Weathering indices and their applicability for crystalline rocks

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Abstract In the recent past, several weathering indices have been proposed to characterize the extent of weathering and weatherability depending upon the nature and requirement of the study. The weathering index provides a quantitative measure of the extent of weathering of rock; hence it can provide input to the prediction models to assess the strength and deformational properties of rocks and classifications of weathered rock material. In the present study some of the important weathering indices, broadly categorized as chemical, (micro) petrographical and engineering weathering indices, are reviewed and studied experimentally for three common rocks of India, namely granite of Malanjkhand, basalt of Nagpur and quartzite of Delhi, along with results of other rocks reported by other researchers. The study reveals that none of the existing chemical weathering indices is valid for genetically different common rock types and useful for engineering purposes. However, loss on ignition (LOI) may provide an approximate estimation of altered minerals (clays and hydroxides) in tested rocks. It has also shown good correlation with petrographic indices and engineering index properties. Among the petrographic indices, crack density (ρ_{cr}) and unsound constituent (an input to the micropetrographic index) indices provide good correlation with engineering index properties. To quantify the extent of weathering in terms of strength degradation due to weathering in rock, an index is suggested – strength ratio (R_s) – which is thepercentage of uniaxial compressive strength (σ_c) of weathered rock with respect to σ_c of fresh rock. Its significance is shown statistically through the relationships with other indices for several rock types including sedimentary and metamorphic rocks.

Résumé Dans un passé récent, plusieurs indices d'altération ont été proposés pour caractériser le degré d'altération et l'altérabilité d'une roche. Donnant une mesure quantitative du degré d'altération, un indice d'altération permet d'alimenter des modèles d'évaluation des propriétés de résistance et de déformabilité des roches, ainsi que des classifications de matériaux rocheux altérés. Dans cette étude, quelques indices importants mesurant l'altération, indices sommairement classés comme chimiques, (micro-) pétrographiques et appliqués à l'ingénierie, ont été reconsidérés et mis en oeuvre expérimentalement pour trois roches communes en Inde, à savoir le granite de Malanjkhand, le basalte de Nagpur et le quartzite de Delhi. D'autres données rapportées par des chercheurs sont prises en compte. L'étude montre qu'aucun des indices d'altération chimique n'est valable pour des roches communes d'origines différentes, ni utile pour des applications d'ingénierie. Cependant, la «perte au feu» peut fournir une estimation des minéraux altérés (argiles et hydroxides) dans les roches testées. De bonnes corrélations sont également établies entre cet indice et les indices pétrographiques ainsi que les indices appliqués à l'ingénierie. Parmi les indices pétrographiques, l'indice de densité de fissures et l'indice des constituants altérés (paramètre d'entrée de l'indice micropétrographique de Irfan et Dearman) donnent de bonnes corrélations avec les indices appliqués à l'ingénierie. Afin de quantifier le degré d'altération en terme de perte de résistance, un indice R_s est défini par le rapport des résistances à la compression simple de la roche altérée et de la roche saine. Son intérêt est montré, d'un point de vue statistique, par comparaison avec d'autres indices pour plusieurs types de roches d'origines sédimentaire et métamorphique.

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Introduction

In nature the inevitable process of weathering produces significant changes in almost all the chemical and physical properties of a material and it is universally recognized that this process will have affected many of the engineering properties of a rock mass. The changes brought about by weathering have been extensively studied in the past from a number of different standpoints depending on the requirements of the study. Commonly, the extent of weathering in rock is measured using whichever of the standard weathering indices is considered most useful for the particular purpose.

This paper examines the important weathering indices suggested for chemical, physical and geotechnical considerations and discusses their limitations and usefulness in various situations. Emphasis is given to the applicability of the weathering indices for common rock types and their significance for engineering geological practice. The existing methods of determining the weathering indices are reviewed and tested in experiments on three common rocks of India: granite from Malanjkhand, basalt from Nagpur and quartzite from Delhi. The results are discussed together with those for other rocks as published in the literature. Statistical correlations between weathering and engineering indices and their significance have indicated some important points which it is considered will be useful for the engineering assessment of weathering in rocks. A weathering index is proposed to quantify the extent of degradation of strength due to weathering, termed the strength ratio (R_s). Its validity is studied through interrelationships with other indices for several common rock types.

Previous work on weathering indices

Several weathering indices have been devised for quantifying the changes in the intrinsic properties of rocks from different points of view, some of which can be related to the engineering properties of weathered rocks. The most commonly used methods can be broadly categorized as chemical, mineralogical–petrographical and engineering indices.

Chemical weathering indices

As pointed out by Hodder and Hetherington (1991) and Knill (1993), a closer understanding of the chemical processes associated with weathering is essential to an understanding of their influence on geotechnical behaviour. Reiche (1943) was probably the earliest researcher to propose a chemical weathering index, such as the weathering potential index (WPI) and the product index (PI):

$$WPI = \frac{[K_2O + Na_2O + CaO + MgO - H_2O]x100}{SiO_2 + Al_2O_3 + Fe_2O_3 + FeO + TiO_2 + CaO + MgO + Na_2O + K_2O} \quad (1)$$

$$PI = \frac{SiO_2\,x100}{SiO_2 + Al_2\,O_3 + Fe_2\,O_3 + FeO + TiO_2} \quad (2)$$

Decreasing WPI implies decreasing mobile cations and increasing hydroxyl water, whereas decreasing PI indicates decreasing silica content with the onset of weathering. Ruxton (1968) observed that none of the chemical indices provides a measure directly related to the total element loss calculated assuming alumina is constant. He took silica loss as total element loss and assumed that alumina remains constant during weathering, such that the ratio of silica to alumina could indicate the degree of weathering. He suggested

$$Silica - Alumina\ Ratio = \frac{SiO_2}{Al_2\,O_3} \quad (3)$$

This has been found to be a good index of chemical weathering in free-draining, acidic environments in humid climates, particularly acidic rocks (Ruxton 1968). For basic and ultrabasic rocks when smectite and vermiculite are produced as a weathering by-product, this index is not suitable (Irfan 1996).

The Parker index (W_p) proposed by Parker (1970) is based on the proportions of the major alkaline metals and their bond strength, with oxygen used as a weighting factor. The index is considered to be applicable to acid, intermediate and basic rocks in all situations where hydrolysis is the main agent of silicate weathering and also to indicate susceptibility to further weathering. It can be expressed as

$$W_p = \left[\frac{2\,Na_2\,O}{0.35} + \frac{MgO}{0.9} + \frac{2\,K_2\,O}{0.25} + \frac{CaO}{0.7}\right] \quad (4)$$

Miura (1973) considered the difference between the mobility of iron in its ferric and ferrous state and proposed the Miura index (MI):

$$MI = \frac{MnO + FeO + CaO + MgO + Na_2\,O + K_2\,O}{Fe_2\,O_3 + Al_2\,O_3 + 3\,H_2\,O} \quad (5)$$

A rather different index was proposed by Rocha-Filho et al. (1985) as the lixiviation index (β'):

$$\beta' = \frac{A_{Weathered}}{(A_{Fresh} + CaO/MgO)} \tag{6}$$

where $A=(K_2O+Na_2O)/Al_2O_3$

Jayaverdena and Izawa (1994) assumed possible relationships between Al_2O_3, SiO_2 and TiO_2 and put forward an index of chemical weathering referred to as the silica-titania index:

$$Si - Ti\ Index = \frac{SiO_2/TiO_2}{(SiO_2/TiO_2) + (SiO_2/Al_2O_3) + (Al_2O_3/TiO_2)} \tag{7}$$

These authors observed a fairly good relationship between Ruxton's ratio, WPI and $H_2O(+)$. Irfan (1996) identified the different behaviour of "mobile" and "immobile" elements during weathering and developed a "mobiles index":

$$Mobiles\ Index(I_{Mob}) = (Mob_{Fresh} - Mob_{Weathered}) \tag{8}$$

where Mob_{Fresh} and $Mob_{Weathered}$ are the total (K_2O+Na_2O+CaO) content in the fresh and weathered rocks respectively.

Hodder (1984) and Hodder and Hetherington (1991) clarified the use of a chemical index as a measure of weathering state with a consideration of thermodynamics. They observed that a suitable chemical index (like the Miura index) could be related logarithmically to the free energy in a weathering reaction which affects the density and strength of a rock.

Mineralogical and petrographical indices

Several mineralogical and micropetrographical parameters have been proposed as the basis for weathering indices in view of their variation with weathering. Lumb (1962) has attempted a mineralogical index based on degree of decomposition (X_d), taking into account the ratio by weight of the quartz and feldspar in decomposed granite. This is expressed as

$$X_d = (N_q - N_{q0})/(1 - N_{q0}) \tag{9}$$

where N_q and N_{q0} are the weight ratio of quartz and feldspar in soil and fresh rock samples respectively.

Mendes et al. (1966) introduced the "micropetrographic quality index" (ki) differentiating the unsound from the sound minerals in the rock. This is given as

$$ki = \frac{\sum_{i=1}^{n} P_i X_i}{\sum_{j=1}^{m} P_j Y_j} = \frac{Sound\ Minerals\%}{(Unsound\ Minerals + Voids + Fissures)\%} \tag{10}$$

where n values of X_i are the percentages of sound minerals or minerals having a favourable influence on the mechanical behaviour of rock, m values of Y_j are the percentages of altered minerals and coefficient P_i and P_j are the weightings to take account of the influence on the individual minerals on the mechanical characteristics of the rock.

Dixon (1969) considered the influence of microfractures by counting the number of fractures intersected when making a squared traverse using the point counting method. Onodera et al. (1974) neglected the effect of mineralogy in the weathering of granite but noted that both the number of cracks and the proportion of open cracks increases with progressive weathering. They introduced the "density of microcracks" (ρ_{cr}) index for physical weathering along a microscope traverse line:

$$\rho_{cr} = 100 \times (total\ width\ of\ cracks/length\ of\ measured\ line) \tag{11}$$

Based on a detailed study of weathered granites in the UK, Irfan and Dearman (1978b, 1978c) proposed a simplified micropetrographic index (I_p), very similar to that suggested earlier by Mendes et al. (1966). According to Irfan and Dearman:

$$IP = \frac{SC\%}{UC\%} \tag{12}$$

where SC is sound constituents (the unaltered resistant minerals of the granite) and UC is unsound constituents (secondary minerals such as muscovite or iron oxide, including microcracks and voids resulting chiefly from weathering).

They also proposed a microfracture index (I_f), very similar to that of Dixon (1969), based on the number of fractures in a 70 mm traverse seen on a thin section of rock under the microscope. They suggested that I_f can be divided into a stained-microfracture index and a clean-microfracture index but gave no guidelines regarding such a distinction. Dick et al. (1994) used the same index in a durability classification of mudrocks, while Beavis (1985) also found that I_f values varied according to weathering grade.

Cole and Sandy (1980) proposed a secondary mineral rating (R_{sm}) for the assessment of road aggregate performance, based on textural distribution and the percentage/stability of secondary minerals:

$$R_{sm} = \sum[(P.M)]TR \tag{13}$$

where P is per cent of secondary minerals, M is stability rating of minerals and TR is textural rating.

A textural coefficient (TC), based solely on the textural characteristics of rocks, such as grain shape, orientation, degree of grain interlocking and relative proportion of grains and matrix (packing density), has been developed by Howarth and Rowlands (1987) as a measure of mechanical performance, percussion and diamond drilling rates. Erosy and Waller (1974) found only a poor relationship between textural coefficient (TC) and mineralogical and engineering properties, however. This may be due to variations in the rock constituents, bonding structure and type and degree of cementation, but studies carried out by Azzony et al. (1996) also showed that TC has a poor relationship with σ_c and other index properties and is of little help in the characterization of weathered rocks. Figures 1 and 2 show both fair and poor relationships between TC and σ_c, illustrating the contradictory claims of the index with regard to engineering petrography. Nevertheless, if studied carefully, a petrographical

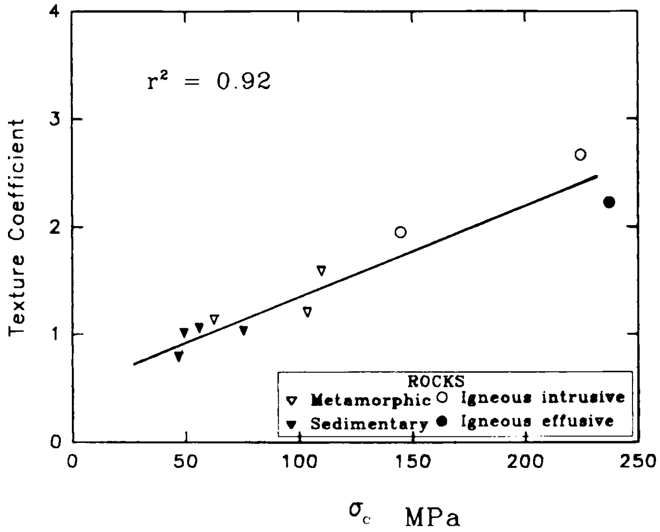

Fig. 1
Variation between texture coefficient and uniaxial compressive strength showing good correlation (Howarth and Rowlands 1987)

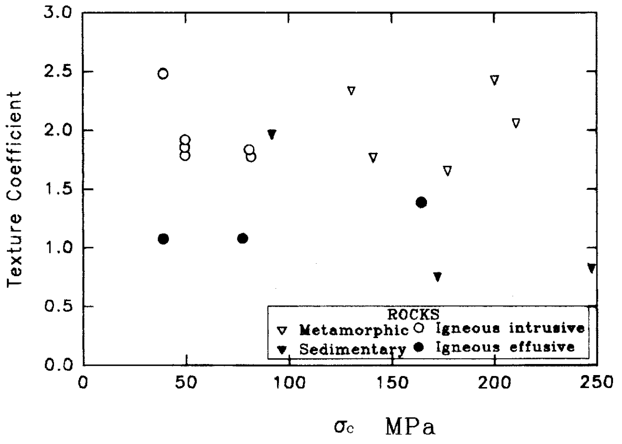

Fig. 2
Variation between texture coefficient and uniaxial compressive strength showing poor correlation (Azzoni et al. 1996)

index may be quite useful in estimating the engineering properties of weakened materials.

Engineering indices

From a geotechnical standpoint, indices based on key engineering properties generally have more applicability than those based on chemistry and mineralogy and are also usually more simple and less time consuming. A simple and rapid test to obtain a quick absorption index (QAI) or void index has been proposed by Hamrol (1961) for the assessment of weathering of granite and schist. Hamrol found a good correlation between QAI and modulus at different weathering stages, which was also recorded by Irfan and Dearman (1978a) and Pasamehmetoglu et al. (1981) for weathered andesites of Turkey. Another index – the coefficient of weathering (K) – was developed by Iliev (1966) based on the ultrasonic velocity of monzonitic rock material. This was expressed as:

$$K = (V_0 - V_w)/V_0 \tag{14}$$

where K is coefficient of weathering, V_0 is velocity of ultrasonic waves in fresh rock and V_w is velocity of ultrasonic waves in weathered rock.

Iliev also proposed a range of values of K for the classification of weathered monzonite and granite. From their detailed study of weathered granite in England, Irfan and Dearman (1978a) concluded that QAI, Schmidt hammer rebound value and point load index (σ_{tp}) could provide a realistic quantitative assessment of weathering grades in the field.

The slake durability index (Sd) was devised by Franklin and Chandra (1972) to assess the durability or weatherability of clastic sedimentary rocks such as mudstone, claystone and shale, particularly useful for rocks with significant clay content. This test was found to be an extremely useful method for defining the difference between a soil and a rock and was subsequently standardized by the ISRM (1981b). Beavis (1985) made an extensive study of various sedimentary rocks (sandstone, shale and claystone) of the Sydney Basin and was surprised to note only a slight increase in Sd in the last stage of weathering. This may be due to secondary silicification of the material, but Beavis warned that the test should be used only for general classification purposes and even then the petrography of the rock must be taken into account. Lee and de Freitas (1988) observed that the Sd is quite useful in the quantification of higher degrees of weathering in Korean granites, while Leung and Radhakrishnan (1990) found a relationship between slake durability and rock strength for sandstone, mudstone and shale in various weathering states. Komoo and Yakub (1990) noted a decreasing trend of Sd_2 (II cycle value) with progressive weathering grade in quartzite, phyllite and schist. In all these rocks, the values of Sd_2 show the highest deviation from the average value at the mid-stage of weathering. This trend was also observed by Ghafoori et al. (1993) for Ashfield shale.

The durability of any rock, but particularly mudrocks, is chiefly controlled by geological factors. Dick et al. (1994) commented that although there are several lithological characteristics governing durability, the quantity of expandable clay minerals can be best correlated with Sd_2. They also found absorption to be a good indicator of the durability of shales. In addition, the Sd_2 index can be used as a quantitative measure of the ratio of rock to soil in a weathered material.

A different type of measure, the abrasion resistance hardness index (Ha), was devised by Conca and Cubba (1986) to study the abrasion hardness and extent of weathering in different rocks – sandstone, gabbro, tonalite and crystalline limestone. They recorded slightly higher values for the more weathered sandstone as a result of silicification, supporting the observations by Beavis (1985), while with igneous rocks (e.g. tonalite), Ha decreased significantly with even a small increment of kaolinite.

In a review of engineering and weathering indices, Martin (1986) pointed out that in principle a simple quantitative degree of weathering scale can be established based on a reliable index of any rock property which changes unidirectionally throughout the weathering process and whose value can be readily determined at any weathering stage.

Rock material

Three important litho-units of India, Malanjkhand granite, Nagpur basalt and Delhi quartzite, were selected for the present study, due to both their widespread occurrence in India and the difference in their genesis and composition, hence their varied resistance to weathering.

Malanjkhand granite

The Malanjkhand granites of Precambrian age (Sikka 1989) occur as country rock in the Malanjkhand Copper Project of Hindustan Copper Limited mines (Fig. 3; longitude 80°43′ and latitude 22°1′) and form a huge granitic terrain. They are mainly medium- to coarse-grained porphyritic rocks and vary in colour from light grey/buff to pink. The mineral constituents are quartz, alkali feldspar, oligoclase and various types of perthite. Secondary minerals, such as biotite, chlorite, epidote and amphiboles, occur in various proportions as well as apatite, sphene, zircon and limonite (Gupta 1997). Perthitic intergrowth is observed in some alkali feldspars. Sikka (1989) notes that in the present climatic conditions of the Malanjkhand area, the granite weathers easily.

Nagpur basalt

The Deccan Trap basalt of Nagpur (Fig. 3; longitude 79°2′ and latitude 21°10′) is Cretaceous to Eocene in age (Alexander 1978). It is hard, compact and melanocratic (dark grey to black) and fine-grained such that the crystals cannot be identified with the naked eye. Under the microscope, plagioclases, pyroxenes and glass are seen to be the major constituents (Gupta 1997), the plagioclase and pyroxene being considerably weathered and oxidized. Labradorite, which is very common among the plagioclases, has a sub-ophitic texture with augite while chlorite and altered magnetite are also present.

Delhi quartzite

The quartzite of the Alwar Series is part of the Precambrian Delhi System (Krishnan 1982). At the sampling site (Fig. 1; longitude 77°15′ and latitude 26°30′) the Delhi quartzite is

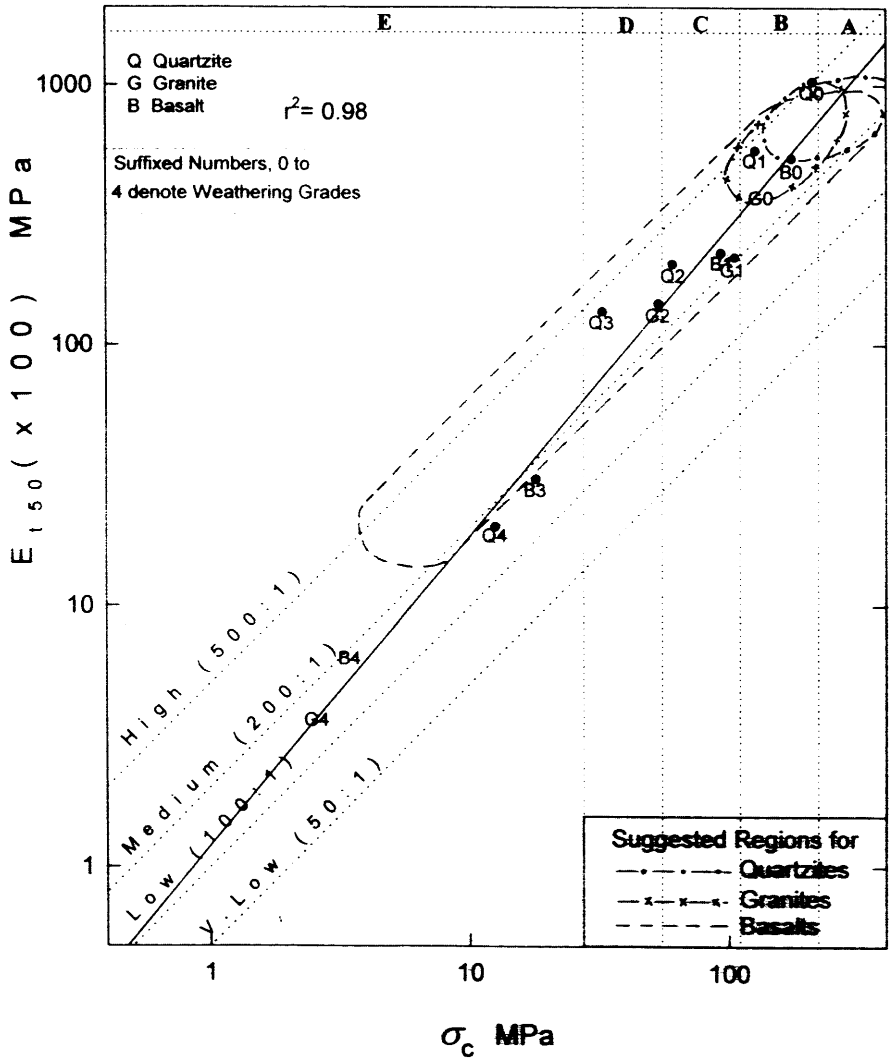

Fig. 3
Relationship between E_{t50} and σ_c, Deere and Miller's (1966) classification of fresh and weathered quartzite, granite and basalt

light to dark grey in colour and predominantly quartz (85 to 95%) with some 5 to13% accessory minerals including muscovite, biotite, feldspars and opaques (Gupta 1997).

The extent of weathering observed ranged from highly weathered at the surface to imperceptible at the bottom of the profile. It is evidenced in a change in colour from pale yellow to dark brown at joints and exposed surfaces. In some places, the surfaces of joints are pitted to varying depths up to 7 mm, probably due to the differential solution of inhomogeneous constituents as a consequence of the leaching of iron oxide.

Recognition of weathered rock material and sampling

The effects of weathering in rocks are progressive and in most cases each stage may be identified by particular geological features. A number of researchers have proposed ways of identifying weathered material; many of these have been critically reviewed by Anonymous (1995) and Gupta (1997) who highlight various attributes of these methods, including their limitations for field use. In the present study, the semi-quantitative approach suggested by Gupta (1997) and Gupta and Rao (1998) for the recognition of the extent of weathering in rock materials is followed. The terms and symbol used are:

(XW_0) Fresh rock
XW_1 Slightly weathered rock
XW_2 Moderately weathered rock
XW_3 Highly weathered rock
XW_4 Completely weathered rock
XW_5 Residual soil

similar to the suggestions by the IAEG (1981) and ISRM (1981a). The initial letter (X) in the symbol is replaced by the initial letter of the rock name (B basalt, G granite, Q quartzite); thus, for example, QW_2 refers to moderately weathered quartzite.

Selected samples of each rock type and weathering grade were collected so that each sample exhibited a uniform distribution of weathering representative of the specific weathered zone. Large sized blocks (ca. 0.4×0.3×0.2 m) were preferred as they would provide a sufficient number of core specimens. Completely and highly weathered samples which were very prone to collapse with disturbance were immediately covered with plaster of Paris and safely transported to the laboratory. Thirty-eight rock samples were collected including three profiles of granite and basalt from Malanjkhand and Nagpur respectively and four profiles of quartzite from Delhi; the locations of the profiles and sampling are shown on Fig. 3.

Laboratory investigation

For the detailed characterization of rock material it is essential to study the mineralogy and petrography of the rocks. Particularly in the case of weathered rocks, such study is neither simple nor solely dependent on a single tool. Some of the techniques used in the study reported here are discussed below.

X-ray diffraction method

Whole-rock analysis was carried out using the powder method. The diffractograms were obtained by XRD radiation (GEIGERFLEX D/max–B with CuKα 1.54 Å). Rock samples were reduced to −10 μm powder by careful grinding. Partly oriented samples were prepared by smearing the acetone-powder paste on the mount. Each sample was scanned from 2θ=5–90°. The peaks of minerals on the diffractograms were identified using the data cards published by the Joint Commission for Powder Diffraction Societies (JCPDS) (1988).

Transmitted light microscopy

This is a basic tool for the study of mineralogy and petrography which allows visual observation of the composition of a rock and the interrelationships between the constituent elements. Nahon (1991) suggests that transmitted light microscopy is particularly useful for the petrographic study of weathered rocks and preferable to other more advanced techniques (Nahon 1991).

Thin sections of the weathered rocks were prepared manually after careful impregnation with epoxy-resin. The samples were carefully ground and polished using kerosene oil to avoid wearing of expandable soil particles. In general, the thickness of the section was approximately 30 μm although with the highly weathered material the slides were somewhat thicker. For each rock type, including residual soils, two thin section slides were prepared totalling a 32 slides to study and analyze the petrographical properties of the above-stated three rock types identified in different weathering states.

The modal analysis was undertaken using an automatic point counter (Eleco E1-144) mounted on a Leitz Orthoplan microscope and a total of 2,000 counts were made for each slide. A fixed increment of 0.5 mm in an E–W direction (with respect to the orientation of the microscope) was used, followed by 0.3 mm in a N–S direction. Selection of the area for the modal analysis was based on the procedures described by Hutchinson (1974). The area percentage for each mineral was calculated assuming the total count was 100% and the results cross-checked using a mosaic of the photomicrographs at a fixed magnification (×20). The total length of traverse was kept to 10 mm (original in section, irrespective of magnification on photograph) and the N–S spacing between the traverse lines was 0.1 mm. A total of 50 traverses were made in each slide covering an area of 25 mm^2 on the thin section and 5,000 grid-squares on the magnified image. This technique is particularly useful in the study of microfractures and was chosen in view of the difficulty of discerning some measurements under the microscope, e.g. the length and width of differently oriented cracks. It was also possible to determine micropetrographic indices such as crack density and microfracture intensity using this method; cracks having a thickness of less than 0.1 mm were ignored in the present study.

Geochemical study: X-ray fluoroscopy

For the estimation of major and trace elements, X-ray fluoroscopy was preferred over other methods of rock/mineral element analysis as it is quick and easy to use. The work was undertaken at the Wadia Institute of Himalayan Geology (WIHG), Dehra Dun using the XRF SRS 3000 Siemens Sequential X-Ray Spectrometer which has the following features:

1. Typical detection limits between 0.1 and 10 ppm.
2. Concentrations up to 100% can be analysed directly with no dilution and with reproducibility better than 0.1%.
3. Eight to 58 samples can be put into the sample holder magazine and the time taken is only a few seconds per element.
4. The light element analysis based on a multilayer analyzer crystal and very coarse collimators is optimized by the Siemens thin-window X-ray tube.

The method of sample preparation followed the recommendations of the WIHG and Johnson and Maxwell (1981). Fused and compressed discoidal pallets were made for the major and trace elements respectively. Fused disc samples were prepared by heating the rock powder (reduced to 200 mesh) with flux at 1,000 °C in a platinum crucible over a microprocessor-controlled fusion instrument (Classie Fluxy, FY, 10117). Compressed discoidal pallets were made by adding Li-tetraborate and Li-carbonate to the sample powder together with a few drops of polyvinyl chloride using a pressure of some 2 MPa for up to 2 min. Loss on ignition [LOI or $H_2O(+)$] was determined using about 1 g of sample and these data used to adjust the XRF results obtained as weight percentage of the elements.

Geotechnical study

Specimen preparation

A total of 280 cylindrical specimens with a 2:1 length:diameter ratio were prepared following ISRM guidelines (1981b). In a similar manner, some 200 discoidal specimens (L/D=0.5) were prepared for axial point load test and Brazilian tests. Not surprisingly, problems were encountered in coring the moderately, highly and completely weathered basalt and granite. These were overcome by preparing cuboid samples with 40-mm sides and prismatic specimens (40×4×20 mm). The weakened samples were carefully cut by a large diamond saw and each freshly cut side immediately covered by a thin layer of plaster of Paris and dried in the oven to prevent the disintegration of the grains, particularly at the edges. The procedure was repeated for each side until the required shape and size was achieved. After drying a fully wrapped specimen, each side was ground with sand paper to remove the layer of plaster of Paris; samples where a very thin, discontinuous and patchy veneer remained were used only for mechanical tests. Problems were also encountered with the cylindrical specimens as it was difficult to lap the ends of completely weathered quartzite; the grains being loosely bonded and prone to detach easily at the edges of the specimen. To overcome this, the lower and top surfaces were covered with a thin layer of Portland cement and then lapped very carefully.

In most cases, the prepared specimens were first oven dried at 105±1 °C for 24 h and then cooled in desiccators before testing. Those used for saturated strength tests were soaked in water for 48 h before the testing.

Physical index properties

The physical index properties such as specific gravity, dry and saturated densities, water absorption, porosity and void ratio were determined for the 13 rock types following the standard test procedures suggested by the ISRM (1981b) and IS:13030 (1991). For granite and basalt, four weathering categories were selected (GW_0, GW_1, GW_2, GW_4, BW_0, BW_1, BW_3 and BW_4) and for the quartzite of Delhi five categories (QW_0, QW_1, QW_2, QW_3 and QW_4). Altogether 208 specimens were tested. For each physical index test the value quoted is the mean of 10 to 25 specimens except for specific gravity when the test was repeated five or six times for each rock category. The void index test was undertaken on 208 specimens following the procedure given by Hamrol (1961).

Sonic wave velocity was measured in both the dry and saturated condition for each rock type following the procedures recommended by the ISRM (1981b). The results of physical properties are given in Table 1.

Strength index tests

Schmidt hammer test

An N-type Schmidt hammer (NR 10:37618 ELE) was utilized for the tests, the hammer applied to horizontally positioned, sawn, cut surfaces for each variety of fresh and weathered rocks. For each rock, at least two surfaces were tested, with a minimum of eight to ten readings taken on each occasion. The test procedures given by the ISRM (1981b) were followed taking into account some important suggestions made by Poole and Farmer (1980) and McCarroll (1991) regarding the repeatability and applicability of the test for the weathered rocks to obtain the *R* value (rebound value, Schmidt hammer). Rock samples in chunk form having at least one sawn-cut surface were used for the test. Nineteen samples were identified and prepared for the test and altogether 223 rebound tests were carried out.

Unconfined compressive strength test

Unconfined compressive strength testing was undertaken on samples of GW_0, GW_1, GW_2, GW_4, BW_0, BW_1, BW_3, BW_4, QW_0, QW_1, QW_2, QW_3 and QW_4 rock types. The tests were carried out on cylindrical specimens (L/D=2) under dry and saturated conditions following the recommendations of the ISRM (1981b). A total of 143 tests were carried out: 5 to 15 specimens to determine the mean value of unconfined compressive strength in dry conditions and 5 to 6 in a saturated state. All the tests were carried out in a loading frame with a maximum loading capacity of 5 MN. A strain-controlled loading machine (capacity 500 T) was used and every effort made to keep the stress rate constant (approx. 1.0 MPa/s) so that the failure occurred between some 5 and 10 min from the start of the test. As the fresh

Table 1
Physical and strength 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) (g/cc)	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
Sat. density (ρ_s) (g/cc)	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
Sat. 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
US wave velocity (dry) (m/s)	5,803	5,410	1,753	1,011	1,357	5,983	3,691	1,849	178	5,760	4,390	1,210	–
US wave velocity (sat.) (m/s)	5,803	5,482	1,829	–	–	5,986	4,437	–	–	6,249	4,836	1,325	–
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_c (dry) (MPa)	207.0	125.6	60.60	32.20	12.40	132.8	102.7	53.01	2.54	172.5	93.2	17.80	3.40
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)	119.7	56.00	4.29	2.00	1.14	51.70	13.40	9.60	0.20	59.70	32.60	1.97	0.10
Deere and Miller (1966) 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 on cuboid and prismatic specimens

and weathered rock materials had a wide range of strengths, stress was measured using two transducers with different capacities and least-count facilities (SENSOTEC model 41/P/N632–03, max. cap. 1 MN; and SYSCON model S14864, max. cap. 50 kN). For moderately, highly and completely weathered granite and basalt (GW_2, GW_4, BW_3 and BW_4), cubic specimens were tested and the results were converted into cylindrical strength by a multiplying factor obtained after testing both cubic and cylindrical specimens for several rock types. The converted strength was used in the further analysis and interpretation.

Mineralogical and textural changes

A number of techniques, such as petrological microscopy, modal analysis (point count method), X-ray diffraction and scanning electron microscopy, were used for the mineralogical and textural characterization of the rocks.

Delhi quartzite

This coarse-grained, light to dark grey Precambrian rock is dominantly composed of quartz (94%). Accessory minerals including mica (1.4%) and opaques (3.5%) are also present with rare feldspar (0.16%). Disintegration features are prominent in the weathered material, marked by a gradual increase of intensity of microfracturing. However, decomposition is also noted in the staining, development of voids, quartz margin dissolution and disappearance of opaque minerals (Fe oxides).

Malanjkhand granite

This coarse-grained Precambrian porphyritic rock consists mainly of feldspar (63%), quartz (28%) and mica (5%). Common accessory minerals are epidote, hornblende and chlorite (4%). Weathering in the Malanjkhand granite is identified through the openness and intensity of microfractures and the development of clay minerals along these. The more heavily weathered material is characterised by broken feldspars and shattered quartz grains, together with an increased clay mineral content.

Nagpur basalt

Upper Cretaceous to Lower Eocene in age, the Deccan Trap basalt is fine grained, hard, compact and melanocratic. Plagioclase (46%), pyroxenes (29%) and glass (12%) are the most abundant minerals. Opaques, hydroxides and chlorite together constitute some 12% of the matrix along with some small voids and cracks (0.4%). In its initial stages, weathering in the basalt is restricted to the boundaries of microfractures and micropores, but the later stages are marked by both a complete transformation of the mineral composition and textural changes as the primary minerals become clay minerals, mainly montmorillonite. Micro- as well as macrofractures are prevalent throughout the material such that the structure is weak and highly compressible. Progressive staining with different colours is marked throughout the weathering scale.

Geochemical variations

The geochemical studies were carried out using the XRF technique to determine the variation in relative abundance of the major elements throughout the weathering sequence of the different rocks. The determined relative mobility of elements in each weathering sequence shows the stability or differential movement of cations with respect to the cations present in the parent material. The following mobility orders for the three rock-weathering sequences have been established:

Garnite Na>Ca> K>Mn>Mg>Si>Fe>Al>Ti
Basalt Na>Ca>Mg>K>Si>Al>Fe>Mn>Ti
Quartzite Na>Ca>Si>Fe>Ti>Al>K

This indicates that, for these rocks, Na followed by Ca and K are the most mobile elements in the weathering process.

Index properties

Almost all the physical and strength properties of the studied rocks were seen to have been affected by weathering (Table 1), but some important variations in strength indices were noted:

1. Weathering in crystalline rocks influences the tensile strength more drastically than the compressive strength, particularly at the initial stages of weathering. This suggests that breaking of intergranular bonds and formation of microfractures reduces the tensile strength significantly.
2. Of the three rocks, the Delhi quartzite was strongest in the fresh state with a σ_c value of 207 MPa, followed by the Nagpur basalt with a σ_c of 173 MPa and the Malanjkhand granite with a σ_c of 133 MPa. All the rocks showed a systematic decrease of σ_c with increased weathering. In the completely weathered grades, the basalt and granite showed a marked reduction of σ_c (98%) with respect to the σ_c of fresh material compared with the slightly smaller reduction (94%) for the quartzitic rock (QW_4).
3. As with the strength, the deformation modulus, E_t, also showed an inverse trend with progressive weathering, although comparison between E_i and E_t indicates that the reduction in E_i is the more significant.
4. The strong correspondence between E_t and σ_c indicates that there is only a marginal variation in the modulus ratio (MR) of the rocks (100 to 500) throughout the weathering grades. Following Deere and Miller's (1966) classification, all the fresh rocks fall in the BM category while the slightly and moderately weathered rocks were categorized as CM and DM respectively and the completely weathered grades as EL (Fig. 4 and Table 1). It is evident that even the highly weathered rocks show little reduction in modulus ratio.

Results and discussion

It has been noted that weathering produces gradational changes in the physico-chemical and mechanical properties of rocks and, ideally, this would be assessed in quantitative rather than qualitative terms. A number of workers have proposed ways in which this could be done, based on various criteria.

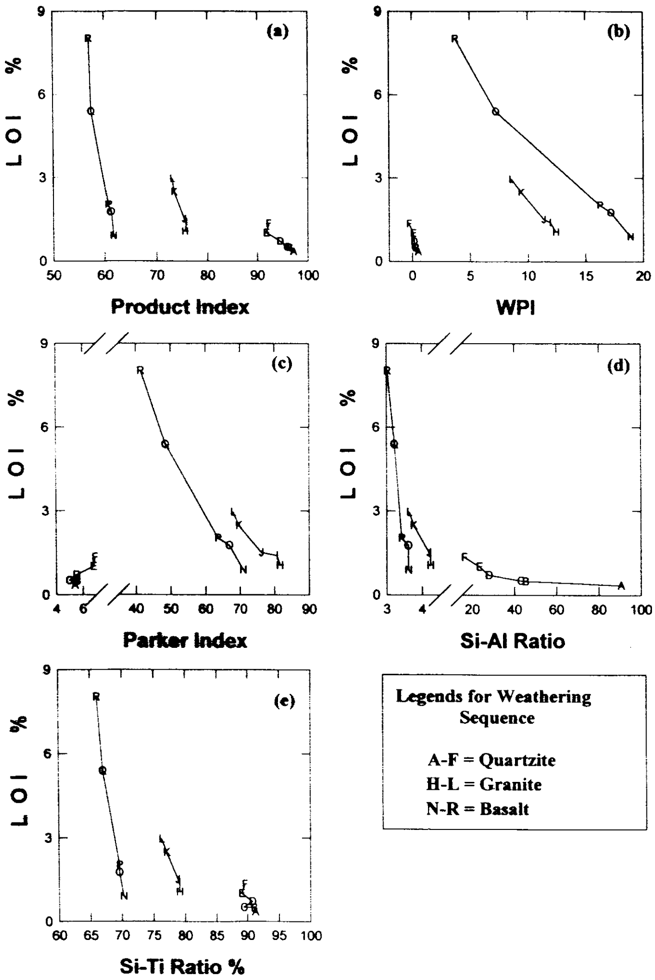

Fig. 4
Variation of loss on ignition with **a** product index, **b** weathering potential index, **c** Parker index, **d** Si–Al ratio and **e** Si–Ti ratio

Chemical weathering indices

Some of the more well-known chemical weathering indices discussed above have been used to determine the weathering state of the three rock types studied. The results are presented in Table 2. It can be seen that the weathering potential index (WPI) (Reiche 1943) provided a good indication of weathering state for the granite and basalt, the index values decreasing with increasing weathering grade (Table 2, column 1). Comparison of the range of values for the different rocks shows that as the SiO_2 content increases in the parent rock, the variation in index value with weathering reduces significantly. This may be due to the fact that the WPI includes alkali and alkaline earth metals as mobile elements and these are dominant in the feldspars of granite and basalt. The index also considers the influence of the variation in volatiles such as $H_2O(+)$ and halides (in terms of LOI) during weathering.

The product index (PI) (Reiche 1943) values were calculated using Eq. (2). This index, which is based on the ratio of SiO_2 to the sum of silica and sesquioxides, appears to be highly sensitive to the silica content in fresh rock,

Table 2
Evaluation of geochemical indices for the rocks tested

Rock grade	WPI 1	PI 2	SAR 3	W_p 4	MI 5	β' 6	Si–Ti 7	I_{Mob} 8	LOI 9
QW_0	0.51	97.1	90.6	5.39	0.62	0.05	91.2	0.00	0.3
QW_1	0.31	96.3	45.3	5.56	0.44	0.02	91.1	0.04	0.5
QW_2	0.21	95.8	43.0	4.97	0.44	0.00	89.4	0.11	0.5
QW_3	0.15	94.5	27.8	5.51	0.38	0.04	90.8	0.03	0.7
QW_4	0.07	91.8	23.4	6.79	0.52	0.10	89.0	0.09	1.0
QW_5	−0.29	92.2	16.3	6.90	0.28	0.08	89.6	0.09	1.3
GW_0	12.43	75.6	4.24	81.6	0.59	0.33	79.1	0.00	1.1
GW_1	11.93	75.8	4.24	80.7	0.58	0.33	79.1	0.16	1.4
GW_2	11.38	75.4	4.20	76.2	0.57	0.33	78.8	0.08	1.5
GW_4	9.41	73.4	3.76	69.6	0.49	0.27	77.1	0.16	2.5
GW_5	8.56	73.0	3.64	67.9	0.45	0.24	76.3	0.16	3.0
BW_0	18.89	61.5	3.61	71.0	0.44	0.10	70.3	0.00	0.9
BW_1	17.13	61.1	3.61	66.8	0.46	0.10	69.6	0.08	1.8
BW_3	16.24	60.7	3.42	63.5	0.41	0.08	69.6	0.09	2.0
BW_4	7.24	57.4	3.23	48.5	0.47	0.09	67.0	0.37	5.4
BW_5	3.76	57.0	3.03	41.4	0.4	0.06	66.1	0.42	8.0

although, as seen in Table 2 (column 2), the variation in index values is very marginal for all the rocks tested.

The silica–alumina ratio (SAR) (Ruxton 1968) varied for the three rock sequences (Table 2, column 3), the index value being highest for the quartzite and least for the basalt. This index also appeared to be affected by the SiO_2 and Al_2O_3 content in the parent rock and hence is less suitable for determining the weathering sequence in basaltic rocks.

The Parker index (W_p) (Parker 1970) indicates the extent of weathering and weatherability in terms of the alkali metals remaining after weathering as the atomic proportion divided by the bond strength of these elements with oxygen. It showed a marginal increase with weathering for quartzite compared with a decrease in index value with increasing weathering of the granite and basalt samples (Table 2, column 4). Although it is claimed that the index is applicable for all the rocks, the small but erratic variation noted for the quartzitic weathered rock and soil suggests it is not suitable for quartzites. However, it may be a useful tool in estimating the susceptibility to weathering for granitic and basaltic rocks.

The Miura index (MI) (Miura 1973) and lixiviation index (β') (Rocha-Filho et al. 1985) were also determined and the results are summarized in Table 2 (columns 5 and 6). Both indices show a consistent variation for the weathering of the granite, but no realistic trend can be discerned for the weathering sequence of the quartzite and basalt.

The silica–titania index (Si-Ti) (Jayaverdena and Izawa 1994), which considers the influence of immobile TiO_2 and Al_2O_3 during the weathering process, was calculated according to Eq. (3). As can be seen from Table 2 (column 7), there is only a small variation in the index values across the weathering spectrum of the three rock types. This may be due to the amount of SiO_2 which is likely to influence the index value for the fresh rock. In addition, the range of index values may be affected by the inherent SiO_2 content of the rocks.

The mobiles index (I_{Mob}) (Irfan 1996) was suggested as a means of assessing weathering based on the decrease in the mobile cations (K_2O+Na_2O+CaO) and the decomposition of feldspar, particularly in a well-drained state. It is determined by using the mole percentage of mobile elemental oxide and varied irregularly for granite and quartzite (Table 2, column 8). This irregularity is most pronounced for quartzite, which may be due to the presence of negligible amounts of feldspars containing mobile elements.

Although it is generally accepted that OH^- ions [both $H_2O(-)$ and $H_2O(+)$] increase as weathering proceeds, very few researchers (Onodera et al. 1976; Jayaverdena and Izawa 1994) have considered the possibility of using $H_2O(+)$ as an index of weathering. LOI was undertaken to test this means of assessing weathering – LOI being equivalent to $H_2O(+)$ if the very small quantities of other volatiles such as halides and sulphur oxides are ignored. For the fresh rock, LOI was highest in the granite and least in the quartzite and a marked increase of LOI was noted with increased weathering in all three rock types. This can be explained by the fact that LOI is related to secondary mineral formation, i.e. hydrated minerals such as clays, limonite, goethite and others. In the residual soil state, basalt showed the highest value of $H_2O(+)$, followed by granite and quartzite. This is not surprising as basaltic soil contains the highest amount of clay minerals, although it must be borne in mind that the amount of $H_2O(+)$ may vary with the type of clay content (Jayaverdena and Izawa 1994).

Some researchers (e.g. Cragg and Loughnan 1964; Parker 1970; Miura 1973), observing that the depletion of silica is often irregular while alkali and alkaline earth metals display a more marked depletion on weathering, suggested that a consideration of Na_2O, MgO, K_2O and CaO would be an appropriate basis for a weathering index. Other workers (e.g. Reiche 1943; Ruxton and Berry 1957; Jayaverdena and Izawa 1994) believe that loss of silica in the mineral structure may represent chemical weathering if alumina and titania are assumed to be almost constant during the weathering process. It has also been noted on a number of occasions that the behaviour of K_2O and CaO is not consistent, as was seen in the case of the quartzitic and basaltic weathering sequences in the present study.

An index based on loss of silica with respect to alumina appears to be more suitable for quartzite than for other rocks, whereas for granite and basalt, indices based on loss of alkali and earth metals seem to provide a better and more consistent variation with weathering. Nevertheless, as LOI varied gradually within approximately similar ranges for all the rocks tested, it is likely this could also be a good indicator of the amount of altered secondary minerals (e.g. clay minerals, hydromica, limonite, goethite) formed by combining with OH⁻ during alteration. Being relatively quick and cheap, this simple index could be very useful for engineering purposes, particularly in the estimation of clay minerals; Fig. 5a–d compares existing weathering indices with LOI.

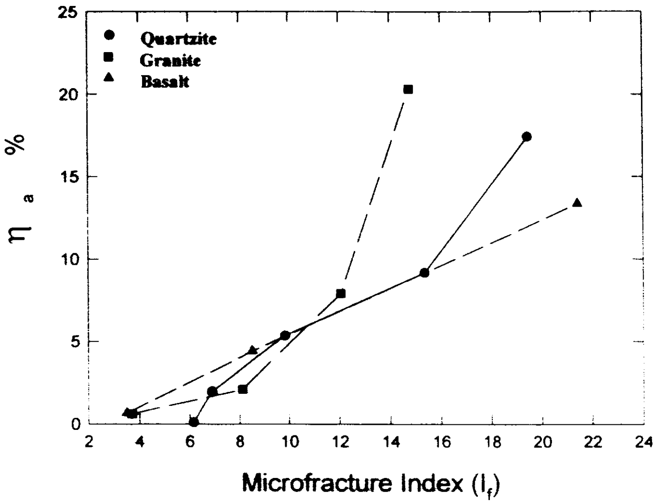

Fig. 5
Variation of porosity with microfracture index for three rocks: quartzite, granite and basalt

Petrographical indices

A number of petrographical methods have been suggested to quantify the fabric and mineralogical properties of rocks. The results obtained for some of the proposed indices are presented in Tables 3, 4 and 5 and an evaluation of their usefulness in estimating the engineering properties of weathered rocks is given below.

Microfracture index

The microfracture index (I_f) values (Dixon 1969; Irfan and Dearman 1978b) were determined for the different weathering grades for the three rock types studied. The distinction between the stained, filled and clean microfractures was not clear; hence the I_f was measured taking into account all the microfractures. The results (Tables 3,4 and 5) show the highest value of 6.2 for fresh quartzite compared with approximately 3.5 for both granite and basalt in their fresh state. This is probably due to the presence of an excessive number of thin,

Table 3
Mineralogical and micropetrographical indices for quartzitic rocks

Indices	QW_0	QW_1	QW_2	QW_3	QW_4
Sound constituents (%)	99.4	98.9	94.9	90.4	74.3
Unsound constituents (%)	0.6	1.1	5.1	9.6	25.7
Micropetrographic index (I_p)	155.3	86.7	18.5	9.4	2.9
Crack density	0.64	1.4	4.6	8.7	16.5
Microfracture index (I_f) (no./cm)	6.2	6.9	9.8	15.4	19.4

Table 4
Mineralogical and micropetrographical indices for granitic rocks

Indices	GW_0	GW_1	GW_2	GW_4
Sound constituents (%)	89.2	82.9	72.6	44.3
Unsound constituents (%)	10.8	17.1	27.4	55.7
Micropetrographic index (I_p)	8.3	4.9	2.9	0.8
Crack density	0.4	1.8	5.0	9.3
Microfracture index (I_f) (no./cm)	3.7	8.1	12.0	14.8

Table 5
Mineralogical and micropetrographical indices for basaltic rocks

Indices	BW_0	BW_1	BW_3	BW_4
Sound constituents (%)	96.6	82.8	70.3	42.1
Unsound constituents (%)	3.5	17.2	29.7	57.9
Micropetrographic index (I_p)	28.0	4.8	2.4	0.7
Crack density	0.4	2.9	8.4	18.6
Microfracture index (I_f) (no./cm)	3.5	8.5	21.4	11.3

hair-like microcracks. For all of the rocks, the index value increased gradually towards the higher weathering grades, corresponding with the development of microfractures with weathering. In the case of the basalt, the index value (I_f) was highest (21.4) for BW_3 and relatively low (11.3) for BW_4, reflecting the reduced microfracture intensity in the completely weathered basalt. This is due to the fact that growth of secondary minerals has masked the cracks and microfractures in such a way that it is difficult to identify microfractures in the clayey microzones. The variations in index properties (e.g. absolute porosity and σ_c) with I_f are shown in Figs. 6 and 7.

Crack density

The results obtained for the crack density (ρ_{cr}) index of Onodera et al. (1974) show that both the openness of microcracks and crack frequency increase with weathering, being directly related to the loosening of the bonds between the mineral grains. In the fresh state, the ρ_{cr} values for all the rocks are approximately the same, although a slightly higher value (0.2% ρ_{cr}) was recorded for quartzite compared with the granite and fresh basalt. The gradual but distinct increase of ρ_{cr} with weathering in all the rocks can be seen in Tables 3, 4 and 5.

Basalt shows the highest increase of ρ_{cr} at BW_4 grade followed by QW_4. The interrelationships observed between ρ_{cr} and engineering index properties are presented in Figs. 8 and 9. As shown in Fig. 8, the ρ_{cr} increases with increasing porosity. The relationship is linear and correlates well with the complete weathering spectrum. Figure 9 shows the relationship between σ_c and ρ_{cr}. A non-linear variation can be observed in this case, with a high value of the coefficient of determination (r^2). As emphasized above, as the mineral content is the primary characteristic of a rock, a suitable petrographical index must include the mineralogical factors as well as fabric characteristics.

Micropetrographic index

The simplified micropetrographic index (I_p) proposed by Irfan and Dearman (1978b, 1978c) was also evaluated for the three rocks studied. The results are presented in Tables 3, 4 and 5 and indicate a decreasing trend with progressive weathering for all the rocks. The maximum decrease was observed for quartzite followed by basalt and granite. The exceptionally high value for fresh quartzite suggests the index may not be suitable for this rock type. Although a good relationship between I_p and strength indices (e.g. σ_c) and E_t has been claimed for granites (Mendes et al. 1966; Irfan and Dearman 1978b, 1978c), Figs. 10 and 11 do not show a good correlation for quartzite and basalt and only a fair relationship between I_p and E_{t50} for the granitic rocks. Figure 12 shows a comparison of the relationships found for other granites together with those for the Malanjkhand granite used in the present study.

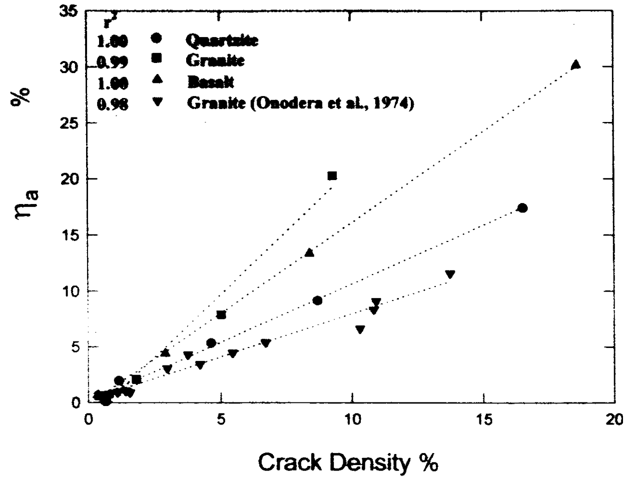

Fig. 7
Correlation between porosity and crack density, ρ_{cr}, for crystalline rocks

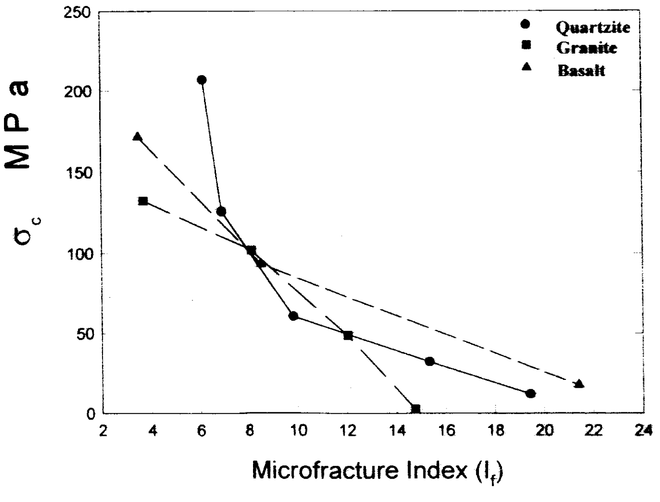

Fig. 6
Variation of uniaxial compressive strength, σ_c, with microfracture index for three rocks: quartzite, granite and basalt

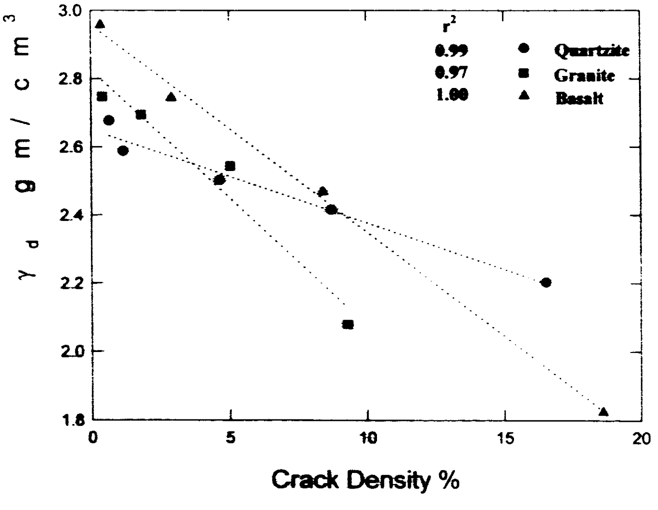

Fig. 8
Correlation between bulk density and crack density, ρ_{cr}, for crystalline rocks

The test results and discussion above suggest that the index values depend solely on mineralogical and textural considerations. The I_f index which only considers the microfracture frequency does not indicate either the width or area percentage of microfracture or the mineralogy. Compared with I_f, the use of ρ_{cr} gives an improved correlation with engineering index properties. Although I_p includes most of the weakening parameters for crystalline rocks, it seems to be valid only for granitic rocks. It is also of note that the test results suggest a very high variation, from very high (theoretically almost infinity) for fresh rock to zero for the completely weathered material, in assumed ideal conditions.

One of the factors of I_p – the unsound constituents (U_c) or percentage of microfractures and voids plus percentage of altered minerals – may be a better concept as it involves most of the important weakening factors for crystalline rocks. Moreover, the range of this index is relatively narrow, i.e. 0 to 100 and is likely to be valid for most of the rocks. The relationships between U_c and index properties are given in Figs. 13, 14, 15 and 16. It can be seen that the results show that an increase in U_c reduces the values of σ_c and E_{t50}, whereas the porosity is increased consistently with the progress of weathering. The U_c index also shows a reasonably good (positive and linear) relationship with the chemical weathering index (LOI), with a good fit of data in all cases (Fig. 16). This may be attributed to the consideration of the influence of secondary mineral content in the U_c index.

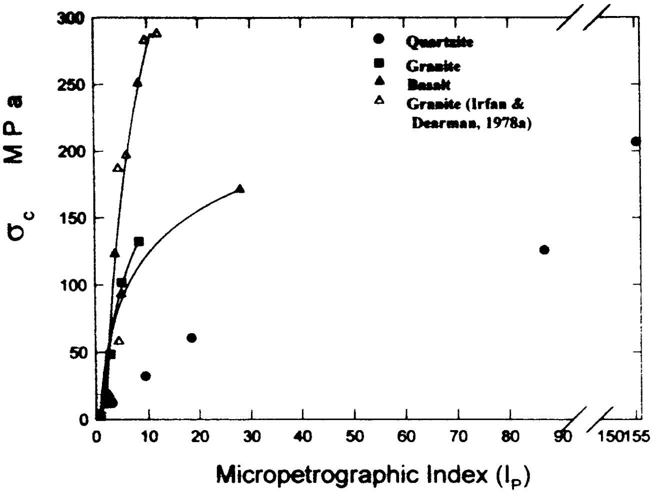

Fig. 9
Plots between uniaxial compressive strength, σ_c, and micropetrographic index for crystalline rocks

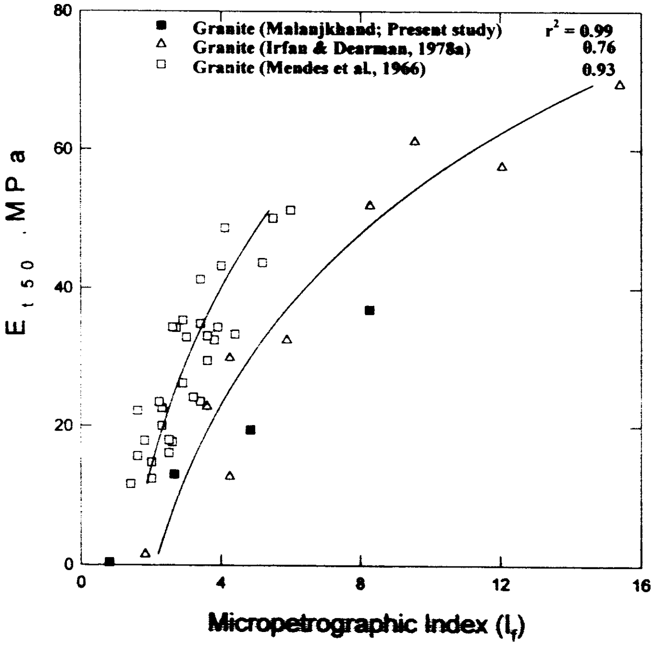

Fig. 11
Plots between tangent modulus, E_{t50}, and micropetrographic index for granitic rocks

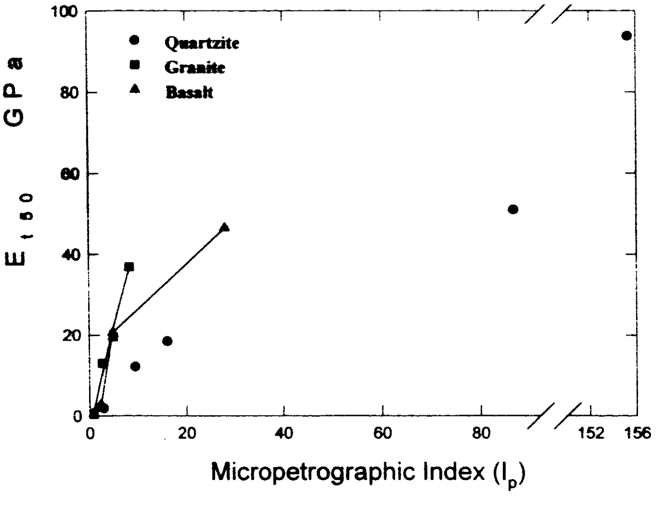

Fig. 10
Plots between tangent modulus, E_{t50}, and micropetrographic index for crystalline rocks

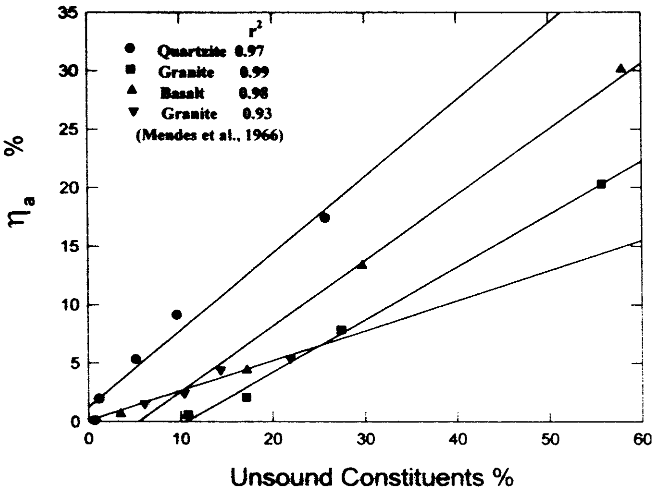

Fig. 12
Correlation of porosity, η_a, with unsound constituents for crystalline rocks

Engineering indices

Although the indices based on chemical and mineralogical characteristics can explain the variations in the basic characteristics of rock material (such as chemical alteration, fabric and mineralogical changes) caused by weathering, the practical advantages of the indices based on these characteristics may be questioned on the ground that their evaluation is experimentally difficult. For this reason, a weathering index based on engineering properties is always to be preferred over other kinds of indices, as the criteria used can be easily and quickly determined in the field as well as in the laboratory. For most geotechnical purposes, the relevance of these engineering weathering indices is based on their ability to predict the engineering performance of weathered rock.

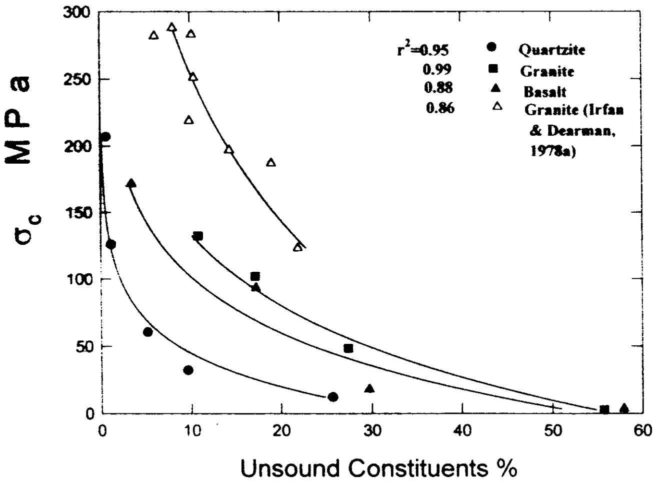

Fig. 13
Correlation of uniaxial compressive strength, σ_c, with unsound constituents for crystalline rocks

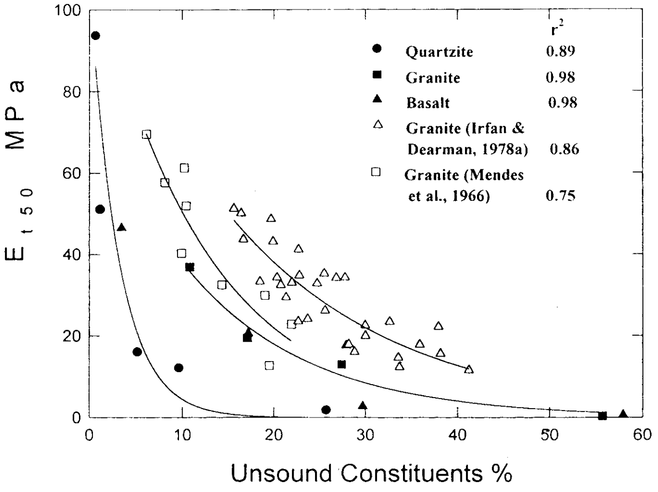

Fig. 14
Correlation of tangent deformational modulus, E_{t50}, with unsound constituents for crystalline rocks

The common weathering indices are discussed below with regard to their applicability for the assessment of the weathering effects on the rock. As the existing indices did not perform particularly well, an attempt has been made to develop a better index based on simple test data.

Strength index properties as weathering indices

The distinct variation in index properties with increasing weathering led several researchers (Duncan and Dunne 1967; Fookes et al. 1971; Onodera et al. 1974; Irfan and Dearman 1978c; Pasamehmetoglu et al. 1981; Saito 1981; Lumb 1962; Johnston and Chiu 1984) to use the standard index tests in the characterization and classification of weathered rocks. However, the applicability of index properties has also been open to question, in view of the large differences in index value for even a single weath-

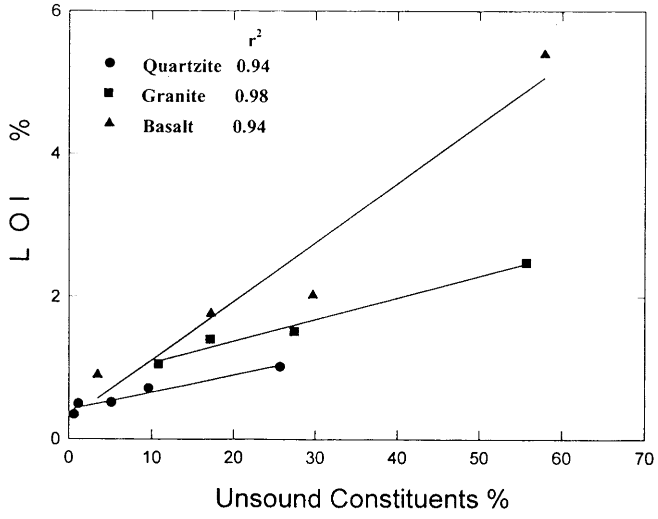

Fig. 15
Correlation between chemical index, LOI and unsound constituents for crystalline rocks

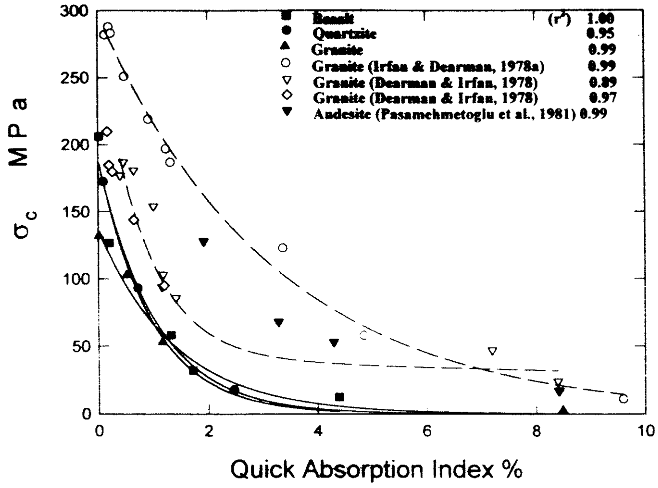

Fig. 16
Correlation of uniaxial compressive strength, σ_c, with quick absorption index (QAI) for crystalline rocks

ering grade in a common rock type (Gupta and Rao 1998). The present study used experimental data from the Malanjkhand granite, Nagpur basalt and Delhi quartzite and compared the values obtained for these with those obtained for other rocks.

Quick absorption index

The index suggested by Hamrol (1961) for assessing weathering state of granitic rock was determined for the three rock types studied. The results for the different weathering classes are summarized in Table 6, which shows a successive increase with increasing weathering grade for each material. The quick absorption index (QAI) is strongly correlated with porosity and hence its variation with strength properties is similar to that observed between porosity and strength indices. Figures 17 and 18 show a negative, non-linear variation of QAI with σ_c and σ_{tp} respectively. The plots also include data of other rocks taken from the literature.

Although the data for each rock type show a good correlation with best-fit lines and there is very little difference in the relationships obtained for the quartzite, granite and basalts of this study, considerable disparity is apparent between the relationships observed for the other four rock weathering sequences (Figs. 17 and 18). There is no obvious explanation for the difference in relationships for the rock data obtained from the literature, which are all granites, although it is possible that there could be procedural differences in determining the QAI or a difference in the petrographic nature of the rocks. However, the data obtained from the experiments show a high degree of correlation and only very small differences between the individual relationships for granite, basalt and quartzite.

Coefficient of weathering

The coefficient of weathering (K) index proposed by Iliev (1966) based on the ratio of the change of Vp between fresh and weathered rock to Vp of fresh rock (Eq. 14) was determined for the three rocks studied; the results are presented in Table 7. The increasing trend, from a zero value for fresh material towards 1 for the completely weathered rock shown, suggested that it might be valuable to investigate the relationship of K with a reliable strength index. A plot of the relationship between K and σ_c is shown in Fig. 19. The linear regression analysis carried out for the results obtained for the three rocks in the present study and for nine other rocks shows a moderate degree of fitness between the data (r^2=0.66). The demarcation lines showing the approximately 99% confidence limit are also drawn. The greatest degree of scatter in the data occurs for the fresh state where σ_c ranges widely for the different rock types. Only a poor to fair relationship is seen between σ_c and K, implying it would not make a good predictor of the weathering state of a rock.

Slake durability

This index is generally accepted as a good indicator of durability or weatherability of rock in a laboratory-simulated weathering environment. The results of the tests undertaken on the three rock types studied are presented in Table 8 as the slake durability index after the second cycle (Sd_2). For comparison, Sd_2 data for different rocks reported in the literature are also presented in Table 9. In each case the reduction in Sd_2 is minimal at the initial stages of weathering but very high towards the end of the weathering sequence, indicating that weatherability, in terms of disintegration, increases with increasing weath-

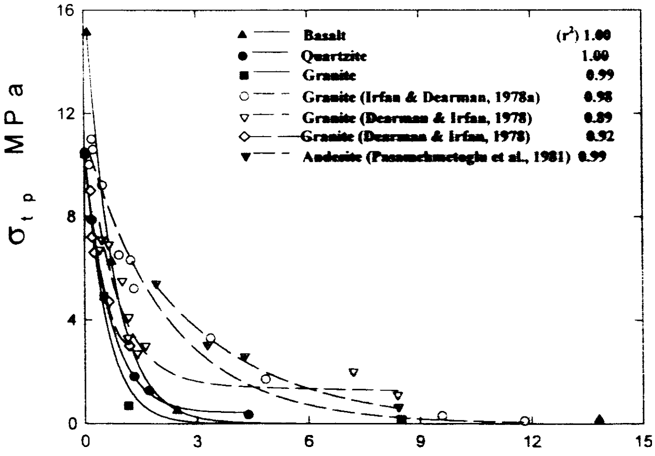

Fig. 17
Correlation of point load strength, σ_{tp}, with quick absorption index (QAI) for crystalline rocks

Table 6
Summary of results of the quick absorption index (QAI) for different rocks. Weathering grades *I* to *V* denote the state of weathering from fresh to completely weathered. They are roughly equivalent among the rocks and categorized here on the basis of available descriptions and classification terms

Rock	Source	Weathering grade				
		I	II	III	IV	V
Andesite	Pasamehmetoglu et al. (1981)	1.92	3.29	4.30	–	8.42
Granite	Irfan and Dearman (1978a)	0.13	0.24	1.24	3.37	11.80
Granite (1)	Dearman and Irfan (1978)	0.17	0.20	0.26	0.65	1.35
Granite (2)	Dearman and Irfan (1978)	0.46	0.65	0.40	1.01	8.40
Granite	Present Study	0.14	0.51	1.16	–	9.03
Basalt	Present Study	0.09	0.72	–	2.57	13.82
Quartzite	Present Study	0.12	0.20	1.32	1.71	4.40

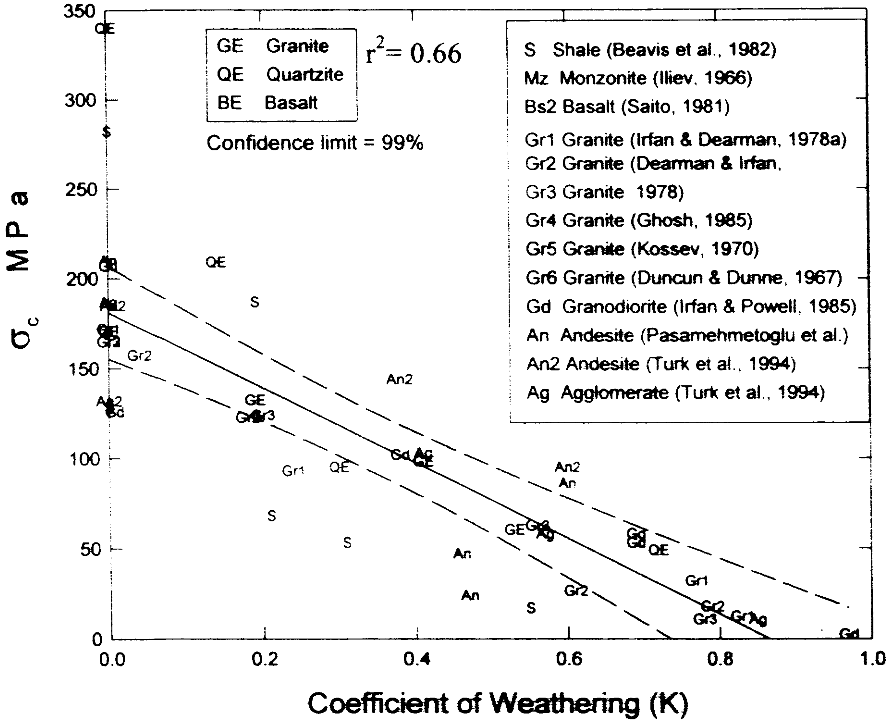

Fig. 18
Interrelationship between uniaxial compressive strength, σ_c and coefficient of weathering, K, for different rock types

Table 7
Summary of results of coefficient of weathering (K) for crystalline rocks. Weathering grades *I* to *V* denote the state of weathering from fresh to completely weathered. They are roughly equivalent among the rocks and categorized here on the basis of available descriptions and classification terms

Rock	Source	Coefficient of weathering grade				
		I	II	III	IV	V
Andesite	Pasamehmetoglu et al. (1981)	0.0	0.21	0.31	0.55	–
Monzonite	Iliev (1966)	0.0	0.19	0.41	0.53	0.72
Granite	Duncan and Dunne (1967)	0.0	0.58	0.74	0.78	–
Granite	Kossev (1970)	0.0	0.04	–	0.18	0.61
Granite	Present study	0.0	0.38	0.69	–	0.97
Basalt	Present study	0.0	0.24	–	0.79	–
Quartzite	Present study	0.0	0.07	0.69	0.77	0.83

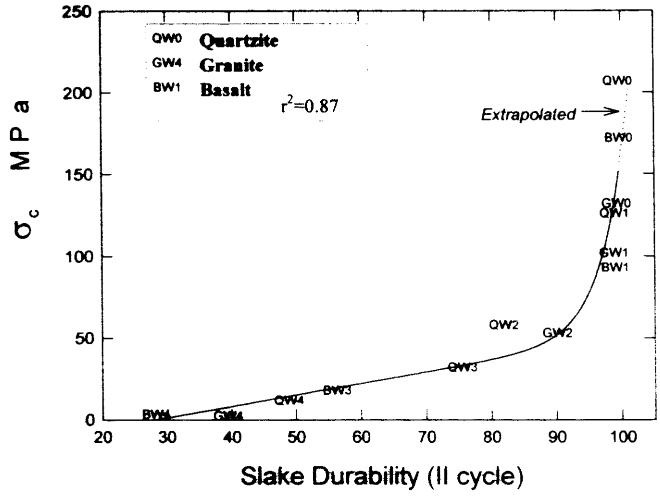

Fig. 19
Correlation between uniaxial compressive strength, σ_c, and slake durability index for granite, basalt and quartzite rocks in fresh and weathered state

ering grade. The relationship drawn between σ_c and Sd_2 for the three crystalline rocks reveals that there is a strong correspondence between the two properties (Fig. 20). This is supported by the high value of the coefficient of determination (r^2=0.87). A similar relationship was also noted for five other sedimentary rocks and a phyllite as shown in Fig. 21. Although the high degree of scatter in the data would not support a relationship between σ_c and Sd_2 for sedimentary rocks, such a relationship appears to be valid for the weathering of crystalline rocks, particularly granite, basalt and quartzite.

Proposed new index

As mentioned earlier, an index should include the properties that are most important for the particular aspects of the rock to be considered. The discussion on the applicability of the index properties indicates unconfined compressive strength to be a reliable strength index which varies consistently throughout the weathering spectrum. However, the direct use of σ_c as an index of weathering for common rocks is considered futile due to the high degree

Table 8
Summary of results of Sd_2 for granite, basalt and quartzite rocks. Weathering grades *I* to *V* denote the state of weathering from fresh to completely weathered. They are roughly equivalent among the rocks and categorized here on the basis of available descriptions and classification terms

Rock	Source	Weathering grade				
		I	II	III	IV	V
Granite (1)	Lee and de Freitas (1988)	99.0	98.0	97.0	44.0	–
Granite (2)	Lee and de Freitas (1988)	99.5	99.0	98.0	50.0	1.0
Granite	Present study	99.2	98.8	90.1	–	39.4
Basalt	Present study	99.6	99.0	–	56.3	28.3
Quartzite	Present study	9.5	98.9	81.9	75.5	48.9

Table 9
Summary of results of Sd_2 for sedimentary rocks. Weathering grades *I* to *V* denote the state of weathering from fresh to completely weathered. They are roughly equivalent among the rocks and categorized here on the basis of available descriptions and classification terms

Rock	Source	Weathering grade				
		I	II	III	IV	V
Shale (cal.)	Beavis et al. (1982)	95.7	92.6	91.6	88.5	–
Shale (dol.)	Beavis et al. (1982)	84.0	86.0	88.0	71.0	71.0
Sandstone (1)	Beavis (1985)	83.0	–	71.0	68.0	–
Sandstone (2)	Beavis (1985)	98.0	96.0	83.0	61.0	–
Sandstone (3)	Beavis (1985)	95.0	94.0	90.0	87.0	–
Sandstone (4)	Leung and Radhakrishnan (1990)	94.0	89.0	75.0	63.0	52.0
Siltstone		95.0	92.0	90.0	40.0	15.0
Claystone	Beavis (1985)	97.0	–	75.0	–	–
Phyllite (dol.)	Beavis (1985)	84.0	86.0	88.0	71.0	71.0

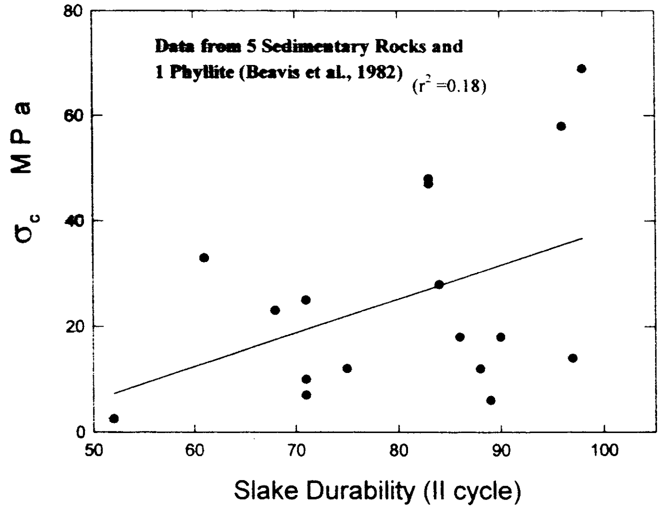

Fig. 20
Correlation between uniaxial compressive strength, σ_c, and slake durability index for sedimentary rocks and a phyllite in fresh and weathered state

of overlapping of the given range of values. Nevertheless, as already mentioned, the weathering state can be measured using a gradually varying property normalized by the value of the same index measured on fresh material. With this in mind, an index has been developed using the ratio of the uniaxial compressive strength of a weathered rock (σ_{cw}) and the compressive strength of its fresh counterpart (σ_{cf}), expressed as a percentage. This is defined as the "strength retention ratio" and can be called in brief the "strength ratio" (R_s):

$$R_s = \frac{\sigma_{CW}}{\sigma_{CF}} x100 \qquad (15)$$

where σ_{cw} and σ_{cf} are the unconfined compressive strength values of the weathered and corresponding fresh rock respectively.

The index R_s can be explained as the retained strength (in terms of σ_c) after weathering. The values of R_s for different grades of several rocks are presented in Table 10 together with the values determined for the Malanjkhand granites, Nagpur basalts and Delhi quartzites. The maximum value is fixed at 100 for fresh rock (W_0), which decreases with progressive weathering.

The relationships of R_s with other weathering indices were examined with respect to its utility in the assessment of weathering in rocks. Figure 22 shows the coefficient of weathering, K, for 12 different rocks and their weathered state plotted against the respective values of R_s. The regression analysis between K and R_s yielded a coefficient of determination r^2=0.82 with confidence limits of 99% (Fig. 22). Comparing the relationships and their correlations for σ_c and Vp, it can be seen that σ_c and K and R_s and K show the highest coefficient of determination – r^2=0.82 for R_s and K compared with 0.68 for σ_c and Vp and 0.66 for σ_c and K. This indicates that the r^2 is improved when the value of the index properties is normalized (by dividing the same index property value in fresh rock) and supports the usefulness of R_s as a weathering index. The deformational modulus E_t also shows a fair correlation with R_s for crystalline (mostly igneous) rocks.

The regression analysis provides the following power relationship between E_t and R_s:

$$E_t = R_s^{1.1} \times 313 \text{ for crystalline rocks } (r^2 = 0.90) \qquad (16)$$

The correlations between the weathering indices indicate that R_s can be acceptable for the assessment of the extent of, as well as the weatherability of, common rocks. The value σ_{cf} must be determined carefully, however, as it influences the index values for all the weathering grades of similar rock.

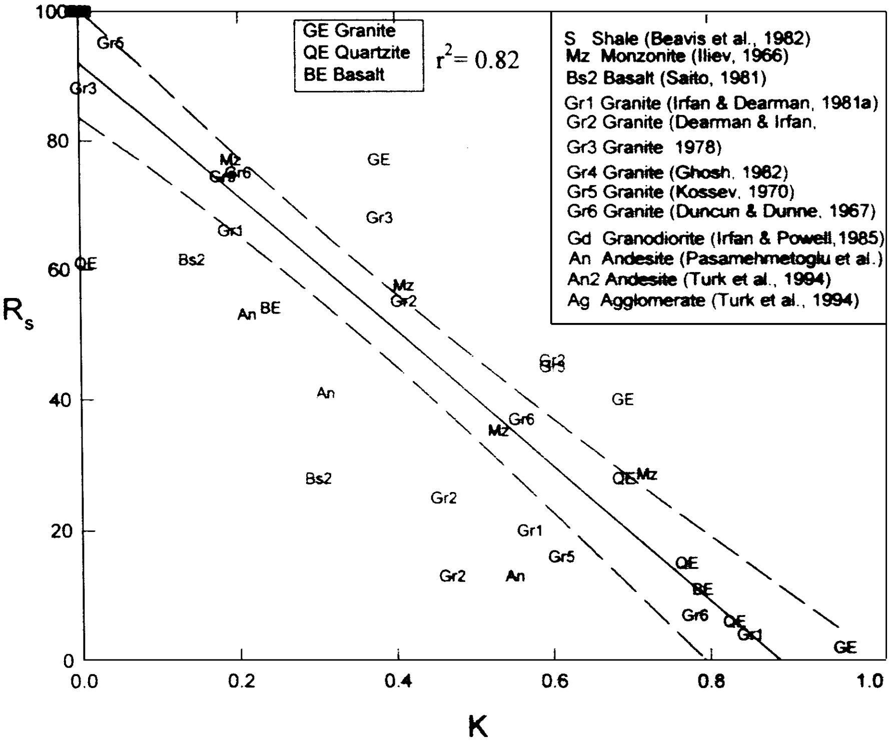

Fig. 21

Correlation between strength ratio, R_s, and coefficient of weathering, K, for different rock types

Table 10

Summary of results of R_s (σ_{cw}/σ_{cf}) for different rocks. Weathering grades *I* to *V* denote the state of weathering from fresh to completely weathered. They are roughly equivalent among the rocks and categorized here on the basis of available descriptions and classification terms

Rock	Source	Weathering Grade				
		I	II	III	IV	V
Shale (cal.)	Beavis et al. (1982)	100	70.2	42.7	18.1	–
Shale (dol.)	Beavis et al. (1982)	100	66.5	51.9	39.0	22.0
Sandstone (1)	Beavis (1985)	100	84.1	68.1	47.8	–
Sandstone (2)	Beavis (1985)	100	71.1	60.5	52.6	–
Sandstone (3)	Beavis (1985)	100	64.3	21.4	–	8.9
Claystone	Beavis (1985)	100	70.0	60.0	50.0	35.0
Agglomerate	Turk et al. (1994)	100	52.8	23.3	17.7	–
Andesite	Turk et al. (1994)	100	–	40.4	–	9.2
Andesite	Pasamehmetoglu et al. (1981)	100	53.1	41.4	13.3	–
Basalt	Saito (1981)	100	61.5	–	28.0	–
Phyllite (dol.)	Beavis (1985)	100	64.3	42.8	35.7	25.0
Phyllite (cal.)	Beavis (1985)	100	62.5	45.0	35.0	15.0
Granodiorite	Baynes et al. (1978)	100	61.5	39.2	15.4	1.9
Granodiorite	Irfan and Powell (1985)	100	73.7	51.3	32.7	8.9
Monzonite	Iliev (1966)	100	77.0	57.5	35.3	28.7
Granite	Duncan and Dunne (1967)	100	50.4	–	8.6	–
Granite	Kossev (1970)	100	68.5	51.5	25.3	16.1
Granite	Irfan and Dearman (1978a)	100	66.3	20.6	–	3.9
Granite (1)	Dearman and Irfan (1978)	100	55.1	25.1	12.8	–
Granite (2)	Dearman and Irfan (1978)	100	68.6	45.2	–	–
Granite	Present study	100	77.3	36.4	–	2.1
Basalt	Present study	100	50.3	–	10.9	2.0
Quartzite	Present study	100	60.7	29.3	15.5	5.8

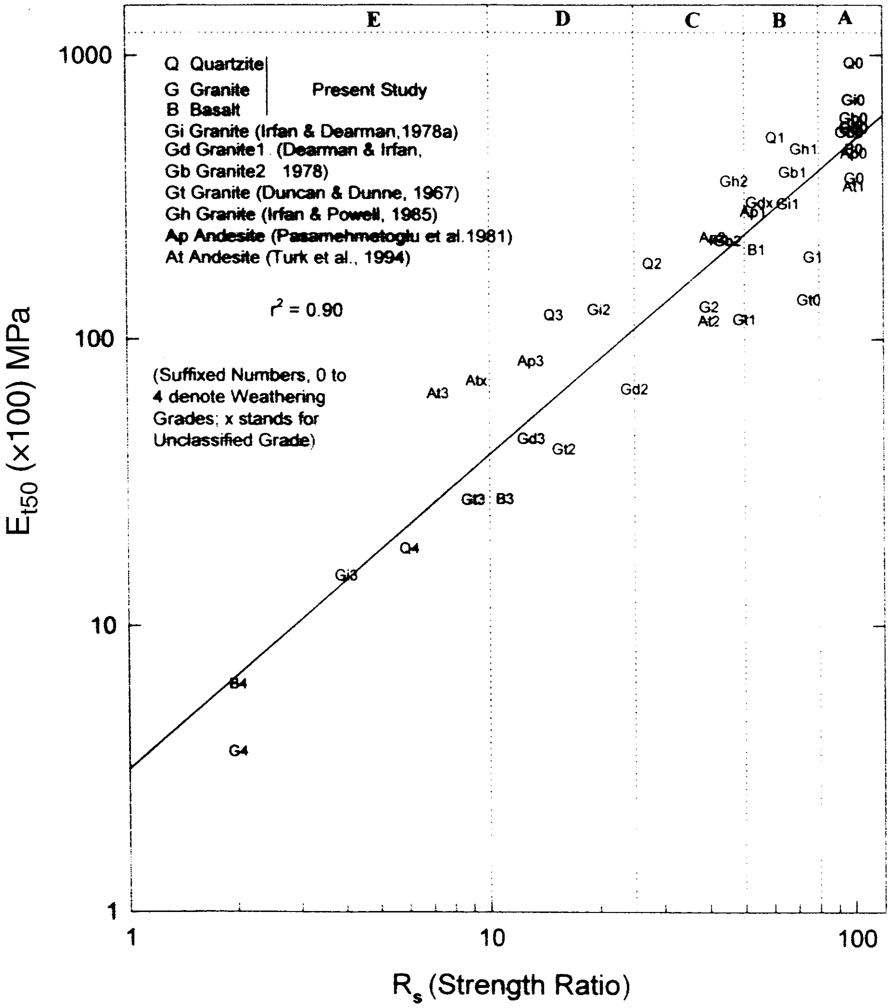

Fig. 22
Correlation between strength ratio, R_s, and tangent modulus, E_{t50}, for different rock types

Conclusions

Almost all chemical, mineralogical, physical and strength properties of a rock are significantly influenced by the extent of weathering. Several indices, some of them exclusively weathering indices, have been proposed to characterize the extent of weathering and weatherability depending upon the requirements of the specific study. These have been broadly categorized as chemical, petrographical and engineering indices.

As with the index and strength properties, deformational modulus E_t is also greatly affected by weathering. This may be due to the fact that both σ_c and E_t decrease systematically with the progress of weathering. A good correlation has been observed between the index properties which vary with the weathering grade of a particular rock (Gupta and Rao 1998, 2000). However, comparison of these relationships for different rock weathering sequences reveals that there is no common relationship between index properties for all the rock types (Gupta and Rao 1998). In general, the index properties of a rock material alone cannot represent the extent of weathering, unless they are compared with the values for the fresh rocks. For the characterization of weathering extent, therefore, indices other than index properties are to be preferred.

1. Although a number of chemical weathering indices are reported in the literature, none can be successfully applied to all the rocks considered in the present study. Weathering potential index (WPI) appears to be valid for all the rocks, but the index is highly sensitive to the alkali content in the parent rock. Loss on ignition (LOI) also appears to be a good indicator of chemical weathering as it reflects the content of altered minerals. It shows a good relationship with the micropetrographic index and also with index properties. However, care must be taken with particular categories of rocks, such as those of hydrothermal origin and rocks dominated by minerals such as amphiboles.
2. Among the few available mineralogical and textural weathering indices, crack density (σ_{cr}) has been found to be a good indicator of fabric changes during weathering but does not involve the altered mineral content and hence does not take into account chemical alteration in the rocks. The unsound constituents (U_c) index was seen to be a reasonable measure of weath-

ering characteristics in terms of both mineralogical and fabric changes. As demonstrated, it is also statistically more significant for engineering purposes.

3. The direct use of index properties such as σ_c and σ_{tp} was not found to be appropriate for the determination of weathering extent. The proposed new strength ratio (R_s) index appears to be promising and may be very useful in quantifying the weathering state, particularly with respect to the degradation of strength due to weathering. Its usefulness is demonstrated through the relationship with other indices for rock types, including sedimentary and metamorphic rocks (Fig. 22). The study has shown that other indices such as coefficient of weathering (K), slake durability (Sd_2) and the quick absorption index (QAI) can also be good indicators of weathering (Figs. 17, 18, 19, 20 and 21).

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