

Compressibilities of Lateritised Granitic Soils near Worsley

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SUMMARY The lateritised kaolinitic clays and silts at the site of the Alumina Refinery near Worsley, some 200 km south of Perth, Western Australia, are the products of residual weathering of a porphyritic granite in a semi-tropical environment. The soils are quasi-overconsolidated, highly leached and contain significant and variable proportions of cementitious iron and aluminium oxides (sesquioxides) throughout their deeply weathered profile. The sesquioxides contribute to their characteristically high strengths, low compressibilities and brittle stress-strain behaviour when loaded. The average Modulus of Elasticity determined from Camkometer testing was 65 MPa and this compares with an average modulus of 26 MPa determined from oedometer testing and 55 MPa back-calculated from the measured settlements produced by a 10m high earthen embankment. Oedometer testing will underestimate the compressibility properties of these soils by a factor up to 3 due to the effects of unavoidable sample disturbance. Camkometer testing and the settlement monitoring of embankment loading provide the most representative measure of the compressibility properties of these soils.

1. INTRODUCTION

The lateritic soils in the Darling Range in the South West of Western Australia are currently involved in major resource developments. An Alumina Refinery presently under construction (1983) near Worsley, some 200 km south of Perth, will on current projections, become the largest producing refinery in the world.

In general, the soils at the Refinery site have been weathered insitu from a porphyritic granite to kaolinitic clays, silts, quartzitic sands, pisolitic gravels and laterite, and contain significant and variable concentrations of iron and aluminium oxides (sesquioxides). The sesquioxides determine the unusual compressibility properties and settlement behaviour of these soils.

The paper discusses the compressibility properties of the residual granitic clays and silts over the site for the Worsley Alumina Refinery, and the most suitable methods of measuring these properties. An accurate measurement of the compressibility properties is a prerequisite for economical foundations.

The findings presented in the paper were obtained by Soil and Rock Engineering Pty. Ltd., from the geotechnical investigations for the Refinery and Mine Infrastructures.

2 DEFINITION OF LATERITIC SOIL

The complicated nature of these soil types is evident by the widely varying definitions of lateritic soils as reviewed by Maignien (1966). For the purposes of the paper, lateritic soils are defined as:

weathered products of granite. 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, pisolitic gravels and iron-enriched laterite.

3 GEOLOGY

The weathering process, that is applicable to the soils at the Refinery site, is Plateau Weathering. Gordon (1984) This has produced a typical lateritised profile containing:

- (i) surface sands (residual quartz) or iron-enriched, pisolitic gravels or cemented laterite depending on the minerals that are predominant in the granite bedrock;
- (ii) red, white, yellow (mottled) variably leached, ferruginated, gibbsitic gravels, clays and silts;
- (iii) white, brown (pallid) kaolinitic clays and silts;
- (iv) permeable and ferruginated, micaceous, quartzitic sands and gravels; and
- (v) moderately weathered porphyritic granite.

The following discussion relates only to the compressibility properties of the residual leached granitic clays and silts. These soil types predominate at the Refinery site.

4 INFLUENCES AFFECTING COMPRESSIBILITY

The compressibilities of the lateritised clays and silts are a complex function of the interaction between the geological, environmental and man made influences. Some of the more significant components of this interaction are presented in Figure 1. The list is not exhaustive.

Climate and ground water are factors primarily responsible for the degree of weathering and lateritisation and have contributed very significantly to the stress history of these soils. The relatively shallow ground water table and the water imbalance (i.e. seasonal evapotranspiration exceeds precipitation in the Worsley environment) have

generated variable suction stress gradients. They have resulted in significant capillary and gravity leaching over a geological time frame.

Leaching is an essential soil lateritisation process. The results of leaching are seen from the range of dry densities and moisture contents. Dry densities varied from 1.05 to 1.75 tonnes.m⁻³ and moisture contents ranged from 10% to 60%. The index properties are highly variable over short horizontal distances and show general trends of decreasing dry density and increasing moisture content with increasing depth in the weathered profile (Gordon and Smith, 1984). The trends suggest that capillary leaching has been the dominant mechanism.

The importance of root channels in accelerating weathering and promoting leaching and transpiration cannot be overstated. Remnant root systems have been observed to depths of 35m at the Refinery Site.

The mineralogy of the parent rock is important in determining the composition of the residually weathered profile and is considered to be the most important determinant in producing the characteristically high variability in the engineering properties of the residual materials. The interaction between the geology and geotechnical properties is the subject of a separate paper (Gordon and Smith, 1984).

Iron and aluminium oxides (sesquioxides) are resistant to the weathering processes and have accumulated within the leached profile. In the prevailing acidic ground water environment (pH measurements range from 3.5 to 6.6), the sesquioxides have coated and cemented the porous aggregations of clayey and silty particles.

Townsend (1971) described lateritic soils as often possessing "a porous granular structure consisting of iron-impregnated clayey material in minute spherical aggregations resembling popcorn balls". The geological and environmental influences have

produced open-voided and cemented materials. Their engineering properties provide evidence that the structure is not dissimilar to that described above (Gordon and Smith, 1984).

Other factors that influence the compressibility properties of these soil types include:

- (i) secondary compression due to the depth (up to 55m in places) and age of the weathering;
- (ii) for a structure, the magnitude of foundation loading, foundation geometry and rigidity and their interaction with geological boundaries will influence the way that the foundation loads are transmitted. As compressibility is, inter alia, a function of the effective horizontal and vertical stresses, the compressibility properties will vary with the degree of soil-structure interaction; and
- (iii) preloading of the foundation soils.

5 MEASUREMENT OF COMPRESSIBILITY

The compressibility properties were measured by:

- (i) oedometer and triaxial testing;
- (ii) pressuremeter (Camkometer) tests; and
- (iii) settlement monitoring of an earthen embankment.

The results are summarised below.

5.1 Oedometer testing

All tests were carried out on granitic clayey and silty soils having a Unified Soil Classification of either ML or MH. The liquid limits varied between 40 and 59 (average 48) and plasticity indices varied between 5 and 25 (average 15). The other index properties are presented in a separate paper (Gordon and Smith, 1984).

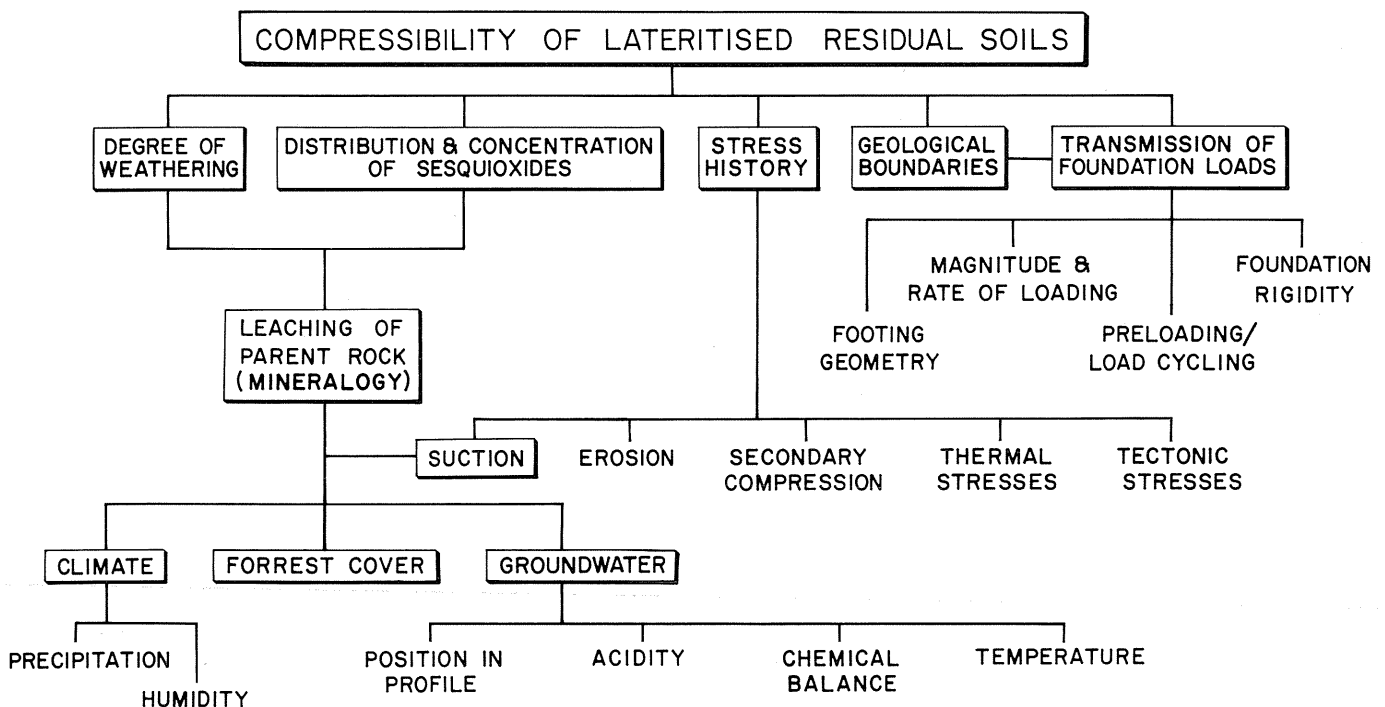


Figure 1. The interaction of factors influencing the compressibility of lateritised soils

A typical 'void ratio vs effective pressure (log scale)' relationship is presented in Figure 2.

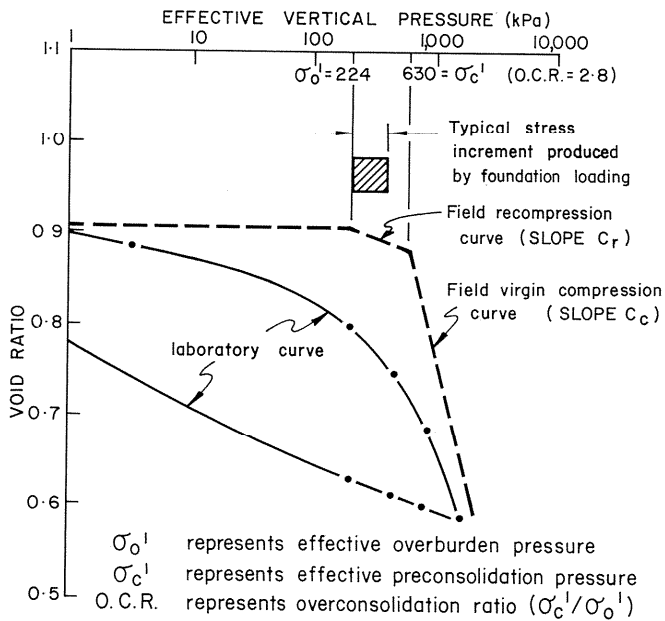


Figure 2. Typical oedometer result

The form of the relationship indicates that the soil is overconsolidated. Superimposed on Figure 2 is the estimated 'field' relationship, derived after correcting for preconsolidation and disturbance influences (Casagrande, 1936 and Schmertmann, 1955). An effective stress increment produced by typical Refinery foundation loads has also been included. The recompression index (C_r), defined as the gradient of the 'field' relationship between the present effective overburden stress and the apparent preconsolidation stress, is the appropriate parameter for settlement analyses.

The results of the oedometer tests are summarised in Table 1.

TABLE 1
SUMMARY OF CONSOLIDATION TEST RESULTS - WORSLEY SOILS

Compressibility Parameter	No of Tests	Range in Results	Average (Coefficient of variation)*
1. Compressibility Index;			
o recompression (C_r)	32	0.01 - 0.08	0.04 (0.50)
o virgin (C_c)		0.13 - 0.55	0.39 (0.50)
2. Overconsolidation ratio	32	1.2 - 4.0	2.7 (0.2)
3. Constrained Modulus of Elasticity E (MPa), applicable to overburden pressure + 200 kPa **	32	7 - 42	26 (0.5)
4. Void ratio	32	0.65 - 1.24	0.90 (0.2)
5. Suction (pF scale)	12	3.3 - 3.9	3.6 (0.1)

* ratio of standard deviation to mean

** foundation stress increment

The rate of consolidation was sufficiently rapid to use 20 minute loading and unloading cycles in the oedometer tests. In all tests, the 90% consolidation times were less than 2 minutes.

The preconsolidation is apparent as only minor overburden erosion is believed to have occurred. The main factors contributing to the apparent preconsolidation are:

- cementation resulting from the sesquioxides precipitated during capillary and gravity leaching;
- matrix and solute suction stress gradients; and
- secondary compression due to the age and depth of the residual weathering.

The geotechnical significance of the apparent preconsolidation is evident from the relative magnitudes of the recompression and virgin compressibility indices. The average recompression index is approximately 10% of the average virgin compressibility index (Table 1).

The compressibilities of these soil types appear low by world standards (Smith, 1984). DeGraft-Johnson and Bhatia (1969) summarised the compressibility properties of lateritised granitic soils from other parts of the world. The range in constrained moduli, computed from the reported coefficients of volume decrease, is 1 to 10 MPa, with an average of 6 MPa.

The range in void ratios is large and indicates highly variable leaching and/or variations in bedrock mineralogy. The average void ratio of 0.9 is high when compared with the void ratios reported for lateritised granitic soils in other parts of the world (Gidigas, 1976).

Total soil suctions were measured using the procedure recommended by Khan (1981). No meaningful correlation was found among the effective overburden pressure, suction and apparent preconsolidation parameters.

In addition, five oedometer tests were carried out on a sample of clayey silt (ML Classification) recovered in a 62mm diameter, thin-walled sampling tube. Pressure increment ratios varying between 1/8 and 2 were used. The objectives were to define the apparent preconsolidation pressure by identifying abrupt transitions in the void ratio vs effective stress relationships and to examine the influence of rate of loading on the compressibility parameters. No sudden decreases in void ratios were measured for vertical effective pressures to 1.6 MPa for the above range of pressure increment ratios. This behaviour is generally associated with the disintegration of fabric bonds of quasi-overconsolidated soils (Winterkorn and Fang, 1975).

In terms of the rate of loading objective, the number of tests was not sufficient to place any statistical significance on the results, and the effects of natural soil variability were not quantified. Nevertheless, the observed trend was a decrease in the recompression index with a decrease in the pressure increment ratio. The recompression index measured for a sample subjected to the lowest ratio of 1/8 was approximately 60% of the index measured for a sample tested using the highest ratio (2).

Two pairs of oedometer tests were carried out on sub samples, cut parallel and perpendicular to the longitudinal axes of the samples taken in thin-walled, 62mm diameter tubes. The one dimensional coefficient of volume decrease vs effective pressure relationships for one pair of tests are presented in Figure 3. The results of both pairs of tests indicate essentially isotropic behaviour.

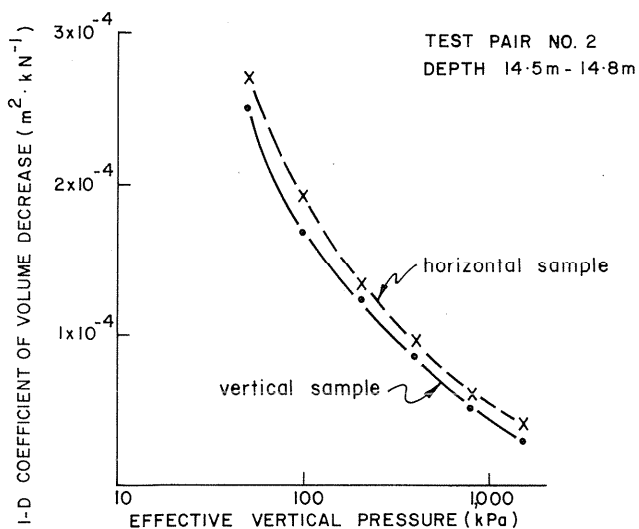


Figure 3. - Results of oedometer tests on horizontal and vertical samples

The void ratios and recompression indices are plotted against dry densities in Figures 4 and 5. The scatter of experimental points in Figure 4 provides a measure of the variability of soil particle densities. The majority of points fall between the 2.3 and 2.7 density contours and suggest the relatively porous nature of the aggregations comprising the soil structure (Gordon and Smith, 1984).

There is no correlation between the recompression indices and dry densities (Figure 5). The reasons for the observed scatter are believed to be due to:

- (i) variable concentrations of the sesquioxides present at any particular dry density; and
- (ii) unavoidable disturbance to the soil structure produced by stress relief during sampling and pre-test preparations.

5.2 Triaxial testing

Cyclic, consolidated, undrained, single-stage, triaxial compression tests were conducted on four samples taken from above and below the water table. These tests were carried out to evaluate the effects of load cycling and strain levels on the elastic moduli. The samples taken from above the water table were tested in their partially saturated condition, and the samples recovered from below the water table were saturated by back pressuring prior to testing.

Each sample was anisotropically consolidated to the estimated insitu stresses and then loaded to strains varying between 0.25% and 4%. At different strain levels, each sample was unloaded to the estimated insitu stresses. The deviator stress vs strain relationship for one of the cyclic triaxial tests is presented in Figure 6.

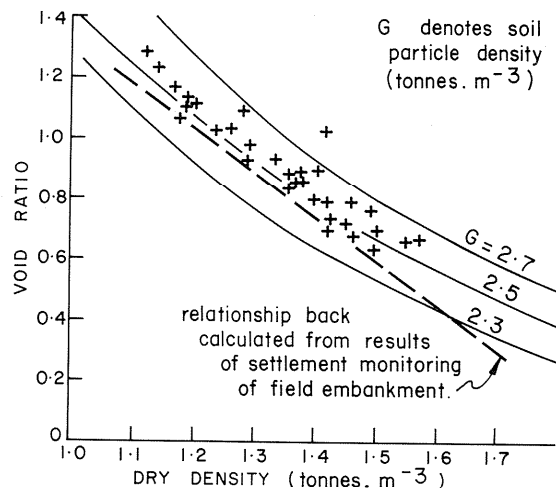


Figure 4. - Void ratios vs dry densities

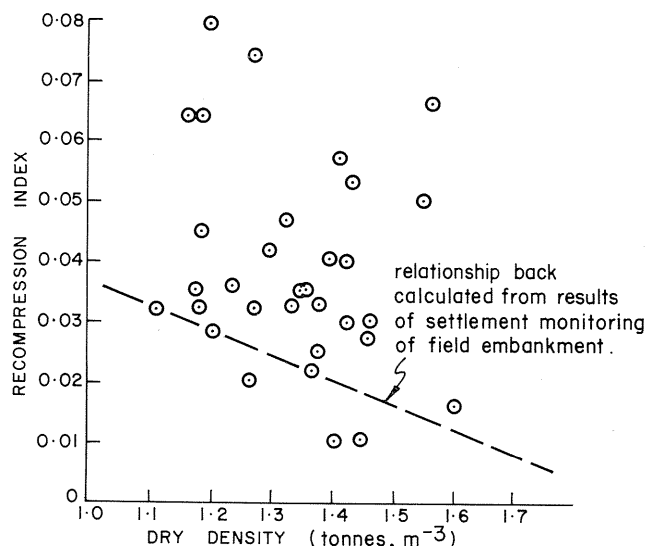


Figure 5. Recompression indices vs dry densities

The salient results are summarised below:

- (i) The soils stiffened appreciably on the first reloading (i.e. $E_2 \approx 2E_1$ in Figure 6). The ratios of the reload to the initial secant moduli of Elasticity varied from 1.8 to 2.5. No significant increases in moduli were observed during subsequent load cycling, (i.e. $E_2 \approx E_3 \approx E_6$, Figure 6). The reload secant modulus is defined as the gradient of the line joining the initial point on the reloading curve to the point where this curve becomes tangential to the extrapolated deviator stress vs strain relationship.
- (ii) No significant increases in the secant moduli were recorded for strains above 1.5%. Figure 6 shows no significant increase after a strain of approximately 0.7%.
- (iii) Very little rebound was observed for all strain levels during the unloading cycles. The hysteresis loops were small indicating the proportions of elastic to plastic deformations were small.

TABLE II

SUMMARY OF CAMKOMETER RESULTS

Parameter	Range in Results	Average (Coefficient of Variation)*
1. Modulus of Elasticity (MPa) from		
(i) initial loading (tangent modulus)	33 - 126	65 (0.45)
(ii) unloading or reloading (secant modulus)	60 - 234	144 (0.40)
2. Modular Ratio (unload:initial)	1.2 - 4.1	2.5 (0.36)
3. Shear Strength (kPa)		
o peak	214 - 806	429 (0.35)
o residual	53 - 408	234 (0.40)
4. Strain level (%) at peak shear strength	0.7 - 2.0	1.2 (0.25)

* ratio of standard deviation to mean.

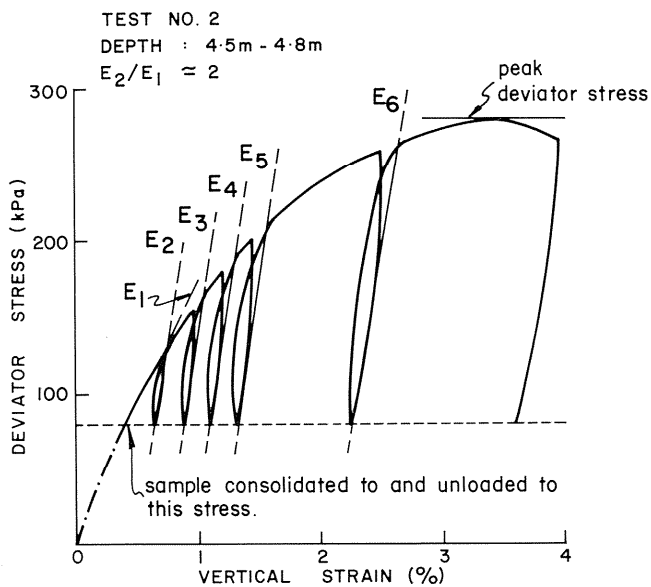


Figure 6 - Results of cyclic triaxial testing

5.3. Camkometer Testing

Fourteen Camkometer tests were carried out in the lateritised granitic clays and silts at four of the sites proposed for the Refinery facilities. The operation of the Camkometer has been described by Wroth and Hughes (1974).

The results of the Camkometer tests are presented in Table II. The shear stress vs strain relationship derived from one of the tests is presented in Figure 7.

The salient features are discussed below:

- (i) The shear stress vs strain relationships are predominantly linear to the peak shear stresses. These stresses are mobilised at relatively low strains varying between 0.7% and 2.0%.
- (ii) The peak shear stresses are high and variable. They are a function of the concentration of the cementitious sesquioxides.
- (iii) The gradients on either side of the peak shear stress are relatively steep (Figure 7). This behaviour is characteristic of the constitutive properties of a non-ductile material (e.g. cast iron).
- (iv) The soils tested by the Camkometer are in a relatively undisturbed state. Therefore, the high coefficients of variation are primarily a measure of the natural variability of these soils.
- (iv) The secant moduli calculated from the unloading and/or reloading curves are on the average 2.5 times greater than the initial tangent moduli. This value is in close agreement with the average modular ratio of 2 determined from the cyclic triaxial testing programme, (Section 5.2).
- (vi) The tabulated strengths and compressibilities can be considered to be drained parameters because of the very rapid consolidation rates of these soils, (Section 5.1).

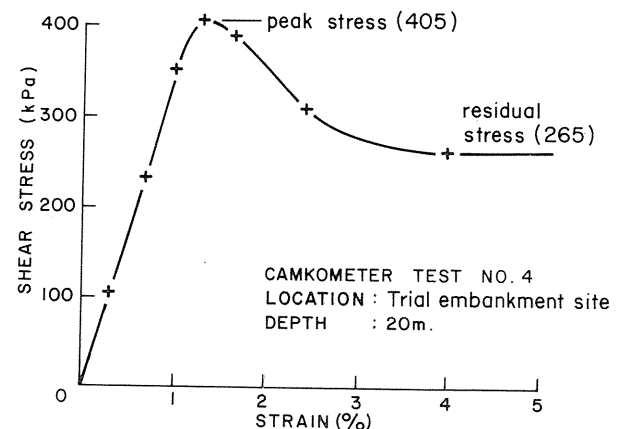


Figure 7. - Shear stress vs strain relationship

5.4. Embankment Loading

A soil embankment 100m long by 80m wide by 10m high was constructed over a 20m thick deposit comprising predominantly lateritised silts and clays containing some sandy and gravelly lenses and overlying granite bedrock. The soils supporting the embankment were instrumented with settlement gauges, remote reading pneumatic piezometers and Gloetz pressure cells. A case history of the settlement monitoring of the embankment has been given in a separate paper (Smith, 1984).

From a back-analysis of the results of the settlement monitoring, the following information was obtained:

- (i) The load vs settlement relationship was linear to the 200 kPa maximum applied pressure.
- (ii) The effective drained Modulus of Elasticity for the entire weathered profile was back-calculated to be 55 MPa. This value is of the same order as the average initial tangent modulus (65 MPa) determined from the Camkometer tests, (Table II).

- (iii) The settlement occurred concurrently with construction. For practical purposes, all settlement had occurred within one week after embankment completion.

From the settlement monitoring results, average relationships between the recompression indices, dry densities, moisture contents and void ratios were back-calculated. Two of these relationships are shown in Figures 4 and 5. They coincide approximately with the lower limits of the scatter band of laboratory results. The relationships are semi-empirical in that the influences of the sesquioxides have not been quantified. The significance of these relationships for the foundation design of the major Refinery facilities has been discussed by the author in a separate paper (Smith, 1984).

6. CONCLUSIONS AND RECOMMENDATIONS

From the information presented in this paper, the following conclusions were reached on the compressibility properties of the lateritised granitic clays and silts at the Worsley Alumina Refinery site. Recommendations are provided on the most suitable methods of determining these properties.

1. The truism that soils are the products of their environment is never better exemplified than by the lateritised granitic clays and silts at the Alumina Refinery near Worsley. The open-voided soil structure is confirmation of the efficacy of the capillary and gravity leaching, that have been essential mechanisms to their formation. Their structure is underpinned by cementitious iron and aluminium oxides (sesquioxides) that have been precipitated during leaching.
2. The soils are quasi-overconsolidated. The overconsolidation is apparent, and is a function of inter alia, the influences of the cementitious sesquioxides, suction stress gradients and secondary compression.
3. The lateritised kaolinitic clays and silts are significantly less compressible than non-lateritised soils of the same Unified Soil Classification. Their compressibilities are more consistent with those measured in dense sands.
4. Laboratory testing will underestimate the elastic moduli (by a factor up to 3) because of irreparable damage to the brittle structure of these soils. The damage is unavoidable and occurs during sampling (stress relief) and pre-test preparation, (extrusion, trimming and soaking).
5. Insitu testing provides the most accurate measure of the compressibility properties of these soil types. Suitable tests include:
 - (i) large scale embankment load testing with settlement monitoring; and
 - (ii) Camkometer, screw plate and conventional plate load testing.

6. Semi-empirical relationships between the compressibility parameters, dry density and moisture contents were back-calculated from the results of the embankment loading. The relationships approximate the lower limits of the scatter in the laboratory results.

7 ACKNOWLEDGEMENTS

The author wishes to acknowledge the co-operation of Worsley Alumina Pty Ltd and Raymond Engineers (Australia) Pty. Ltd., and to thank them for their permission to publish this paper.

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