Weathering effects on the strength and deformational behaviour of crystalline rocks under uniaxial compression state

A.S. Gupta, K. Seshagiri Rao *

Department of Civil Engineering, Indian Institute of Technology Delhi, Hauz Khas, New Delhi 110016, India

Received 16 September 1998; accepted for publication 28 May 1999

Abstract

Uniaxial compression tests were performed on different categories of weathering of three lithological units: Malanjkhand granite; Nagpur basalt; and Delhi quartzite, occurring in central and northern parts of India. The deformational behaviour is studied in terms of variation in tangent modulus (E_{t50}) and initial modulus (E_i) due to weathering. The power relationship between uniaxial compressive strength (σ_c) and E_{t50} shows strong correspondence for weathering sequence of common rock types. This relationship has been established by regression analysis and significant correlation parameter (coefficient of determination, $r^2=0.87$) for crystalline rocks. It is shown that there is a systematic decrease in stiffness ratio, that is, ratio of tangent modulus and uniaxial compressive strength with increased weathering state. Comparison of E_{t50} and E_i values has shown that E_{t50} decreases more gradually than E_i, and reduction is more drastic for E_i values with an increased degree of weathering in all the three rock types. The mode of failure has been found to be influenced by weathering extent in rocks. A brief account is given of the intrinsic characteristics of fresh and weathered rocks and mineralogical changes produced by weathering investigated quantitatively. Correlation drawn between the petrographical and mechanical indices has shown that mechanical properties are apparently dependent on the intrinsic characteristics of weathered rocks.

Keywords: Deformability; India; Uniaxial compressive strength; Weathered rocks; X-ray diffraction

1. Introduction

In geotechnical investigations involved with surface and subsurface works, the evaluation of strength and deformability of rock and rock mass is frequently needed. These measurements become more difficult if the rocks encountered are influenced by weathering. The study of strength and deformational behaviour of rock under uniaxial compression condition is of vital importance, and not only provides basic material characteristics or design indices but also serves as useful data in analysis where the rocks are at a shallow depth. Most engineering works are confined to shallow depths where weathering has a dominant role to play and affects almost all the properties of rocks.

In this paper, the effects of weathering on three crystalline rocks (granite, basalt and quartzite) of India are shown to result in a progressive change in strength and deformability. The objectives of this paper are to study the petrological controls on the degradation of mechanical properties; to investigate the relationship between strength and deformational indices; and add the data of previous research for comparison of the relationships observed in the current study.

First, a brief review of the previous work on the influence of weathering on strength and deformability of crystalline rocks is presented. The material characterization and intrinsic properties are discussed in detail. The sampling method is given along with technique for specimen preparation. The failure mode of tested rocks was observed and discussed with reference to changes produced by weathering. The relationship between uniaxial compressive strength (σ_c) and tangent modulus (E_{t50}), that is, stiffness ratio, has been studied for 14 different rocks and their weathered varieties. The influence of mineralogical and textural variation due to weathering has also been investigated. The significance of each relationship has been evaluated through regression analysis and the calculated value of coefficient of determination (r^2).

2. Previous work: influence of weathering on mechanical properties

2.1. *Strength behaviour*

The uniaxial compressive strength (σ_c) has always been considered as a most reliable index for strength estimation of rocks. It also serves as a basic input for establishing the strength and deformability of the parent rock mass through empirical relationships. The weathering results in an immediate and significant reduction in the compressive strength (σ_c) of rocks. It has been unanimously observed by several researchers that rock material becomes more porous, soft, friable and weakened as the grain to grain bonding disrupts and microfractures and new minerals formed (Anon, 1995). In extremely strong rocks such as granite, the loss of strength between fresh (I) and moderately weathered (III) varieties may be as high as 80% (Dearman and Irfan, 1978). The breaking of bonds between mineral grains and the development of microfractures are responsible for the loss in strength (Beavis, 1985). It is clear that σ_c decreases gradually with an increase in the weathering state. Because of the reliability and consistency in the result, σ_c has often been used for measuring the degree of weathering. Lumb (1983) has noticed that the strength of several weathered granites and granodiorite depends on the mode of failure whether it is cataclasis or premature shear plane failure of the specimens.

Very few data exist relating to the effect of weathering on tensile strength (σ_t). Generally, rock materials are known for their low tensile strength and in weathered conditions the strength decreases drastically (Pasamehmetoglu et al., 1981; Turk et al., 1994). Based on a detailed study of tensile strength of clastic sedimentary rocks, Beavis (1985) observed as much as 75% loss in the tensile strength of fresh claystone compared with its slightly weathered grades due to the development of microfractures. It has been observed that the effects of weathering on tensile strength are not always dramatic as is the case for σ_c. However, the reverse is expected in crystalline and igneous rocks in which microfractures effectively control the tensile strength rather than compressive strength.

2.2. *Deformational behaviour*

The development of microfractures augmented by weathering and the transformation of brittle minerals by soft clays result in a significant loss of elasticity. Similar to strength variations, the tangent modulus (E_{t50}) values also gradually reduce with weathering. The influence of relict and secondary bonding and clay content on deformational and shear behaviour has been investigated by Ebuk et al. (1993) for weathered granites. Under uniaxial compression, variation of tangent modulus with increasing weathering grades has been studied by Hamrol (1961), Iliev (1966), Duncan and Dunne (1967), Irfan and Dearman (1978a), Irfan and Powell (1985) for granitic rocks; Pasamehmetoglu et al. (1981), Turk et al. (1994) for andesites; Beavis (1985), Beavis et al. (1982) for sedimentary rocks; and Dobereiner and Porto (1993) for gneiss. All of them noticed that weathering resulted in a reduction in the tangent modulus and an increase in the failure strain.

2.3. *Failure pattern in weathered rocks*

Physical models of the rock can provide useful information particularly when examining the mode of failure, as suggested by Bieniawski (1984). Several studies have been undertaken to observe the failure pattern in variety of rocks. Raisbeck (1973) reported that the mode of failure in a particular rock is dependent on the degree of weathering along with other weakening features like planes of weakness. He observed that tensile failure is most likely in fresh greywacke, whereas slightly weathered greywacke shows composite shear failure under unconfined compression. Shear failure through matrix was observed in completely weathered greywacke. Lumb (1983) also reported that highly strong and fresh granite fails violently with cataclasis failure whereas shear plane failures are most common in rocks belonging to Grades II, III and IV (of Moye's weathering classification). He statistically showed that the number of shear plane failure cases increase with increasing grade in Grades II, III and IV specimens.

3. Geology of rocks and field study

Most of the Indian rocks, which are quite old, have been considerably weathered since they have been exposed to a tropical-subtropical environment several times in the geological past. Permo-carboniferous, Neogene and other periods were marked with tropical climate prevailing in India (Krishnan, 1982). During these periods the Indian continent was much hotter ($\geq 40°C$) and humid than today. The land mass was positioned in the equatorial region during this period. Therefore, very low annual temperature range and heavy rainfall throughout the year could be expected during this period. The area in all likelihood, was covered by thick tropical forest and prone to intense rock weathering (Sen and Guha, 1987).

For an understanding of the pattern of weathering, detailed field studies were conducted over several vertically exposed rock–soil profiles. Malanjkhand granite, Nagpur basalt and Delhi quartzite rocks were selected for the study because of the differences in their composition and genesis, and hence varied resistance to weathering. The weathering profiles developed in different parts of the Indian lithological units (Gupta and Rao, 1998) are briefly discussed in the following sections.

3.1. Malanjkhand granite

This is a country rock of Precambrian age exposed in Malanjkhand copper deposit and forms a huge granitic terrain around Malanjkhand, encompassing >1500 km^2 in the states of Madhya Pradesh and eastern Maharashtra. Three profiles were selected at both the hanging and the footwall of the quarry. They are exposed as vertical slopes, comprised of several benches from the crest of the pit (RL 590) to the base (RL 484). A complete depth of 100 m was available for the profile study.

Mostly, the granites are medium to coarse grained porphyritic type and vary in colour from light grey to buff colours and pink shades. The mineral constituents are chiefly quartz, alkali felspar, oligoclase and various types of perthites. The secondary minerals such as biotite, chlorite, epidote and amphiboles occur in various proportions with some accessory minerals like apatite, sphene, zircon and limonite (Gupta, 1997). Perthitic intergrowth is also observed in some alkali felspars. The area is intruded by a few dikes and mineralization is associated with quartz veins and quartz monzonites.

Under the existing climatic conditions of Malanjkhand area, granite weathers easily (Sikka, 1989). They are severely weathered at and a few metres below ground surface, but traces of weathering are easily marked even up to 90 m depth. The development of weathering is more pronounced below the hills as compared to the flat or low lying areas (Gupta and Rao, 1998).

3.2. Nagpur basalt

Basalt of Deccan Trap, exposed at Nagpur, was studied at three profiles in road aggregate quarries at Lava and Khondali villages and deep foundation excavation sites at Savarkar Nagar. The area of study that lies in the western part of the Nagpur city, has almost monolithic geology. Three stratigraphic units of the Deccan Trap have been reported in succession by Alexander (1978). The basalt which is a part of Lower Trap (Upper

Cretaceous to Lower Eocene) completely occupies the area and is often overlain by Quaternary alluvium and black cotton soil. At some places, Lametas (Upper Cretaceous) and Gondwana rocks are visible but remained unexposed near the studied area.

The basaltic rock is hard, compact, melanocratic, dark grey to black and fine grained. The crystals are unable to be identified through naked eye. Under the microscope, plagioclases, pyroxenes and glass are apparent as the major constituting fractions (Gupta, 1997). Labradorite which is very common among plagioclases shows subophitic texture with augite. It is also observed that plagioclase and pyroxene are considerably weathered and oxidized. Chlorite and altered magnetite were reported along with other minerals.

3.3. Delhi quartzite

The quartzites of the Delhi were studied at exposed areas of south Delhi and the Delhi–Harayana border. Five profiles were selected at different places where full development of weathering is featured within the rocks. The quartzites are of Alwar series of Delhi system belonging to the Precambrian age (Early or middle Proterozoic; ca 2 BY). Primarily, Delhi quartzites are of sedimentary origin which have been subjected to various degree of metamorphism (Krishnan, 1982). The rocks of Delhi System rest over older gneisses and Raialos with a great unconformity and are overlain by the Vindhyans. The base of the quartzite is not exposed and rock is intruded by pegmatites [age 713–915 MY; after Tyagi (1980)]. At many places the quartzites are covered by recent alluvium.

The rock is light to dark grey in colour and predominantly composed of quartz. It is observed that 85–95% of quartz with few accessory minerals like muscovite, biotite, felspars and opaques (5–13%) constitutes the Delhi Quartzite (Gupta, 1997).

The extent of weathering was observed ranging from highly affected at surface to being invisible at the bottom of the profile. The weathering extent is generally marked by a variable degree of staining. This is identified in various colours and hues from pale-yellow to dark brown at the joints and exposed surfaces. At some places, pitted surfaces of joints are noticed which may be ascribed to the action of differential solution of inhomogeneous constituents. This is due to the excessive leaching of Fe-oxides that dissolve under certain solution action. The size of pits varies from 7 mm to microscopic level.

4. Material identification

Generally, the stages of weathering are sequential and gradational, and each stage of weathering is followed successively by the next increasing stage of weathering. Each of the stages is characterized by several features like, discolouration, staining, altered/unaltered minerals, textural changes and other visible features. Relative strength is very important in practice to assess the competence of rocks. Though sometimes, it gives vague expression but if studied qualitatively as well as quantitatively it could act as good tool in differentiating the weathering grades.

In the present study, relative strength was assessed qualitatively by geological hammer and pick, knife and nail. Further, Schmidt hammer was also used to quantify the strength parameter. Observations showed that few recognition characteristics vary continuously throughout all the stages of weathering but some factors are limited within certain grades in the complete weathering scale. The present opinion is in good agreement with findings of Lee and de Freitas (1988).

A set of five recognition factors has been identified and used to cover all the important visual characteristics changing in the complete weathering spectrum. These are: discolouration and staining; texture and fabric; disintegration; decomposition; and relative strength. The description of these parameters is detailed by Gupta (1997). Based on these recognition factors the weathered materials were categorized into six grades which are described briefly in Table 1 for weathered granite. The terms and symbols are adopted as suggested by IAEG (1981) and ISRM (1981a), since

Table 1
Categories and description of weathered granite

Grades	Visual identification description
Fresh rock (W_0)	Grey or pink coloured. No discolouration. Grains have a vitreous lustre. Virtually no major cracks are present.
Slightly weathered (W_1)	No significant staining. Dull lustre of minerals. Grains are tightly bonded. Few felspars are gritty. Hair line cracks are visible in small quantity.
Moderately weathered (W_2)	Slightly stained. Few grains are gritty in appearance. Altered microcracks are visible, but they are tight. Few felspars (plagioclase) are decomposed. Felspar can be scratched. Sample can be broken by one firm blow of a geological hammer.
Highly weathered (W_3)	Discoloured and highly stained into a pale brown colour. Most grains are gritty and clayey. Loosely bonded fractured grains of quartz. Microcracks are filled with clays. Few felspars are undecomposed.
Completely weathered (W_4)	Completely discoloured. Specks of white clays are present. Very loosely bonded grains. Microfractures are open and filled with clay and air. Sample can be crumbled by fingers.
Residual soil (W_5)	Original texture is lost. Samples become granular with virtually no strength.

the description remains almost the same (Table 1). For recognition, the initial letter of the rock name is prefixed by the grade symbol, for example, QW_2 stands for moderately weathered quartzite.

5. Sampling and test specimens and test procedures

Samples of identified weathering grades were collected to represent each rock type and weathering grade. Grab sampling method was adopted in a biased way so that each sample exhibited uniform distribution of weathering and representation of the weathered zone. Large sized blocks (ca 40 cm × 30 cm × 20 cm) were preferred which were capable of providing a sufficient number of core specimens. Completely weathered and other weakened samples that were highly prone to collapse by disturbance, were immediately covered with plaster of Paris and safely transported to the laboratory. All the test specimens were prepared in the laboratory through coring with special care taken to obtain high quality cores. As coring was sometimes difficult, cubical and prismatic specimens 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 removed by dry grinding and only well prepared specimens were selected for laboratory testing. Specimens once prepared were tested for physical properties (Gupta and Rao, 1998) and point load, line load and Brazilian tests according to the methods suggested by ISRM (1981b) and IS10082 (1981).

The uniaxial compressive strength test was conducted on cylindrical specimens ($L/D=2$) under dry and saturated conditions. Simultaneously, deformational response to compressive stresses was also measured with the help of two pairs of electrical strain gauges (for axial and diametral strain) fixed at the middle portion of the curved surface of specimen with epoxy resin adhesive. The number of tests carried out over different variety of rocks and procedures followed as per the suggested methods by ISRM (1981b).

In order to record mineralogical abundance and textural features in each rock type and their weathered derivatives thin sections were studied under the petrological microscope. Modal analysis was undertaken by employing an automatic point counter (Eleco, model E1–144) mounted on Leitz Orthoplan Microscope. The mineralogical variation throughout the weathering sequence of each rock has been studied through X-ray diffraction (XRD). Whole rock analysis was carried out using the powder technique. The diffractograms were obtained by using an advanced instrument XRD model GEIGERFLEX D/max-B (Rigaku, Japan) with Cu Kα (1.54 Å) radiation.

6. Results and discussion

6.1. Mineralogical variation

6.1.1. Malanjkhand granite

X-ray diffraction data of different weathering grades of granite reveals significant variation in the mineralogy throughout the weathering sequence. Minerals such as orthoclase, microcline, albite, oligoclase, muscovite, quartz and biotite are distinct with their sharp peaks [Fig. 1(a and b)]. Tourmaline and epidote are also noticed with feeble peaks in fresh granite (GW_0). Kaolinite and illite clay minerals are identified in higher weathering grades and residual soils [Fig. 1(d) and (e)]. The peak of quartz (at 1.548 Å) shows a slight reduction in intensity with increased weathering stages. At the higher weathering grades, shifting of muscovite peaks and appearance of illite are also observed.

6.1.2. Nagpur basalt

Mineralogical changes studied through the peaks obtained from the whole rock analysis show appearance and disappearance of certain minerals throughout the weathering range from fresh basalt to residual basaltic soil [Fig. 2(a)–(e)]. Plagioclase and pyroxene are the most prominent peaks along with small peaks of olivine and zeolites. Amongst the zeolites, laumontite and mesolite were identified (Brack, 1974). Retarded peaks of plagioclase and pyroxenes can be noticed in samples of BW_3 grade as shown in Fig. 2(c). Montmorillonite and goethite peaks are noticeable in the same rocks. Peaks for plagioclase felspars are reduced in residual soil, whereas most of the peaks are identified as belonging to montmorillonite [Fig. 2(e)].

6.1.3. Delhi quartzite

A comparative study of the diffractograms of fresh quartzite and its weathered varieties shows that most of the peaks of minerals (mostly of quartz) are identical in all the grades. Quartz peak at 1.548 Å shows a slight reduction in its intensity towards higher degree of weathering [Fig. 3(a)–(f)], indicating a disruption of the quartz crystal along a certain lattice plane. A small peak of kaolinite appears in the QW_4 and QW_5 grades. The peaks of goethite and felspar are also observed in some stages. Hematite may be present, which is identified by the peak of 1.452 Å [$I/I_0 = 35$; JCPDS (1988)].

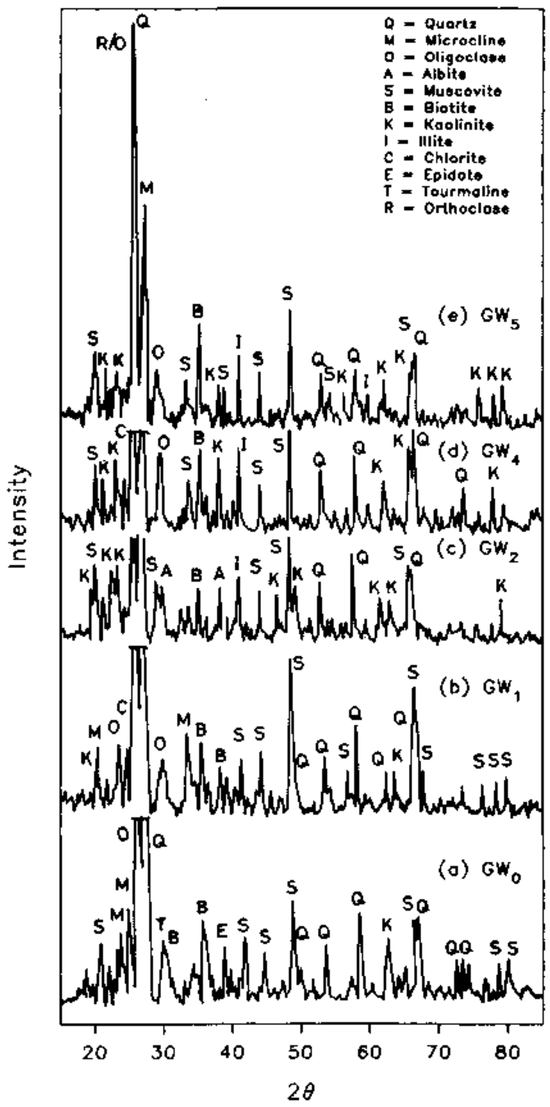


Fig. 1. X-ray diffractograms of fresh and weathered varieties of granite and granitic residual soil.

6.2. Physical properties

Important physical properties, such as specific gravity, dry and saturated densities, moisture

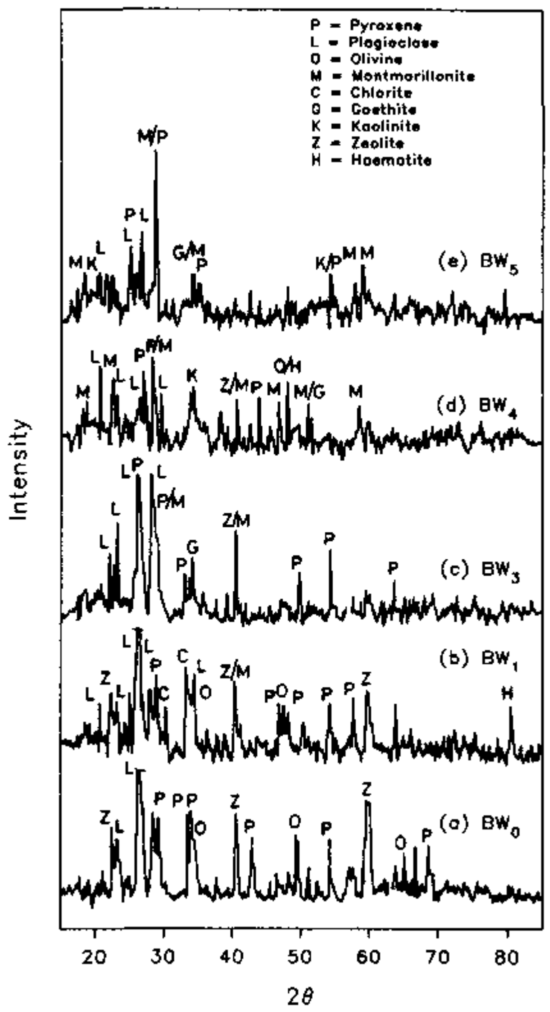


Fig. 2. X-ray diffractograms of fresh and weathered varieties of basalt and basaltic residual soil.

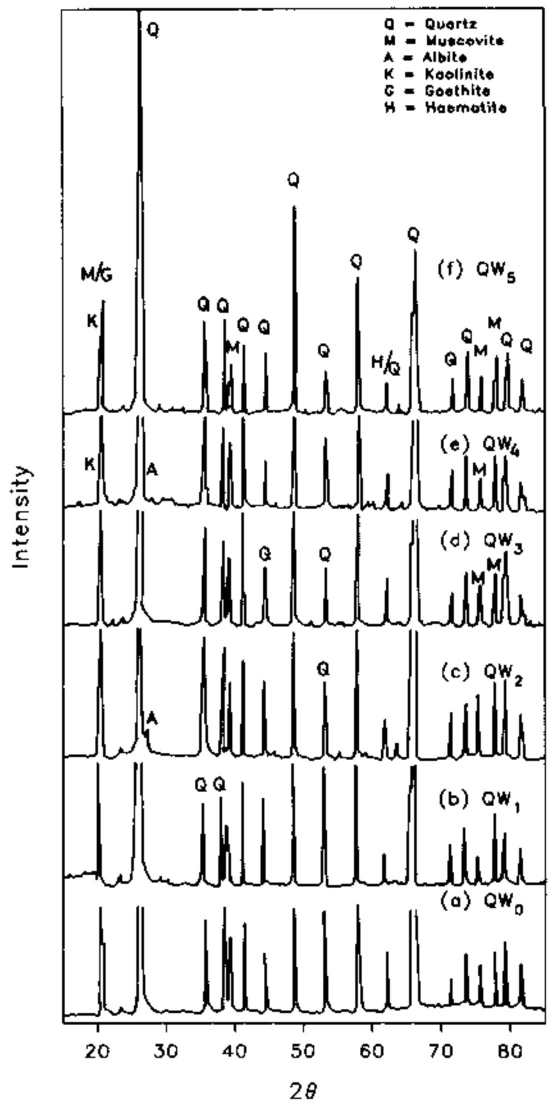


Fig. 3. X-ray diffractograms of fresh and weathered varieties of quartzite and quartzitic residual soil.

content, void ratio, absolute and effective porosities and quick absorption index were evaluated. Generally, for each physical index of the selected weathered grade the value quoted is the mean from 10 to 25 test specimens and is given in Table 2. The results of densities, absolute and effective porosity, void ratio and saturated moisture content are also in the table.

The porosity increases with the weathering sequence for all the rocks. In quartzitic rocks, the absolute and effective porosities are increased from ca 0.1% (fresh) to ca 17 and ca 11%, respectively. Basalt showed the highest increase in porosity with weathering, from ca 0.66% in fresh rock to ca 30% for BW_4. In these samples there was little difference between absolute and effective porosities indicating that voids and microfractures are not well connected. 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 abso-

Table 2
Physical index properties of fresh and weathered rocks

Index properties	Quartzite					Granite				Basalt			
	QW_0	QW_1	QW_2	QW_3	QW_4	GW_0	GW_1	GW_2	GW_4	BW_0	BW_1	BW_3	BW_4
Sp. gravity (G)	2.68	2.64	2.65	2.66	2.67	2.78	2.74	2.61	2.61	2.98	2.89	2.85	2.61
Dry density (ρ_d) kg m^{-3} (10^3)	2.68	2.59	2.50	2.42	2.20	2.75	2.69	2.54	1.97	2.96	2.74	2.47	1.82
Saturated density (ρ_s) kg m^{-3} (10^3)	2.68	2.60	2.54	2.47	2.31	2.75	2.71	2.58	2.19	2.96	2.79	2.56	2.12
Saturated moisture content (%)	0.02	0.25	1.62	2.02	4.89	0.03	0.58	1.37	11.10	0.22	1.82	3.86	16.19
Void ratio (e)	0.001	0.02	0.06	0.10	0.21	0.01	0.02	0.09	0.32	0.001	0.06	0.16	0.43
Porosity (absolute) (η_a) (%)	0.11	1.97	5.54	9.16	17.44	0.61	2.09	7.89	24.41	0.66	5.24	13.54	30.13
Porosity (effective) (η_e) (%)	0.07	0.65	4.06	4.89	10.83	0.09	1.46	3.28	21.92	0.64	4.97	9.50	29.52
Quick absorption index (%)	0.02	0.20	1.32	1.71	4.39	0.01	0.51	1.16	9.03	0.09	0.72	2.47	13.82

lute porosity ca 24% and the effective porosity 22% compared with 0.1 and 0.5%, respectively, for fresh granite. These observations correspond to those recorded earlier by Irfan and Dearman (1978b) and Dobereiner and Porto (1993). Similar trends have also been observed for the saturated moisture content, the void ratio and quick absorption index.

6.3. *Unconfined compressive strength*

In terms of unconfined compressive strength (σ_c), fresh quartzite is the strongest rock with a value of $\sigma_c = 207$ MPa followed by basalt (173 MPa) and granite (133 MPa) as shown in Table 3. Along the weathering sequences of these rocks, σ_c successively decreases at each increasing weathering stage. Basalt and granite show an almost similar declining trend of σ_c with a reduction of $\sim$98% in completely weathered grade (W_4) when compared with σ_c for their fresh counterparts. Quartzite exhibits a lesser reduction, that is, 94% in QW_4.

The influence of water saturation on the uniaxial compressive strength of tested rocks has been studied for different weathering grades. Earlier study shows that the presence of water in a rock leads to several mechanical and some chemical effects, the most important of which is probably the reduction in effective stress. The water tend to reduce the surface energy and crystal strength, resulting in that the mechanical strength of the rock is lowered and the deformability increased (Turk and Dearman, 1985). Colback and Wiid

Table 3
Experimental results for strength index properties of fresh and weathered rocks

Strength index properties	Quartzite					Granite				Basalt			
	QW_0	QW_1	QW_2	QW_3	QW_4	GW_0	GW_1	GW_2	GW_4	BW_0	BW_1	BW_3	BW_4
σ_{tb} (dry) (MPa)	20.47	13.55	7.25	3.61	1.39	16.13	14.47	1.91[a]	0.97	27.46	16.25	1.90[a]	0.21[a]
σ_{tb} (saturated) (MPa)	20.45	12.31	6.99	3.64	1.04	15.12	9.46	0.88[a]	0.04[a]	25.47	13.49	0.86[a]	–
σ_c (dry) (MPa)	207.03	125.60	60.60	32.20	12.40	132.80	102.70	53.01	2.54	172.55	93.2	17.80	3.40
σ_c (saturated) (MPa)	206.22	116.59	53.96	26.99	9.04	108.72	82.46	33.43	0.48	145.48	73.91	8.97	–
E_{t50} (dry) (GPa)	93.75	51.14	16.07	12.18	1.86	36.84	19.46	12.99	0.36	46.51	20.63	2.77	0.63
E_i (dry) (GPa)	119.70	56.00	4.29	2.00	1.14	51.70	13.40	9.60	0.20	59.70	32.60	1.97	0.10
ν (dry)	0.19	0.19	0.22	0.21	0.39	0.19	0.21	0.25	–	0.19	0.26	0.27	–
$\sigma_{c(dry)}/\sigma_{c(sat.)}$	0.99	0.92	0.89	0.84	0.73	0.82	0.80	0.63	0.19	0.84	0.79	0.50	–
D–M[b] Classification	BM	CM	DM	DM	EL	BM	CM	DM	EL	BM	CM	EL	EL

[a] Instead of Brazilian tests, line load tests were carried out due to prisamtic specimens.
[b] D–M, Deere and Miller (1966).

(1965), Bell (1978) and Rao (1984) studied the influence of fluids and water vapour and found time dependent loss of strength measured in sandstones.

Under saturated condition, σ_c of each grade of the rocks is marginally decreased. The effect of saturation on σ_c is highest in basaltic weathering sequence whereas, a reduction in σ_c is seemingly very slight in quartzitic rock. Furthermore, this reduction becomes more pronounced towards higher weathering stages than in fresh grade in all the rocks. The reduction in strength (σ_c) has been shown in terms of ratio of $\sigma_{c(sat.)}$ and $\sigma_{c(dry)}$ in Table 3. Apparently, loss of strength increases as the weathering grade increases, which implies that though the samples were immersed for 48 h and the possibility of chemical decomposition contributes insignificantly, increase of pore water pressure due to an increase in porosity results in an overall reduction in effective strength. Dobereiner and de Freitas (1990) have suggested that the difference in the percentage reduction of σ_c due to the presence of fluid would be attributed to differences in the area of grain to grain contact, variable porosity and the spatial distribution of cement.

6.4. *Tensile strength (indirect)*

It may be discerned from Table 3 that there is a difference in increasing orders of σ_c and σ_{tb} for the three fresh rocks. Unconfined compressive strength has the highest value for fresh quartzite, whereas the highest value of σ_{tb} has been observed for fresh basalt. This suggests that the grain size and texture have more importance in controlling the tensile strength rather than compressive strength along with other factors, like grain strength and microfractures. The highest value of Brazilian tensile strength (σ_{tb}) is observed to be 26.5 MPa for fresh basalt followed by 20.5 MPa for quartzite and 16.1 MPa for granite.

Due to the difficulty in preparing cored specimens, some cubical and prismatic specimens were tested under line load test. Therefore, the results may not be comparable with Brazilian tensile strength even for the same rock type. Quartzites (fresh and weathered), which have a complete range of σ_{tb} values, show an orderly decreasing trend with the advance of weathering grade.

6.5. *Stress–strain behaviour in unconfined compression*

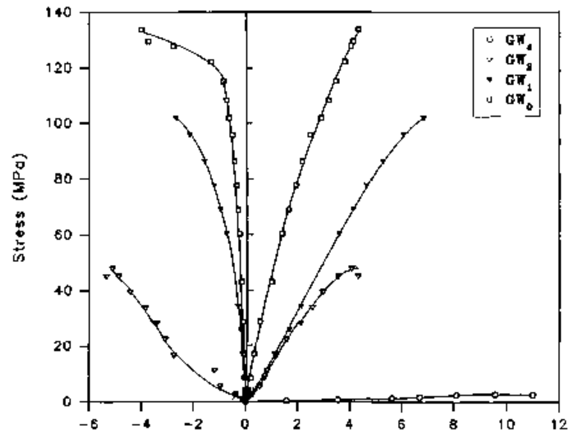
The stress–strain curves in unconfined state are plotted and presented in Fig. 4(a–c) for granite, basalt and quartzite, respectively. These figures show that fresh granite, basalt and slightly weathered quartzite behave almost linear-elastically (or quasi-elastically) over the full stress range. Hence, in these cases initial tangent modulus (E_i) remains almost equal to the tangent modulus (E_{t50}), at 50% of the failure strength as shown in Table 3.

The slightly weathered granite (GW_1) shows a feeble plastic behaviour at the very low stress level after which it behaves elastically or quasi-elastically. Slightly weathered basalt (BW_1), on axial compression, deforms elastically at certain stress level and later, on the verge of failure, it shows strain-softening [Fig. 4(b)].

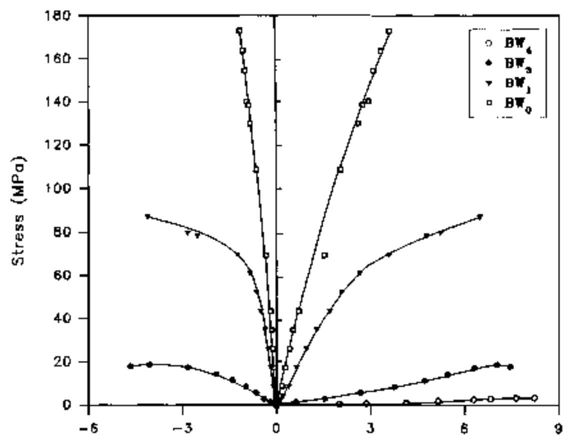
The GW_2 and QW_2 (moderately weathered rocks) show strain-hardening with initial tangent modulus less than E_{t50} at the beginning of loading at low compressive stress. At ca 50% of the axial stress value, both the rocks show almost linear behaviour after which they finally fail with strain-softening, as indicated in Fig. 4(a and c).

Highly weathered quartzite (QW_3) and all the completely weathered rocks also show similar behaviour of deformation. For these cases, the value of E_i always remains less than that of E_{t50} (Table 3). Fig. 4(a)–(c) clearly indicate that the initial part of plastic deformation is increased with increasing weathering effects. It is important to state that the onset of weathering, which results in immediate formation of microcracks and voids, changes deformational behaviour at three stages of loading. In a generalized inference, the mid-portion of the stress–strain curves remains elastic, and the length of elastic range decreases with increasing weathering grades. However, an initial portion of strain-hardening is also increased with weathering. Similarly, strain-softening appears to be increasing at the last portion of the stress–strain curve with an increase in weathering.

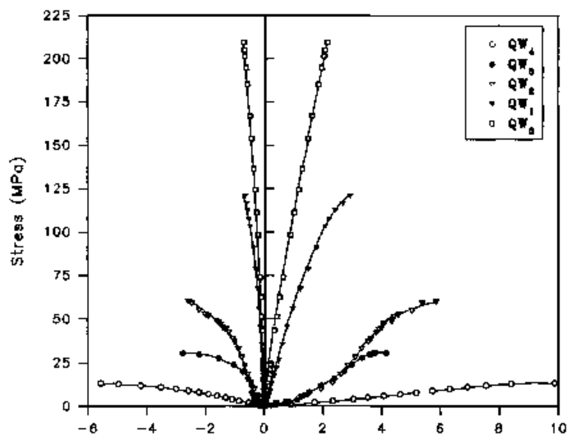
In view of the above discussion, the stress–



(a)



(b)



(c)

Fig. 4. (a) Stress–strain curves for fresh and weathered varieties of granite. (b) Stress–strain curves for fresh and weathered varieties of basalt. (c) Stress–strain curves for fresh and weathered varieties of quartzite.

strain curves for weathered crystalline rocks can ideally be categorized according to their shapes and corresponding weathering grades (Fig. 5).

6.6. *Deformational moduli*

The deformational parameters in unconfined compression condition have been graphically determined form stress–strain curves [Fig. 4(a)–(c)]. The initial tangent modulus, E_i is measured at the portion of stress–strain curve at initial loading, whereas tangent modulus, E_{t50} is measured at 50% of the failure strength. The maximum value of tangent modulus is observed as 94 GPa in fresh state of quartzite under dry conditions. This is followed by basalt with E_{t50} ~46 GPa and granite with E_{t50} as ~34 GPa. Similar to other strength properties, E_{t50} also shows an inverse trend with a progressive weathering grade. A reduction in modulus value from all the fresh rocks to their respective W_4 grades is roughly similar ranging between 98 and 99%. The results and variation of values are in accord with the findings of previous research.

The tangent modulus values under saturated conditions are lower than the values for dry specimens in all the weathering stages. This variation is considerable for granite and basalt but the same is not significant in quartzite. Table 3 reveals that E_i decreases more drastically than E_{t50} with the advancement of weathering in all cases.

6.7. *Poisson's ratio*

To examine the rock deformability more closely, particularly in terms of volumetric deformation, the measurement of both axial and lateral strains is quite significant. The Poisson's ratio (ν), ratio of lateral to axial strain has been measured at 50% of the failure strength for most of the cases except GW_4 and BW_4 rock specimens (Table 3). No lateral strains were obtained with the GW_4 and BW_4 grades due to premature failure of strain measuring system. Poisson's ratio was recorded as 0.19 for fresh category of the three rocks tested. It is apparent in Table 3 that the value of ν increases with increasing stage of weathering in all rock types. The disruption of grain to grain bond-

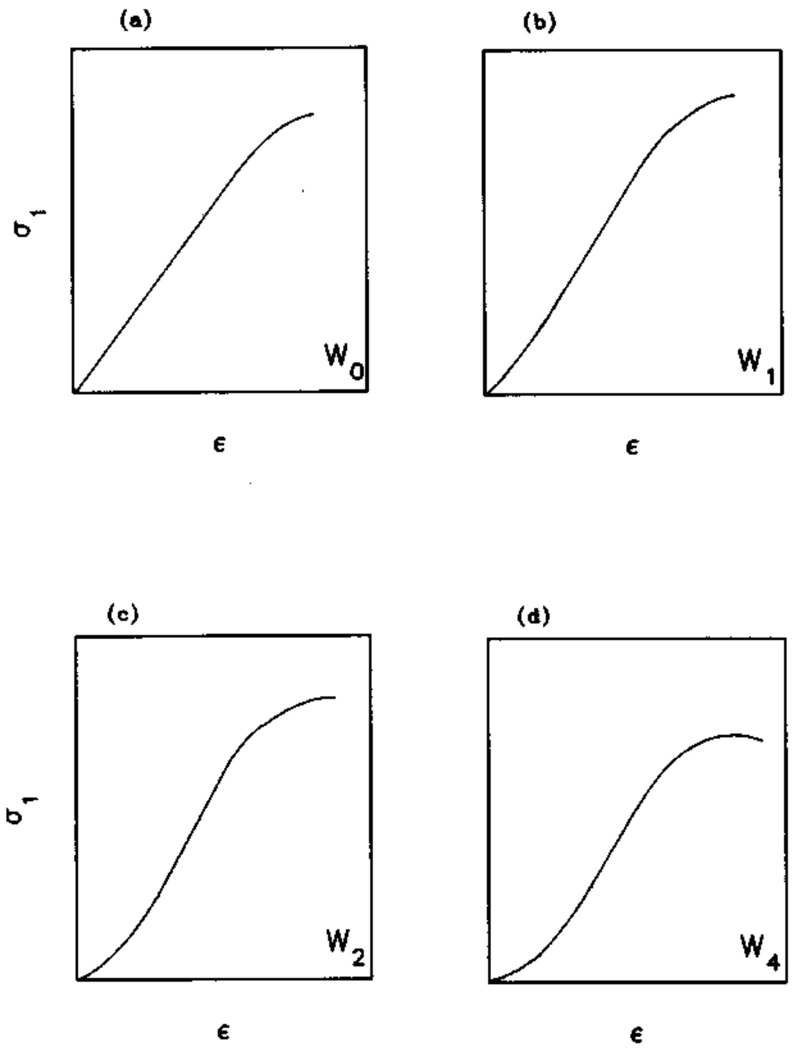


Fig. 5. Generalized stress–strain curves for (a) fresh, (b) slightly weathered, (c) moderately weathered and (d) completely weathered crystalline rocks under uniaxial compression conditions.

ing, increased microfracture and the development of secondary minerals which overall weaken the rock material in the due course of weathering, might be the reasons for the increase in v.

6.8. Relationship between modulus value and strength index properties

Comparison of the modulus value with the tensile strength indices and compressive strength seems quite significant, particularly when all the strength properties decrease with weathering in the rock material. The tangent modulus value (E_{t50}) decreases linearly with the indirect tensile strength σ_{tb}, as shown in Fig. 6. It also shows that the trend of best fit line observed in current study is in accord with the trend observed for the data reported in previous studies (Dearman and Irfan, 1978; Pasamehmetoglu et al., 1981; Beavis, 1985). It should be noticed that each weathering sequence has significant degree of correlation between E_{t50} and σ_{tb}. However, the difference is distinct between

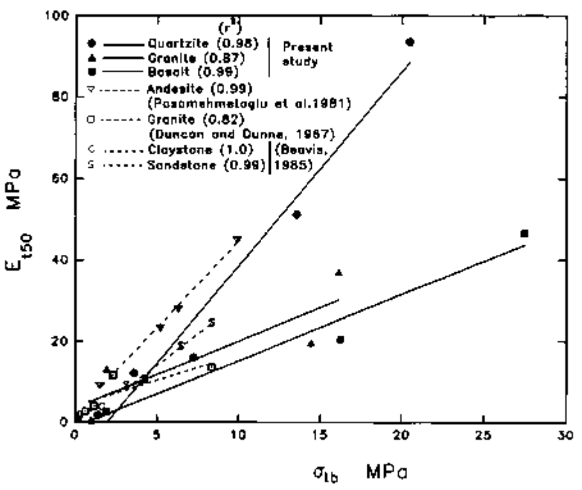


Fig. 6. Relationship between E_{t50} and σ_{tb} for different rocks.

trends of best fit lines for different rock types. This restriction for deriving a common relationship is valid for all the rock types.

Based on the experimental data of σ_c and E_t, the weathered derivatives of the three rocks were classified according to the ranges of σ_c and stiffness ratio (σ_c/E_{t50}) suggested by Deere and Miller (1966). The category of each rock is graphically shown in Fig. 7 and strength classes according to the Deere and Miller Classification (1966) are mentioned in Table 3. In Fig. 7, fenced regions suggested by Deere and Miller (1966) for common granites, basalts and quartzites are also illustrated. The plot of the test results shows that the suggested region of a particular rock type embraces only the data points of fresh and slightly weathered rocks. This implies that regions are valid for common rock types in fresh and less weathered state. As the range values of the σ_c and modulus ratio is quite wide for a classified category in Deere and Miller Classification, it seems that a possible relationship between σ_c and E_{t50} could be significant in providing the more accurate data. Considering this, regression analysis between σ_c and E_{t50} has been carried out. The relationship is best expressed by power function and illustrated in Fig. 8 for the results of granite, basalt, quartzite and other rocks (Duncan and Dunne, 1967; Dearman and Irfan, 1978a; Pasamehmetoglu et al., 1981; Irfan and Powell, 1985; Turk et al., 1994) having different

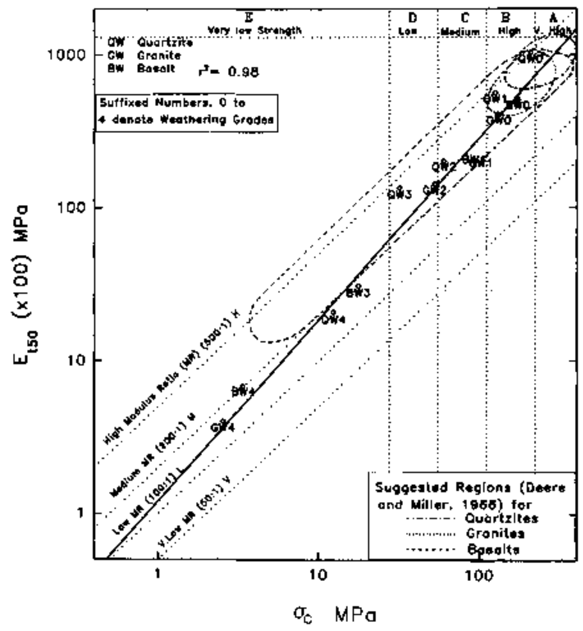


Fig. 7. Relationship between E_{t50} and σ_c and regions for fresh and weathered quartzite granite and basalt in Deere and Miller's classification.

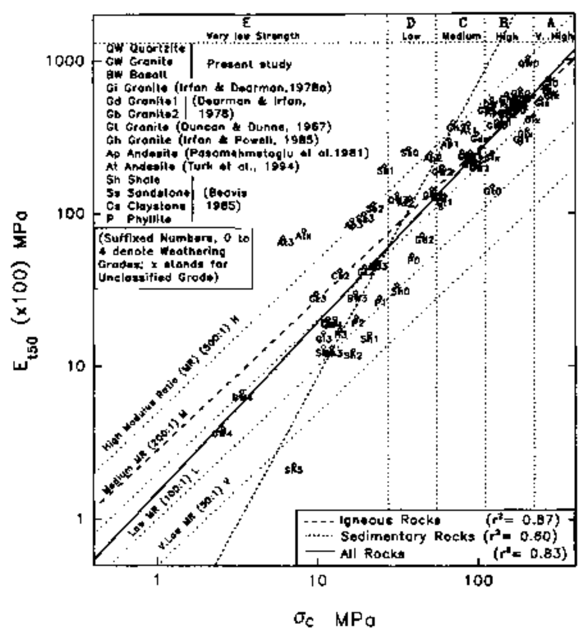


Fig. 8. Correlation between E_{t50} and σ_c for different rock types.

degrees of weathering. Fig. 8 depicts a close variation of the points falling between a stiffness ratio (E_t/σ_c) of 100–500. Regression analysis of all the available data yields a good correlation ($r^2=0.83$) for the best-fit line expressing the following relationships:

$$E_t=\sigma_c^{0.98}\times 286\ldots\text{for igneous rocks } (r^2=0.87), \tag{1}$$

$$E_t=\sigma_c^{1.91}\times 80\ldots\text{for sedimentary rocks } (r^2=0.60), \tag{2}$$

$$E_t=\sigma_c^{1.11}\times 150\ldots\text{for all rocks } (r^2=0.83). \tag{3}$$

This seems to be valid throughout the weathering range, particularly for igneous rocks. Attempts were made to observe the variation in the modulus value for different degrees of weathered sedimentary and metamorphic rocks. Fig. 8 also shows that the available data points of calcareous phyllite (Beavis, 1985) are much closer to that of Strut Meadows shale (Beavis et al., 1982) and following a similar trend, whereas Hawkesbury sandstone (Beavis, 1985) has a different course of variation between E_{t50} and σ_c with progressive weathering. However, the insufficient data and low r^2 values restrict the applicability of the relationship for weathered sedimentary and metamorphic rocks.

Since the classified notations (Figs. 7 and 8) are based on a wide range of σ_c and modulus ratio in classification, it may give false impression of accuracy of data. Moreover, the suggested fenced regions seem to be valid for only fresh rocks, one might consider using the given relationships [Eqs. (1)–(3)] in order to obtain the E_{t50} for a rock at any stage of weathering, if σ_c is known.

6.9. *Failure pattern in weathered rocks*

Regarding fracture initiation under compression, Bieniawski (1967) explained that the grain boundaries close as stress increases, then elastic deformation follows with fracture initiation and at last, stable fractures propagate. Ultimately, the rocks fail with fractures developed from the coalescence of several microfractures.

Gramberg (1989) differentiated three types of primary fracture phenomena: direct tensile brittle fracture; axial cleavage fracture; and a complex conjugate shear zone formed by open direct tensile cracks. Direct tensile brittle fracture can further be categorized into three types, based upon the nature of loading: tensile; bending; and torsion. In his view, the axial cleavage fracture is generally the result of compression where cleavage cracks develop in the direction of compression and may occur in three forms:

1. axial mono-fracture, usually observed in fine grained rocks and glass;
2. axial multi-cleavage fractures also observed in fine grained rock dividing the specimen into thin laminae; and
3. axial cataclasis in coarse grained rocks with granitic structure, where cataclasis involves intensive fracturing.

The third type of primary fracture phenomena is the result of stress differentiation, and during compressive tests numerous small shear zones, oriented in an en-echelon fashion, develop inside the specimen. This type is called multi-shear cataclasis in which sometimes small axial microcracks will occur at the same time, resulting:

1. by buckling, bending out of the specimen gradually or suddenly where the specimen fails violently; and
2. by shearing off where originally the solid rock changes to a granular-like structure of the loose granular mass.

Usually weak rocks fail in such a mode (Gramberg, 1989).

The mode of failure in a particular rock is always influenced by the intrinsic properties of material and mode of testing, and if rock is weathered, it also depends on the degree of weathering. In the present study, observations were made on the failure pattern of the rock specimens loaded in an unconfined state. Most of the fresh variety of basalt and quartzite, and slightly weathered quartzite specimens fail violently releasing the stresses instantaneously with axial tensile-fractures parallel to the direction of loading; the developed fracture patterns are shown schematically in Fig. 9. In some cases three clean tensile-fractures were noticed passing vertically through the specimen and making a 60° angle from each other measured at the flat surface.

Fresh granite also follows the same trend of

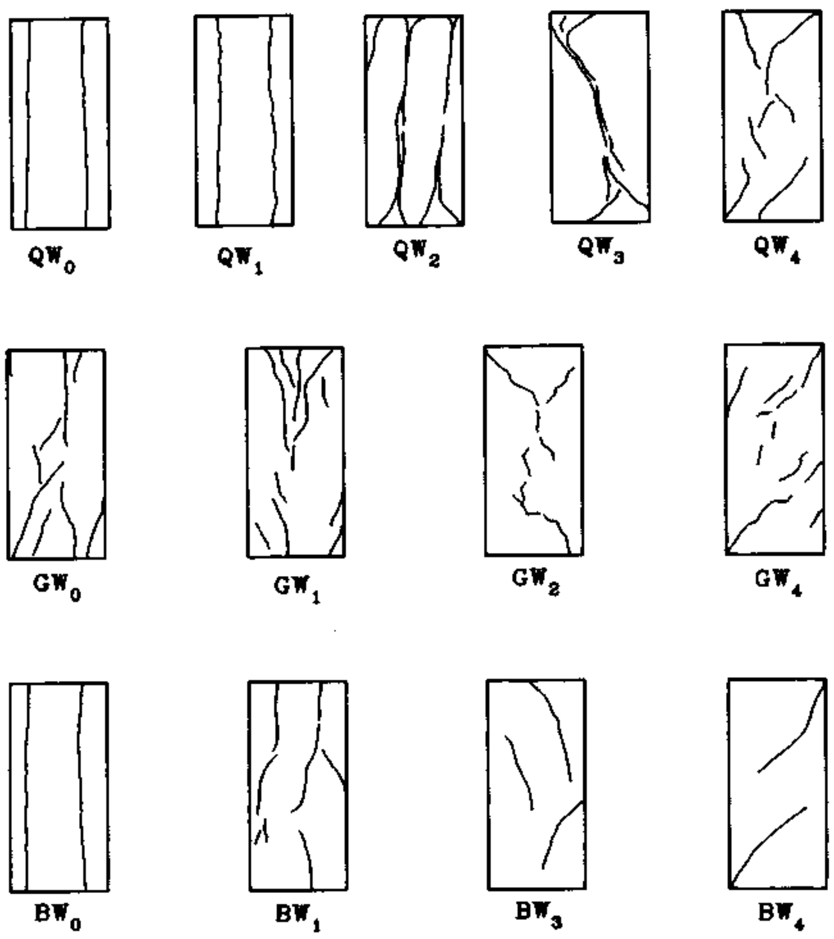


Fig. 9. Diagrammatic view of the typical fracture pattern developed in quartzites, granites and basalt under unconfined compression.

axial cataclasis fracture associated with little more fracturing near top surface. In a few specimens of fresh basalt, premature failure was also observed due to failure along the pre-existing incipient cracks. However, such cases are excluded in the general inference. The majority of the failures were of the composite shear and induced tensile type in slightly weathered granite and basalt, and moderately weathered quartzite specimens.

Shear failures, that is, complex conjugate failures in terms of Gramberg (1989), are more prevalent in moderately weathered granite and highly weathered quartzite whereas, in highly weathered basalt, the shear failures took paths along the planes of weakness. Completely weathered specimens of all the rocks failed in shear through the rock matrix and they are not associated with conjugate tensile failure splitting. Bulging of the specimen sides was observed in almost all such cases. However, in completely weathered quartzite (QW_4) specimens, the failures had exceptionally preferred pre-existing planes of weakness.

There appears a clear distinction among the failure patterns of crystalline rocks with different weathering grades under uniaxial compression. One can categorize the modes of failure in rocks of different weathering grades by the generalized observations given in Table 4.

Table 4
Classification of weathering grades based on the general observation of failure mode under uniaxial compression

Weathering grade	Mode of failure
Fresh	Splitting and tensile
Slightly weathered	Tensile + shear
Moderately weathered	Shear + tensile
Highly weathered	Shear
Completely weathered	Shear + bulging

6.10. *Influence of mineralogy and texture*

The engineering properties of rock material depend on intrinsic characteristics such as mineralogical composition and texture. Although several studies have been carried out, yet there exist no well established theory regarding dependency of petrographical characteristics on mechanical properties of rocks. In the present study, to know the mineralogical and textural changes brought about by weathering, representative specimens were studied under the microscope and quantitative estimations of mineralogical and textural features were recorded by the point counting method.

All the tested fresh rocks are composed of silicate minerals having different percentages of free quartz. It has been noted earlier that quartz content in sedimentary rocks could be a possible factor governing the strength, particularly σ_c (Smart et al., 1982; Rao, 1984). However, in the present study, comparison of σ_c of fresh rock types indicate that the order of the σ_c values do not correspond with the order of the quartz content in the rocks. This suggests that factors other than quartz content are more important in controlling the strength behaviour. Textural features, such as microfractures, pores and voids seem to be more dominant factors in determining the strength of the fresh rock material. The mineralogical and textural changes produced by weathering play a major role in governing the strength and deformational behaviour of rocks. In order to investigate the influence of both mineralogical and textural variation on strength and deformability of rocks during weathering, petrographical indices were determined and correlated with mechanical properties. Sound and unsound constituents (Irfan and Dearman, 1978b) were determined (Table 5) based on the area percentage of minerals under the microscope. The unsound constituents (U_c) which include the area percentage of altered minerals, microfractures and voids provide an adequate measure of the effect of compositional and textural degradation in rocks, whereas sound constituents (S_c) includes primary and unaltered minerals. Figs. 10 and 11 show the variation of σ_c and E_{t50} with U_c respectively for the results of the three rocks and their four weathering grades with previously reported data for differently weathered granites (Mendes et al., 1966; Irfan and Dearman, 1978a,b).

The statistical parameter of the fitness of the relationship shows good confidence, as the coefficient of determination (r^2) fall between 0.86 and 0.99 for the different rock types. The nature of relationship which can be generalized as being a negative exponential for the tested rock is in good agreement with the relationship observed for the published data. In Figs. 10 and 11 the respective

Table 5
Sound and unsound constituents for fresh weathered rocks

Grade	Sound constituents			Unsound constituents		
	Granite	Basalt	Quartzite	Granite	Basalt	Quartzite
W_0	89.2	96.6	99.4	10.8	3.5	0.6
W_1	82.9	82.8	98.9	17.1	17.2	1.1
W_2	72.6	–	94.9	27.4	–	5.1
W_3	–	70.3	90.4	–	29.7	9.6
W_4	44.3	42.1	74.3	55.7	57.9	25.7

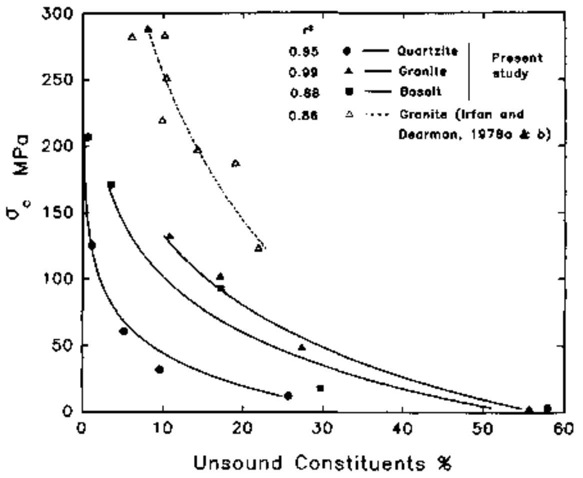


Fig. 10. Correlation of σ_c with unsound constituents.

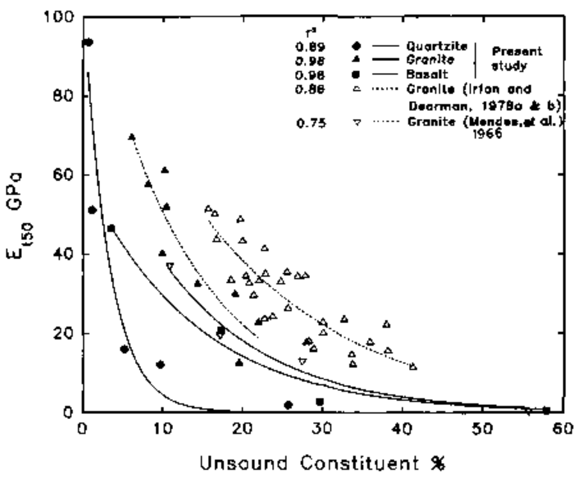


Fig. 11. Correlation of E_{t50} with unsound constituents.

reduction in σ_c and E_{t50} with increasing U_c is gradual for granites and basalt, whereas for quartzite a relatively sharp decrease in σ_c and E_{t50} as U_c increases, was observed. Though such a deviation in trend is feeble, it can be attributed to the primary composition of fresh quartzite and the apparent deficiency of altered clay minerals in weathered quartzite. Overall, this relationship reflects mineralogical and textural control on strength and deformability under uniaxial compression.

7. Conclusions

The present study was carried out in an attempt to understand the changes in strength and deformational behaviour liable to occur due to weathering action in three important Indian rocks: Malanjkhand granite; Nagpur basalt; and Delhi quartzite.

Tests were performed on carefully prepared specimens on fresh and differently weathered specimens in order to find out the compressive strength, the indirect tensile strength, the tangent and initial moduli; and the failure pattern. Weathering processes appreciably changed the mineralogical, physical and mechanical properties of granite, basalt and quartzite. Apart from the common observations on changes in all the properties, a few conclusions can be marked distinctly:

1. The stress–strain relationship reveals that specimens of fresh rocks behave linear-elastically and in some cases quasi-elastically, whereas in progressive weathering stages the specimens deform plastically with characteristic S-shaped stress–strain curves.
2. In general, the rocks deform with increasing failure strain with progressive weathering grades. This is due to the disruption of the material skeleton by microfractures, clay minerals and voids. A few anomalies in failure strain were also pointed out which may be due to premature failure of specimens. As expected, Poisson's ratio at 50% of the failure strength was observed with increased weathering.
3. The experimental results exhibited more drastic reduction in initial modulus (E_i) than the tangent modulus (E_{t50}) with increasing weathering stages. Unconfined tangent modulus has a strong correspondence with the σ_c value in all weathering stages of common rock types, particularly crystalline rocks. The goodness of power relationship is signified by the high values of the coefficient of determination.
4. Under uniaxial compression strength–deformation dependency on weakening factors was investigated through the variation of σ_c and E_{t50} with U_c. The negative exponential relationship was justified by regression analysis.

References

Alexander, P.O., 1978. Petrogenesis of low quartz normative Deccan tholeiites. 3rd Indo-Soviet Symposium on Earth Sciences, Bangalore, India.

Anon, 1995. The description and classification of weathered rocks for engineering purposes: Engineering Group Working Party Report (Geol. Soc. London). Q. J. Engng Geol. 28 (3), 207–242.

Beavis, F.C., 1985. Rock weathering. Engineering Geology. Blackwell Scientific, Melbourne.

Beavis, F.C., Roberts, I., Minskaya, L., 1982. Engineering aspects of weathering of low grade metapelites in an arid climatic zone. Q. J. Engng Geol. 15, 29–45.

Bell, F.G., 1978. Petrographical factors relating to porosity and permeability in Fell sandstone. Q. J. Engng Geol. 11, 113–126.

Bieniawski, Z.T., 1967. Mechanism of brittle fracture of rock. Int. J. Rock Mech. Min. Sci. 4, 395–430.

Bieniawski, Z.T., 1984. Rock Mechanics Design in Mining and Tunnelling. Balkema, Rotterdam.

Brack, D.U., 1974. Zeolite Molecular Sieves, Structure, Chemistry and Use. Wiley Interscience.

Colback, P.S., Wiid, B.L., 1965. Influence of moisture content on the compressive strength of rocks. In: Proc. 3rd Canad. Symp. Rock Mech., Dept. Min. Tech. Survey, Toronto, pp. 65–83.

Dearman, W.R., Irfan, T.Y., 1978. Classification and index properties of weathered coarse grained granites from SW England. Proc. 3rd Int. Cong. IAEG, Madrid 2 (2), 119–130.

Deere, D.U., Miller, R.P., 1966. Engineering Classification and Index Properties for Intact Rock, Technical Report No. AFNL-TR-65-116. Air Force Weapon Laboratory, New Mexico.

Dobereiner, L., de Freitas, M.H., 1990. Geotechnical properties of weak rocks. Geotechniques 36, 79–94.

Dobereiner, L., Porto, C.G., 1993. Consideration on the weathering of gneissic rocks. In: Cripps, J.C., Coulthard, J.M., Culshaw, M.G., Forster, A., Hencher, S.R., Moon, C.F. (Eds.), The Engineering Geology of Weak Rocks, Proc. 26th Annual Conf. of Engg. Grp. of the Geol. Soc. Leeds, 193–205.

Duncan, N., Dunne, M.H., 1967. A regional study of the development of residual soils. In: Proc. 4th African Reg. Conf. Soil Mech. Foundn. Engg, Cape Town, 109–119..

Ebuk, E.J., Hencher, S.R., Lumsden, A.C., 1993. The influence of structure on the shearing mechanism of weakly bonded soils derived from granites. In: Cripps, J.C., Coulthard, J.M., Culshaw, M.G., Forster, A., Hencher, S.R., Moon, C.F. (Eds.), The Engineering Geology of Weak Rocks, Proc. 26th Annual Conf. of Engg. Grp. of the Geol. Soc. Leeds, 207–215.

Gramberg, J., 1989. A Non-conventional View on Rock Mechanics and Fracture Mechanics. Balkema, Rotterdam. (published for the Commission of European Communities, Rotterdam).

Gupta, A.S., 1997. Engineering behaviour and classification of weathered rocks. Ph.D. thesis submitted to Indian Institute of Technology, Delhi.

Gupta, A.S., Rao, K.S., 1998. Index properties of weathered rocks: inter-relationships and applicability. Bull. Engng Geol. Env. Springer-Verlag 57, 161–172.

Hamrol, A., 1961. A quantitative classification of weathering and weatherability of rocks. Proc. 5th Int. Conf. Soil Mech. Found. Engng 7 (3), 771–774.

IAEG, 1981. Rock and soil descriptions for engineering geological mapping. Report by the IAEG Commission on Engineering Geological Mapping. Bull. Int. Assoc. Engng Geol. 24, 235–274.

Iliev, I.G., 1966. An attempt to estimate the degree of weathering of their physico-mechanical properties. Proc. 1st ISRM Cong., Lisbon 2 (3), 109–114.

Irfan, T.Y., Dearman, W.R., 1978a. Engineering classification and index properties of a weathered granite. Bull. Int. Assoc. Engng Geol. 17, 79–90.

Irfan, T.Y., Dearman, W.R., 1978b. Engineering classification and index properties of a weathered granite in Cornwall, England. Q. J. Engng Geol. 11, 233–244.

Irfan, T.Y., Powell, G.E., 1985. Engineering geological investigations for pile foundation on a deeply weathered granitic rock in Hong Kong. Bull. Int. Assoc. Engng Geol. 32, 67–80.

IS10082, 1981. Method of Test for Determination of Tensile Strength by Indirect Tests on Rock Specimens. Indian Standard Institution.

ISRM, 1981a. Basic geotechnical description of rock masses. Int. Soc. for Rock Mech., Commission on Standardization of Laboratory and Field Tests. Int. J. Rock Mech. Min. Sci. Geomech. Abstr. 18, 85–110.

ISRM, 1981b. In: Brown, E.T. (Ed.), Pergamon Press, Oxford.

JCPDS, 1988. Powder diffraction file. Group Mineral Index. Inter. Center for Diffraction Data, 1601 Parklane, Swarthmore, Pennsylvania 19081.

Krishnan, M.S., 1982. Geology of India and Burma. 6th ed., CBS, Delhi.

Lee, S.G., de Freitas, M.H., 1988. A revision of the description and classification of weathered granite and its application to granites in Korea. Q. J. Engng Geol. 22, 31–48.

Lumb, P., 1983. Engineering properties of fresh and decomposed igneous rocks from Hong Kong. Engng Geol. 19, 81–94.

Mendes, F.M., Aires-Barros, L., Rodrigues, F.P., 1966. The use of modal analysis in the mechanical characterization of rock masses. Proc. 1st Int. Cong. ISRM, Lisbon 2 (20), 217–223.

Pasamehmetoglu, A.G., Karpuz, C., Irfan, T.Y., 1981. The weathering classification of Ankara andesites form rock mechanics point of view. Proc. Int. Symp. Weak Rocks, Tokyo 1, 185–190.

Raisbeck, D., 1973. Strength parameters for weathered sandstone. N. Zealand Engng 28 (9), 254–260.

Rao, K.S., 1984. Strength and deformational behaviour of sandstones. Ph.D. Thesis submitted to Indian Institute of Technology, Delhi.

Sen, A.K., Guha, S.K., 1987. The geochemistry of the weathering sequences — presentand past — in and around the Pottangi and Panchpatmali bauxite bearing plateaus, Orrissa, India. Chem. Geol. 63, 233–274.
Sikka, D., 1989. Malanjkhand: Proterozoic porphyry copper deposit, MP, India. J. Geol. Soc. India 34, 487–504.
Smart, B.G.D., Rowlands, N., Issac, A.K., 1982. Progress towards establishing relationships between the mineralogy and physical properties of coal measure rocks. Int. J. Rock Mech. Sci. Geomech. Abstr. 19, 81–89.
Turk, N., Dearman, W.R., 1985. In: Influence of water on engineering properties ofweathered rocks. In: Cripps, J.C. (Ed.), Engng Geol. Spl. Publ., Geol. Society, London.
Turk, N., Koca, M.Y., Yuzer, E., Qztas, T., Erdogan, M., 1994. Engineering geological problems of the first phase of the Izmir Metro in: Proc. 7th Int. IAEG Cong. Lisbon, 4259–4264.
Tyagi, A., 1980. Mineralogical and geochemical changes leading to formation of clay deposits in Mehrauli area, South Delhi. Ph.D. Thesis, Delhi University.