s)	5138	6039	17	5760	4070	4726	12	4390	976	1371	10	1210	–	–	–	–
US wave velocity (sat.) (m/s)	5850	6449	17	6249	4444	5040	8	4836	1045	1452	8	1325	–	–	–	–

Table 7
Experimental results for strength index properties for fresh and weathered granite

Strength index properties	GW_0				GW_1				GW_2				GW_4			
	Min	Max	No	Av	Min	Max	No	Av	Min	Max	No	Av	Min	Max	No	Av
SHVR.	64	70	15	68.0	45	59	12	52.1	24	36	16	28.0	6	12	16	9.5
I_s (dry) (MPa)	10.03	10.92	5	10.4	6.75	8.20	5	7.90	2.31	2.96	6	2.87	0.02	0.44	6	0.16
I_s (sat.) (MPa)	7.86	9.06	5	8.59	3.27	3.47	5	3.39	0.25	0.68	6	0.40	0.01	0.02	6	0.01
σ_{tb} (dry) (MPa)	16.80	14.50	5	16.1	13.7	16.0	5	14.47	1.09	2.39	6	1.91[1]	0.9	1.10	7	0.97[1]
σ_{tb} (sat.) (MPa)	13.70	17.40	5	15.1	7.52	12.1	6	9.46	0.56	1.15	6	0.88	0.01	0.07	7	0.04[1]
σ_c (dry) (MPa)	120.9	140.6	5	132.8	102.0	103.7	5	102.7	48.1	62.2	15	53.01	2.17	2.94	6	2.54
σ_c (sat.) (MPa)	99.96	121.1	5	108.3	81.1	84.2	5	82.46	32.5	34.3	5	33.43	0.43	0.54	5	0.48

[1] Instead of Brazilian tests, line load tests were carried out due to prismatic specimens

Schmidt hammer value

As seen in Tables 7, 8 and 9, the Schmidt hammer rebound numbers (SHVR) vary between 66 for quartzite and 70 for basalt. The mean rebound numbers indicate a decrease in value with increase in weathering for all rocks and hence the Schmidt hammer values are almost directly comparable with the different weathering states.

Point load (Is)

The point load value for fresh quartzite and granite was approximately 10.5 MPa while that for basalt was approximately 15 MPa. Again the point load strength decreases with increasing weathering such that W_4 materials may have a 99% reduction in strength compared with the fresh material. As anticipated, the saturated specimens showed lower values than those tested dry. With quartzite, the difference between the dry and saturated Is values was small, being more pronounced for granite and basalt, particularly at higher weathering grades.

Indirect tensile strength (σ_{tb})

The Brazilian tensile strength varied between 26.5 MPa for fresh basalt to 16.1 MPa for granite. It is of note that due to the difficulty in preparing cored specimens, cubic and prismatic specimens were tested under line load. As a consequence, the results may not be comparable with the Brazilian tensile strength, even for the same rock type. Fresh quartzite had a Brazilian tensile strength of 20.5 MPa which decreased progressively with weathering grade.

Unconfined compressive strength (σ_c)

As seen in Tables 7, 8 and 9, the fresh quartzite had a UCS value of 207 MPa, the basalt 173 MPa and the granite 133 MPa. Basalt and granite showed a similar decline in UCS strength with a reduction of approximately 98% in the completely weathered material compared with the fresh variety. The effect of saturation on the UCS value is most pronounced in basaltic rocks while only a very small reduction was noted in the quartzitic rocks.

Relationship between index properties

Comparisons have been made between the different rock types in fresh and weathered conditions.

For the research reported here, the data available in the literature for different rock types (generally igneous) from different parts of the world have been collated. Linear and

Table 8
Experimental results for strength index properties for fresh and weathered quartzite

Strength index properties	QW$_0$				QW$_1$				QW$_2$				QW$_3$				QW$_4$			
	Min	Max	No	Av	Min	Max	No	Av	Min	Max	No	Av	Min	Max	No	Av	Min	Max	No	Av
SHVR.	60	69	16	66.18	44	54	20	47.73	31	36	24	33.14	21	28	28	26.08	—	—	—	—
I_s (dry) (MPa)	9.98	10.85	5	10.49	7.51	8.15	6	7.86	1.53	1.98	6	1.80	7	1.26	0.25	0.46	7	0.34		
I_s (sat.) (MPa)	9.92	10.84	5	10.31	7.14	8.40	6	7.69	1.85	1.66	6	1.54	0.95	1.07	7	1.00	0.23	0.38	6	0.27
σ_{tb} (dry) (MPa)	17.99	21.72	6	20.47	13.31	13.71	6	13.55	6.23	8.14	6	7.25	3.43	3.78	7	3.61	1.00	1.81	7	1.39
σ_{tb} (sat.) (MPa)	19.56	21.71	6	20.45	11.38	13.34	6	12.31	6.13	8.08	6	6.99	3.12	4.27	7	3.64	0.91	1.10	8	1.04
σ_c (dry) (MPa)	204.1	209.6	5	207.0	120.9	129.9	5	125.6	58.28	61.70	6	60.6	30.69	33.64	6	32.20	11.0	13.4	6	12.4
σ_c (sat.) (MPa)	202.4	207.1	5	206.2	106.7	127.8	5	116.6	51.01	56.90	6	53.96	22.93	31.73	6	26.99	8.38	9.70	6	9.04

Table 9
Experimental results for strength index properties for fresh and weathered basalt

	BW$_0$				BW$_1$				BW$_3$				BW$_4$			
	Min	Max	No	Av	Min	Max	No	Av	Min	Max	No	Av	Min	Max	No	Av
SHVR.	68	71	15	69.6	42	46	20	43.8	16	23	20	19.8	4	5	21	6.4
I_s (dry) (MPa)	14.79	15.55	5	15.15	6.05	6.88	5	6.23	0.64	1.01	5	0.49	0.04	0.43	6	0.17
I_s (sat.) (MPa)	11.49	13.21	5	12.21	3.71	6.88	6	5.83	0.26	0.71	6	0.40	—	—	—	—
σ_{tb} (dry) (MPa)	26.09	28.80	6	27.46	14.50	18.15	5	16.25	1.78	2.11	8	1.90[1]	0.07	0.33	8	0.21[1]
σ_{tb} (sat.) (MPa)	23.95	26.09	5	25.47	12.90	13.85	6	13.49	0.63	1.01	8	0.86[1]	—	—	—	—
σ_c (dry) (MPa)	169.6	174.1	5	172.6	87.18	99.00	5	93.2	15.68	18.97	5	17.8	2.50	3.91	5	3.4
σ_c (sat.) (MPa)	143.1	148.01	5	145.5	72.17	75.65	5	73.91	8.60	9.20	6	8.97	—	—	—	—

[1] Instead of Brazilian tests, line load tests were carried out due to prismatic specimens

non-linear regression analyses have been undertaken to establish the best possible relationships between the variables.

Porosity and other index properties

The relationship between absolute porosity and point load, Brazilian index and unconfined compressive strength values is shown in Figs. 3, 4 and 5, respectively, and can be generalised as being negatively exponential. The figures show a relatively sudden decrease in strength between 0 and 5% absolute porosity, likely to represent the less weathered rock. This is particularly pronounced with the point load and Brazilian index tests (Figs. 3, 4) where the strengths fall to some 30% of their initial value when the absolute porosity is some 5%. In the case of the UCS strength (Fig. 5) however, the reduction is more gradual as the porosity increases.

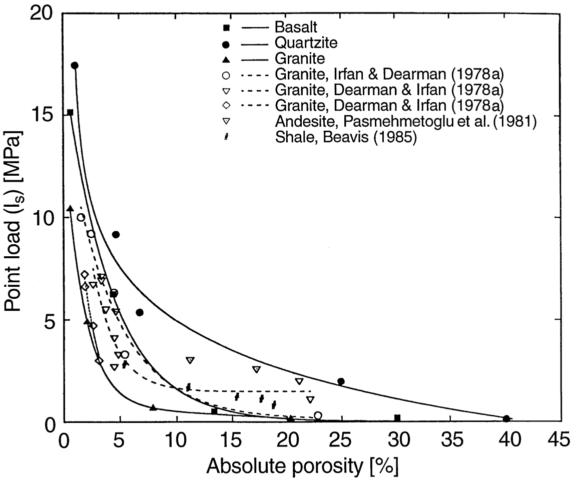

Fig. 3
Variation of I_s with absolute porosity for fresh and weathered crystalline rocks

Ultrasonic velocity and strength index properties

Figures 6, 7 and 8 show the variation between measured compressional wave velocity and UCS, Is and Brazilian strength values. It can be seen that in general, there is a positive correlation between the maximum compressional wave velocity and strength for all the rocks types. It is noted, however, that this may not be linear and as shown in the figures, the best fit line may be curved.

Schmidt hammer values and other strength index properties

Figures 9, 10 and 11 indicate a positive relationship between UCS, Brazilian index and point load value and the Schmidt hammer rebound number. It is noted from Fig. 9 that for each of the rock types, distinct linear trends are present, in part due to the initial strength of the unweathered rock; the granite in the present study having a UCS value of approximately 130 MPa compared with that of 280 MPa published by Irfan and Dearman (1978a). A relatively good correlation also exists between the Schmidt hammer and Brazilian test but no obvious straight line relationship is apparent with the point load value.

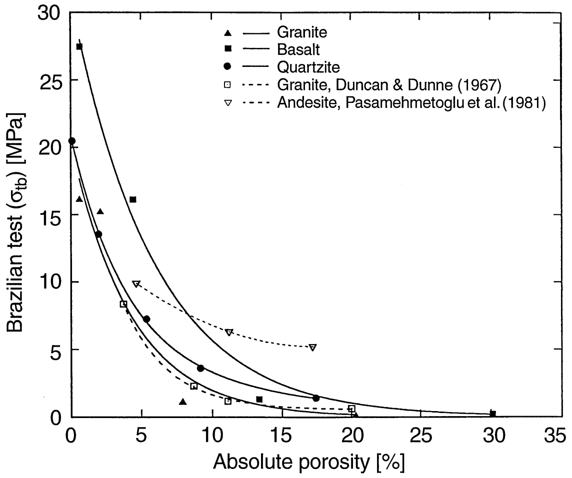

Fig. 4
Variation of σ_{tb} with absolute porosity for fresh and weathered crystalline rocks

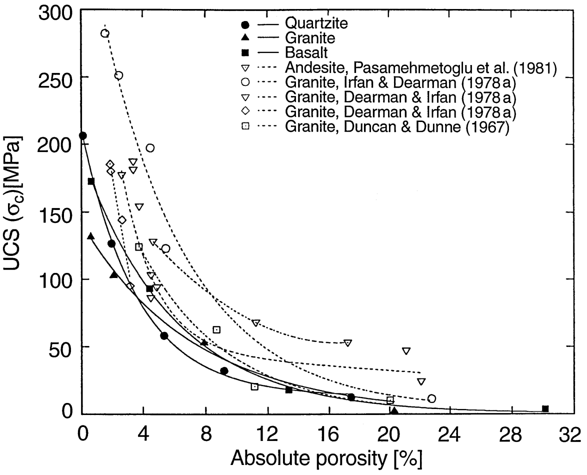

Fig. 5
Variation of σ_c with absolute porosity for fresh and weathered crystalline rocks

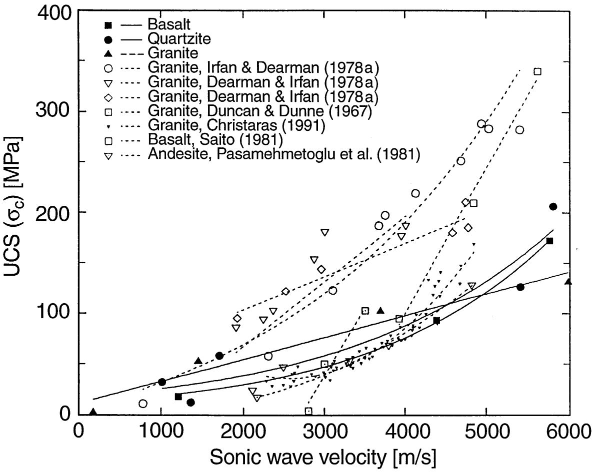

Fig. 6
Variation of σ_c with V_p for fresh and weathered crystalline rocks

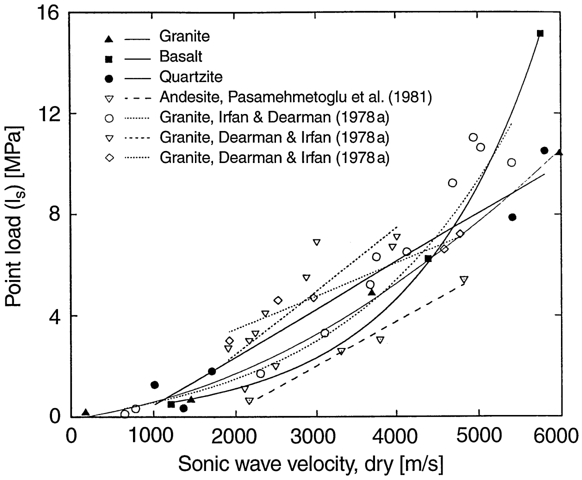

Fig. 7
Variation of I_s with V_p for fresh and weathered crystalline rocks

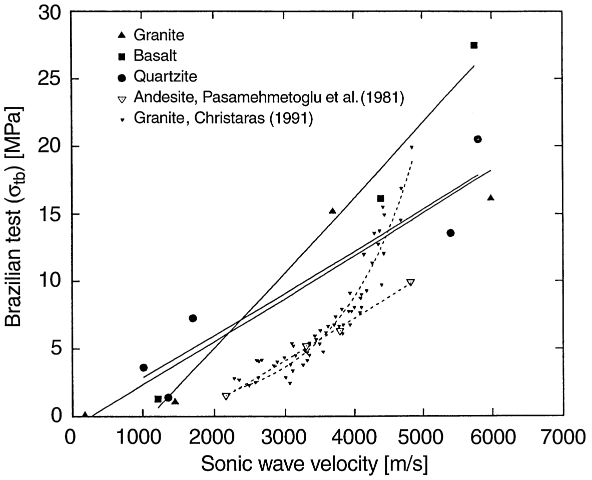

Fig. 8
Variation of σ_{tb} with V_p for fresh and weathered crystalline rocks

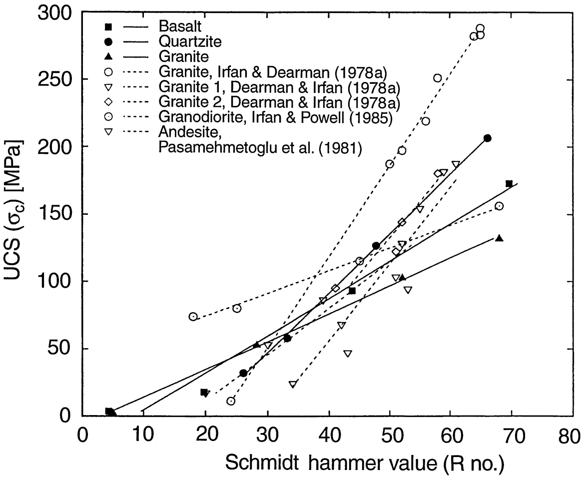

Fig. 9
Correlation between σ_c and Schmidt hammer value for different crystalline rocks

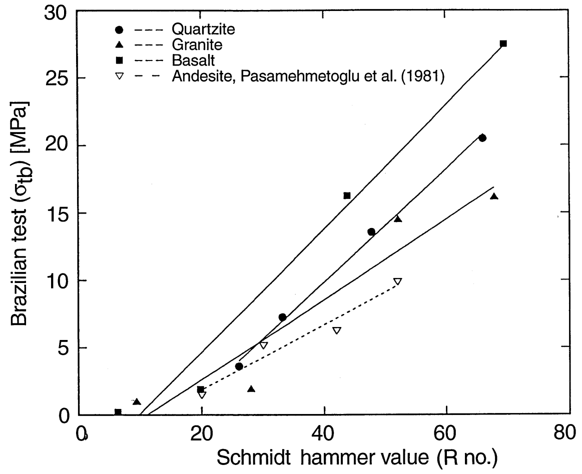

Fig. 10
Correlation between σ_{tb} and Schmidt hammer value for different crystalline rocks

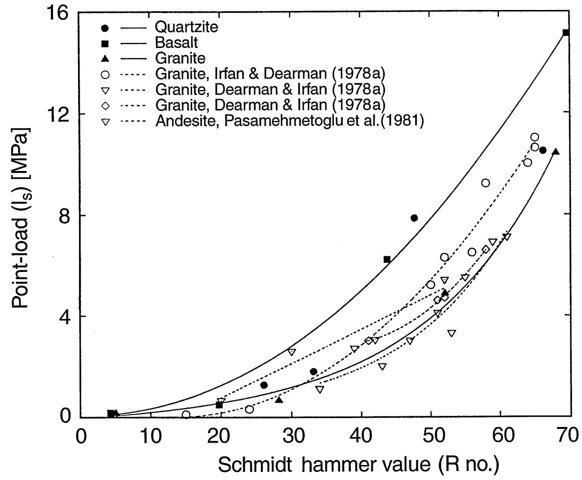

Fig. 11
Correlation between I_s and Schmidt hammer value for different crystalline rocks

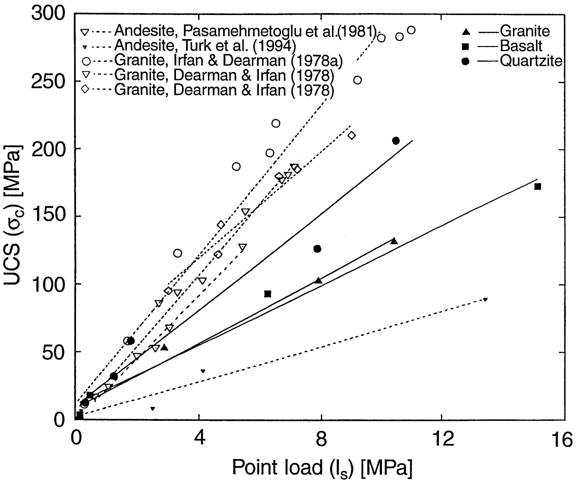

Fig. 12
Relationship between σ_c and I_s for fresh and weathered crystalline rocks

Indirect tensile strength and compressive strength

Figure 12 shows there is a clear linear relationship between the point load strength and compressive strength. It also indicates that the conversion factor ranges from 6 to 27, even for one type of rock. It will be noted that for granite, basalt and quartzite, the factors are 12, 16 and 18, respectively. Table 10 shows the value of conversion factor for different rock types in their fresh state and weathered state. It will be noted that whilst a conversion factor is valid for fresh and slightly weathered materials, towards the higher grades the conversion factor for a particular rock varies considerably with its state of weathering. This indicates caution should be exercised with the use of any UCS/Is factoring, particularly for the more highly weathered materials.

A similar situation is seen for the relationship between the UCS value and the Brazilian index (Fig. 13).

Table 10
Conversion factors, *K* or (UCS/I_s) for different rocks in their fresh and weathered state

Rock	**Source**	**Weathering grade**				
		I	**II**	**III**	**IV**	**V**
Shale (calc.)	Beavis et al. (1982)	8.4	8.3	6.4	4.2	–
Shale (dol.)	Beavis et al. (1982)	11.8	12.7	14.9	10.2	5.5
Agglomerate	Turk et al. (1994)	5.9	6.1	8.6	16.4	–
Andesite	Turk et al. (1994)	8.7	8.7	3.3	32.0	–
Andesite	Pasamehmetoglu et al. (1981)	23.7	22.4	20.5	26.6	–
Granodiorite	Irfan and Powell (1985)	14.2	12.8	11.4	12.3	85.0
Granite	Irfan and Dearman (1978a)	28.2	36.0	34.1	36.7	–
Granite	Dearman and Irfan (1978a)	26.3	25.1	31.8	23.5	21.8
Granite	Dearman and Irfan (1978a)	23.3	25.7	30.6	31.7	–
Granite	Present study	12.7	12.9	18.3	–	15.6
Basalt	Present study	11.4	14.9	–	36.7	20.0
Quartzite	Present study	19.7	16.2	32.2	26.7	36.5

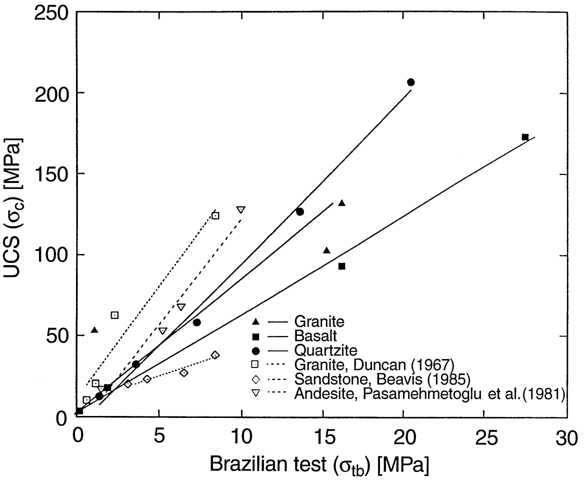

Fig. 13
Variation of σ_c with σ_{tb} for different rocks

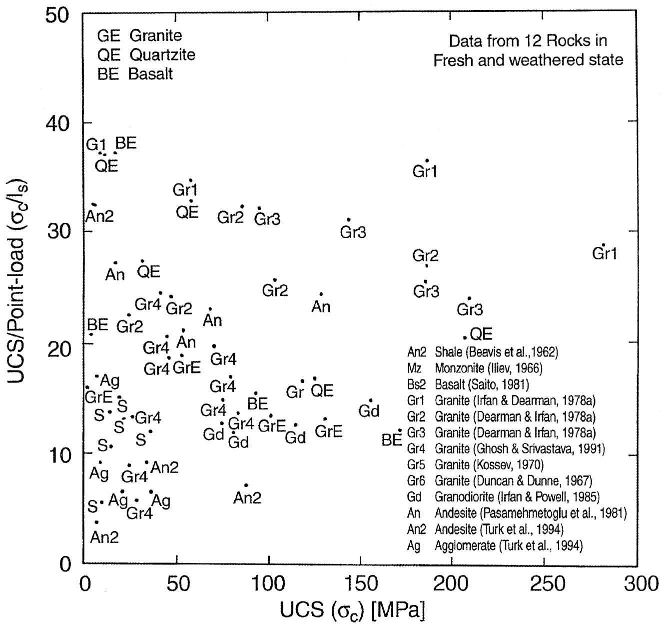

Fig. 14
Plot between conversion factor, *K* (i.e. σ_c/I_s) and σ_c for 12 different rocks

It will be noted from Fig. 14 that when the UCS value is divided by the point load value and plotted against the UCS value, there is no obvious trend for the twelve rocks included in the diagram.

Conclusions

The weathering process appreciably changes the strength properties of the Malanjkhand granite, Nagpur basalt and Delhi quartzite. Almost all the index properties have been found to vary progressively with the state of weathering. It has been noted that:

1. Weathering influences the tensile strength more strongly than the compressive strength, particularly at the initial stages of weathering.
2. Although there is a significant difference in the relationships between various index properties and weathering states, these vary according to both rock type and the property measured.
3. The unconfined compressive strength varies consistently with weathering grade while the point load test and Schmidt hammer test is less applicable for other than fresh or slightly weathered material.

The study has indicated that the factor relating point load strength and UCS strength changes with differing weathering states. As a consequence, even for a single rock type, no one factor can be used for an entire weathering profile.

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