The characterization of granitic saprolitic soils
La caractérisation des sols saprolitiques de granite

J.B.MASSEY, Geotechnical Control Office, Hong Kong
T.Y.IRFAN, Geotechnical Control Office, Hong Kong
A.CIPULLO, Geotechnical Control Office, Hong Kong

SYNOPSIS: The engineering properties of saprolites and residual soils are not related uniquely to grain size and void ratio, but are governed by the microfabric of the soils, which is a function of the nature and intensity of the weathering and alteration processes which have taken place. The weathering microenvironment is frequently highly variable, even in relatively uniform geological profiles. This paper describes the findings of field and laboratory studies undertaken to characterize microfabric, and examines the relationship between microfabric and the deformation and shear behaviour of granitic saprolites.

INTRODUCTION

Saprolitic soils formed from insitu chemical weathering and alteration of rocks in tropical climates generally do not exhibit properties normally associated with sedimentary soils, and present problems in analysis and design because of their different engineering properties and extreme variability. The relationships which have been successfully developed for transported soils, relating the results of soil classification tests and various engineering properties, do not seem to hold for tropical saprolitic soils. This partly stems from the difficulty of determining a meaningful grain size distribution for these soils, partly from the variability of grain size, voids and products of decomposition even within a particular sample, and also to a large extent from the presence of weak bonding and microfabric, either retained from the parent rock or generated during weathering (Irfan 1988).

The terms "residual soil", "saprolitic soil" and "lateritic soil" have sometimes been used interchangeably to describe and classify the various components of both weathering profile and products. In this paper, the term "residual soil" is restricted to the topmost soil zone of the weathering profile which has lost all of the original rock fabric, and the term "saprolite" is used as a general term to describe that portion of the weathering profile which has retained the original rock fabric and structure, but is a soil in terms of consistency and strength. In rocks of all types, hydrothermal alteration is an equally important mechanism akin to chemical weathering, particularly for igneous rocks. Although the resultant products may be very similar, the effects of the two processes can however be distinguished by the type of structural control and the material variations recognised in the field and in the laboratory.

In Hong Kong, a six-fold material grading scheme, based on Moye (1955), has traditionally been used to characterize the weathering state of the rock material (GCO 1984). In this scheme, the term decomposition is used to describe the weathering state of rock material, with grades I, II and III (fresh, slightly and moderately decomposed respectively) used for rock, and grades IV, V and VI (highly and completely decomposed, and residual soil) for soil and soil-like materials.

In the mountainous terrain of Hong Kong, residual soils are generally very thin or absent, whereas thick saprolites have developed over commonly occurring igneous and volcanic rocks. The stability of both existing and new slopes formed in the latter material is conventionally assessed analytically by limit equilibrium methods (e.g. Morgenstern & Price 1965) using shear strength parameters determined in the laboratory, generally by triaxial testing and, more recently, by direct shear testing. These tests are considered the most satisfactory means of establishing likely ranges of shear strengths for the soil portion of the weathering profile (Brand 1985).

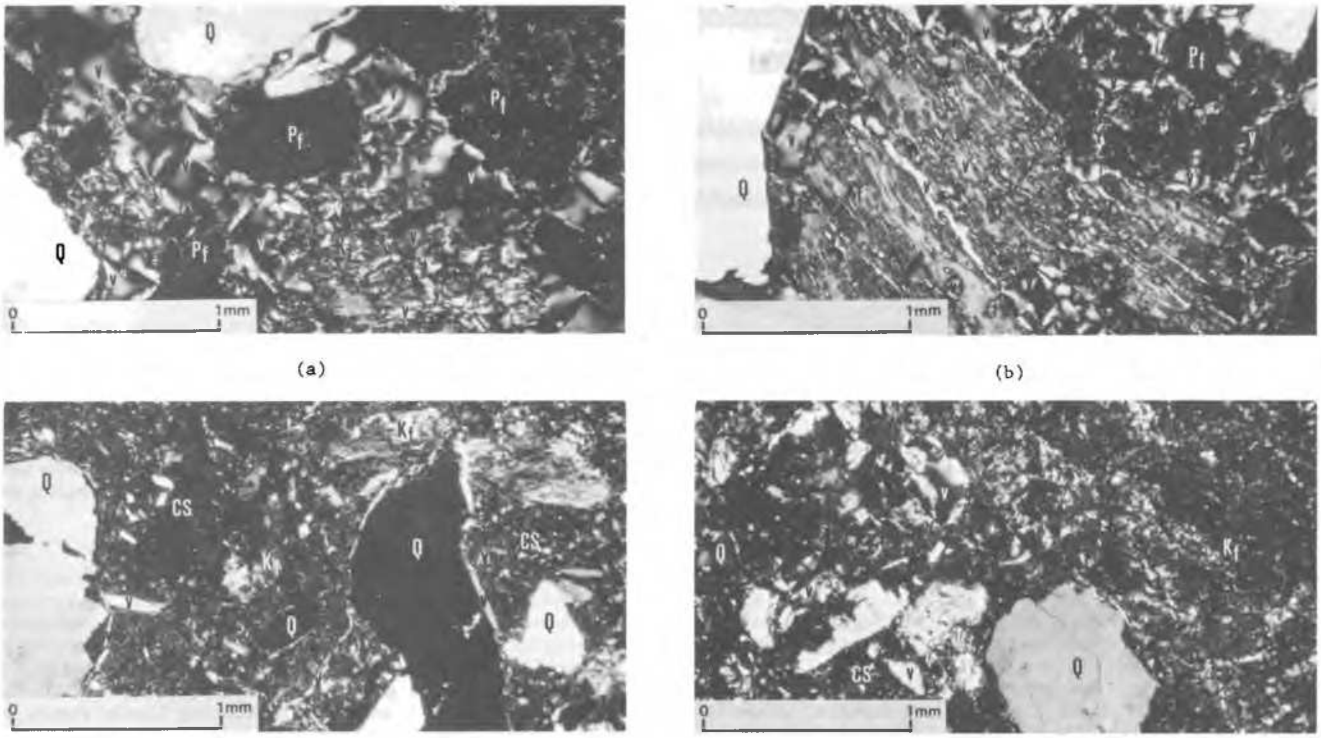
A research programme is being carried out by the Geotechnical Control Office to investigate the shear behaviour of saprolitic soils in Hong Kong by (i) studying the microfabric of representative samples from selected localities by the use of observational and quantitative techniques, and (ii) relating the index and shear strength properties of the selected soils to the degree and type of weathering, alteration and the associated microfabric.

This paper presents some preliminary results of this investigation and discusses the effect of microfabric on the engineering behaviour of saturated granitic saprolitic soils tested in direct shear and triaxial compression. The results of oedometer and isotropic stress tests are also briefly discussed.

WEATHERING INDICES AND MICROFABRICS

The use of index tests for the engineering assessment of weathered rocks with particular reference to Hong Kong is discussed by Martin (1986). Although many of the quantitative indices have been specifically developed to characterize degree of weathering for coarse-grained igneous rocks (Lumb 1962, Irfan & Dearman 1978a), some have also been applied to fine-grained igneous rocks (Weinert 1964, Dearman et al. 1987). Good correlations have been reported between test indices and engineering properties of weathered granite (Onodera et al 1974, Irfan & Dearman 1978a). Chemical indices, such as ignition loss (Sueka et al 1985), pH and specific gravity of feldspars (Matsuo & Nishida 1968) are a relatively accurate measure of degree of chemical alteration of mineral constituents.

The micropetrographic index Ip described by Irfan & Dearman (1978a) gives insight into the changing mineralogical and microcrack regimes involved in progressive weathering and hydrothermal alteration and may be used to characterize decomposed rock in terms of its physical and chemical state. The decomposition index



(a) (b)

(c) (d)

Figure 1. Photomicrographs (crossed polarized light) of granitic saprolite. (a) Decomposed granite from block sample SH8 illustrating the very porous alkali feldspar microstructure (grey areas marked V in K_f are voids and microcracks), completely decomposed, non porous plagioclase (P_f) and microfractured quartz (Q). (b) Typical porous, honeycombed microstructure (etch-pits, trenches) in alkali feldspar from block sample SH8. (c) Decomposed granite from block sample SH3 (transition zone) showing areas of collapsed microstructure (marked CS) composed of fragments of quartz and feldspars in a clayey matrix. (d) Altered granite from block sample KP3 showing a large alkali feldspar grain, completely altered and iron stained with no honeycombed microstructure (top right) and an area of collapsed microstructure (CS) composed of quartz grains in a dense clayey matrix (left)

X_d described by Lumb (1962) has been used to quantify the degree of decomposition of feldspars in relation to selected engineering properties of granitic saprolites.

The parameters determined from many of the classical laboratory methods have not been found to accurately reflect the degree of weathering of the residual and saprolitic soils, or their engineering properties. Although residual and saprolitic soils show similar characteristics to sedimentary soils in terms of permeability, drained strength envelope, cohesion intercept and yield stress, they are complex materials and their engineering properties are greatly influenced by the microfabric developed from the weathering processes (Vaughan 1985).

The term microfabric is used here to mean the geometric arrangement of particles, including particle size distribution and porosity, which may be studied by optical and electron microscopy. The objective of microfabric studies is to classify and quantify the various fabric aspects in order that these can be correlated with engineering properties. Collins (1985a) proposed a microfabric characterization scheme for use in engineering studies appropriate to saprolitic and residual soils, in order to provide a rational and solid framework which can be extended and added to as the need arises. Baynes & Dearman (1978), in their study of granite weathering, concluded that microfabric reflects the duration and intensity of weathering, and that it is common to find varied microfabric within the same specimen, indicating different weathering micro-environments. In the case of granites, they related the microfabric to the degree to which feldspars have been weathered, to the proportion of clay produced during the decomposition processes, and also to the extent to which particles have been eluviated from the system.

SITE DESCRIPTION, WEATHERING AND ALTERATION

The two sites selected for this study are located, respectively, at Shouson Hill on Hong Kong Island and at King's Park on the Kowloon Peninsula. The former site occupies part of a relatively flat hilltop above a 10-15 m high cut slope, while the latter is situated on the western upper flank of a small hill rising out of the relatively flat surroundings. The bedrock is granite at both sites and, at Shouson Hill, the rock is of a commonly occurring type, with typical mineral composition, grain sizes of 1 mm to 4 mm, and occasional feldspars up to 10 mm. The granite occurring at the

King's Park site forms a separate intrusion and is atypically porphyritic, with feldspar crystals up to 20 mm in size set in a groundmass of quartz, feldspars and abundant biotite of grain sizes between 1 mm and 5 mm.

The granite at both sites is weathered to a saprolitic soil to depths of over 30 m, which can generally be described as completely decomposed or grade V material (GCO 1984). Considerable variations resulting from chemical decomposition, physical disintegration and localised hydrothermal alteration occur throughout the Shouson Hill site, whereas the saprolite at King's Park shows both the effects of more intense hydrothermal alteration and later weathering. Irfan (1988) distinguished six types of soil at the Shouson Hill site in terms of degree of decomposition of mineral constituents, disintegration and type of alteration.

A thin (1 m to 2 m) residual soil layer is present over the saprolite at Shouson Hill, whereas at King's Park this portion of the weathering profile was probably removed by slope formation works in previous years.

SAMPLING

A number of block samples were hand-trimmed from trial pits and trenches at both sites at a depth of 1.5 m and 2 m. Of the block samples selected from Shouson Hill, two were from the completely decomposed saprolite, one was obtained from the transition zone from saprolite to residual soil and was characterized by partial fabric loss and one showed marked localised effects of hydrothermal alteration (Table I). All samples from King's Park showed an intense degree of alteration and slight fabric loss, with feldspars decomposed to clayey pseudomorphs, biotite decomposed to soft colourless flakes, extensive iron oxide staining and localised cementation.

QUALITATIVE MICROFABRIC CHARACTERIZATION

Thin sections were prepared from selected test blocks after initial impregnation with epoxy resin mixed with organic blue dye. The latter enabled differentiation between the insitu voids and microcracks, and those produced by the sectioning process. Microfabric elements examined under an optical microscope included mineral composition, type and state of alteration of mineral constituents, grain boundary relationships, and the nature and distribution of microcracks and voids. The finer microfabric features such as type and packing of clay minerals, and weathering-induced grain surface features, which are beyond the capability of the optical microscope, were not determined.

Petrographic examination of thin sections from the Shouson Hill samples indicated that degree of weathering and alteration, and related microfabric, vary between samples as well as within individual samples. The plagioclase feldspars have been completely altered to dense clay aggregates, with pores generally absent or poorly developed. A few 'book-form' grains, possibly of kaolinite, and small amounts of longer flakes (up to 0.1 mm) of sericite are also present, with kaolinite increasing in amount in both the transition (SH3) and the altered (SH5) samples. Alkali feldspars show a porous, honeycombed microstructure (Figure 1a and 1b) and varying degrees of formation of voids and microcracks (i.e. a high degree of the solution or 'etch-pit' type weathering of Berner & Holdren 1977). Alteration to clay minerals is limited except in sample SH5 for which thin sections cut from the altered portion commonly showed areas of clay decomposition products in the alkali feldspars, particularly in those adjacent to quartz/kaolinite veins. Quartz content varies from sample to sample, and even between thin sections from the same block sample (Table I). Quartz is highly fractured by a network of microcracks up to 0.5 mm wide, mostly clean or partially infilled, and with slight solution effects along both microcracks and grain boundaries. Biotite shows various types and degrees of decomposition.Few partially altered grains are present in the least decomposed samples (SH6, SH8), with some converted to iron oxide skeletons and most grains decomposed to various fine grained minerals, probably of muscovite and kaolinite composition, with open cleavage planes and partly disturbed structure. All samples from Shouson Hill show a high degree of porosity in the form of individual voids up to 1.5 mm in size, microcracks throughout the fabric, and open grain boundaries. Small areas of a structureless and less porous clay matrix with angular quartz and, to a lesser extent, partially decomposed feldspar fragments (i.e. collapsed fabric) occur in some sections, particularly those from the transition zone sample SH3 (Figure 1c).

Samples from the King's Park site also showed microfabric variations, although these were not as pronounced as in the Shouson Hill samples. Almost all feldspars are completely altered to clay minerals, probably of kaolinite composition, locally occurring in book-forms or clusters of grains. Areas of altered feldspars are stained with reddish brown iron oxides locally masking fabric details and with occasional feldspars reduced to porous iron oxide skeletons. Alkali feldspars are also mostly decomposed to clay minerals and exhibit only a limited amount of the very porous, honeycombed microstructure observed in the Shouson Hill samples. In addition to highly fractured quartz grains, angular silt-size quartz fragments set in a matrix of structureless clay minerals and iron oxides are present as infill in microcracks and other areas of lost fabric (Figure 1d). Biotite shows varying alteration products, generally of the same type and extent as for the Shouson Hill samples with, in addition, partial replacement by iron stained clay minerals and small amounts of chlorite.

QUANTITATIVE MICROFABRIC CHARACTERIZATION

Micropetrographic Index

The point-counting technique described by Irfan & Dearman (1978a) was employed to determine the modal percentages of the altered and unaltered mineral constituents, voids and microcracks. The micropetrographic index, I_p, was calculated from the modal analysis using the following formula :

$$Ip = \frac{\%\ \text{Sound constituents}}{\%\ \text{Unsound constituents}} = \frac{\%\ (\text{Sound primary minerals})}{\%\ (\text{Secondary minerals + voids + cracks})}$$

The results of the micropetrographic analysis are given in Table I for both the Shouson Hill and King's Park samples. The results of modal analysis on thin sections cut from slightly weathered corestones from both sites are also shown on the Table.

In general, the King's Park samples showed more intense chemical decomposition, with altered mineral contents of 47 to 58% and less porous fabric, with the content of voids and microcracks between 18 and 24%. The unaltered feldspar content was less than 2% in the King's Park samples, compared with 7 to 10% for the samples from the Shouson Hill site except for the transition soil sample with about 3%. I_p values were generally below 0.35 for the King's Park samples, except for block KP4 where it was influenced by the higher quartz content. An average

Table I. Results of quantitative microfabric characterisation

Block/ Sample No.	Description	Unaltered Feldspars %	Altered Feldspars %	Quartz %	Biotite %	Altered Biotite %	Other %	Microcracks and Voids %	Sound Minerals %	Altered Minerals %	Total Unsound %	I_p	Xd_{mod}
SH8	Decomposed Granitic Soil	10.2	40.5	24.3	0.1	1.9	0.1	22.9	34.7	42.4	65.3	0.53	0.62
SH6	Decomposed Granitic Soil	9.4	41.4	21.5	0.8	3.0	0.0	23.7	31.7	44.4	68.1	0.47	0.73
SH3	Transition Granitic Soil	2.7	55.6	25.2	0.0	3.0	0.0	13.5	27.9	58.6	72.1	0.39	0.92
SH5-2w	Decomposed Granitic Soil	10.2	28.9	32.9	0.0	4.2	0.0	23.6	43.1	33.1	56.7	0.76	0.94
SH5-4a	Altered Granitic Soil	9.4	46.2	18.7	0.2	1.6	0.0	24.0	28.3	47.8	71.8	0.39	-
-1a	Altered Granitic Soil	7.0	46.2	22.7	0.0	4.4	0.0	19.5	29.7	50.6	70.1	0.42	-
-3a	Altered Granitic Soil	5.5	47.2	22.9	0.0	0.9	0.0	23.5	28.4	48.1	71.6	0.40	-
		7.3	46.5	21.4	0.1	2.3	0.0	22.3	28.7	48.8	71.2	0.40	0.97
	Fresh Granite	68.2	2.0	28.0	0.7	0.3	0.1	0.6	97.0	2.3	2.9	33.4	-
KP1	Altered Granitic Soil	1.7	49.3	18.4	0.1	6.6	0.2	23.7	20.4	55.9	79.6	0.26	-
KP2	Altered Granitic Soil	1.8	45.6	23.0	0.0	11.9	0.1	17.6	24.9	57.5	75.1	0.33	0.85
KP3	Altered Granitic Soil	1.1	52.5	24.4	0.0	3.5	0.3	18.0	25.8	56.0	74.0	0.35	-
KP4	Altered Granitic Soil	0.8	45.6	32.4	0.0	1.2	0.1	19.9	33.3	46.8	66.7	0.50	-
	Fresh Granite	58.5	2.1	33.3	5.6	0.0	0.3	0.2	97.3	2.1	2.3	42.2	-

I_p of 0.4 was obtained for the altered samples SH5-a from Shouson Hill. The extreme variability of soil constituents even within the same block sample is examplified by the wide range of values obtained for sample SH5, depending on the location of the thin section within the block.

The results of modal analysis agree with the qualitative microfabric assessments, indicating that this technique can be used to characterize some of the fabric elements of saprolitic soils.

Modified Degree of Decomposition Index

A modified "degree of decomposition" index, Xd_{mod}, based on Lumb (1962), was determined for the blocks subjected to laboratory testing and other selected samples as described by Irfan (1988).

The degree of decomposition index gives only an indication of the degree of decomposition of feldspars. Structural fabric elements such as cracks, voids, and the decomposition state of other mineral constituents (e.g. biotite) are not taken into account. Feldspars in various states of decomposition even within each grain, with altered and unaltered portions occurring together, are usually counted as 'feldspar' in the normal method of determination of X_d, resulting in an erroneous count of the true unaltered feldspar pseudomorphs. Iron oxide cementation of wholly altered feldspar pseudomorphs may also affect the results, as observed with the King's Park samples. With these considerations in mind, a modified technique of finger crushing of partially decomposed feldspars was adopted, and Xd_{mod} values were determined (Table I). This gave a more accurate indication of unaltered feldspar content of the soil, and resulted in relatively higher index values than those reported by Lumb (1962) for Hong Kong decomposed granites. The mean Xd_{mod} value of 0.85 obtained for a King's Park decomposed granite sample does still not reflect the almost complete degree of decomposition of feldspars observed under the microscope, indicating that some of the completely decomposed feldspars cemented strongly by iron oxides were not broken down by finger pressure.

RELATIONSHIP BETWEEN MICROFABRIC AND SOIL INDEX PROPERTIES

Granitic Soil Microfabric : Some Considerations

The petrographic examination of saprolitic soil samples from both sites revealed that varied soil microfabric is produced even within a particular sample, and that this is related to both the initial fabric of the parent rock and to the history and microenvironment of weathering and hydrothermal alteration processes. Both weathering and alteration processes involve formation of new minerals, the loss of material by solution and gain of material by precipitation. A secondary bonding may develop from these processes as distinct from relict bonding (i.e. bonding related to the original rock fabric).

The microfabric produced from weathering of feldspars can vary from dense, highly packed clay mineral aggregates to very porous, honeycombed, partially altered grains. In the Shouson Hill samples, plagioclase feldspars have been completely altered, generally to densely packed clay mineral aggregates but still preserving the original grain outline (pseudomorphs) with few or no pores. Alkali feldspars have a variable but generally very porous, honeycombed structure with little evidence of chemical decomposition (except in hydrothermally altered samples).

The porous structure may have resulted from leaching of clay minerals and colloids or from extensive direct solution etching of feldspars (Berner & Holdren 1977) without forming clay minerals. Dearman & Baynes (1979) reported that direct solution etching is a dominant process in the early stages of weathering with the formation of structurally controlled prismatic etch-pits and prismatic etch-trenches in the chemically weathered granites of southwest England. Prismatic etch-trenches may extend uniformly through a crystal producing a very porous regular structure with irregularly scattered clay mineral flakes. Where solution has been active, open honeycomb-like structures are produced in advanced stages of weathering while, in more stagnant areas, feldspars are decomposed to clay minerals with little leaching out and void formation.

Collapse of highly porous unstable feldspar structure may occur in advanced stages of weathering resulting in an aggregate of angular solution remnants with possible association of clay mineral aggregates and forming true residual soils with decreased void ratios. Partially collapsed areas were observed in the transition soil sample from Shouson Hill.

The effects of hydrothermal alteration are widespread at Shouson Hill, generally decreasing away from the quartz veins. The altered portion of block sample SH5 which had the lowest void ratio also had a less porous feldspar structure with significantly high clay mineral content (Table II). It is probable that the early hydrothermal processes altered the plagioclase feldspars, particularly adjacent to lines of structural weakness but also throughout the rock mass. This is particularly true of the King's Park site where the granite is intensely altered in the vicinity of the sampling locality and all the feldspars, including alkali feldspars, have been completely decomposed to clay minerals. The soil is stained reddish brown and possibly weakly cemented by iron oxide compounds released mainly from the decomposition of biotite which can form up to 20% of the original rock. The final product is a soil with a clayey microfabric, containing up to thirty percent of both agglomerations and individual quartz grains of sand and fine gravel size, in parts weakly cemented by iron oxide. The more recent leaching effects are not as intense as for the samples from Shouson Hill (i.e. less porous). This is due to this site being on the side of a steep slope where water infiltration and leaching effects would be less intense than on a gentler hilltop.

Void Ratio and Dry Density

Significant variations in initial void ratio, e_o, occurred not only between mean values of block samples, but also between individual test specimens cut from the same block. For the saprolitic soil from Shouson Hill, mean e_o values varied between 1.01 and 1.17 for the blocks and between 0.92 and 1.44 for the individual test specimens. The dry densities were determined to be 1.21 to 1.31 x 10^3 kg/m^3 for the blocks and 1.07 to 1.37 x 10^3 kg/m^3 for individual specimens (see Table II for selected test results). Initial moisture contents were also variable: 14.6 to 20.0% for the blocks and 10 and 24% for the specimens.

In general, the least weathered samples showed generally lower dry densities, lower moisture contents, lower degrees of saturation and higher void ratios in comparison with the more intensely weathered samples of the transition soil type. The altered soil samples from Shouson Hill showed the highest dry densities and moisture contents and the lowest void ratios amongst the Shouson Hill saprolites. The altered saprolitic soil samples from King's Park gave much higher dry densities of 1.27 to 1.62 x 10^3 kg/m^3, and much smaller void ratios of 0.72 to 1.11 for the individual test specimens.

The relative percentages of microcracks and voids (Table I) determined using the micropetrographic method generally agreed with the mean values for direct shear test specimens, with the least weathered samples giving higher void ratios, for example, compared with the transition soil samples. Generally lower values were obtained for King's Park altered saprolite compared with the Shouson Hill decomposed saprolite.

Metastability

Laboratory determined mean e_o values for Shouson Hill block samples have been plotted against Xd_{mod} on the "microstructure characterization plot" (Collins 1985b) in Figure 2. Xd_{mod} value was determined only for one block from King's Park and this is also shown in the Figure. The chart, in general, indicates that a range of fabrics is possible for any given e value depending on degree and types of weathering, and that a range of fabrics is also possible for any X_d value depending on degree of leaching. This chart should however be viewed in the light of the comments made earlier on X_d determination, that it is affected by degree and type of pretreatment and also iron oxide cementation. This is particularly apparent in the altered King's Park sample, where the X_d should have been much nearer to 1.0 based on microscopic observations, but where a lower value of 0.85 was obtained because of iron oxide cementation. The chart, however, provides a general framework for microfabric characterization.

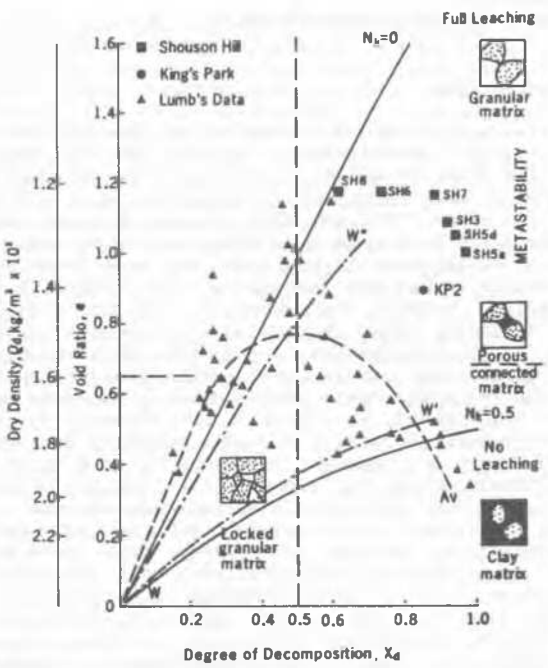


Figure 2. Microstructure characterization plot (After Lumb 1962, Baynes & Dearman 1978 and Collins 1985b)

The void ratios for Shouson Hill samples are generally higher than those reported by Lumb (1962) for the granitic soils of Hong Kong. Due to their low densities, they all fall in the potentially metastable zone proposed by Baynes & Dearman (1978) and plot near the full leaching line somewhere between the "granular matrix" and "porous connected matrix" of Collins (1985b). Observations of soil microfabric and field condition agree with this chart for normally decomposed saprolite, where a highly porous microfabric composed of resistant quartz grains connected by clayey plagioclase bridges (altered plagioclases) and porous, honeycombed alkali feldspars is formed due to significant leaching resulting from the well drained nature of the site and intense seasonal rainfall.

Figure 2 also indicates that the critical void ratio for metastability is about 1.2 for the Shouson Hill saprolites. Petrographic examination indicates that beyond this value collapse of porous structure occurs (e.g. transition soil sample SH3 in the Figure) and saprolitic soil gradually transforms into residual soil near the surface, with continued wetting and drying. The upper surface at Shouson Hill, has, in fact, transformed into residual soil. This also agrees with the field observations of Brink & Kantey (1961).

The densities of altered saprolitic samples from King's Park are higher, near to 1.60 x 10^3 kg/m^3. Structureless, collapsed areas were present, but to a smaller extent, in some of the samples taken within 1 or 2 m of the cut slope berm. As stated earlier, because of modification of the hillside by cutting, it is not known whether a true residual soil layer developed at this site. The soil fabric is much denser, i.e. less porous, due to the effects of both hydrothermal alteration and cementation by iron oxide released mainly from decomposition of abundant biotite.

Particle Size

It is known that determination of particle size distribution of saprolitic and residual soils is sensitive to the test procedures used, e.g. use of pestle and mortar to crush soil, type of dispersing agent, amount of agitation, etc. (Gidigasu 1975, Mitchell & Sitar 1982).

The large variations in grading reported by Lumb (1962) for granitic soils in Hong Kong have been found in the materials tested from both sites. The individual direct shear and triaxial test specimens from King's Park had the following ranges of grain size : fine gravel content, G = 2-20%, sand content, S = 40-60%, silt content, M = 19-39% and clay content, C = 6-16%. From the specimens tested in direct shear from Shouson Hill, these ranges were : G = 22-52%, S = 18-50%, M = 7-34% and C = 0-10%.

In general, decomposed saprolite specimens from Shouson Hill showed the smallest clay contents, with the altered specimens showing the highest clay contents. However, even the clay contents of the intensely altered King's Park specimens rarely exceeded 15%, even when various pretreatment methods were used. The petrographic analysis, however, indicated that the clay content, assuming all the altered (secondary) minerals are of clay size fragments, is appreciably higher than those obtained in sieve analyses (Table I). In soils having a considerable content of free iron oxides, oven drying may result in apparent decrease in clay content (Brenner et al 1978). Petrographic examination and Xd_{mod} determination carried out in this study revealed that some mineral constituents, particularly alkali feldspars, are in various states of decomposition even within a test specimen. Clay minerals and other alteration products of clay size are locked-in in partially altered grains and hence cannot be dispersed unless mechanically vigorously broken down. In the King's Park saprolite, weak cementation by iron oxide appears to influence the particle size resulting in lower than usual clay content.

Table II. Results of direct shear tests on selected individual specimens (Numbers in brackets are mean values for test block)

Specimen No.	Description	Dry Density	Initial Void Ratio	Particle Size				Normal Stress	Shear Strength
		X10³ kg/m³	e_o	G %	S %	M %	C %	σ kPa	τ kPa
SH8-1	Decomposed Granitic Soil	1.23 (1.21)	1.14 (1.17)	40	45	12	3	40	50
SH6-1	Decomposed Granitic Soil	1.21 (1.21)	1.16 (1.17)	40	48	9	3	40	46
SH6-2	Decomposed Granitic Soil	1.17 (1.21)	1.26 (1.17)	45	38	14	3	40	49
SH5-1	Decomposed Granitic Soil	1.28 (1.29)	1.05 (1.05)	36	34	25	5	40	48
SH5-2	Decomposed Granitic Soil	1.27 (1.29)	1.07 (1.05)	34	38	22	6	40	44
SH5-a	Altered Granitic Soil	1.31 (1.31)	1.01 (1.01)	31	37	25	7	40	37
SH3-1	Transition Granitic Soil	1.30 (1.30)	1.09 (1.09)	31	42	18	9	40	30
SH8-2	Decomposed Granitic Soil	1.21 (1.21)	1.17 (1.11)	36	47	13	4	150	140
KP2-4	Altered Granitic Soil	1.33 (1.31)	0.92 (0.93)	8	50	28	14	36	39
KP2-8	Altered Granitic Soil	1.33 (1.31)	0.93 (0.93)	9	43	37	11	170	122

It is thus no surprise that the relationships derived between grading parameters and engineering properties for the transported soils cannot be directly applied to saprolitic soils. This partly stems from the difficulty of determining a meaningful grain size and, of course, to a greater extent from the presence of bonding (both the relict primary bonding and the secondary bonding generated during the weathering process in these soils. In addition to weathering and alteration effects, variations in the grain size of soils are also due to variations in the initial grain size of the original rock.

Plasticity characteristics determined on fines are also likely to be affected by pretreatment methods, presence of iron oxides and presence of some unusual clay minerals such as halloysite. Gidigasu (1975) gives a detailed treatment of this subject.

RELATIONSHIP BETWEEN MICROFABRIC AND ENGINEERING PROPERTIES

Oedometer and Isotropic Stress Tests

Oedometer tests were carried out on 75 mm diameter by 19 mm thick hand-trimmed specimens from Shouson Hill, and some conventionally plotted results are shown in Figure 3. Despite the weak relict primary bonding observed in thin section and the secondary bonding which may have been generated during the weathering and alteration processes, the e-log p curves do not display a clearly defined yield stress. This is confirmed by linear plots of the data (not shown here), as suggested by Vaughan (1985), and may be due to specimen disturbance, to the small specimen thickness in relation to maximum particle size, or to bedding error in the measurement of vertical displacement. Alternatively, the initial yield point for this material may be at such low applied stress that it is not detected by the test due to the magnitude of the first load increment (25 kPa).

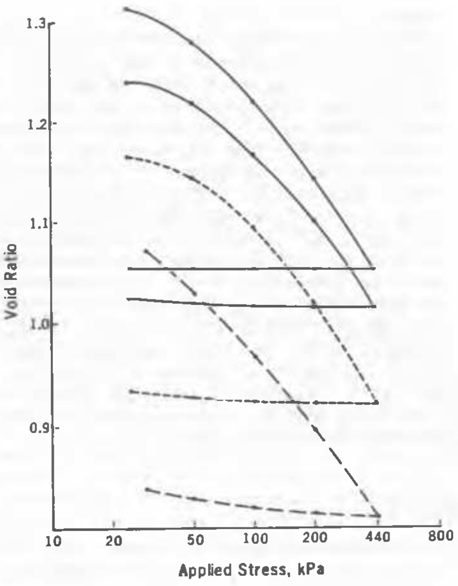


Figure 3. One dimensional consolidation curves from 75 mm diameter x 19 mm thick oedometer - Shouson Hill. Solid and dashed lines indicate different block samples

An isotropic stress test on a 100 mm diameter by 200 mm specimen of the King's Park material yielded a similar result, as shown by the conventional and linear plots in Figures 4 and 5, more in keeping with the more intensely weathered and altered, and less porous, microstructure observed in that material.

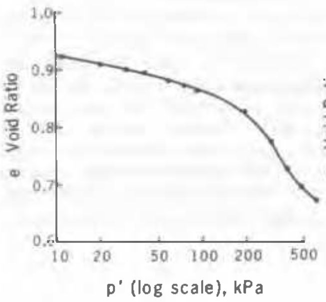


Figure 4. Conventional plot of void ratio versus effective consolidation pressure for isotropic stress test

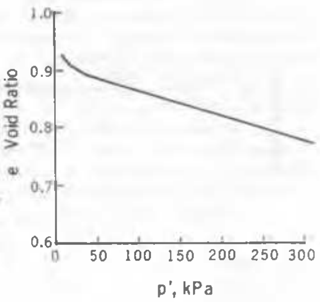


Figure 5. Linear plot of void ratio versus effective consolidation pressure for isotropic stress test

Triaxial and Direct Shear Tests

In this paper, discussion of shear behaviour is confined to single stage consolidated undrained ($\overline{CU}$) triaxial tests with pore pressure measurement, single stage consolidated drained (CD) triaxial tests, and single stage consolidated drained direct shear tests, all on saturated specimens.

In triaxial tests, saturation was achieved by applying a back pressure of 300 to 400 kPa in gradual increments while maintaining an effective confining pressure on the specimen of 5 kPa, prior to consolidation and shearing at the rate of 0.05 mm/min (1.5% axial strain per hour). 100 mm diameter by 200 mm specimens of the King's Park saprolite were hand-trimmed from block samples and subjected to $\overline{CU}$ and CD triaxial tests at initial effective confining pressures ranging from 10 kPa to 300 kPa. The stress paths from these tests are shown in Figure 6. It is apparent from the undrained stress paths that there exists a region of critical effective confining pressure around about 60 kPa for this material, below which the material derives additional strength from dilatancy, and possibly also from the shearing of weak bonds. Pore pressure response in the $\overline{CU}$ tests (Figure 7) and specimen volume change during shear in the CD tests (Figure 8) was broadly consistent with this. Below σ'_3 = 40 kPa the specimen volume is tending to increase with axial strain after an initial reduction; above σ'_3 = 40 kPa the specimen volume is tending to remain constant or decrease. There is no apparent difference in the average magnitude of the drained and undrained strengths. The average strength envelope can be defined above the critical pressure by the straight line c' = 7.5 kPa, ø' = 31°, the additional strength in the lower stress range being derived from dilation and possibly also from weak bonding. The critical pressure is a function of the weathering microenvironment of the specimens tested (Vaughan & Kwan 1984) and is largely independent of the insitu overburden stress. It can therefore be expected to vary over a substantial range, even within a relatively small sampling area.

Direct shear tests were performed on 100 mm square by 20 mm thick specimens of the King's Park material, and on 100 mm square by 44 mm thick specimens of Shouson Hill material, all hand trimmed from block samples, employing the test procedures described by Cheung et al (1988). Specimens were saturated by soaking under low head and an applied normal stress of 5 kPa for periods ranging from 16 to 24 hours, prior to consolidation and shearing under applied normal stresses ranging up to 240 kPa. The King's Park specimens were sheared at the rate of 0.08 mm/min., and the Shouson Hill specimens at 0.06 mm/min. Selected results for both materials are shown in Figure 9. These exclude results obtained from the Shouson Hill altered saprolite. As in the triaxial test, the average shear strength envelope for each material can be described by a straight line through the origin, with dilation and weak bonding increasing the shear strength in the lower normal stress range. In the higher normal stress range, the strength of the King's Park material measured in direct shear is not significantly different from that obtained from $\overline{CU}$ and CD triaxial tests, with ø' = 32°. The increase in strength due to dilation and weak bonding in the lower stress range is also similar, ranging up to about 10 kPa. The average strength of the Shouson Hill decomposed saprolite is much higher, with ø' = 39° and strength increase due to dilation and weak bonding at lower stresses ranging up to about 20 kPa. It is significant to note this large difference in average shear strength between the King's Park and Shouson Hill materials, because both would be broadly described as "completely decomposed fine- to medium-grained granite" and the strength difference could not be predicted on the basis of grading and voids ratio alone.

The dilatant behaviour at low normal stresses inferred in the direct shear test results is generally supported by the vertical displacements observed during the tests (Figure 10). In the low applied normal stress range, these typically show an initial volume reduction at low horizontal displacement, which may be due to gradual compression of the soil fabric, as weak primary and secondary bonds are progressively broken and porous

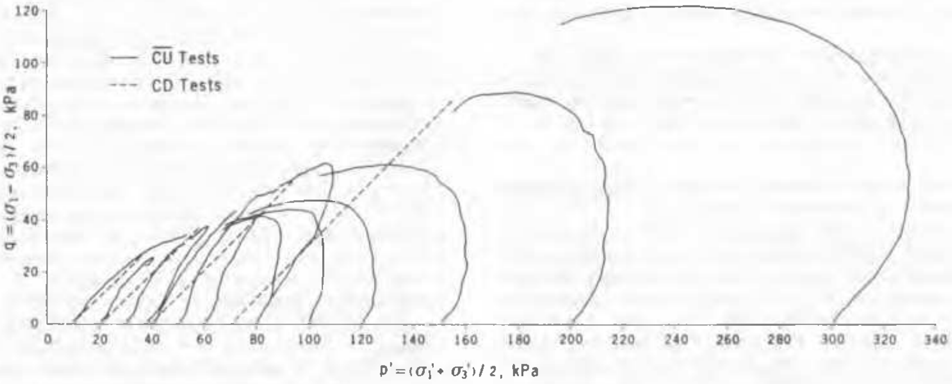


Figure 6. Stress paths from $\overline{CU}$ and CD triaxial tests on specimens from King's Park

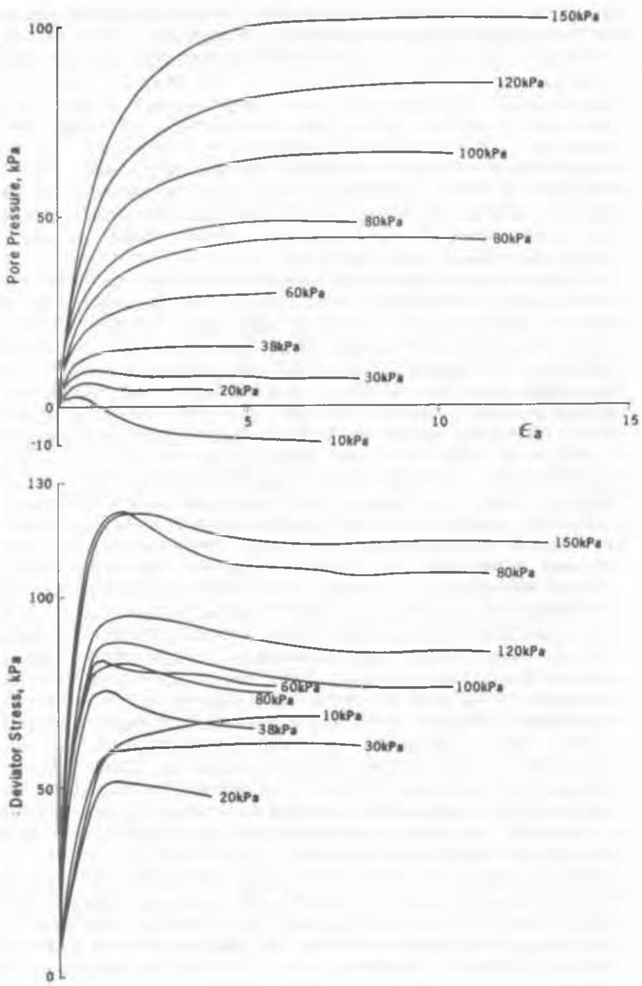


Figure 7. Plots of axial strain versus deviator stress and pore pressure from $\overline{CU}$ triaxial tests on specimens from King's Park

honeycombed feldspars collapse (Irfan 1988). This is followed, in the less weathered specimens, by dilation at higher horizontal displacement, as quartz grains and unaltered feldspar fragments come into contact. The magnitude of possible bedding errors and the influence of these on the measured vertical displacements has not been examined.

In the higher applied normal stress range, shearing is accompanied by continuous volume reduction throughout the test. At these stresses, much of the weak bonding would be expected to have been destroyed by collapse of individual fabric elements during soaking and consolidation.

Figure 10 shows shear stress/horizontal displacement curves for a number of specimens from Shouson Hill, all tested in direct shear under an applied normal stress of 40 kPa. Significant differences in strength and in the shape of the stress/strain curve can be observed between specimens; the transition soil and altered saprolite exhibit lower shear strengths than the less intensely weathered specimens. These strength differences cannot be fully accounted for by the initial void ratios or particle size distributions shown in Table II. However, there is a good correlation between strength and the Ip values for the individual specimens. Clearly defined peaks are evident in the stress/strain curves for specimens with little or no fabric loss, but are absent or indistinct for the transition and altered soils. These differences are also reflected in the volume change behaviour during shear. The transition soil and altered soil generally follow the same pattern as the less weathered soil, but with less pronounced dilation or no volume change following the initial compression, in keeping with the higher clay mineral content in these specimens.

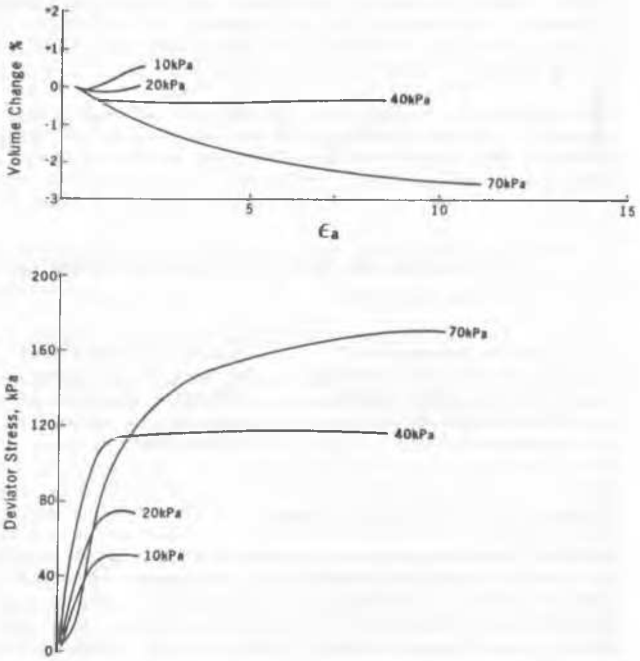


Figure 8. Plots of axial strain versus deviator stress and volume change from CD triaxial tests on specimens from King's Park

The less pronounced microfabric variation in the King's Park specimens is reflected in the smaller scatter of shear strength data shown in Figure 9, and in the more consistent Ip values in Table I. The difference in the average strengths of specimens from the two sites is also well reflected in the average Ip values, and is consistent with the generally more intense chemical decomposition evident in the King's Park specimens. Figure 10 shows the vertical displacement during shear of two test specimens from King's Park, under applied normal stresses of 36 and 170 kPa respectively. The volume change behaviour at 36 kPa is very similar to that of the altered saprolite from Shouson Hill, consistent with the higher clay mineral content of these two soil types. At 170 kPa, the volume reduction during shear is much less than in the Shouson Hill specimen sheared at 150 kPa shown in the same Figure, in keeping with the less porous, more clayey fabric of the King's Park specimen. This implies that the volume reduction in the less weathered Shouson Hill sample is due in part to continuing breakdown of fabric elements.

The potentially metastable condition indicated by the Xd_{mod} values for the Shouson Hill specimens is not manifested by any sudden collapse on loading or shearing, but rather by gradual compression due to the collapse of individual porous feldspars. The contribution of weak bonding to the strength of the material is uncertain, but it is likely to be small. Irfan (1988) has suggested that partial destruction of the bonds in "completely decomposed" materials may occur as a result of stress relief during sampling, disturbance during trimming of the smaller test specimens, volumetric disturbance and softening during back-pressure saturation or soaking, and application of confining stress or normal stress in the higher stress range. The stronger bonds present in a less weathered material such as "highly decomposed" granite would be expected to yield a significant cohesion intercept in the lower stress range, and a clearly discernible yield stress (Vaughan 1985, Irfan 1988).

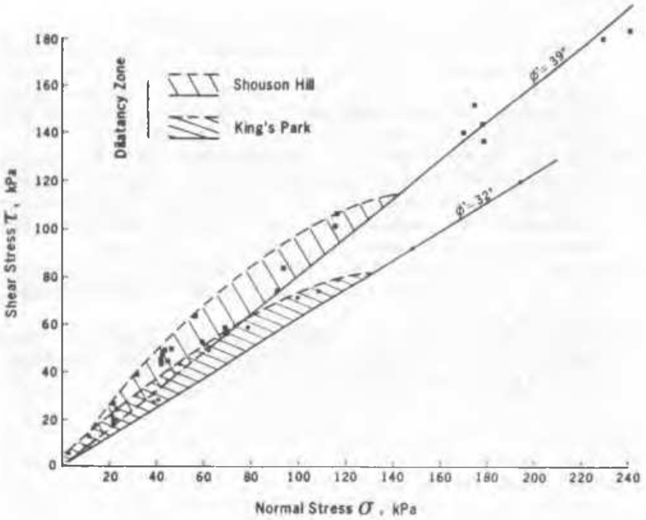


Figure 9. Plot of normal stress versus shear stress at failure from direct shear tests on specimens from Shouson Hill and King's Park

CONCLUSIONS

The shear strength and deformation behaviour of saprolitic and residual soils are a function of the microfabric derived from weathering and alteration processes, which can vary significantly over small areas, even within a relatively uniform geological profile.

Broad categorization of soils in terms of rock type and weathering, and results from the soil classification tests routinely applied to sedimentary soils, are not a sufficient basis alone for classifying samples or predicting shear strength and deformation behaviour. Determination of a 'true' or indicative particle size distribution for this purpose is problematical. Observation and characterization of the soil microfabric has been found to correlate well with behaviour observed in shear strength tests, and the micropetrographic index could be a very useful parameter for detailed classification of saprolites and residual soils.

The shear strength envelope of granitic saprolitic or residual soils can be broadly characterized by two separate modes of behaviour over different ranges of confining stress. In the lower stress range, additional strength is derived from dilation and the shearing of weak primary and secondary bonds. The critical pressure separating the two modes of behaviour is a function of the microfabric derived from weathering, and can be expected to vary significantly over small areas. The volume change or pore pressure response during shear is a useful indicator of the mode of behaviour. Consolidation tests should reveal a yield stress which would be a useful indicator of behaviour due to bonding, but this was not discerned in the very weakly bonded materials examined in this study, possibly due to masking by other influences.

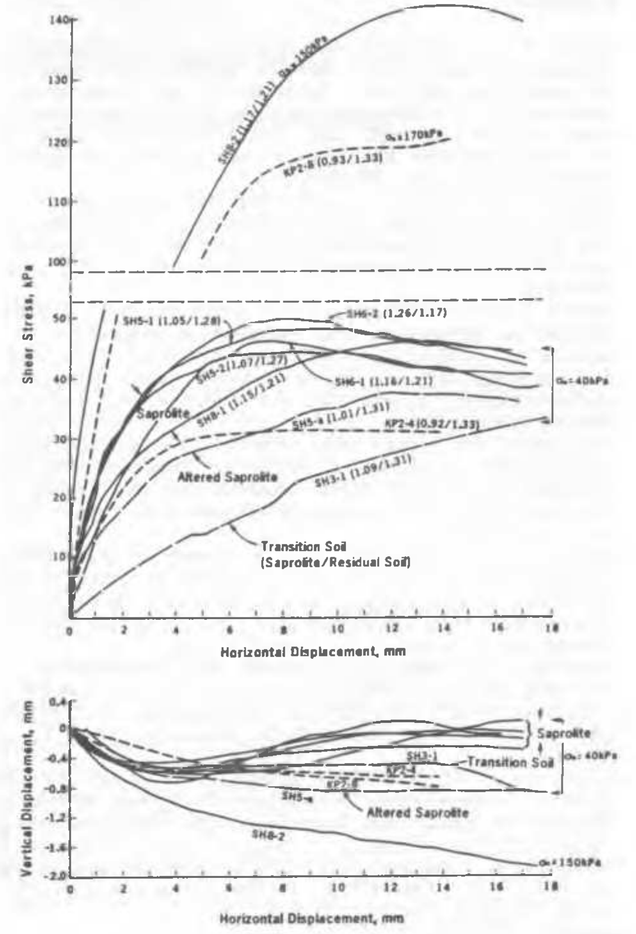


Figure 10. Plots of shear stress and vertical displacement versus horizontal displacement from direct shear tests on specimens from Shouson Hill and King's Park (Numbers in brackets are initial void ratio/dry density)

Hydrothermal alteration has been found to have a very significant influence on shear strength, and detection of the effects of any hydrothermal alteration should form part of geotechnical investigations in saprolites.

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