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Characteristics of residual soils in Singapore as formed by weathering

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Abstract

Residual soils are weathering products of rocks that are commonly found under unsaturated conditions. The properties of residual soils are a function of the degree of weathering. A series of index properties, engineering properties, mercury porosimetry tests and scanning electron microscope (SEM) examinations were performed on residual soils from two major geological formations in Singapore. The results indicate that the variation in the index and engineering properties as well as microstructural characteristics of the residual soils with depth can be related to the degree of weathering. An increase in the degree of weathering results in an increase in pore volume and produces a larger range of pore-size distribution. The variation in the pore volume and the pore-size distribution through a profile of weathered rock can be used as an indicative measure of the variation in the degree of weathering with depth.

Keywords: Residual soil; Weathering; Index property; Soil microfabric; Soil–water characteristic curve; Shear strength

1. Introduction

A full understanding of the engineering characteristics of residual soils, from bed rock to totally weathered soil, is required for the design and construction of foundations and for tunnelling and slope stability studies in this type of soil. Singapore, located in a tropical climate, is dominated by residual soils from two major geological formations: the Bukit Timah granitic formation and the Jurong sedimentary formation. These residual soils comprise two-thirds of Singapore's land area.

The geology of Singapore consists of four main formations: (a) igneous rocks consisting of the Bukit Timah granite and the Gombak norite, occupying the north and central-north region; (b) sedimentary rocks

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of the Jurong formation, occupying the west and southwest region; (c) Quarternary deposit of the Old Alluvium in the eastern region; and (d) recent alluvial deposits of the Kallang formation, distributed throughout the island (Public Works Department, 1976; Leong et al., 2002), as shown in Fig. 1.

The Bukit Timah granite is mainly an acidic igneous rock formed during the Triassic period and forms a batholith at the centre of Singapore, extending about 8 km north to south and 7 km east to west. The weathering of the Bukit Timah granite has been rapid and extensive, with an average depth of weathering of 30 m and is primarily due to chemical decomposition under the humid tropical climate (Zhao et al., 1994a). Its dominant, granitic component is grey and medium to coarse-grained, and consists of cream or pale yellow feldspar, smoky quartz and smaller proportions of reddish-brown biotite and dark hornblende. The Gombak Norite is an association of noritic and gabbroic rock, which outcrops in a restricted area (Bukit Panjang and Bukit Gombak) in the centre of the island (Fig. 1). These rocks are coarse-grained and plagioclase-rich, with varying amounts of orthopyroxene minerals in an intergranular structure.

The Jurong formation covers the south, southwest and west of Singapore, with a variety of sharply folded sedimentary rocks, including conglomerate, sandstone, shale, mudstone, limestone and dolomite. It was deposited during late Triassic to early or mid-Jurassic. The formation has been severely folded and faulted in the past as a result of tectonic movement.

Singapore's climate is hot and humid equatorial, with no marked dry season. The temperatures vary little throughout the year with an annual average temperature of 26.6 °C and a mean relative humidity of 84% (Meteorological Service Singapore, 1997). The average annual rainfall in Singapore varies between 2000 mm around the fringes of the island to about 2300 mm in the central region (Meteorological Service Singapore, 1997). The rainfall is usually greatest in the months of November to January (the north-easterly monsoon) but rain falls in all months of the year, with an average of 179 rainy days in a year. Rainstorms are short, intense and generally have a limited spatial extent, with intensities typically ranging between 20 and 50 mm/h, although short duration (5 min) rainfall intensities can exceed 100 mm/h (Sherlock et al., 2000).

Residual soil properties vary from region to region due to their heterogeneous nature and highly variable degree of weathering, controlled by regional climatic and topographic conditions and the nature of bedrock. Previous site investigation and characterization studies of rainfall-induced slope failures (e.g. Rahardjo et al., 2000) and underground cavern construction (e.g. Zhao et al., 1995, 1999) in Singapore have revealed that large amounts of tropical rainfall combined with hot and humid climatic conditions favour weathering of the bedrock to a considerable depth and to a varying degree. As a result, the engineering properties of the residual soils also vary with depth. Therefore, the residual soil from a particular region needs to be

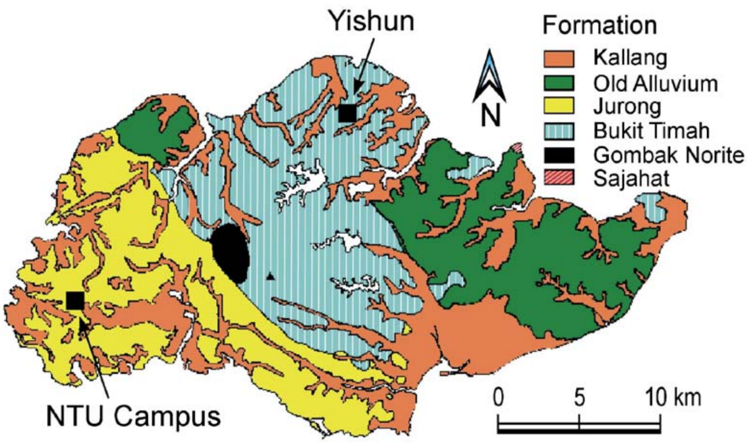

Fig. 1. Generalised geological map of Singapore and soil sampling locations (modified from Pitts, 1984).

characterised individually for an appropriate assessment of its engineering behaviour.

Characterising changes in the engineering properties of a weathered residual soil has recently been a concern of civil engineers in relation to the stability of slopes, underground space construction and tunnelling. Most previous studies (e.g. Public Works Department, 1976; Tan et al., 1980; Pitts, 1984; Poh et al., 1985; Zhao et al., 1994a,b; Sharma et al., 1999; Kar-Winn et al., 2001) have emphasised the geological or engineering characteristics of residual soils from different formations in Singapore. However, these studies have not explicitly examined the relationship between degree of weathering and engineering characteristics of residual soils or the variation in microfabric nature and pore-size distribution with respect to the degree of weathering.

The objectives of this paper are (i) to characterise the engineering properties of weathered residual soils and (ii) to examine the microfabric nature and pore-size distribution of residual soils from two major geological formations in Singapore.

2. Methodology

Soil samples for the study were collected from typical residual soil slopes of two geological formations in Singapore (Fig. 1). Residual soils of the Bukit Timah granitic formation were taken from a slope at Yishun while residual soil samples of the Jurong sedimentary formation were taken from the Nanyang Technological University-Civil and Structural Engineering (NTU-CSE) slope located in the Nanyang Technological University campus as shown in Fig. 1 (Rahardjo et al., 2000).

Soil samples were collected from boreholes using a Mazier sampler (i.e., a triple tube core barrel sampler). A complete set of samples from one borehole was taken from each formation (see Fig. 3, borehole Y3 for Yishun slope and borehole N3 for the NTU-CSE slope in the Bukit Timah granitic and Jurong sedimentary formations, respectively). Index property tests were used to identify basic engineering properties of the soils. Particle size analysis, specific gravity, density and Atterberg limit tests were the main index property tests performed in accordance with ASTM (1992) and BSI (1990). Mineral compositions of the residual soils from different depths were determined using X-ray diffraction (XRD) analysis on air-dried samples. The shear strength and permeability of the residual soils were determined for samples from different depths corresponding to different degrees of weathering. Consolidated, drained triaxial compression tests under saturated and unsaturated conditions were performed to determine the shear strength of the soils following the procedures outlined by Fredlund and Rahardjo (1993). Pressure plate tests were conducted to obtain the soil–water characteristic curves (SWCC) of the residual soils. The saturated coefficient of permeability was calculated from one-dimensional oedometer test results at an effective stress corresponding to the depth. The unsaturated coefficient of permeability function was established using the SWCC and the saturated coefficient of permeability. The procedures for obtaining the SWCC from pressure plate tests and the unsaturated coefficient of permeability function are described by Fredlund and Rahardjo (1993).

Scanning electron microscope (SEM) tests were conducted to determine the microfabric nature of soils at various depths. The specimens for SEM examination were prepared by freeze-drying to minimize changes of soil microfabric due to shrinkage. The pore-size distribution of soils at various depths was determined by a mercury intrusion porosimetry (MIP) machine (Autopore III) and the tests were carried out in accordance with BSI (1992).

3. Results and discussion

3.1. Weathering profile characteristics

Data from all borehole logs (six boreholes in each slope, but with only three boreholes are visible on the cross-sectional view of the slope; Fig. 3) were combined to produce the generalized weathering profile characteristics of the two formations. The six-grade weathering classification of Little (1969), as shown in Fig. 2, was used to produce the weathering profile of the two formations. The soil profile characteristics are shown in Fig. 3.

Two distinct types of residual soils were found in the boreholes of the Bukit Timah formation (Yishun slope). The upper portion of the soil (0 to 9 m depth,

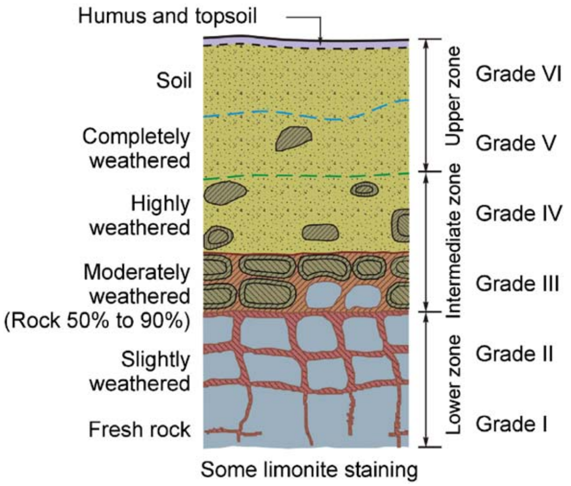

Fig. 2. Typical weathering profile of residual soils (from Little, 1969).

borehole Y3) was totally weathered and transformed into Grade VI residual soil (Fig. 3a). The soils of this layer are clayey silt with smooth-textured soil particles, and the remnant parent rock is not observed. The soil colour ranged from reddish-brown to orange-brown. At about 9 m depth, the colour gradually changes from orange-brown to yellowish-brown with white spots.

From 9 to 21 m depth, completely weathered (Grade V) granitic rock was observed. The colour changed gradually from yellowish to whitish with green and grey spots. The most apparent manifestation of residual soil at this layer was the rough texture of soil particles.

The Jurong sedimentary soil profile in the NTU-CSE slope (Fig. 3b, borehole N3) has a purple clayey silt residual soil surface layer (Grade VI) and a completely weathered rock layer (Grade V) at 1 to 2 m depth from the ground surface. These upper layers are underlain by a mixture of highly weathered sandstone (Grade IV) that runs down to 20 m depth. From 3 to 7 m depth a layer of weathered purple sandstone was encountered and between 7 and 8 m depths a purple weathered siltstone with white spot was encountered. Below 8 m depth, light orange and pink silty weathered sandstone was encountered. Between 12 and 19 m depth, porous orange and brick-red silty sandstone was encountered. Moderately weathered purple sandy siltstones (Grade III) with white spots occupy the layer between 19 and 27 m depth.

3.2. Effect of weathering on mineral composition

Mineral contents of residual soils from different depths in the Bukit Timah granitic and the Jurong sedimentary formations as obtained from XRD analyses are shown in Table 1. Major clay minerals such as kaolinite, illite and serpentine are well developed in the Grade VI residual soil layer of the Bukit Timah granitic formation and their proportions increase with

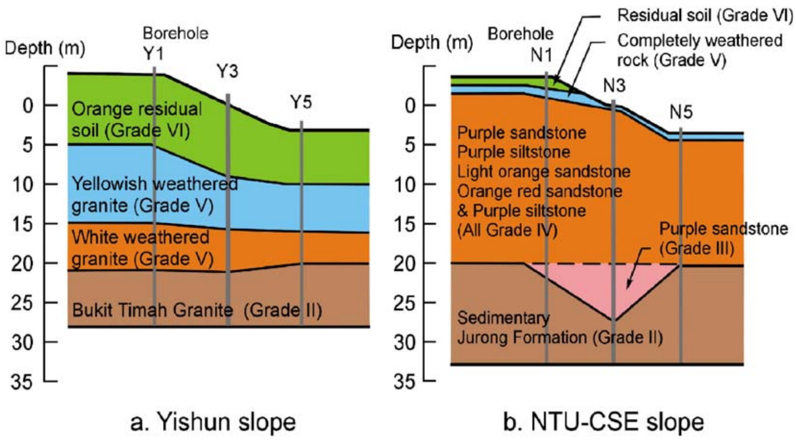

Fig. 3. Typical weathering profile of residual soil from (a) Bukit Timah granitic formation (Yishun slope); (b) Jurong sedimentary formation (NTU-CSE slope).

Table 1
Summary of major mineral composition of residual soils from Singapore

Depth (m)	Grade	Quartz (%)	Feldspar (%)	Mica (%)	Kaolinite (%)	Illite (%)	Serpentine (%)
Bukit Timah granitic formation							
4–5	VI	–	–	–	51	25	24
8.5–9.5	VI	18	–	–	45	20	17
13–14	V	18	15	14	38	15	–
20–21	V	20	12	–	37	17	14
Jurong sedimentary formation							
3–4	IV	~ 95	–	–	–	–	–
8–9	IV	~ 95	–	–	–	–	–
13–14	IV	~ 100	–	–	–	–	–
25–26	III	~ 100	–	–	–	–	–

increasing degree of weathering. Kaolinite is the dominant clay mineral throughout the depth of the Bukit Timah granitic formation. This observation is in agreement with the results of Poh et al. (1985). The proportion of Kaolinite increases as the degree of weathering increases (Table 1). On the other hand, the proportion of quartz decreases as the degree of weathering decreases. Feldspar and mica are only observed in the Grade V completely weathered rock portion (9 to 21 m depths). Illite and serpentine were formed during weathering and their proportions also increase with increase in the degree of weathering. The major mineral of the residual soils from the Jurong sedimentary formation is quartz.

3.3. Effect of weathering on molecular water content

Results of loss on ignition (LOI) tests on samples from different depths are shown in Table 2. The LOI test generally measures the molecular water content in soil minerals (Nishida, 1998). Since most water is contained in the crystal structure of clay minerals rather than in the rock minerals, the test gives an indication of clay content of the samples. For the Bukit Timah granitic residual soil, the LOI value increased with increasing degree of weathering (2% in Grade V completely weathered rock to about 5% in Grade VI residual soil). This is due to the formation of clay minerals in the residual soil layer. The LOI test results from Grade III moderately weathered sandstones and Grade IV highly weathered sandstones of the Jurong sedimentary formation were generally low. No clear increase or decrease of LOI through the soil profile can be discerned for the Jurong sedimentary formation.

Table 2
Loss on ignition (LOI) results of residual soils from Singapore

Depth (m)	Degree of weathering	Soil type	Loss on ignition[a]
Bukit Timah granitic formation			
4–5	Grade VI	Sandy silt	4.8%
8.5–9.5	Grade VI	Sandy silt	5.1%
14–15	Grade V	Silty sand	2.0%
Jurong sedimentary formation			
2–3	Grade IV	Silty sand	0.5%
7.5–8.5	Grade IV	Silty sand	1.1%
14–15	Grade IV	Silty sand	0.9%
25.5–26.2	Grade III	Silty sand	0.8%

[a] Average of two samples at each depth.

3.4. Effect of weathering on index properties

Index property test results indicated that as weathering extends to greater depths, appreciable variations in particle size distribution, specific gravity, natural water content, total density, liquid and plastic limits are observed.

3.4.1. Particle size distribution

Figs. 4 and 5 show the particle size distributions of residual soils from various depths of the Bukit Timah granitic and the Jurong sedimentary formations, respectively. Two distinct particle size distributions were observed from the Bukit Timah granitic formation (Fig. 4). The upper portion (0 to 10 m depth) had a fines content of about 50% and was highly plastic (MH, Unified Soil Classification System). At deeper

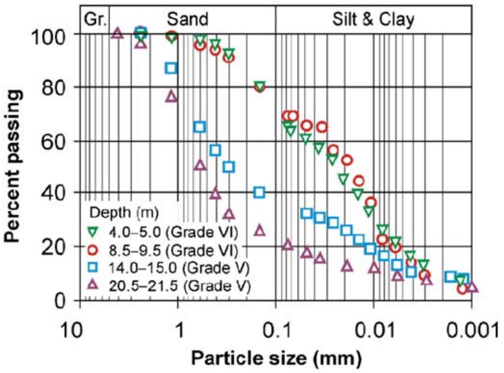

Fig. 4. Particle size distributions of residual soils at different depths from the Bukit Timah granitic formation (Yishun slope).

depths (10 to 20 m) the coarse-grained fraction is more than the fine-grained fraction (the fines content was less than 50%) and the soil type changed to silty sand (SM, Unified Soil Classification System). This implies that the fines content decreases with depth as the degree of weathering decreases. On the other hand, almost all the soils from different depths of the Jurong sedimentary formation (Fig. 5) were coarse-grained, with fines contents between 20% and 40%. No distinct variation in the particle size distribution with depth could be observed for residual soils from the Jurong sedimentary formation.

3.4.2. Specific gravity

Specific gravity depends on the mineralogy of a soil and it can reflect the history of weathering (Tuncer and Lohnes, 1977). The mineralogy of residual soils varies considerably depending on the parent rocks and weathering processes.

The specific gravity of the residual soils from the Bukit Timah granitic formation ranged from 2.55 at shallower depths to 2.78 at greater depths (Fig. 6). These results agree closely with the results of Kar-Winn et al. (2001) for Grades V and VI granitic residual soils.

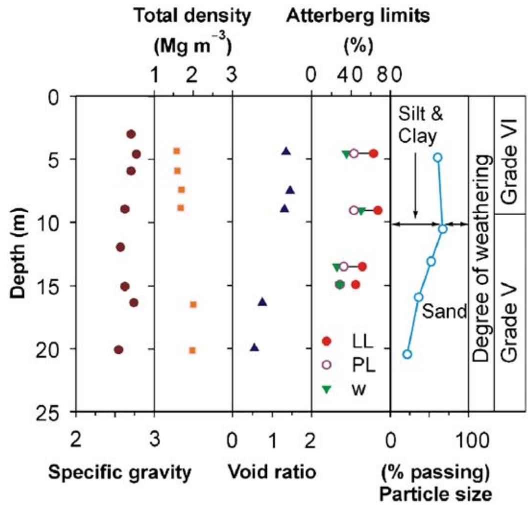

Fig. 6. Index test results of residual soils from different depths of the Bukit Timah granitic formation (Yishun slope).

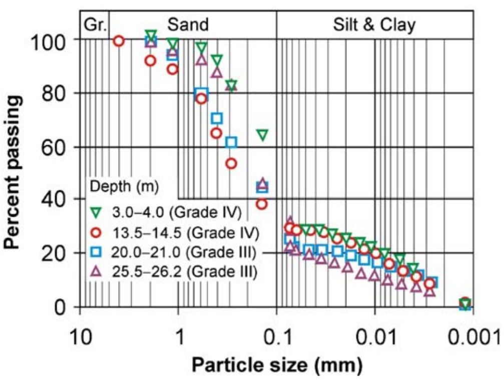

Fig. 5. Particle size distributions of residual soils at different depths from the Jurong sedimentary formation (NTU-CSE slope).

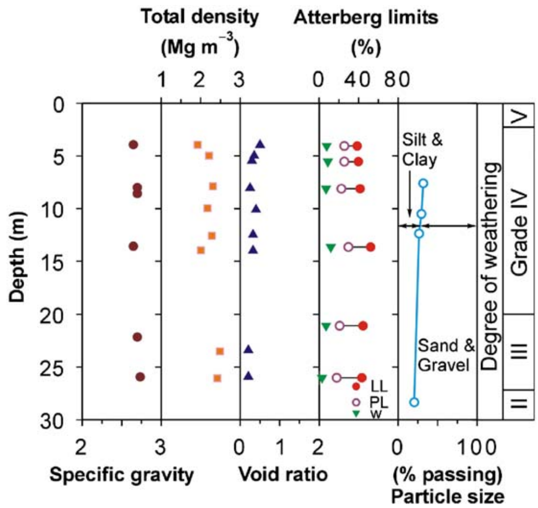

Fig. 7. Index test results of residual soils from different depths of the Jurong sedimentary formation (NTU-CSE slope).

The specific gravity of the residual soils from the Jurong sedimentary formation ranged from 2.65 to 2.75, its value increasing slightly with depth (Fig. 7). This could be accounted for by the presence of minerals other than quartz in the deeper layers that have a higher specific gravity than quartz (Aung, 2001).

3.4.3. Total density and void ratio

Weathering leads to a porous structure due to the considerable leaching of minerals from the soil. Water and air replace the soluble minerals resulting in a porous structure. In the upper layers of residual soils, porosity and void ratio are higher, therefore the water and air phases occupy more space compared to the lower layers. As a result, total density is lower near the surface. At greater depths porosity decreases, resulting in an increase in total density. Therefore, the variation in total density as well as the variation in dry density reflects the variation in the degree of weathering. The total density of the residual soils from the Bukit Timah granitic formation ranged from 1.6 to 2.0 Mg/m^3 with increasing depth. The total density of residual soils from the Jurong sedimentary formations was relatively higher, ranging from 1.9 to 2.5 Mg/m^3 with increasing depth. For both residual soils the void ratio appeared to decrease with depth (Figs. 6 and 7) reflecting the variation in the degree of weathering.

3.4.4. Atterberg limits

The variation of index test results with depth and hence with the degree of weathering of the Bukit Timah granitic and the Jurong sedimentary formations are shown in Figs. 6 and 7, respectively. The liquid limit of residual soils from the Bukit Timah granitic formation ranged between 20% and 40% and the plastic limit ranged between 40% and 60% (Fig. 6). The water content was close to the liquid limit at depths between 3.5 and 4.5 m and gradually became closer to the plastic limit at greater depths. The water content ranged from 20% to 40% and was about constant between the ground surface and 10 m depth, gradually decreasing below 10 m depth. The liquid limit and plastic limit both appeared to be almost constant at depths between 4 and 9 m, gradually decreasing below 9 m depth, with decreasing degree of weathering. This could be attributed to the decrease in fines content at greater depths and less formation of clay minerals in the completely weathered granite (Grade V) layer.

The variation of liquid limit and plastic limit of the residual soils from the Jurong sedimentary formation depends on the type of parent rock: sandstone, siltstone or mudstone. At depths between 5 and 8 m, the soil was a silty-sand and its liquid limit was low. The liquid limit between 13.5 and 14.5 m depth was slightly high due to the presence of sandy silt. The plastic limit and water content show a slight decrease with depth but no distinct variation is noticeable from depth to depth (Fig. 7). This could be due to less weathering in the profile of the Jurong sedimentary formation as compared to the Bukit Timah granitic formation.

3.4.5. Effect of weathering on pore-size distribution

The effect of weathering on micropore size was assessed using mercury intrusion porosimetry tests. The relationship between cumulative pore volume and mean micropore diameter for residual soils from different depth in the Bukit Timah granitic and Jurong sedimentary formations is shown in Figs. 8 and 9, respectively. In general, the soil profile from the Bukit Timah granitic formation, which is relatively more weathered (see weathering profile, Fig. 3a), has a higher cumulative pore volume than the profile from the less weathered Jurong sedimentary formation (see Fig. 3b). This is in good agreement with the higher void ratios and the lower total densities of the Bukit Timah profile (Fig. 6) as compared with the void ratios and total densities of the Jurong profile (Fig. 7).

Figs. 8 and 9 indicate that the majority of the micropore size was in the range from 0.01 to 10 μm for residual soils from the Bukit Timah granitic and

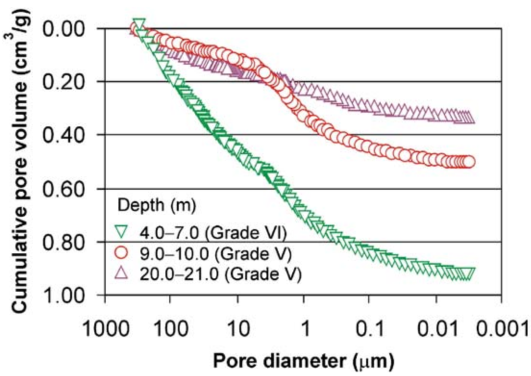

Fig. 8. Pore-size distribution of residual soils from different depth of the Bukit Timah granitic formation.

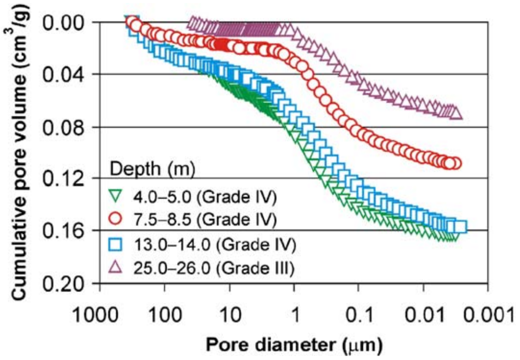

Fig. 9. Pore-size distribution of residual soils from different depth of the Jurong sedimentary formation.

Jurong sedimentary formations. Mercury started to intrude the micropores significantly at diameters between 4 and 6 μm for residual soils from the Bukit Timah granitic formation (Fig. 8). For the Jurong sedimentary formation, mercury intruded the micropores at various diameters ranging between 0.6 and 6 μm (Fig. 9).

Figs. 8 and 9 also show that the cumulative micropore volume decreased with increasing soil depth. Flattening of the pore-size distribution curve for soils at greater depths in the Bukit Timah formation (20 to 21 m; Fig. 8) indicates that fewer micropore sizes less than 0.1μm existed in the deeper soil layers. The trend of the pore-size distribution curves at shallow depths (4 to 7 m and 9 to 10 m; Fig. 8) reveals that various micropore sizes less than 0.1 μm existed in the soil sample at shallow depths. In addition, the results in Figs. 8 and 9 also indicate that the cumulative micropore volume decreased with increasing soil depth or decreasing degree of weathering. In other words, an increase in degree of weathering would result in a higher cumulative pore volume and a larger range of micropore size distribution.

3.5. Effect of weathering on engineering properties

3.5.1. Soil–water characteristic curves

The soil–water characteristic curve (SWCC) is a measure of the water storage capacity of soil at various matric suction values. The ability of a soil to retain water varies with matric suction. Therefore, the coefficient of permeability is not a constant in unsaturated soils but is a function of matric suction because water can only flow through water-filled pores. The matric suction at which a soil starts to become unsaturated is called the air-entry value. The air-entry value of a soil depends on its structure. Its value varies with particle size distribution as well as pore-size distribution. As the grain size and the inter-particle and intra-particle pores of a soil increase, the ability of the soil to maintain saturation decreases. When a soil becomes more weathered, more clay minerals are formed and the ability of the soil to retain water under high matric suctions increases or the air-entry value of the soil increases. Therefore, the SWCC of a soil reflects its pore-size distribution and hence the degree of weathering.

The SWCCs of the residual soils from different depths in the Bukit Timah granitic and the Jurong sedimentary formations are shown in Figs. 10 and 11, respectively. The SWCCs of the Bukit Timah granitic formation (Fig. 10) show that the volumetric water content begins to drop significantly around 100 kPa matric suction (the air-entry value) for Grade V completely weathered rocks from 13 to 17 m and 20.5 to 21.5 m depth. For Grade VI residual soils from depths of 4 to 6 m and 8.5 to 9.5 m, the volumetric water content begins to drop at around 150 kPa matric suction (the air-entry value) because of the higher content of fine particles. In addition, the saturated volumetric water content of Grade VI residual soils (4 to 9.5m) is higher than that of Grade V completely weathered rocks (13 to 21.5m). In other words, the

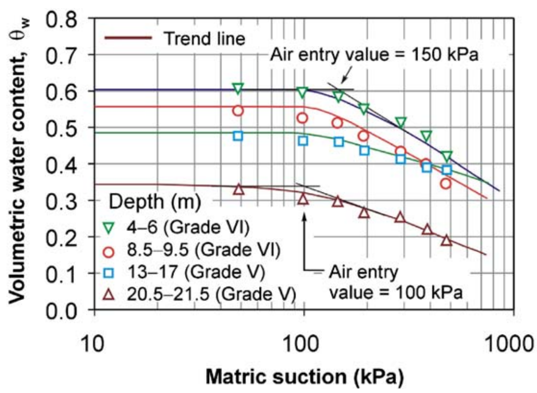

Fig. 10. Soil–water characteristic curves of residual soils from different depths of the Bukit Timah granitic formation (Yishun slope).

saturated volumetric water content and the air-entry value decrease with depth as the degree of weathering decreases.

Similar trends can also be observed in the SWCCs of residual soils from the Jurong sedimentary formation (Fig. 11) except for the soil from 13 to 14 m depth. This inconsistency may be due to the difference in the parent rock type. The air-entry value of the residual soils from the sedimentary Jurong formation was found to be around 300 kPa, which is much higher than the air-entry value of the residual soils from the Bukit Timah granitic formation (100 to 150 kPa). This could be attributed to the small pore-sizes in the residual soils of the Jurong sedimentary formation as compared to the pore-sizes of the residual soils from the Bukit Timah granitic formation. The void ratio varies with depth from 0.5 to 0.2 in the Jurong sedimentary formation, while the void ratio varies from 1.5 to 0.5 in the Bukit Timah granitic formation, indicating the different pore-sizes that exist in each formation.

3.5.2. Permeability

The saturated coefficients of permeability of the residual soils from different depths in the Bukit Timah granitic and the Jurong sedimentary formation are shown in Table 3. The saturated coefficients of permeability of the residual soils from the Bukit Timah granitic formation appear to be higher than the saturated coefficients of permeability of residual soils from the Jurong sedimentary formation. This again could be attributed to the smaller pore-sizes in the Jurong sedimentary residual soils when compared with the pore-sizes of the Bukit Timah granitic residual soils.

Table 3
Saturated coefficients of permeability of residual soils from different depths

Depth (m)	Degree of weathering	Soil type	k_s (m/s)
Bukit Timah granitic formation			
8.5–9.5	Grade VI	Clayey silt	4.0×10^{-9}
16–17	Grade V	Silty sand	5.9×10^{-9}
20.5–21.5	Grade V	Silty sand	7.0×10^{-9}
Jurong sedimentary formation			
4.5–5.5	Grade IV	Silty sand	0.5×10^{-9}
12–13	Grade IV	Silty sand	1.3×10^{-9}
21–22	Grade III	Sandy silt	0.3×10^{-9}

The permeability functions for residual soils from different depths in the Bukit Timah granitic and the Jurong sedimentary formations are shown in Figs. 12 and 13, respectively. Fig. 12 shows that the coefficients of permeability (unsaturated) for Grade VI residual soils from depths between 4 and 5 m and 7 and 8 m decreased sharply with an increase in matric suction beyond 500 kPa. However, the coefficients of permeability for Grade V completely weathered rocks from depths between 16 and 17 m and 20 and 21 m decreased gradually even at matric suctions beyond 500 kPa and this difference may be attributed to the smaller pore-sizes that exist in Grade V as compared to those in Grade VI.

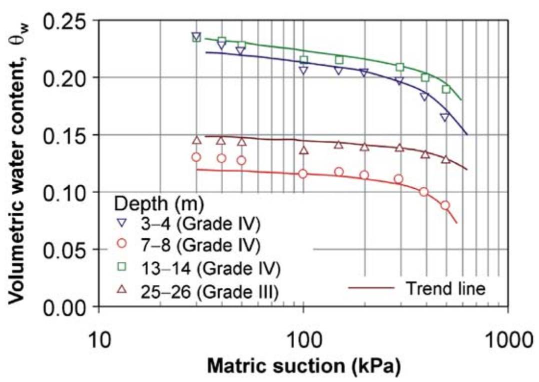

Fig. 11. Soil–water characteristic curves of residual soils from different depths of the Jurong sedimentary formation (NTU-CSE slope).

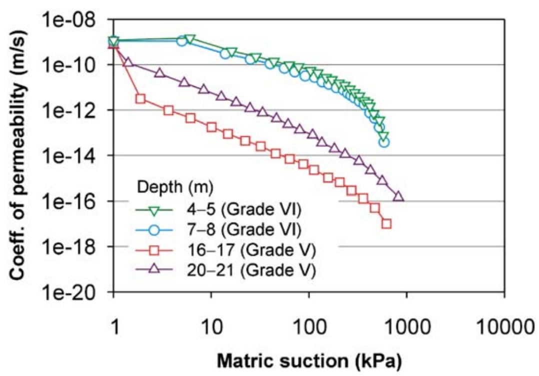

Fig. 12. Permeability functions of residual soils from different depths of the Bukit Timah granitic formation (Yishun slope).

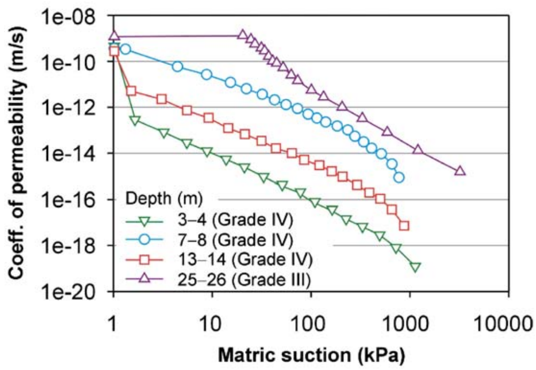

Fig. 13. Permeability functions of residual soils from different depths of the Jurong sedimentary formation (NTU-CSE slope).

3.5.3. Shear strength parameters

A summary of shear strength parameters of residual soils from the Bukit Timah granitic and Jurong sedimentary formations is shown in Table 4. The effective cohesion, c', and the effective friction angle, ϕ', for the residual soils from various depths (shown in Table 4) were evaluated using the Mohr–Coulomb failure envelope. The failure envelopes were found to be linear. The shear strength parameters in general show an inverse relationship with the degree of weathering. While the degree of weathering generally decreases with depth, the shear strength parameters of residual soils from both (the Bukit Timah granitic and the Jurong sedimentary) formations appear to increase with depth.

The effective cohesion, c', of Grade VI residual soil from the Bukit Timah granitic formation was 26 kPa and it decreased significantly between 13 and 12 kPa for Grade V completely weathered rocks at deeper depths. On the other hand, the effective friction angle, ϕ', of Grade VI residual soil from the Bukit Timah granitic formation was 27° and it increased significantly to 35° for Grade V completely weathered rocks. As the degree of weathering decreases with depth, the fines content of the soil also decreases and so does the effective cohesion (Table 4). Apart from the fines content, the type of clay minerals and in situ bond strength are also important factors that affect the effective cohesion of a soil. On the other hand, as the coarse particle content increases with soil depth in this formation (see Fig. 4) the effective friction angle also increases with depth and reaches a maximum value of 38° for Grade V completely weathered rock at 15 to 21 m depth. The texture, size and distribution of soil particles influence the effective friction angle.

The variation of shear strength parameter, ϕ^b, with matric suction for the Bukit Timah granitic formation shows a trend similar to that observed in the effective friction angle. At low matric suctions, the ϕ^b value increased with depth, as the degree of weathering decreases and the content of coarse particles increases at greater depth. However, at high matric suctions (200 kPa) the ϕ^b value decreased with depth from 8° for Grade VI residual soils at shallow depth to a minimum of 4° for Grade V completely weathered granite at greater depth (Table 4). The fine grained soils (Grade VI) have a higher water content than the coarse-grained materials (Grade V), and therefore, the Grade VI residual soils will have a higher ϕ^b value at high matric suctions, compared to the ϕ^b value of the Grade V materials.

For the Jurong sedimentary formation, the effective cohesion of Grade IV materials at 3 to 4 m depths was found to be very high (125 kPa) and the corresponding effective friction angle ϕ' was 42° (Table 4). This could be attributed to the very high bond strength between the individual particles of the weathered rocks of Grade IV. For the weathered rocks between 4.5 and 5.5 m depth, the effective cohesion decreased to 55 kPa and the effective friction angle increased to 51°. This decrease in effective cohesion and corresponding increase in effective friction angle could be due to a change in particle size between these two layers (3 to 4 m and

Table 4
Summary of shear strength parameters of residual soils from different depths

Depth (m)	Soil type	Grade	c' (kPa)	ϕ' (°)	ϕ^b (°)
Granitic Bukit Timah formation					
5–9	Sandy silt	VI	26	27	29 to 8
10–15	Silty sand	V	13	35	35 to 6
15–21	Silty sand	V	12	38	35 to 4
Sedimentary Jurong formation					
3–4	Purple silty sand	IV	125	42	N.A
4.5–5.5	Purple silty sand	IV	55	51	40
9–10	Orange silty sand	IV	35	45	35
22–24	Purple silty sand	III	225	50	N.A

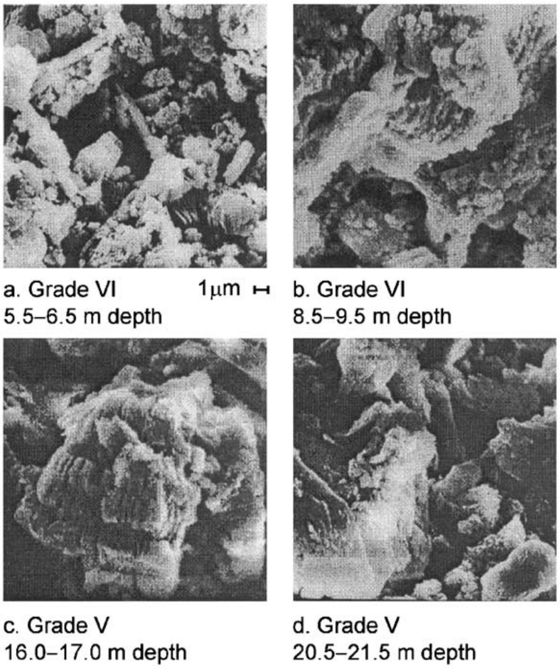

Fig. 14. SEM images at 5000 × magnification of residual soils from the Bukit Timah granitic formation at depths of (a) 5.5–6.5 m; (b) 8.5–9.5 m; (c) 16–17 m; (d) 20.5–21.5 m.

4.5 to 5.5 m depth). The shear strength parameters of Grade IV highly weathered sandstone from 9 to 10 m depth were lower than those from 4.5 to 5.5 m depth, perhaps due to a weaker bond strength. The shear strength of Grade III moderately weathered sandstone was very high. The effective cohesion for this weathered sandstone was as high as 225 kPa and the effective friction angle was 50°.

In the Jurong sedimentary formation, the general trend of shear strength parameters with depth is not as distinct as that for the Bukit Timah granitic formation. This could be due to the existence of different types of parent rocks in the Jurong sedimentary formation. The Jurong formation was formed in stratified layers of sandstone, siltstone and mudstone. Therefore, even with the same exposure to weathering as the Bukit Timah granitic formation, the different types of sedimentary rocks in the Jurong formation exhibited more heterogeneous weathering products and diverse shear strengths.

3.6. Effect of weathering on microfabric characteristics

Scanning electron microscope (SEM) images of residual soils from different depths in the Bukit Timah granitic and the Jurong sedimentary formation at a magnification of 5000 × are shown in Figs. 14 and 15, respectively.

SEM images for the Bukit Timah granitic formation revealed that the surfaces of particles at depths between 5.5 and 9.5 m (Fig. 14a and b) were weathered, with voids on the surface of the soil particles, and exhibit a highly porous structure. The surfaces of particles at depths between 16.5 and 21.5 m (Fig. 14c and d) where the weathering effect is less are smooth. There is no sign of any intra-elementary pores and it appears to be less porous in nature.

According to the microfabric characterization introduced by Collins and McGown (1974), at the elementary level the microfabric of the Bukit Timah formation from 8.5 to 9.5 m depth (Fig. 14b) was

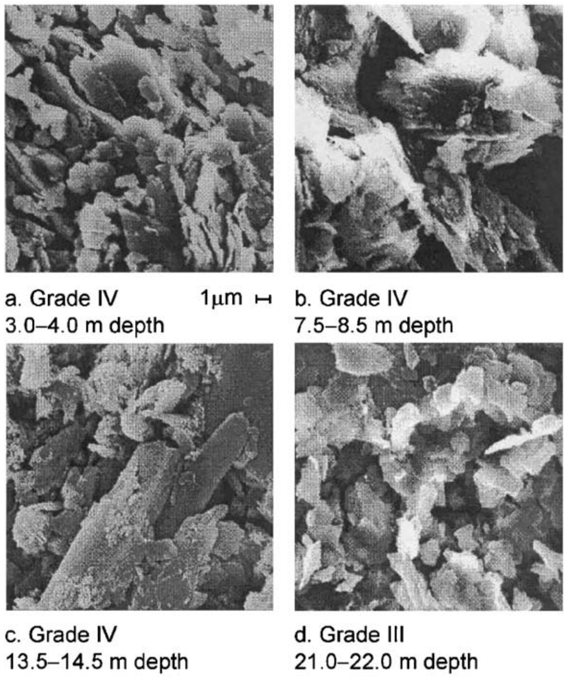

Fig. 15. SEM images at 5000 × magnification of residual soils from the Jurong sedimentary formation at depths (a) 3–4 m; (b) 7.5–8.5 m; (c) 13.5–14.5 m; (d) 21–25 m.

dominated by clay-size clusters, whereas the fine particles from 20.5 to 21.5 m depth (Fig. 14d) have close contact in granular form. At the assemblage level, soil microfabric from 8.5 to 9.5 m depth shows that some granular particles are covered with kaolinite and montmorilonite clay matrix. Soil particles from 20.5 to 21.5 m are mostly granular, with few examples of bonding at the inter-particle level. Platy-shaped kaolinite particles were found to exist separately in the soil microfabric at this depth.

SEM images of the Jurong sedimentary formation revealed that soil particles at depths between 3 and 4 m (Fig. 15a) had a highly bonded fabric structure. The higher shear strength parameters ($c' = 125$ kPa, $\phi' = 42°$; see Table 4) observed in Grade IV purple sandstone from that depth interval are a consequence of this highly bonded fabric structure of the soil. SEM images of the soil from 13.5 to 14.5 m depth (Fig. 15c) revealed it to be highly weathered and porous with most of the loose fine particles having been leached out leaving the unweathered coarse particles. Platy-shaped particles were observed in the weathered rocks between 21.0 and 22.0 m depth (Fig. 15d) and the structure of the weathered rock was very dense. The sandstones over this interval were moderately weathered and bonding among particles was very strong resulting in high shear strength characteristics of the soil (see Table 4).

4. Conclusions

The degree of weathering of the residual soils from the Bukit Timah granitic formation appeared to be reasonably uniform, decreasing only gradually with increasing depth. The degree of weathering of the residual soils from the sedimentary Jurong formation was variable, normally dependent on the parent rock types such as mudstone, siltstone and limestone. The results of the analysis of index properties, engineering properties, SEM and porosimetry tests indicated that the variation in the properties of the residual soils at different depths was largely influenced by the pore-size distributions that vary in accordance with the degree of weathering. A higher degree of weathering would result in a higher pore volume and a larger range of pore-size distribution. It is therefore possible to use the variation in the pore volume and the pore-size distribution through a weathered profile as an indication of the variation in the degree of weathering with depth.

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