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Lateritic Soils near Worsley: The Interaction of Geology and Geotechnology

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SUMMARY The lateritic soils at the site of the Alumina Refinery near Worsley, located some 200km south of Perth, Western Australia are the residual products of the weathering of Precambrian granite and dolerite in a semi-tropical environment. Plateau weathering has given rise to four distinct zones of which the pallid zone is dominant. The soils in this zone are predominantly highly leached kaolin clays having an open-voided structure comprised of aggregations of clayey minerals cemented together by sesquioxides. Their residual engineering properties including high shear strengths and low compressibilities are presented and explained in terms of the geological structure and the mineral compositions of the residual soils and bedrock. The paper concludes with a soil formation model, that has been inferred from the interaction between the geological causes and geotechnical effects.

1 INTRODUCTION

Lateritic soils are the dominant surface materials in Australia, Africa, South America, Burma, Malaya, India and New Guinea. They are the residual products of tropical weathering of basic or acidic parent rocks, rich in ferro-alumino silicates, quartz, feldspars and micas.

The geological-environmental influences that are necessary for the formation of lateritic soils include:

(i) a heavy rainfall, preferably seasonal;

(ii) high temperatures throughout the year;

(iii) a rock mass with minerals susceptible to chemical weathering;

(iv) groundwater movements and leaching by acidic groundwaters; and

(v) the presence of a dense forest cover.

The geological relationship to the geotechnical properties of the lateritised rocks, clays and silts of the Worsley Alumina Refinery area, are presented in this paper. The site is located near Worsley in the Darling Ranges approximately 200km south of Perth, Western Australia. The lateritic profiles of the weathered dolerite and granite rocks and their formation are discussed in a separate paper (Gordon, 1984)

The Worsley soils have many interesting and unusual geotechnical properties that are different from those reported elsewhere as resulting from tropical weathering. This paper discusses some of the characteristic geotechnical properties in the context of their origins and geological structure.

The findings presented were obtained by Soil and Rock Engineering Pty. Ltd. in their geotechnical investigations for the infrastructures of the Mine, Water Resources, Refinery, Conveyor Route and Port facilities of the Worsley Alumina Refinery Project.

2 DEFINITION OF LATERITIC SOILS

The universal and complicated nature of lateritic soils is evident by the widely varying definitions of laterite as summarised by Maignien (1966). In this paper, lateritic soils have been defined as:

> the weathered products of grandiorite, granite gneiss, granite and dolerite. The residual soils have a structural framework of red and yellow, hydrated iron and aluminium oxides and contain significant proportions of kaolin and quartz. They include decomposed rocks, sands, silts, clays, concretionary gravels and crusts of iron-enriched caprock.

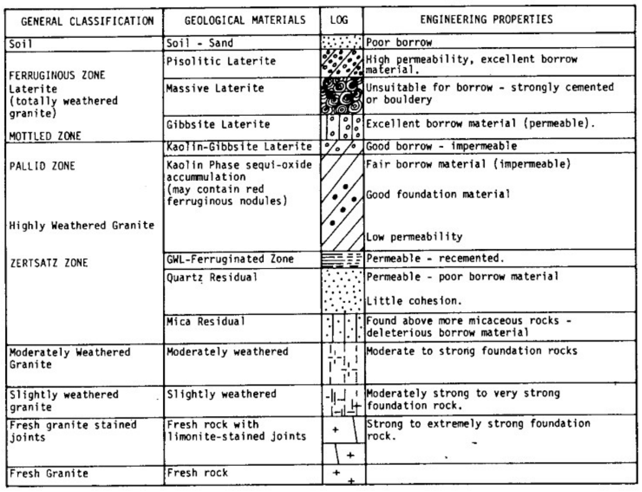
3 GEOLOGY

The genesis of the Worsley lateritic soils from Precambrian porphyritic granite and dolerite is discussed by Gordon 1984 in a separate paper presented at this conference. The dominant rock types, both show distinctive modes of weathering, defined as the Plateau (high elevation and deep ground water) and Valley (water saturation) weathering profiles. At the sites of the Refinery processing facilities, all soils are the products of Plateau weathering.

Lateritic weathering for a granitic rock includes granodiorite, granite or gneiss and means the complete transformation of the cohesive fabric of quartz, microcline, plagioclase and hornblende into a layered sequence of some seven distinct soil and rock types consisting of secondary minerals with alteration extending to 60m or more from the surface. Essential zones of the weathered profile are:

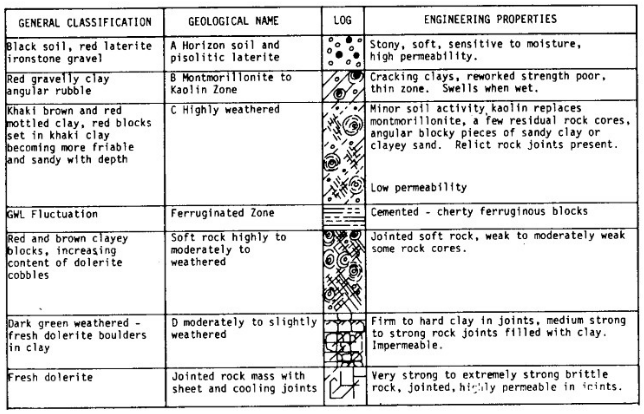
(i) a highly ferruginized surface zone;
(ii) a mottled zone - variably ferruginised and decreasing with depth;
(iii) a pallid zone; and
(iv) the zersatz zone of rock decomposition.

Profiles derived from the Plateau weathering of granitic and doleritic rocks are summarised on Figures 1 and 2.



GENERAL CLASSIFICATION	GEOLOGICAL MATERIALS	LOG	ENGINEERING PROPERTIES
Soil	Soil - Sand		Poor borrow
FERRUGINOUS ZONE Laterite (totally weathered granite)	Pisolitic Laterite		High permeability, excellent borrow material.
	Massive Laterite		Unsuitable for borrow - strongly cemented or bouldery
MOTTLED ZONE	Gibbsite Laterite		Excellent borrow material (permeable).
PALLID ZONE	Kaolin-Gibbsite Laterite		Good borrow - impermeable
Highly Weathered Granite	Kaolin Phase sequi-oxide accummulation (may contain red ferruginous nodules)		Fair borrow material (impermeable) Good foundation material Low permeability
ZERTSATZ ZONE	GWL-Ferruginated Zone		Permeable - recemented.
	Quartz Residual		Permeable - poor borrow material Little cohesion.
	Mica Residual		Found above more micaceous rocks - deleterious borrow material
Moderately Weathered Granite	Moderately weathered		Moderate to strong foundation rocks
Slightly weathered granite	Slightly weathered		Moderately strong to very strong foundation rock.
Fresh granite stained joints	Fresh rock with limonite-stained joints		Strong to extremely strong foundation rock.
Fresh Granite	Fresh rock		

Figure 1. Plateau lateritic weathering profile of normal granite



GENERAL CLASSIFICATION	GEOLOGICAL NAME	LOG	ENGINEERING PROPERTIES
Black soil, red laterite ironstone gravel	A Horizon soil and pisolitic laterite		Stony, soft, sensitive to moisture, high permeability.
Red gravelly clay angular rubble	B Montmorillonite to Kaolin Zone		Cracking clays, reworked strength poor, thin zone. Swells when wet.
Khaki brown and red mottled clay, red blocks set in khaki clay becoming more friable and sandy with depth	C Highly weathered		Minor soil activity, kaolin replaces montmorillonite, a few residual rock cores, angular blocky pieces of sandy clay or clayey sand. Relict rock joints present. Low permeability
GWL Fluctuation	Ferruginated Zone		Cemented - cherty ferruginous blocks
Red and brown clayey blocks, increasing content of dolerite cobbles	Soft rock highly to moderately to weathered		Jointed soft rock, weak to moderately weak some rock cores.
Dark green weathered - fresh dolerite boulders in clay	D moderately to slightly weathered		Firm to hard clay in joints, medium strong to strong rock joints filled with clay. Impermeable.
Fresh dolerite	Jointed rock mass with sheet and cooling joints		Very strong to extremely strong brittle rock, jointed, highly permeable in joints.

Figure 2. Plateau lateritic weathering profile of dolerite

Essentially seven distinct visual zones, characterized by mineralogical and textural differences, can be distinguished:-

(i) surface silica sands;
(ii) loose to medium dense pisolitic laterite, mainly goethite;
(iii) indurated nodular or platy massive goethite with cavities or pipes lined with gibbsite;
(iv) the mottled zone with red nodules of goethite in a yellow, gibbsitic clay matrix;
(v) the pallid or kaolin zone with clay minerals mainly of kaolin knitted into granular spherical aggregations, by iron and/or aluminium oxides (sesquioxides), with an inter-granular framework leaving an open-voided structure;
(vi) a loose aggregation of altered micas and quartz and iron enrichment in the decomposition or zersatz zone;
(vii) granitic bedrock in the moderately weathered state with feldspars altered to kaolin.

The Worsley Plateau profiles are different from those of the lateritic soils present in other parts of Western Australia. The materials are more deeply altered. In doleritic soils, montmorillonite that is usually produced in the drier environments has been largely altered further to produce kaolin. The valley profiles have no known equivalents elsewhere in Western Australia, and this accords with the area having the highest rainfall and densest forest in the South West. The present day climatic conditions of the South West are considered to reflect in a comparative way the more extreme climate deduced as being present when the lateritic weathering process was commenced in Pliocene time (Gentilli J,).

The alteration by the lateritization process of both doleritic and granite rock types has been so profound that the near surface materials - pisolitic and massive laterite - do not conform to any of the accepted definitions of weathering. There is no relict structure of the original rock type, and some of the weathered materials in the ferruginous zone are in the form of a rock, not of a soil. The definitions of 'extremely weathered' and 'completely weathered' do not apply and a new term (totally weathered) and indeed a new scale of weathering has to be formulated to include these materials (Gordon 1984).

4 ENGINEERING PROPERTIES (PALLID ZONE)

4.1. General

This section discusses the general engineering properties of the Plateau weathered lateritised clays and silts of the pallid or kaolin zone.

4.2 Atterberg Limits

Gidigasu (1976) and Lyons (1971) provide many examples of the effects of different sample preparations on varying the Atterberg limits of lateritic soils. The Atterberg limits of the Worsley soils were determined by:

(i) drying in a 50°C oven and testing in accordance with the recommended procedures of AS 1289 (1977); and
(ii) mechanically mixing the sample with distilled water for 5 minutes and sub-sampling over a 425 micron sieve. The excess water was removed with a Buchner funnel under a vacuum. The fractions finer than 425 microns were cured at a moisture content greater than the estimated liquid limit. The tests were then conducted from a wet to dry state with air drying between each stage. In all other respects, the tests were carried out in accordance with the recommended procedures of AS 1289 (1977).

183 Atterberg tests were carried out using the above procedures. No significant changes were observed in the Atterberg limits other than those that could be attributed to natural soil and operator variability.

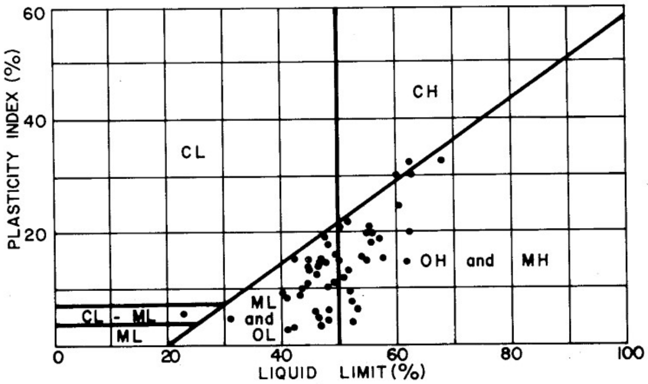


Figure 3. Plasticity properties of granitic clays and silts

The Atterberg limits measured for some of the doleritic soils are shown on Figure 4.

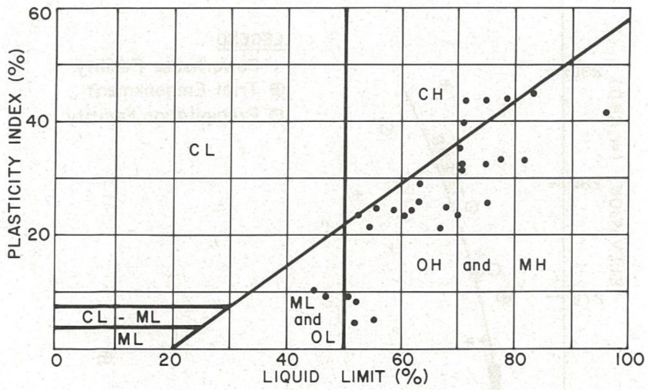


Figure 4. Plasticity properties of doleritic clays and silts

The soil types are generally classified as either ML or MH in accordance with the Unified Soil Classification System.

4.3. Dry Densities/Moisture Contents

Dry densities between 1.05 and 1.75 tonnes m^{-3} were measured in the granitic and doleritic soils of the pallid zone. Moisture contents varied between 10% and 60%. Typical variations in dry densities and moisture contents with depth are shown in Figures 5 and 6.

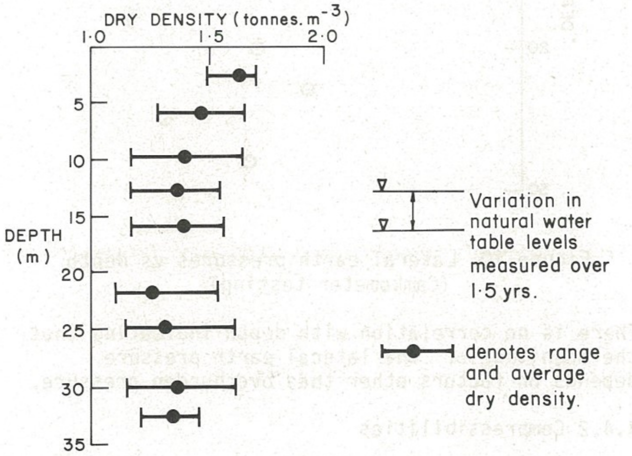


Figure 5. Distribution of dry densities with depth

Soil particle densities varied between 2.3 and 2.9 (average 2.5). The relatively low particle densities suggest that the clayey aggregations forming the framework of these soils are either porous and/or contain halloysite. No evidence of this mineral was found from X-Ray diffraction testing or from the results of the Atterberg limit testing on samples subjected to different pre-test preparations (Section 4.2). The small particle densities are probably caused by air trapped in the iron-coated clayey aggregations. Townsend (1971) described the structure of lateritic soils as "a porous granular structure consisting of iron-impregnated clayey materials in minute spherical aggregations resembling pop corn balls".

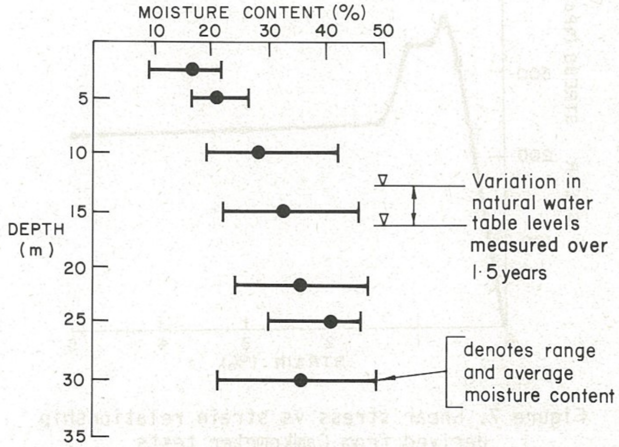


Figure 6. Distribution of moisture contents with depth

Dry densities vary significantly over small distances indicating variability in the degree of weathering and lateritisation of different rock types. Figure 5 shows a trend of decreasing dry density to a depth of approximately 20m. The trend suggests that leaching produced by the upward movement of the ground water (capillary leaching) may have been the dominant weathering mechanism in these soils.

4.4 GEOTECHNICAL PROPERTIES (PALLID ZONE)

The shear strengths and compressibilities of these soil types were measured in the field by Camkometer testing and were back-calculated from the results of embankment loading, and in the laboratory, these properties were measured by oedometer and triaxial testing. The results of these tests have been presented in separate papers (Smith (1984)(a) (b)). The salient results are presented below.

4.4.1 Shear Strengths/Constitutive Properties

The peak shear stresses measured in 14 Camkometer tests ranged between 214 and 806 kPa with an average of 429 kPa. The peak stresses were mobilised at strains between 0.7% and 2.0% (average, 1.2%). The post peak strength behaviour varied from strain softening to strain hardening. Residual shear stresses varied between 53 and 408 kPa (average 234 kPa). Where strain hardening occurred, the residual shear stress was selected at an arbitrary strain of 4%.

A stress-strain relationship derived from one of the Camkometer tests is presented in Figure 7. It can be seen that the maximum shear stress of 370 kPa is mobilised at a small radial strain of 0.7% and reduces to a residual value of 240 kPa at a radial strain of 1.6%.

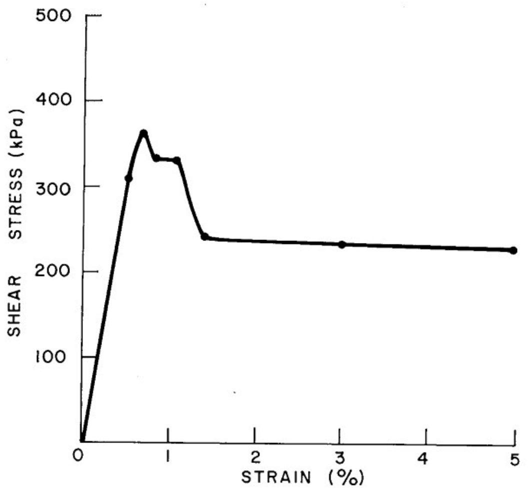


Figure 7. Shear stress vs strain relationship derived from Camkometer tests

The peak shear stresses measured in the Camkometer test programme are plotted against depth in Figure 8. There is a general trend of decreasing shear strength with depth. An explanation for this behaviour is that the concentration of the cementitious sesquioxides reduces with increasing depth in the weathering profile. This is consistent with the consequences of the capillary leaching mode of weathering and with the observed variations in dry densities and moisture contents (Section 4.3).

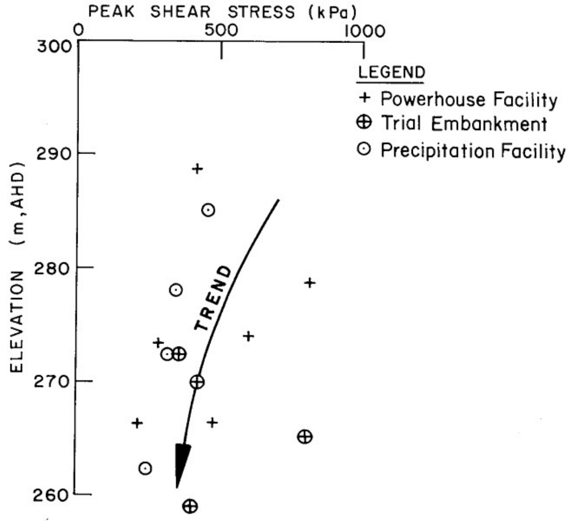


Figure 8. Peak shear stress vs depth (Camkometer testing)

Soil sensitivities are plotted against depth in Figure 9. The sensitivity (i.e. ratio of peak to residual strengths) varied from 1 to 8, with an average of 2.3. There is a trend of decreasing sensitivity with increasing depth.

The lateral earth pressures, as measured by the Camkometer programme, are plotted against depth in Figure 10.

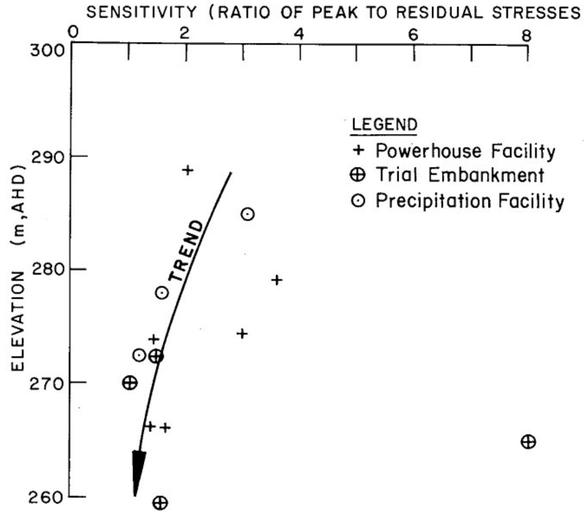


Figure 9. Sensitivity vs depth

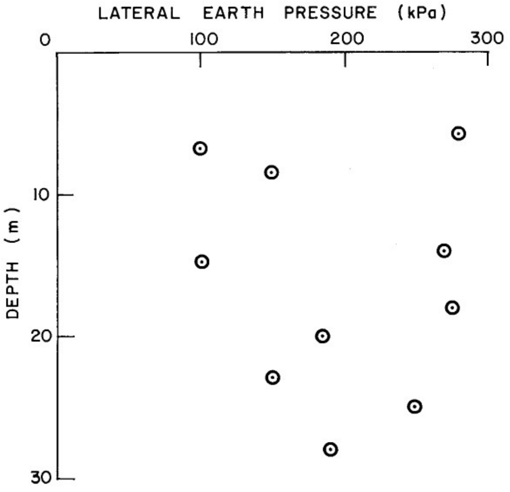


Figure 10. Lateral earth pressures vs depth (Camkometer testing)

There is no correlation with depth indicating that the magnitude of the lateral earth pressure depends on factors other than overburden pressure.

4.4.2 Compressibilities

The recompression indices measured in 32 oedometer tests ranged from 0.01 to 0.08, with an average of 0.04 and a standard deviation of 0.02. The virgin compressibility indices varied between 0.13 to 0.55 (average 0.39, standard deviation 0.19). Overconsolidation ratios varied from 1.2 to 4.0, (average 2.7, standard deviation 0.6).

The times measured for 90% of primary consolidation to occur were generally less than 2 minutes.

The range in constrained Moduli of Elasticity, computed from the above recompression indices and using a foundation stress increment of 200 kPa, was 7 to 42 MPa with an average of 26 MPa. These values are significantly higher than the constrained moduli computed from the reported compressibilities of some lateritised granitic soils in other parts of the world (DeGraft-Johnson and Bhatia, 1969).

The horizontal moduli computed from the results of the Camkometer testing, ranged from 33 to 126 MPa (average 65 MPa) for the initial loading cycle, and 60 to 234 MPa (average 144 MPa) for the unloading and/or reloading cycle. The initial loading moduli were determined for strains to 0.5%, and in the majority of tests, were tangent moduli. An average Poisson's ratio of 0.4, determined from the Camkometer tests results, was used to convert the shear moduli, (determined by differentiation of the cell pressure vs cavity strain relationships) to elastic moduli.

The effective modulus back-calculated from the results of the settlement monitoring of an embankment loading was 55 MPa. The average strain produced by the embankment was 0.4% (Smith, 1984 (b)). The effective modulus approximates the average horizontal modulus obtained from Camkometer testing suggesting that the soils behave isotropically for engineering purposes. The results of oedometer testing, carried out on both horizontal and vertical samples, indicated isotropic behaviour (Smith, 1984 (a)).

The majority of the embankment settlement occurred concurrently with load application (Smith, 1984 (b)).

5 THE INTERACTION BETWEEN GEOLOGY AND GEOTECHNOLOGY

All soils are the products of geological-environmental influences, but none more so than the lateritised clays and silts at the Refinery site. The interaction between the geology and geotechnology of these soils has been based on geological studies carried out by Gordon (1984) and has been inferred from their engineering properties (Smith 1984 (a), (b)). There is a need to carry out studies to further quantify this interaction. New techniques are called for, such as electron microscopy using ultra thin sections and replicas (Smart, 1973), that were not available commercially at the time of the investigation.

Table I discusses the engineering properties presented above in the context of the geological structure and genesis of the lateritised pallid zone soils and presents the conclusions to this paper.

6 ACKNOWLEDGEMENTS

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TABLE I PROPERTIES, CAUSES AND EFFECTS OF PALLID ZONE SOILS NEAR WORSLEY

Engineering Properties and Geotechnical Significance	Geological Structure and Mineralogy	Inferred Formation Model
1. ATTERBERG LIMITS (%) The Atterberg limits of the granitic and doleritic clays and silts generally plot below the A line of the Plasticity Chart (Unified Soil Classification). For granitic soils, liquid limits vary between 26% and 68% and plastic limits vary between 16% and 44%. For doleritic soils, the liquid limits between 42% and 96% and plastic limits vary vary between 24% and 55%. No significant changes in the Atterberg limits were measured in testing from dry to wet and wet to dry states. The lateritised soils insitu are generally less expansive than non lateritised, temperate-zoned soils of similar Unified Soil Classification. No special requirements apply for minimum foundation embedment depths in these soils.	Generally non lateritised, and temperate-zoned soils containing kaolin, illite and montmorillonite plot above the A line of the Plasticity Chart. The lower plasticity indices of the pallid zone soils near Worsley are the result of relatively small specific surface areas of the clay minerals. The sesquioxides have coated the surfaces of the clay minerals and have bonded them into larger aggregations that are held in a framework of sesquioxides. The oxidic coatings reduce the electro-chemical forces that are responsible for the adsorbed water. The plasticity properties of the clay minerals are thus modified by the soil's textural characteristics.	Three main models are available to describe the influence of ground water movements on the insitu weathering of igneous rocks and the attendant laterisation of the weathered profile. The models are: (i) per ascendum; (ii) per descendum; and (iii) alternating (i) and (ii). All models embody the interaction among climatic factors (precipitation, humidity, temperature), land useage (forest, open plain), groundwater and bedrock mineralogy. The model that is considered appropriate for the Worsley soils is (iii). Leaching appears to have been the most dominant weathering and lateritisation mechanism. Dry density measurements indicate that up to 65% of the original rock mass has been removed. In the Worsley environment of today, annual evapotranspiration exceeds precipitation. In Pliocene times, there is evidence that temperatures were hotter, rainfalls were an order of a magnitude greater and there was an annual imbalance between precipitation and evapotranspiration. The climate has resulted in alternating upward and downward ground water movements in response to suction stress gradients and gravity forces respectively, but with a nett upward movement. The acidic ground water has dissolved the highly soluble alkalies and alkaline-earth bases, and these have been removed from the profile. The poorly soluble iron and aluminium cations have been transported throughout the profile by the seasonally-induced ground water movements and by the action of tree roots. Iron is produced from the alteration of the ferro-magnesian minerals and is present as mainly goethite and minor hematite.
2. DRY DENSITY (tonnes.m^{-3}) The following apply to the granitic and doleritic pallid zone soils: (i) variable between 1.05 and 1.75 (average 1.35); (ii) trend of decreasing dry density with depth; (iii) significant variability in horizontal and vertical directions; and (iv) soil particle densities vary between 2.3 and 2.9 (average 2.5). The soil structure is open-voided and has high localised stresses in the contact zones of the clayey aggregations. It is impossible to obtain undisturbed samples irrespective of sampling techniques for strength and consolidation testing in the laboratory. Sampling in thin-walled tubes and pre-testing preparations will remould and disturb the soil's structure.	The average specific gravity of the Worsley granite is 2.75 and dolerite is 3.05. The weathering of these rocks into aggregations of clay minerals with residual quartz has produced an open-voided soil in the pallid zone. The average density of 1.35 tonnes.m^{-3} contrasts with the above specific gravities, and results from the presence of numerous pores and open voids, that are filled with air and water. The variability in the dry densities reflects the: (i) variable bedrock mineralogy (ii) concentration of iron oxides that depends on (i), also on ground water influences and the depth of the weathered profile. The soil particle density is low suggesting the presence of entrapped air in the aggregations and/or presence of halloysite. No halloysite was encountered in X-ray diffraction testing or was evident from the results of Atterberg limit testing.	
3. MOISTURE CONTENT (%) The moisture contents measured in both the granitic and doleritic soils varied between 10% and 60% (average 35%) and generally increased with depth. The combination of decreasing dry density and increasing moisture content with depth has resulted in a relatively uniform bulk density (1.8 $\pm$ 0.2 tonnes/m^3).	The high natural moisture contents are consistent with the open-voided structure of the pallid zone soils. The increasing moisture content with depth reflects both its increasing proximity to ground water and the greater moisture retention capabilities of the clay minerals as a result of lower amounts of iron oxides present at depth. The variability is dependent on both the sample and bedrock mineralogy	

TABLE I PROPERTIES, CAUSES AND EFFECTS OF PALLID ZONE SOILS NEAR WORSLEY

Engineering Properties and Geotechnical Significance	Geological Structure and Mineralogy	Inferred Formation Model
4. SHEAR STRENGTH (kPa) Camkometer testing in granitic and doleritic pallid zone soils revealed: (i) peak shear stresses varying between 214 and 806 kPa (average 429 kPa); (ii) the stress vs strain relationships are linear to the peak strengths; (iii) peak stresses are mobilised at strains between 0.7% and 2.0%; (iv) residual shear stresses vary between 53 and 408 kPa (average 234 kPa); and (v) sensitivities (peak/remoulded stresses) varied between 1 to 8 and decrease with depth. Shallow foundation systems are generally appropriate. Bearing capacity criteria will not govern foundation design as the factor of safety against shear failure is generally in excess of 3. The high residual stresses will result in large ground "freezes" during interruptions in pile driving. Trial piling programmes are recommended to select the most suitable pile section(s) and hammers to ensure that the piles can be driven to the target depths. Steep slopes can be utilised for cuttings in these soil types. Camkometer testing should be carried out to ascertain the most realistic residual stress parameters for design.	The shear strengths are higher than would be expected from kaolinitic minerals, and are principally influenced by genetic and compositional factors. The high strengths are the result of the sesquioxides that have cemented the aggregations of clayey minerals into a structural framework. Soil behaviour is isotropic as the aggregated particles form a three dimensional network. As the concentration of the sesquioxides decrease with depth, so the shear strength reduces. External loads are transmitted to the clayey aggregations and generate very high shear stresses at the aggregation contacts. When the contact stresses exceed the shear strength of the cementitious oxides, the clayey aggregations are displaced and interlock into a more stable structural configuration. With further deformation, the oxide coatings fracture exposing larger surface areas of the clayey minerals to the pore water. On remoulding, the strengths reduce and the plasticity increases.	Iron is transported in its ferrous state but precipitates out under aerobic conditions where it is oxidised to its ferric and immobile state. Aluminium is derived from the alteration of the feldspars and occurs principally in the form of gibbsite and kaolin. The aluminium oxides are transported vertically upward through the profile by evapotranspiration processes and precipitate from solution in the mottled zone overlying the pallid zone and underlying the highly ferruginised surface zone. The ferric and aluminium oxides coat and bound the aggregations of clayey minerals and residual quartz into a three dimensional network. In the oxygen rich, near surface horizon, nodular or massive concretions have been produced by successive depositions of ferric oxides that have precipitated from the transpiring ground waters. The transportation of the sesquioxides by capillary leaching processes has occurred over greater distances than have been previously considered to be possible, (Maignien 1966). The transportation mechanism is not fully understood but may be associated with biological activity and the presence of the dense forest cover with ubiquitous root systems extracting oxygen and even minerals from the partially - saturated pallid zone above the ground water table, and extending the acidic environment.
5. RECOMPRESSION INDEX (Cr) and MODULUS OF ELASTICITY (E, MPa) (Range measured from 32 oedometer tests) (i) $0.01 \leq Cr \leq 0.08$ (average 0.04); (ii) $7 \leq E \leq 42$ (average 26); and (iii) overconsolidation ratios vary from 1.2 to 4. (Properties measured from 14 Camkometer tests) (i) $32 \leq E \leq 126$ (average 65); (ii) there is a general trend of decreasing moduli with depth; (iii) all moduli were computed from 0 to 0.5% strain range; (iv) compressibility properties are isotropic; and (v) the unloading moduli to the initial loading moduli ratio varies from 1.2 to 4.1 (average 2.5). The design of economical shallow foundations depends on accurately estimating foundation settlements. Linear elastic theory is generally valid. The compressibility properties should be determined by Camkometer or large scale loading tests. The number of tests should be adequate to define the natural variability. Oedometer testing will over-estimate soil compressibilities by a factor up to 3. Foundation designs based on laboratory derived parameters will be very conservative.	The low compressibility properties of the lateritised pallid zone soils are primarily due to the presence of a sesquioxide-cemented framework of clayey aggregations, suction stresses and secondary compression, resulting from the age and depth of the lateritised profile. Minor overburden erosion of some 2m is believed to have occurred at the Refinery site. The aggregated and open-voided structure is brittle and the three dimensional network gives rise to isotropic behaviour. The variability is a function of the concentration of the sesquioxide cements at the aggregation contacts and the mineralogy of the residual soil and bedrock.	