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A STUDY OF THE WEATHERING OF THE BUKIT TIMAH GRANITE PART B : FIELD AND LABORATORY INVESTIGATIONS**

ÉTUDE DE L'ALTÉRATION DU GRANITE DE BUKIT TIMAH (SINGAPOUR) 2^{e} PARTIE : ÉTUDES SUR LE TERRAIN ET EN LABORATOIRE**

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Abstract

Field investigations consisting of surface seismic refraction and electrical resistivity surveys, drilling and downhole geophysical logging of the rock mass and of the residual soil indicate that the weathering of the Bukit Timah granite has been rapid and is primarily caused by chemical decomposition due to the tropical climate in Singapore. The granite is usually overlain by a thick layer of residual soil. Laboratory tests indicated a large reductions of the material strength, the modulus of elasticity, the rock mass quality and other mechanical properties of the weathered granite. Apart from the mechanical properties of the residual material and/or of the weathered granite rock, physical properties including density, water content, Atterberg's limits, grain size distribution, permeability, sonic velocity and electrical resistivity were also studied in order to assess the weathering grade and the weathering processes.·

Résumé

Les études de terrain ont comporté des mesures géophysiques (sismiques, réfraction superficielle et résistivité électrique), ainsi que des forages et des enregistrements, de diagraphie dans la masse rocheuse et dans le sol résiduel. Elles ont montré que l'altération du granite de Bukit Timah a été rapide et causée principalement par une décomposition chimique due au climat tropical de Singapour. Le granite est en général recouvert d'une couche épaisse de sol résiduel. Les essais de laboratoire ont montré une importante diminution de la résistance du module d'élasticité, de la qualité du massif rocheux et des autres caractéristiques mécaniques du granite altéré. En dehors des caractéristiques mécaniques du sol résiduel et/ou du granite altéré, les propriétés physiques ont également été étudiées, incluant la densité, la teneur en eau, les limites d'Atterberg, l'analyse granulométrique, la perméabilité, la vitesse du son et la résistivité électrique, qui ont permis de définir des processus et des degrés d'altération.

Introduction

The Bukit Timah granite is the most predominant rock in Singapore covering about one third of the area of the island. It has been a source of aggregates during the past thirty years, although most of the granite quarries have given way to other development and environmental protection (Zhou & Zhao, 1992). It is realized more and more in Singapore that the granite rock could be used for underground construction and underground space development.

In conjunction with a feasibility study of the Bukit Timah granite for underground cavern construction, field and laboratory studies on the weathering of the Bukit Timah granite have been carried out since the degree of weathering will have a great impact on its use as a construction material. Field investigation and laboratory analysis have been performed to characterize the physical and mechanical properties of the residual soil and of the weathered granite for engineering purposes.

The Bukit Timah granite is an acidic igneous rock formed in lower middle Triassic period. The granite varies from granite through adamelite to granodiorite. There is considerable hybridization of the rock within the formation and evidence of assimilation (PWD, 1976; Pitts, 1984). The rock is usually light grey and medium to coarse grained (2-5 mm). The main minerals are quartz (30 %), feldspar (60 %), biotite and hornblende.

Field observations in some granite quarries indicate that the weathering of the Bukit Timah granite has been rapid and that is primarily caused by decomposition. The granite may be overlain by a thick layer of residual soil, mainly sandy clayey silt. In some locations, a layer of reddish brown sandy silty clay with a thickness of a few meters has been found above the clayey silt which indicates the occurrence of secondary weathering. There is little variation in the weathering grade of the residual soil and corestone are rare. However, the increase of

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the average grain size with depth indicates that the weathering decreases with depth. There is a steady but marked increase of the clay content ofthe residual soil toward the ground surface. The residual soil of the Bukit Timah granite is generally stiff to hard and has totally lost its rock texture and most of its strength. In many low lying areas, a sudden change from Grade VI to III or possibly II is common. The residual soil is often stratified due to re-deposition of iron compounds as hard pans, zones of fines enrichment or fines depletion, and concentrated organic layers (Zhao *et al.*, 1994).

Field investigations and laboratory tests

Surface seismic refraction and electrical resistivity surveys, drilling, conventional and geophysical logging of the boreholes have been conducted to study the weathering of the Bukit Timah granite (Lee *et al.*, 1993). The results from borehole logging and laboratory testing are summarized in later sections.

Vertical profile were obtained from boreholes at the top of the hills and at low laying areas for comparative studies. The boreholes were usually located a few hundreds meters apart. Detailed borehole geophysical logging, induding P– and S-wave seismic velocities, microelectrical resistivity, and γ–γ density, and borehole mechanical and hydraulic tests were carried out in the boreholes in the residual soil and in the weathered granite.

Laboratory tests of the residual soil and of the rock were conducted in conjunction with the field investigations. Density, water content, gain size distribution, Atterberg's limits and indexes were determined. Chemical analyses of acidity were also carried out.

The physical and the mechanical properties of the fresh and of the weathered granite were determined by a variety of laboratory tests, including density and porosity, point load index and uniaxial compressive strength. Modulus of elasticity, seismic velocity, electrical resistivity and permeability of rock mass were also determined during the field investigation.

Patterns of weathering

The weathering of the rock is complete at the surface, and decreases gradually and progressively with increasing depth. The most common type of weathering of granite in the hot climate is perhaps the corestone type. This type of weathering has been observed in many locations (e.g., Fookes *et al.*, 1971; Thomas, 1974; Malone *et al.*, 1992). The formation of corestone, however, is due to the rapid weathering along the discontinuities in the rock mass.

The weathering pattern in the Bukit Timah granite is mainly of stratified type, with few corestones. The vertical profile shows stratified layers with a sharp boundary between the residual soil and the slightly to moderately weathered rock. The highly weathered layers are commonly left out. Fig. 1 shows some actual profiles logged from boreholes through the residual soil into the fresh Bukit Timah granite. The boreholes, which were located a few hundreds meters apart, showed similar vertical weathering profiles of stratified type. The same features have been observed in the Bukit Timah granite quarries (Zhao *et al.*, 1994).

Table 1 : Pattern of weathering observed in some boreholes.

Borehole 2		Borehole 7		Borehole 11	
Depth (m)	Weathering grade	Depth (m)	Weathering grade	Depth (m)	Weathering grade
0-0.5	VI (top soil)	0-1.0	VI (top soil)	0-2.2	VI (fill)
0.5-10.0	VI	1.0-18.1	VI	2.2-26.4	VI
10.0-18.2	V	18.1-22.0	V	26.7-38.4	V
18.2-29.0	I	22.0-24.3	II	38.4-43.1	fault zone
29.0-30.3	II	24.3-31.9	fault zone	43.1-50.0	II
30.3-100.0	I	31.9-33.8	II	50.0-58.0	III
		33.8-90.0	I	58.0-68.3	II

Properties of the residual soil

Undisturbed sampling and standard penetration test (SPT) were taken every two meters in boreholes in the residual soil. Various analyses were carried out to determine the properties of the residual soil. The results below are determined from one typical borehole.

Density and Water Content

Fig. 1 shows the variation with depth of the density of saturated residual soil, the dry density and the water content. The plot indicates a clear decrease of the water content and an increase of the dry density with increasing depth. The increase of the density of the saturated soil with increasing depth is not significant and often masked by a high groundwater table.

Grain Size Distribution

The change of the grain size distribution with depth seems to reflect the degree of secondary weathering.

Fig. 1 : Variation of density and water content of residual soil with depth.

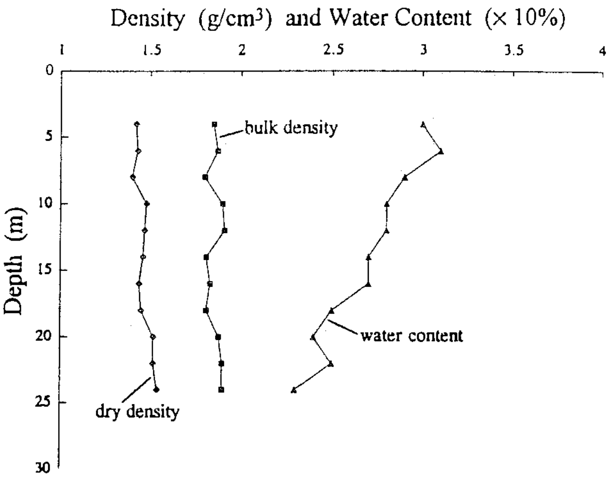


Fig. 2 : Variation of grain size distributions of residual soil with depth.

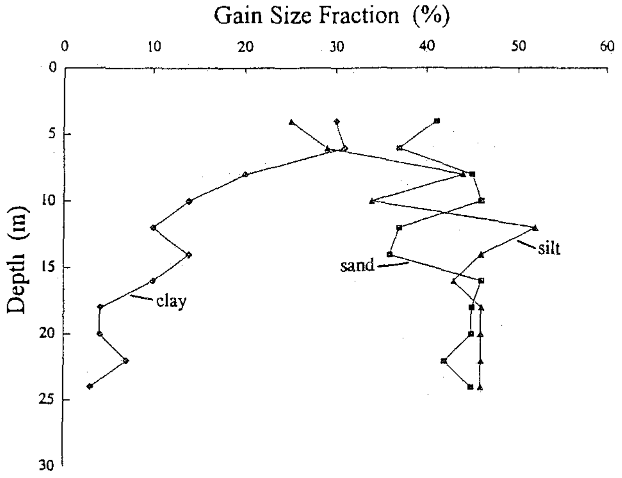


Fig. 4 : Variation of SPT penetration resistivity of residual soil with depth.

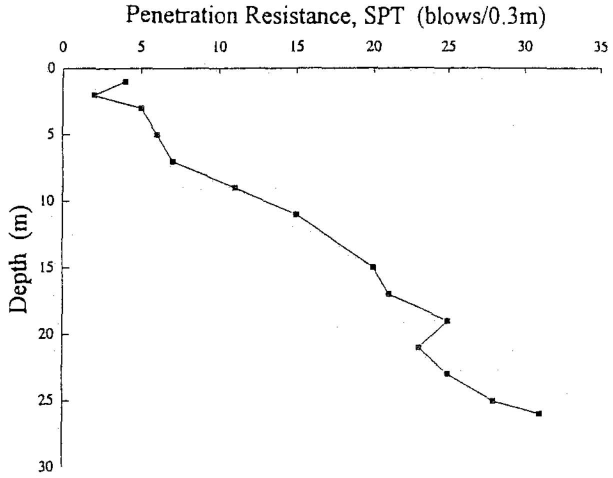


Fig. 3 : Variation of Atterberg's limits and plasticity index of residual soil with depth.

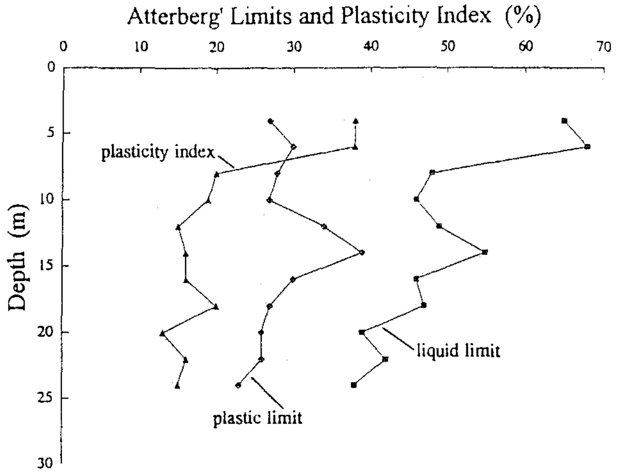
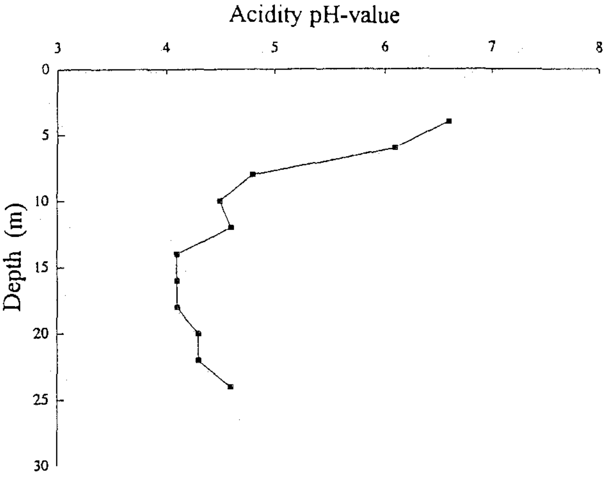


Fig. 5 : Variation of acidity pH-value of residual soil with depth.



Particularly the silt and the clay fractions of the soil are affected, as shown in Fig. 2. The clay fraction decreases significantly with depth while the silt content is increased. The sand fraction, in general, increases with increasing depth.

Atterberg's Limits

The liquid and the plastic limits have been plotted in Fig. 3 together with plasticity index. The liquid limit decreases rapidly with increasing depth, as well as the plasticity index, while the plastic limit does not indicate conclusive trend.

Standard Penetration Test

Standard penetration test (SPT) showed that the penetration resistivity increases with the depth (Fig. 4). The soil varied from soft at the ground surface to hard near the weathered rock.

Chemical Analysis

Chemical analysis was carried out to determine the variation of pH-value with the depth as shown in Fig. 5. The results indicated that the top soil has the pH-values close to 7.0. The residual soil below 6 meters tends to be acid with pH values as low as 4.1. The pH value seems to increase near the bedrock head. It should be noted that the pH-value of the fresh granite rock is about 10, a rather high value since the granite is classified as an acid rock. The pH-value of about 7.0 close to the ground surface indicates that the soil has likely been influenced by rainfall and vegetation.

Properties of the weathered rock

The weathered granite has been investigated to study the variation of the engineering and the mechanical properties. The results as determined from several boreholes are summarized below.

Density and Porosity

The variation of the density and of the porosity of the Bukit Timah granite at various degree of weathering is shown in Figs. 6 and 7. The results have been compared with the results obtained by Baynes *et al.* (1978) on the Dartmoor granite of southwest England. As expected, the density of rock decreases gradually with the increasing degree of weathering. The porosity, on the other hand, increases rapidly with the weathering grade. At weathering Grade V, the porosity is as high as 20 %, compared with a porosity of only 0.2 % for the fresh granite.

Rock Mass Quality

The rock quality designation (RQD) is perhaps a more suitable parameter to describe the weathering due to physical disintegrating, as the value of RQD corresponds to the number of fractures per unit length. The variation of the RQD is not significant for the chemical weathering of the Bukit Timah granite at Grades I, II and III (Fig. 8). The variation of the RQD becomes significant at high weathering grades. Similar as well as contradictory results have obtained by Beavis (1985) for dolomitic phylite and calcareous phylite in Australia.

Fig. 6 : Variation of saturated density of weathered granite with weathering grade.

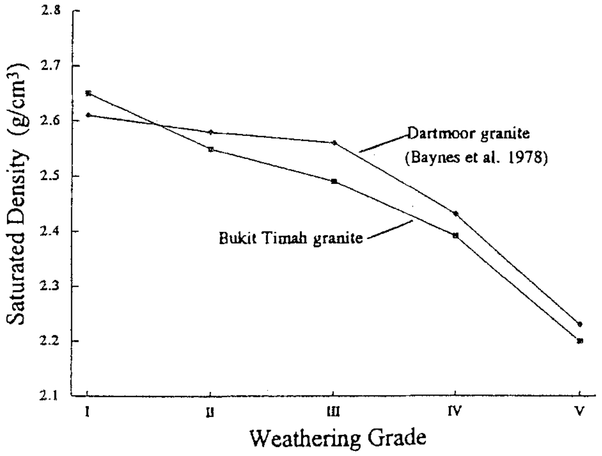
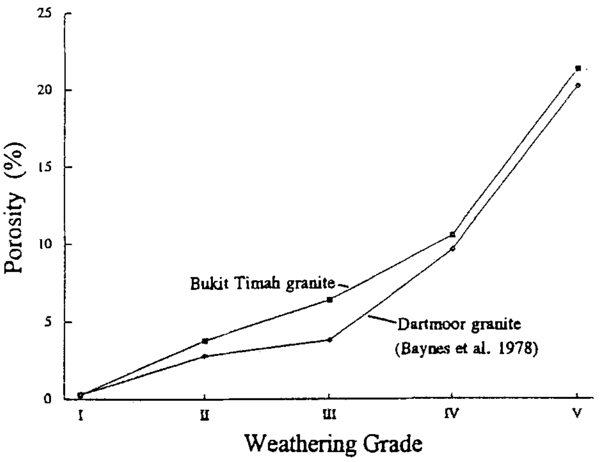


Fig. 7 : Variation of porosity of weathered granite with weathering grade.



Uniaxial Compressive Strength

The uniaxial compressive strength is the most useful index to assess the mechanical properties of the rock material as well as the weathering of the rock. The strength decreases significantly with increasing weathering, as shown in Fig. 9. The moderately weathered (Grade III) Bukit Timah granite loses 40 to 60 % of its original strength. The Harcourt granodiorite of Australia (Beavis, 1985), however, loses its strength very rapidly and the uniaxial compressive strength of Grade III is only 20 % of the strength of Grade I. The rate of reduction in strength indicate dearly that the uniaxial compressive strength is higly cnntrolled by the weathering grade.

Fig. 8 : Variation of rock quality designation (RQD) with weathering grade.

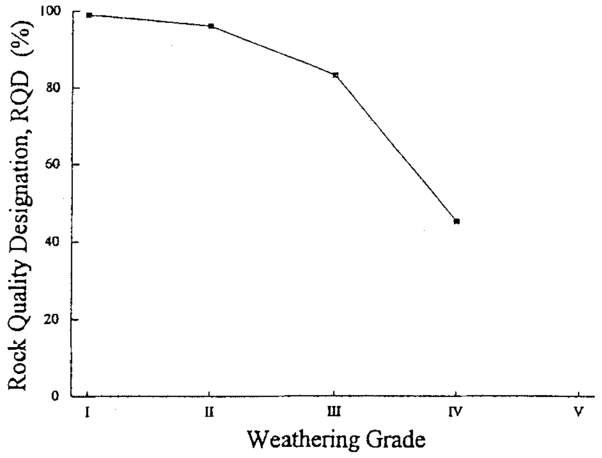
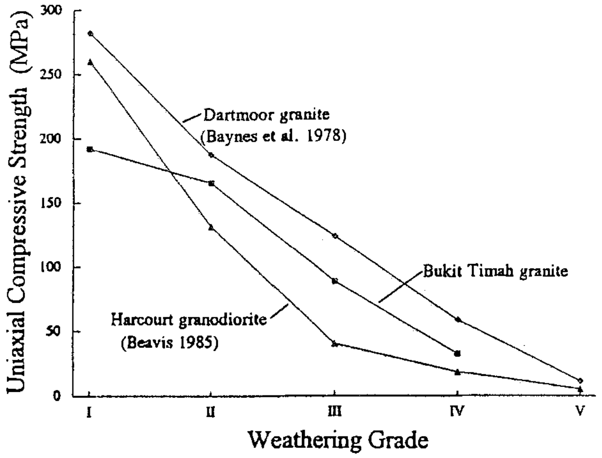


Fig. 9 : Variation of uniaxial compressive strength of weathered granite with weathering grade.



Point Load Index

The variation of point load index with the degree of weathering is expected to show a similar trend as the uniaxial compressive strength. The results obtained from the Bukit Timah granite in Fig. 10 have been compared with the results obtained from the Dartmoor granite (Fookes *et al.*, 1987). As the point load index is generally less accurate than the uniaxial compressive strength, large number of tests are required to provide meaningful results. Misleading data such as those shown on Fig.10 for the Dartmoor granite can be avoided by careful testing of a relatively large number of samples.

Modulus of Elasticity

The strength and the modulus of elasticity decreased with increasing weathering, as shown in Fig. 11. The modulus decreased steadily from Grade I to Grade V for the rock material as shown by the Dartmoor granite (Baynes *et al.*, 1985). The modulus of elasticity of the Bukit Timah granite as determined from the seismic velocity and is therefore corresponds to the modulus of rock mass. Fig. 11 shows that the modulus no longer decreases after Grade IV. Highly weathered rock mass is generally highly fractured, and the modulus of elasticity of the rock mass is often extremely low due to the open fractures.

Sonic Velocity

The sonic velocity of the rock mass is controlled by the porosity of the rock material and the fracture frequency (and aperture) of the rock mass. The variation of the P– and the S–wave velocities of the Bukit Timah granite rock mass with the weathering grade are presented in Fig. 12. Similar to the modulus of elasticity, the seismic velocity in the rock mass decreases rapidly from Grade III to IV (Fig. 11) due to the fractures. It is noticed that the shear wave velocity does not vary much from Grade I to III, but decreases suddenly at Grade IV.

Fig. 10 : Variation of point load index of weathered granite with weathering grade.

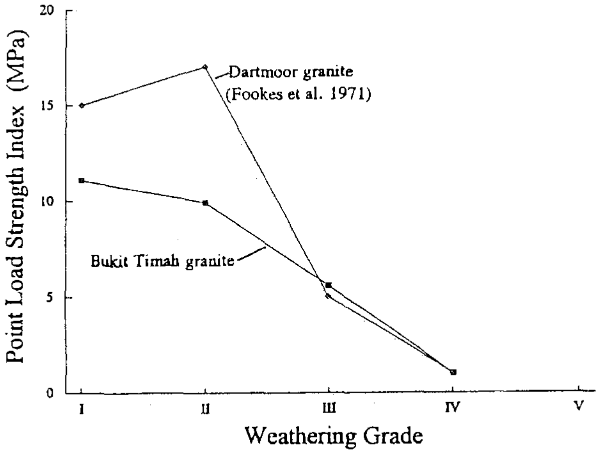


Fig. 11 : Variation of modulus of elasticity of weathered granite with weathering grade.

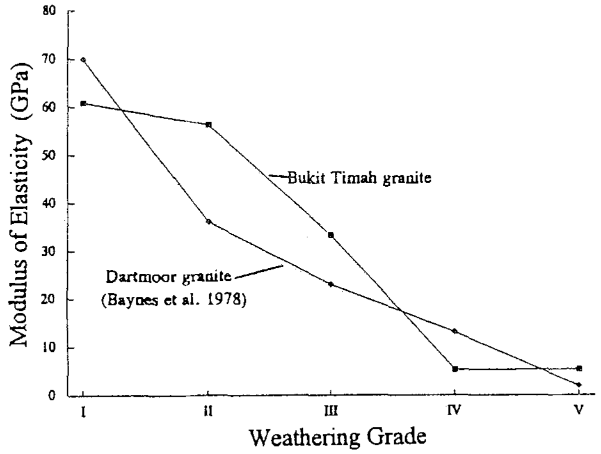


Fig. 12 : Variation of P– and S-wave velocities of weathered granite with weathering grade.

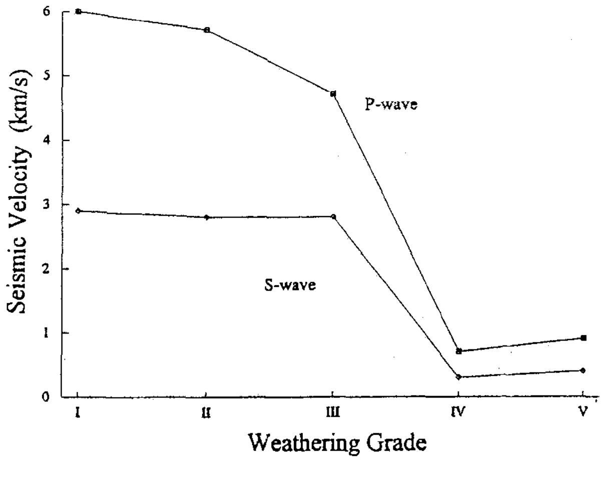


Fig. 13 : Variation of electrical resistivity of weathered granite with weathering grade.

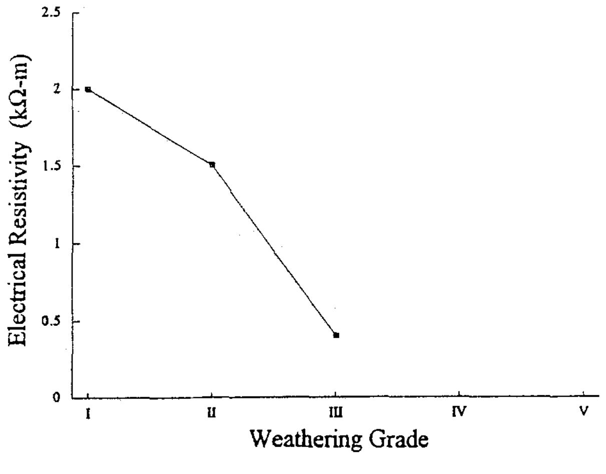
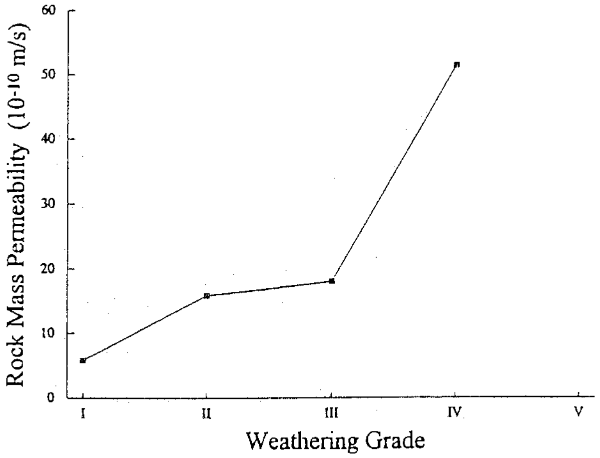


Fig. 14: Variation of rock mass permeability with weathering grade.



Electrical Resistivity

The electrical resistivity of rock mass with the weathering is expected to vary in a similar fashion as the seismic velocity. However, the resistivity was only determined for Grade I to III. No data was obtained for the more weathered zones. The results in Fig.13 show rapid reduction in the resistivity with increasing weathering.

Rock Mass Permeability

As the weathering increases, the rock material and the rock mass become more porous and more permeable. As shown in Fig. 14, the rock mass permeability increases gradually from Grade I to II. At grade IV, the mass permeability is high because the rock mass is highly weathered and higly fractured.

Discussion

Physical, mechanical and hydraulic properties of the weathered granite varies significantly with the degree of primary weathering (of the rock) and secondary weathering (of the residual soil). The primary weathering can be identified as outlined by Zhao *et al.* (1994) by studying the decomposition and the mechanical characteristics of the rock. Secondary weathering occurs within the residual soil and requires laboratory determination.

The results presented in Figs. 1, 2, 3, 4, 5 and 6 show that the secondary weathering alters further the properties of the soil. Changes of the dry density, the water content, the clay content, the plastic index and the SPT N-value can be used for identification and classification of secondary weathering. It should be noted that in Fig. 1, the change of the water content from 30 to 32 at around 7 meters depth is likely caused by the groundwater table. There is an apparent sudden reduction of the clay content, the water content and the plasticity index below 6 meters depth. Field observations often indicate that there is a layer with reddish brown sandy silty clay with thickness of up to 6 meters above the clayey silt.

The variations of the density, the rock quality destination (RQD), the strength and the modulus of elasticity with the weathering grade have aise been studied for other rocks and granites (e.g., Fookes *et al.*, 1971; Baynes *et al.*, 1978; Beavis, 1985). The study of the weathering of the Bukit Timah granite shows similar results as for the Dartmoor granite of England (Fookes, *et al.*, 1971; Baynes *et al.*, 1978) and for the Harcourt granodiorite of Australia (Beavis, 1985), as well as for other Australian rocks (Beavis, 1985). The uniaxial compressive strength reduces rapidly with the weathering and up to 60 % of strength loss occurs in the moderately weathered rock compared with the fresh granite. The rock mass permeability increases with the weathering (Fig.14), but, it should be noted that the filling of the fractures by debris may reduce the permeability and thus the flow of water through the rock mass.

There is a sudden reduction of the modulus of elasticity, the electrical resistivity and the seismic velocities of the rock mass between Grade III and Grade IV. There is also a rapid increase of the rock mass permeability between the two grades at the same time. This may be due to the increased fracturing since the fractures reduce significantly the modulus of elasticity, the resistivity and the seismic velocity.

Conclusions

Field and laboratory studies on the weathered Bukit Timah granite show that the rock has been weathered up to 70 meters depth, and that the main mechanism of weathering is chemical decomposition. The high temperature and the high annual precipitation produce secondary weathering of the residual soil. The weathering profiles and field observation suggest that the weathering of the Bukit Timah granite is stratified with weathered layers and there is a sharp boundary between residual soil and slightly to moderately weathered granite.

The investigation shows that the variation of the physical and mechanical properties of the residual soil with depth has been caused by secondary weathering. The results suggest that the water content, the clay content, the plasticity index and other properties can be used to assess the degree of secondary weathering.

The observed changes of the rock mass and the rock material characteristics comply with other similar studies. The rock mass quality, the density, the rock strength, the modulus of elasticity, the seismic velocity and the resistivity decrease with the weathering, while the rock mass permeability and the porosity increases.

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