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Characterizing a weathering profile over serpentinite in the Senaling area, Negeri Sembilan Darul Khusus

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Abstract: Three broad morphological zones can be differentiated; the top, 2.5 m thick, pedological soil comprising IA and IB sub-zones of brown, soft clays, and IC1 and IC2 sub-zones of reddish brown, stiff silty clays with lateritic concretions and lateritized core stones. The intermediate, 1.5 m thick, saprock zone consists of brown, stiff, silty clays with indistinct relict fault planes and core-stones, whilst the bottom bedrock zone consists of serpentinite with effects of weathering along discontinuity planes. Constant volume samples show the earth materials to be rather loose with dry unit weights of 10.32 to 16.28 kN/m^3 and porosities of 39 to 60%. Particle size distributions are variable with depth; silt contents decreasing from 38 to 58% in saprock to 28 to 44% in the pedological soil zone. Increasing fine clay (<2 μm) contents up the profile from 34 to 43% in saprock to 40 to 51% in sub-zones IA and IB indicate that pedological processes result in continued disintegration of weathered serpentinite. Plastic and liquid limits have limited variation ranging from 24 to 33%, and from 36 to 50%, respectively. Weathered rims around core-stones show alteration of serpentinite to start with the opening-up of grain boundaries and formation of micro-cracks (Stage 1) followed by staining along chrysotile veinlets (Stage 2). More extensive staining then occurs with decomposition (to clay minerals) of most antigorite and chrysotile grains (Stage 3) and ending with formation of a brown, stiff silty clay (Stage 4). Increasing stages of weathering are marked by decreasing dry unit weights and uniaxial compressive strengths, but increasing apparent porosities. It is concluded that in situ alteration of serpentinite through lowering of an unconfined groundwater table has led to development of the weathering profile.

Keywords: Serpentinite, weathering profile, pedological soil, saprock, groundwater lowering

INTRODUCTION

Deep weathering profiles are found in Peninsular Malaysia as a result of favorable tectonic and environmental settings that have facilitated prolonged and pervasive chemical weathering throughout most of the Cenozoic Era (Raj, 2009). The earth materials of these profiles are known as 'residual soils' in geotechnical literature and said to have characteristics that are quite different from those of 'transported or sedimentary soils' (Wesley, 2009). It has also been said that many present-day concepts in soil mechanics may or may not be relevant to 'residual soils' as the concepts were developed through the study of remoulded sedimentary soils with an emphasis on stress history and separation into normally consolidated, and over-consolidated, soils (Wesley, 2009).

There is very limited published data on the geotechnical properties of earth materials in weathering profiles over basic and ultrabasic igneous bedrock in Malaysia. A study of three deep weathering profiles over basalt, granite and schist (with depths to bedrock of 16, 27 and 10 m, respectively) furthermore, has shown that they have rather similar physico-chemical properties despite differences in parent material (Hamdan & Burnham, 1996). It was thus concluded that the rain forests of Peninsular Malaysia over old, deeply weathered soils, had 'closed' nutrient cycling systems where the cationic nutrients are in equilibrium with the main input from the atmosphere; there being negligible contribution of nutrients from weathering of bedrock material. That older soils on a wide range of parent materials tend to be very similar chemically, explains why similar forest growth is found over different geological substrata in Malaysia (Hamdan & Burnham, 1997).

Physico-chemical analyses of 12 soil samples over serpentinite in the Kuala Pilah area showed them to have large clay (21 to 72%), but variable silt (7 to 69%), and low sand and gravel (<10%), contents (Tan & Eng, 2004). The specific gravity of soil particles was relatively large (2.77 to 3.65) due to the presence of iron oxides, whilst liquid limits exceeded 50% and the plasticity index between 6% and 48%. The soils had large natural moisture contents (26 to 69%) due to the large clay contents that allowed high

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adsorption or retention of soil moisture. Chemical analyses of pore fluids showed them to be slightly acidic (pH 5.2 to 5.8) with low conductivities (-0.02 to 0.20 millisiemens/cm) that reflected low dissolved cations due to continuous leaching by percolating water (Tan & Eng, 2004).

In view of the scarce study of "serpentinite formations", Mahsa Tashakor *et al.* (2014) investigated the geochemistry of serpentinite soils from four outcrops in Peninsular Malaysia at Bukit Rokan and Petasih in Negeri Sembilan, and at Cheroh and Bukit Malim in Pahang. Geochemical analyses of 15 superficial weathered samples indicated that they were depleted in silica and essential plant nutrients (as calcium, potassium and phosphorus), but remarkably rich in chromium, nickel and cobalt. It was thus concluded that serpentinite derived soils were non-conducive environments for fauna and flora (Mahsa Tashakor *et al*., 2014).

At a weathering profile over the Kuantan Basalt, three broad morphological zones were differentiated, i.e. an upper, 3.60 m thick pedological soil, an intermediate, 1.12 m thick, saprock and a lower bedrock of vesicular olivine basalt (Raj, 2021). Clay and silt contents increased up the profile with a corresponding decrease in sand and gravel contents; colloid contents in particular increasing from 10 to 15% in saprock through 30 to 40% in saprolite and exceeding 57% in solum. Thin-sections of weathered rims showed alteration of the basalt to start with the formation of micro-cracks (Stage 1) followed by their staining and decomposition of olivine crystals (Stage 2) and then the decomposition of augite (Stage 3), and plagioclase feldspar (Stage 4), crystals. An increase in apparent porosity, but decrease in unit weights and specific gravity, reflected these stages of weathering; the boundary between 'rock' and 'soil' material occurring when all olivine and augite crystals had decomposed (Stage 4). The study concluded that the weathering profile resulted from in situ alteration of basalt due to lowering of an unconfined groundwater table; pedological processes giving rise to further alteration (Raj, 2021).

In the course of a study on the characterization of weathering profiles in Peninsular Malaysia was investigated a profile developed over serpentinite in the Senaling area of Negeri Sembilan Darul Khusus (Raj, 1983). In this article is discussed the characterization of the profile based on the field differentiation of weathering zones and sub-zones and laboratory determination of their physical and soil index properties. Weathering of the bedrock is also discussed and is based on the study of thin-sections and slices of weathered rims around core stones. Effects of weathering are here discussed in terms of changes in physical and soil index properties of the weathered materials rather than chemical parameters in view of the continuous leaching that has occurred at weathering profiles in the Peninsula (Hamdan & Burnham, 1996; Tan & Eng, 2004).

GEOLOGICAL SETTING OF WEATHERING PROFILE

Several small bodies of ultrabasic igneous rock are found in Peninsular Malaysia and largely outcrop as elongated, elliptical shaped bodies on the eastern flanks of the north-south trending Main Range. These mainly serpentinite bodies have an average width of 1 km and are everywhere characterized by shallow, clayey surface soils that are mapped as the Sungai Mas Soil Series by the Malaysian Soil Survey Department (Law, 1967).

The investigated weathering profile was exposed during excavation works for widening of the road shoulder along the Kuala Pilah - Tampin trunk road, some 4 km to the south of Senaling village in Negeri Sembilan Darul Khusus (Figure 1). The exposed bedrock (Figure 2) is a strongly jointed and sheared serpentinite which occurs as an elliptical shaped intrusive body within pre-Lower Permian quartz-mica schists (Khoo, 1974). A number of

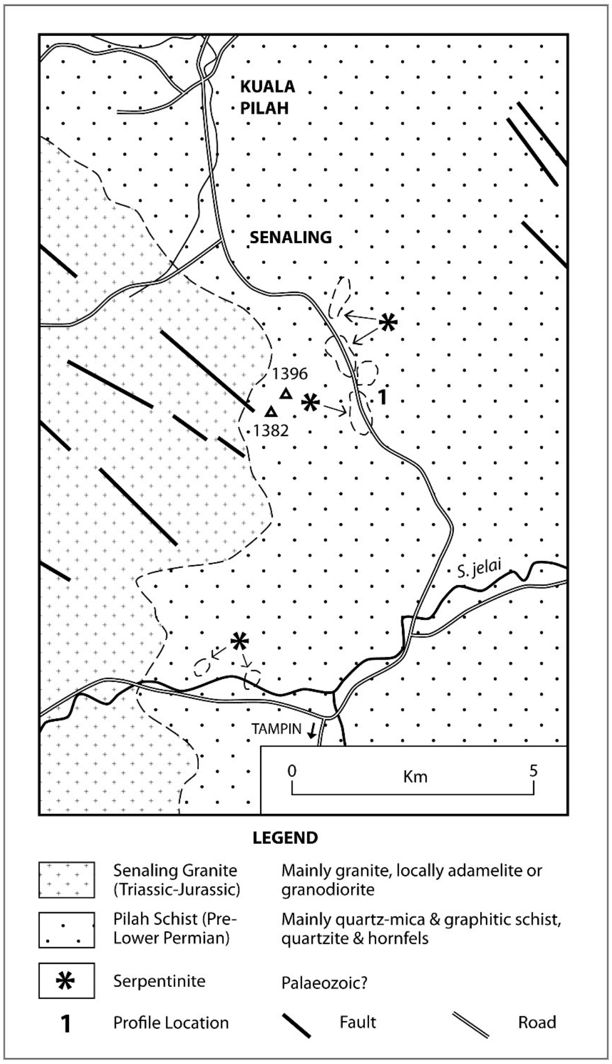

Figure 1: Geology map of the Senaling area, Negeri Sembilan Darul Khusus (Khoo, 1974).

Figure 2: View of exposed weathering profile.

other smaller and similar shaped, serpentinite bodies are exposed at nearby sites and all show shallow, weathering profiles. The origin of the serpentinites is uncertain though they are usually believed to result from the alteration of basic or ultra-basic flows that were probably inter-bedded with the pre-metamorphosed sediments of the schists (Wilbourn, 1933).

In hand specimens, the serpentinite shows various colours ranging from pale green through greenish grey to black and is cut by numerous criss-crossing veinlets of yellowish green chrysotile. In thin-sections, the rock is seen to be mainly made up of anhedral antigorite crystals with lesser chrysotile crystals occurring as criss-crossing veinlets. Dark opaque iron oxide and chromite grains are also seen in accessory amounts with some zeolite, calcite and phlogopite crystals. Obscure relicts of olivine and pyroxene occurring as ooid areas of completely serpentinized minerals have also been reported (Mutalib, 1973).

METHODOLOGY

The exposed earth materials were first described in the field in terms of the Soil Survey Manual for Malayan Conditions (Leamy & Panton, 1966); the pedological features described including colour, consistence, soil structure and texture as well as the content of concretions and organic matter. Geological features were also described, in particular, the textures and structures of the original serpentinite bedrock now indistinctly to distinctly preserved in the weathering profile. Lateral similarity in the pedological and geological features was then used to differentiate weathering zones and sub-zones.

In order to better describe the earth materials present, constant volume samples were then collected at various depths (Figure 3) to determine their physical and soil index properties (samples S1 to S15). Brass tubes of 4 cm length and 7.6 cm internal diameter were used for sample collection; the tubes having a constant wall thickness of 0.3 cm except at one end where the lower half tapered to 0.15 cm thick to provide a cutting edge. Prior to sampling, the tubes were externally greased to facilitate entry into the soil while the surface materials were cleared to a depth of 0.3 m to minimize surface influences.

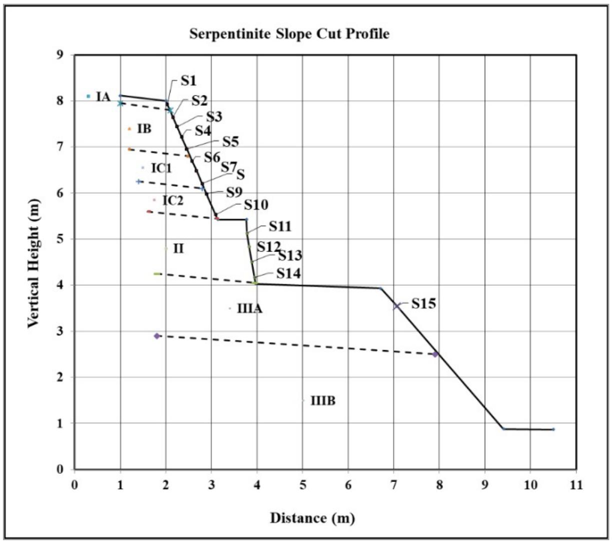

Figure 3: Slope profile and sample locations.

The sampling tubes were sealed and taken to the laboratory where their moisture contents, unit weights and densities were determined before the specific gravity of constituent mineral grains was measured using a pycnometer (ASTM, 1970). Porosities, void ratios and degrees of saturation of the samples were then calculated before the plastic and liquid limits of the fine fractions (<0.42 mm size) were determined (ASTM, 1970). Particle size distributions of the samples were next determined using the sieving, and sedimentation, methods for the coarse (>0.0625 mm diameter), and fine (<0.0625 mm diameter), grained fractions, respectively (ASTM, 1970). The main minerals present in the gravel, sand and silt sized fractions were identified with the aid of a binocular microscope, whilst X-ray diffractograms of the clay fractions were prepared under normal, glycolated, and 500°C heated, conditions to determine the minerals present (Raj, 1983).

Several core-stones were also collected and diamond-sawn into slabs of variable thickness. The weathered rims of the slabs were then studied with a hand lens to identify differences in visible features as staining, colour, texture and the appearance of mineral grains. Thin-sections of the weathered rims were also studied with a petrological microscope to identify changes in texture and mineralogy. Variations in the visible features as well as textural and mineralogical changes were then used to define generalized stages of weathering of the serpentinite bedrock.

Small tetrahedral blocks of the different stages of weathering were then sawn-out from the slabs (samples A1 to A25) and their unit weights, densities and apparent porosities determined by the saturation and buoyancy method (ISRM, 1979). The specific gravity of the constituent mineral grains of the different blocks was also determined with the use of a pycnometer (ASTM, 1970). Several tetrahedral blocks (samples B1 to B24) were also loaded to failure in a compression load frame following standard procedure in order to determine uniaxial compressive strengths (ISRM, 1981).

RESULTS

Weathering zones and sub-zones

Differences in pedological and geological features allow differentiation of three broad weathering zones, i.e. an upper pedological soil (zone I), an intermediate saprock (zone II), and the lower bedrock (zone III) (Table 1).

The pedological soil is 2.5 m thick and can be separated into IA and IB sub-zones (solum) as well as the IC sub-zone (saprolite) (Table 1). The solum consists of brown to yellowish brown, soft clays with many plant roots, whilst the saprolite consists of reddish brown, stiff silty clays with lateritic concretions and lateritized core-stones. Variable amounts of lateritic concretions allow distinction of upper IC1, and lower IC2, sub-zones (Table 1).

The saprock is 1.5 m thick and consists of brown, stiff silty clays that in their lower part contain serpentinite core-stones and indistinct to distinct, relict fault planes. The bedrock zone is a continuous outcrop of serpentinite and can be separated into an upper sub-zone (IIIA) with effects of weathering along and between joint planes, and a lower sub-zone (IIIB) with effects of weathering only along joint planes (Figure 4).

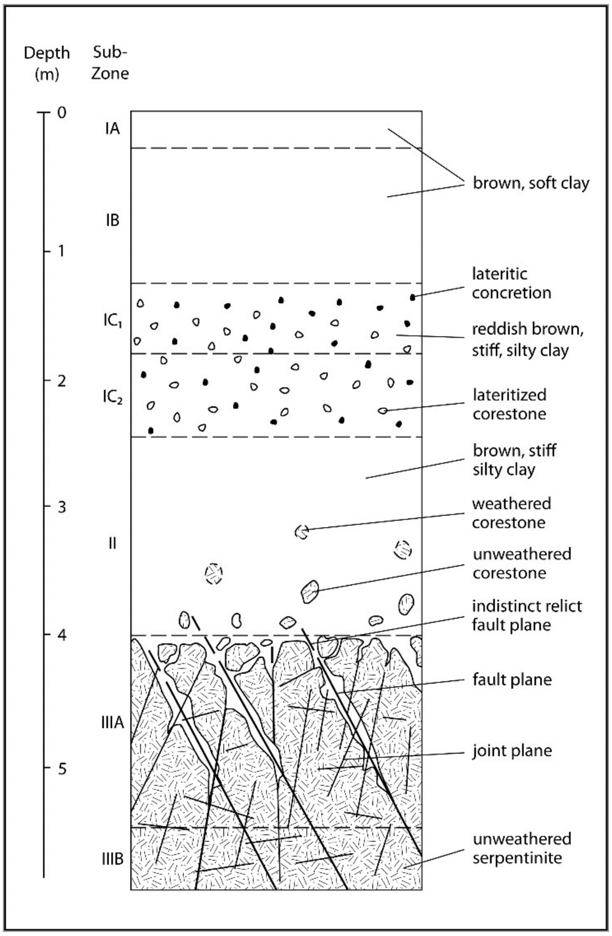

Figure 4: Schematic sketch of morphological features in the weathering profile.

Table 1: Field descriptions of weathering zones and sub-zones.

Zone & Sub-zone	Vertical Depth (m)	Field Description
IA	0.0 - 0.2	Brown (10YR4/3), soft clay; sub-angular blocky moist; friable dry; many roots; boundary wavy, clear.
IB	0.2 - 1.2	Dark yellowish brown (10YR4/4), soft clay; sub-angular blocky moist; friable dry; porous; many roots; boundary irregular, gradual.
IC1	1.2 - 1.9	Reddish brown (5YR4/3), stiff, silty clay; sub-angular blocky moist; friable dry; few roots; many angular lateritized core-stones & lateritic concretions; boundary irregular, gradual.
IC2	1.9 - 2.5	Reddish brown (5YR4/4), stiff, silty clay; sub-angular blocky moist; friable dry; abundant lateritized core-stones & lesser, lateritic concretions; boundary irregular, gradual.
II (Saprock)	2.5 - 4.0	Brown (7.5YR4/4), stiff, silty clay; friable dry; some partly altered core-stones; fresh core-boulders & indistinct to distinct relict fracture planes in lower part of zone; boundary irregular, diffuse
IIIA (Bedrock)	4.0 - 5.5	Continuous outcrop of serpentinite with weathering effects (staining & alteration to silty clay) along & between joint & fault planes; boundary irregular, diffuse.
IIIB (Bedrock)	>5.5	Continuous outcrop of serpentinite with weathering effects (staining & alteration to silty clay) along joint & fault planes.

Physical properties of earth materials in the weathering profile

Constant volume samples show the earth materials to be rather loose; sub-zones IA and IB with dry unit weights of 10.32 to 11.95 kN/m^3, sub-zones IC1 and IC2 with values of 11.17 to 14.12 kN/m^3, and saprock (zone II) with values of 13.66 to 16.28, kN/m^3 (Table 2). Values of dry density mirror those of dry unit weight; sub-zones IA and IB with values of 1,052 to 1,218 kg/m^3, sub-zones IC1 and IC2 with values of 1,139 to 1,439 kg/m^3, and saprock with values of 1,392 to 1,660 kg/m^3 (Table 2). Minimum values of dry unit weight and density in sub-zone IA, but maximum values in saprock indicate a general decrease in compactness of the earth materials up the weathering profile.

The specific gravity of soil particles is quite variable; sub-zones IA and IB with values of 2.58 to 2.65, and sub-zones IC1 and IC2 and upper saprock with values of 2.65 to 2.75 due to the many lateritic concretions present (Table 2). The specific gravity of soil particles from lower saprock and sub-zone IIIA is also relatively large from 2.75 to 2.85 due to the iron oxide and chromite grains present.

Porosities are relatively large; sub-zones IA and IB with values exceeding 50%, whilst sub-zones IC1 and IC2 and upper saprock have values of 39 to 50% (Table 2). Porosities of lower saprock and sub-zone IIIA are also relatively large and exceed 45%. Void ratios reflect the large porosities with sub-zones IA and IB as well as IIIA having ratios exceeding 1.13, whilst sub-zones IC1 and IC2 and zone II have void ratios of 0.63 to 1.01 (Table 2).

Field moisture contents are variable but increase with depth; the pedological soil zone with contents of 25.3 to 28.7%, whilst the saprock and sub-zone IIIA have contents of 20.5 to 43.7% (Table 2). Degrees of saturation distinctly increase with depth; the pedological soil zone with 51 to 81%, upper saprock with 88 to 90%, and lower saprock and sub-zone IIIA with values exceeding 99% (Table 2). Increasing degrees of saturation with depth thus indicate the presence of an unconfined groundwater table in the bedrock zone.

Soil index properties of earth materials in the weathering profile

Particle size distributions are variable with depth, though gravel contents are extremely low (<1%) except for one sub-zone IC1 sample with 3.5% due to the presence of many lateritic concretions. Sand contents are more variable; the solum and saprock with 5 to 24%, and the saprolite with 9 to 30%. Silt contents are of limited variability from 28 to 44% in the pedological soil, and from 38 to 58% in saprock and sub-zone IIIA (Table 3).

Total clay contents are distinctly variable; the solum with contents exceeding 45%, whilst the saprolite has contents of 26 to 49%, and the saprock and sub-zone IIIA with contents of 32 to 50%. Fine clay (<2 µm size) contents generally increase up the profile, with 34 to 43% in saprock and sub-zone IIIA, but 16 to 45% in saprolite, and 40 to 51% in solum. Colloid (<1 µm size) contents also generally increase up the profile with 30 to 39% in saprock and sub-zone IIIA, but 12 to 40% in saprolite, and 36 to 50% in solum (Table 3). Increasing

Table 2: Physical properties of earth materials in the weathering profile.

Sample No.	Sub-zone	Depth (m)	Dry Unit Weight (kN/m^3)	Dry Density (kg/m^3)	Specific Gravity Particle	Porosity (%)	Void Ratio	Water Content (%)	Degree Saturate (%)
S1	IA	0.08	10.32	1,052	2.60	60	1.47	28.7	51
S2	IB	0.36	11.28	1,150	2.61	56	1.27	27.9	57
S3	IB	0.56	11.79	1,202	2.58	53	1.15	27.8	63
S4	IB	0.78	11.62	1,185	2.65	55	1.24	27.6	59
S5	IB	1.04	11.95	1,218	2.65	54	1.18	25.3	57
S6	IC1	1.31	11.17	1,139	2.65	57	1.33	25.9	52
S7	IC1	1.53	14.07	1,434	2.70	47	0.88	25.4	78
S8	IC1	1.80	14.12	1,439	2.72	47	0.89	26.5	81
S9	IC2	2.02	13.33	1,359	2.70	50	0.99	25.4	70
S10	IC2	2.47	13.16	1,341	2.70	50	1.01	26.4	70
S11	II	2.87	16.09	1,640	2.75	40	0.68	22.2	90
S12	II	3.15	16.28	1,660	2.70	39	0.63	20.5	88
S13	II	3.49	15.20	1,549	2.82	45	0.82	28.7	99
S14	II	3.83	13.66	1,392	2.75	49	0.98	35.0	99
S15	IIIA	4.45	12.48	1,272	2.85	55	1.24	43.7	100

Table 3: Index properties of earth materials in the weathering profile.

Sample No.	Sub-zone	Gravel (%)	Sand (%)	Silt (%)	Total Clay (%)	Plastic Limit (%)	Liquid Limit (%)	Fine Clay (<2 µm) (%)	Colloids (<1µm) (%)
S1	IA	0.0	19	28	53	24	36	51	50
S2	IB	0.1	5	48	47	26	36	43	39
S3	IB	0.0	21	32	47	27	43	43	38
S4	IB	0.4	9	43	48	28	43	43	38
S5	IB	0.0	21	34	45	27	47	40	36
S6	IC1	3.5	12	40	44	30	47	39	34
S7	IC1	0.0	19	33	48	29	50	43	40
S8	IC1	0.1	9	42	49	28	47	45	39
S9	IC2	0.0	30	44	26	30	47	24	21
S10	IC2	0.0	20	34	46	31	Ind	16	12
S11	II	0.8	10	39	50	33	Ind	38	33
S12	II	0.0	24	38	38	27	43	43	39
S13	II	0.1	9	50	41	27	43	34	30
S14	II	0.0	10	58	32	31	47	39	34
S15	IIIA	0.0	8	49	43	33	52	40	32

Note: Ind means indeterminate

fine clay and colloid contents up the profile, especially within the pedological soil (zone I), clearly point to the role of pedological processes in continued disintegration of completely weathered bedrock.

Plastic limits are of limited variation within the profile; the pedological soils with values of 24 to 31%, and saprock and sub-zone IIIA with values of 27 to 33% (Table 3). Liquid limits show some variation; the solum with values between 36 and 47%, whilst the solum and saprock have values between 43 and 50% (Table 3). In view of these results, the earth materials at the weathering profile can be classified as inorganic silts and clays of low plasticity in terms of the Unified Soil Classification System (Wagner, 1957).

X-ray diffractograms

X-ray diffractograms show broad and low reflection peaks as a result of high background values that reflect the large content of colloids present (Figure 5). Kaolinite-smectite mixed layer clay minerals are interpreted to be present in view of the narrow, symmetrical peaks at 12.30° 2θ (7.20 Å) and 24.80° 2θ (3.59 Å) and the broad reflection band from about 11 Å to 14 Å on the untreated diffractograms (Thorez, 1975). The narrow, symmetrical peaks do not shift in the glycolated diffractograms, though the broad reflection band shifts towards 13 Å to 17 Å. In the 500°C heated diffractograms, the reflection at 7.20 Å disappears, whilst the reflection at 3.59 Å is reduced

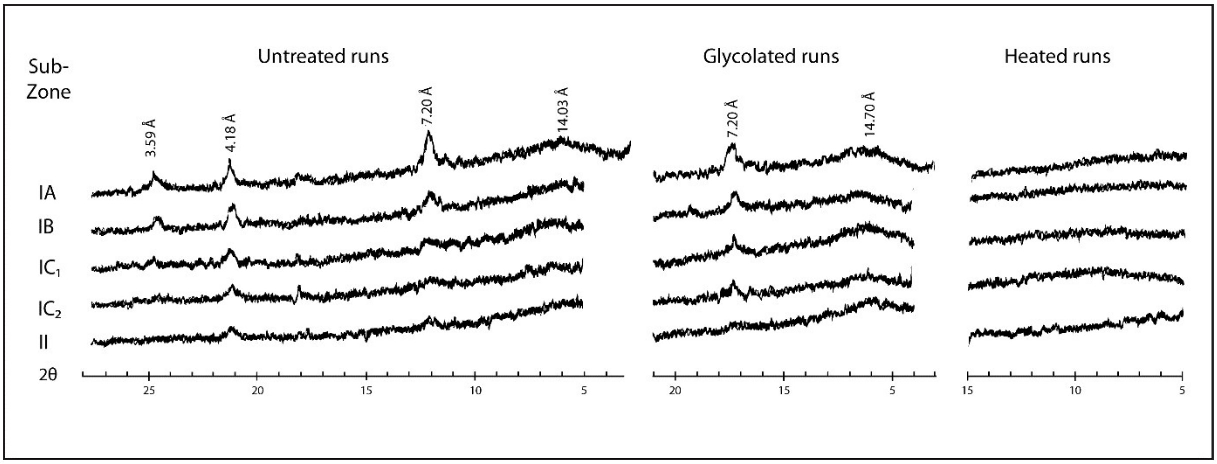

Figure 5: X-ray diffractograms of clay sized fractions in the weathering profile.

in intensity and the broad reflection band is replaced by a single reflection peak of about 10 Å. Goethite is also present in the clay sized fraction and identified by the broad reflection at 21.75° 2θ (4.18 Å) in the untreated scans.

Weathering of serpentinite rock material

Hand specimens, and thin-sections, of the narrow (1–3 cm thick) weathered rims around core-stones show alteration of the serpentinite to follow a limited number of generalized stages (Table 4). Alteration starts with the opening-up of grain boundaries and formation of micro-cracks (Stage 1) followed by staining along chrysotile veinlets (Stage 2). More extensive staining then occurs with decomposition (to clay minerals) of most antigorite and chrysotile crystals (Stage 3). Continued decomposition of antigorite and chrysotile crystals then results in a brown, stiff silty clay (Stage 4) which readily disaggregates when dry samples are agitated in water; a criterion that allows it to be classified as "soil" material (Terzaghi & Peck, 1948). Stage 3 weathered serpentinite thus represents the transition between "rock" and "soil" material.

Differences in physical properties reflect weathering of the serpentinite; increasing stages of weathering marked by a decrease in dry unit weight and density, but an increase in apparent porosity (Table 5). Fresh serpentinite has a dry unit weight between 24.72 and 26.14 kN/m^3, and dry density between 2,520 and 2,666 kg/m^3, whilst stages 1 and 2 weathered serpentinite have corresponding values between 21.06 and 24.72 kN/m^3, and between 2,148 and 2,520, kg/m^3, respectively. Stage 3 weathered serpentinite which is transitional between "rock" and "soil", however, has dry unit weights between 17.05 and 20.21 kN/m^3 and dry densities between 1,738 and 2,017 kg/m^3 (Table 5). Fresh serpentinite furthermore, has an apparent porosity of less than 2.7%, whilst stages 1 and 2 weathered serpentinite have values between 3.7 and 17.3%, and stage 3 an apparent porosity between 21.6 and 30.7% (Table 5).

Differences in uniaxial compressive strength also reflect the different stages of weathering, though there is much scatter in the results due to the inherent chrysotile veinlets that impart an anisotropy to tested specimens (Table 6). Fresh (unaltered) serpentinite has a uniaxial compressive strength ranging from 118.2 to 182.0 MPa, whilst stage 1 weathered serpentinite has values between 28.3 and 98.6 MPa, and Stage 2 weathered serpentinite values between10.3 and 21.6 MPa (Table 6). Stage 3 weathered serpentinite that represents the transition between weathered "rock" and "soil" has a uniaxial compressive strength of between 5.1 and 7.9 MPa (Table 6).

DISCUSSION

Comparison with published literature

Grain size distributions of samples from the pedological soil profile in the present study are comparable with those reported in the earlier study involving soil samples over serpentinite in the Kuala Pilah area (Tan & Eng, 2004). Similar large clay contents (>21%) as well as variable silt contents (7 to 69%), and low sand and gravel contents (<10%) are seen in both sets of samples. Weathered earth materials over serpentinite in the Oe-yama

Table 4: Generalized stages of weathering of serpentinite.

Stage	Hand specimen Features	Thin-section Features
0	Dark green to black, rock material with criss-crossing, yellow green to white veinlets. Mineral grains appear fresh & unaltered. (Unweathered serpentinite).	Unaltered, fine grained antigorite crystals with veinlets of fresh chrysotile crystals. Grain boundaries tight. Many opaque, iron oxide & chromite grains.
1	As Stage 0 (unweathered rock material) but some open grain boundaries & micro-cracks. (Slightly weathered serpentinite).	As Stage 0 (unweathered rock material) but some open grain boundaries & micro-cracks.
2	As Stage 0 (unweathered rock material) but brown stains along veinlets. Many open grain boundaries & micro-cracks. Mineral grains appear unaltered. (Moderately weathered serpentinite)	Brown stains along chrysotile veinlets. Antigorite & chrysotile crystals appear unaltered. Many open grain boundaries & micro-cracks. Many iron oxide & chromite grains seen.
3	Light to dark brown "rock material" with distinct relict texture. Does not disaggregate when agitated in water. Mineral grains all appear altered. (Highly weathered serpentinite).	Brown stains pervade relict antigorite & chrysotile grains (altered to clay minerals). Grain boundaries & micro-cracks are open. Many opaque, iron oxide & chromite grains seen.
4	Brown, stiff silty clay soil. Disaggregates when agitated in water. Coarse fraction of iron oxide & chromite grains. (Completely weathered serpentinite)	X-ray diffractions show clay fraction to consist of mixed layer kaolinite & smectite.

Table 5: Physical properties of generalized stages of weathering of serpentinite.

Sample Number	Stage of Weathering	Dry Unit Weight (kN/m^3)	Porosity (%)	Dry Density (kg/m^3)	Specific Gravity Particles
A1	0	25.79	0.44	2,629	2.641
A2	0	26.14	1.30	2,666	2.701
A3	0	25.69	1.48	2,620	2.659
A4	0	25.13	2.72	2,562	2.634
A5	1	24.72	3.70	2,520	2.617
A6	1	24.20	5.03	2,467	2.598
A7	1	24.19	7.08	2,466	2.654
A8	1	23.18	8.13	2,364	2.573
A9	2	23.43	10.68	2,389	2.675
A10	2	23.36	10.76	2,382	2.669
A11	2	22.61	11.65	2,306	2.610
A12	2	22.61	12.38	2,305	2.631
A13	2	21.97	13.24	2,240	2.582
A14	2	21.67	15.43	2,210	2.613
A15	2	21.84	15.58	2,227	2.638
A16	2	21.06	17.30	2,148	2.597
A17	3	20.21	21.58	2,061	2.628
A18	3	19.69	22.97	2,008	2.607
A19	3	19.78	24.38	2,017	2.667
A20	3	17.05	30.74	1,738	2.510
A21	4	15.27	38.53	1,557	2.533
A22	4	15.45	39.40	1,576	2.600
A23	4	15.66	42.04	1,597	2.755
A24	4	13.91	44.06	1,419	2.536
A25	4	12.54	51.86	1,279	2.656

and Seki-no-miya districts of central Japan, however, show more variable grain size distributions with sand contents of 37.5 to 72.0%, silt contents of 15.5 to 29%, and clay contents of 7 to 43.5% (Matsukura *et al.*, 2000).

The specific gravity (2.58 to 2.85) of soil particles in the present study is quite similar to those (2.43 to 2.92) reported for weathered earth materials over serpentinite in the Oe-yama and Seki-no-miya districts of central Japan (Matsukura *et al.*, 2000). The present values are, however, not as high as those (2.77 to 3.65) reported in the earlier study of Tan & Eng (2004); the difference likely due to variations in iron contents.

Moisture contents in the present study (25.7 to 43.7%) are comparable with those (26 to 69%) reported in the earlier study (Tan & Eng, 2004); the large moisture contents reflecting the large clay contents present. These moisture contents are also comparable with those (36.3 to 85.3%) reported for weathered earth materials over serpentinite in the Oe-yama and Seki-no-miya districts of central Japan (Matsukura *et al.*, 2000). Plasticity indices (8 to 21%) of samples in the present study are similar to those (6 to 48%) reported in the earlier study (Tan & Eng, 2004), though liquid limits (36 to 52%) are more variable in comparison with the results (>50%) of the earlier study.

Evolution of weathering profile

The differentiation of three broad zones within the weathering profile is based on the pedo-weathering profile concept (Tandarich *et al.*, 2002) and is closely similar to the three alteration zones differentiated in a 140 cm thick weathering profile over serpentinite near La Roche in central France (Caillaud *et al.*, 2004). The three alteration zones, from bottom to top, are (a) unweathered rock, (b) saprock where coherent rock structure was still preserved and primary minerals still interconnected, and (c) saprolite where the texture of the original rock had been destroyed and replaced by a mixture of clay associated with oxy-hydroxides and relics of primary minerals. The saprolite was separated into a lower saprolite with prismatic structure

Table 6: Uniaxial compressive strengths of generalized stages of weathering of serpentinite.

Sample Number	Stage of Weathering	Uniaxial Compressive Strength (MPa)	Uniaxial Compressive Strength (psi)	Bulk Unit Weight (kN/m^3)	Orientation Sample
B1	0	182.02	26,398	25.55	Layering perpendicular or gently dipping to direction of loading
B2		155.78	22,593	25.23	
B3		130.01	18,856	25.47	
B4		124.82	18,102	24.97	
B5		118.20	17,143	25.87	
B6	0 & 1	98.63	14,304	25.44	Layering parallel or steeply dipping to direction of loading
B7		97.01	14,070	24.96	
B8		79.62	11,548	25.66	
B9		76.31	11,068	25.47	
B10		66.34	9,622	24.95	
B11		45.10	6,541	25.16	
B12		43.18	6,262	25.62	
B13		38.04	5,517	23.96	
B14		33.34	4,835	24.60	
B15		28.30	4,105	24.84	
B16	2	21.58	3,128	24.80	Layering with stains at variable orientations to direction of loading
B17		15.69	2,275	20.09	
B18		11.80	1,712	19.82	
B19		10.49	1,522	21.00	
B20		10.30	1,493	21.14	
B21	3	7.85	1,138	19.58	
B22		6.86	995	21.00	
B23		5.88	853	20.05	
B24		5.10	739	19.30	

generated by wetting and drying cycles in the deeply argillized rock, and an upper saprolite with polyhedric structure. Overlying the saprolite was as allochthonous deposit that contained feldspars and quartz resulting from weathering of the Masif Central (Caillaud *et al*., 2004).

Differentiation of the three broad weathering zones clearly substantiates the view of Carroll (1970) that chemical weathering at the outer part of the lithosphere takes place in two stages; the first stage being the production of rotten rocks, on which the second stage, soil formation, takes place. The first stage is geochemical weathering, and is mostly the inorganic alteration of solid rocks, but in the second stage, the effects of vegetation, both living and dead, together with the effects of metabolism of micro-organisms living in the geochemically altered rock materials, are added by the continued inorganic processes (Carroll, 1970).

The pedological soil (zone I) of the present study is thus considered to result from alteration of bedrock by both geochemical and pedological processes, whilst the saprock (zone II) results from alteration of bedrock by geochemical processes. Increasing fine clay and colloid contents upwards within the pedological soil clearly point to the role of pedological processes in continued disintegration of completely weathered bedrock (saprolite).

The present location of the unconfined groundwater table in the bedrock zone furthermore, indicates that lowering of the water table with time has given rise to leaching and alteration of the bedrock. Such continuous leaching by percolating water has in fact been considered to give rise to the low dissolved cations in weathered soils over serpentinite in the Kuala Pilah area (Tan & Eng, 2004).

CONCLUSIONS

It is concluded that the weathering profile can be differentiated into three broad zones; an upper pedological soil (zone I), an intermediate saprock (zone II) and the underlying bedrock (zone III). The 2.5 m thick, pedological soil consists of brown, soft to stiff, silty clays and can be separated into IA, IB, IC1 and IC2 soil horizons (sub-zones). The 1.5 m thick saprock consists of brown, stiff, silty clays with indistinct relict fault planes and core-stones, whilst the bedrock consists of serpentinite with effects of weathering along, discontinuity planes.

Constant volume samples show the earth materials to have dry unit weights ranging from 10.32 to 16.28 kN/m^3, and porosities of 39 to 60%. Particle size distributions are variable with silt contents decreasing upwards from 38 to 58% in saprock to 28 to 44% in the pedological soil. Increasing fine clay (<2 µm) contents upwards from 34 to 43% in saprock to 40 to 51% in sub-zones IA and IB indicate that pedological processes have led to continued disintegration of weathered serpentinite.

Weathered rims around core-stones show alteration of serpentinite to start with the opening-up of grain boundaries and formation of micro-cracks (Stage 1) followed by staining along chrysotile veinlets (Stage 2). More extensive staining then occurs with decomposition (to clay minerals) of most antigorite and chrysotile grains (Stage 3) and finally formation of a brown, stiff silty clay (Stage 4). Increasing stages of weathering are marked by decreasing dry unit weights, dry densities and uniaxial compressive strengths, but increasing apparent porosities.

It is concluded that in situ alteration of serpentinite through lowering of an unconfined groundwater table has led to development of the weathering profile.

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CONFLICTS OF INTEREST

The author has no conflicts of interest to declare that are relevant to the content of this article.

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