Some Properties of Weathered Greywacke

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SUMMARY.- The behaviour of weathered greywacke from a particular site in Wellington is discussed. The degree of weathering varied considerably and so the material was classed visually into four categories using a scheme for classifying weathered rock similar to that of Fookes and Horswill. The results of the usual soil mechanics classification tests confirmed the grading system as did the results of tests for the mechanical properties. Characteristic ranges of values for the various properties were found for each grade. Furthermore reasonable correlations were found between the void ratio of the material and the values of the mechanical properties.

I.- INTRODUCTION

Much of Wellington is built on an extensive deposit of greywacke which is found in various stages of decomposition ranging from unweathered rock to highly plastic clay. The material whose properties are discussed in this paper was obtained from one particular site in Wellington during the course of an investigation for a multistorey building. Although all the material present is weathered greywacke the degree of weathering varies considerably and in addition the stratigraphy is not simple. The overall assessment of the site and prediction of the likely performance of any foundation constructed there would be greatly facilitated if some means of sorting the material into characteristic types could be developed.

On the basis of visual logging it was possible to class the material into four grades. Similar approaches have been used elsewhere. Knill and Jones (Ref.1) have used a visual grading scheme for classifying weathered and/or fractured rock at dam sites whilst Ward, Burland and Gallois (Ref.2) have classed chalk into five grades to assess its deformation properties and Chandler (Ref.3) has used a fourfold grading scheme in discussing the properties of weathered marl. These have demonstrated that it is possible to classify weathered materials visually into grades which are confirmed by the values for the various properties. Each grade is associated with a characteristic range of values for properties such as density and modulus values. Saunders and Fookes (Ref.4) have compared these and other systems in a paper on the significance of rock weathering to foundation engineering. In Ref.4 information about the properties of a range of weathered rocks is summarised and it is apparent that there is little information available about the properties of weathered sandstone of which greywacke is a type. In New Zealand the term greywacke is applied to poorly sorted well indurated sandstone (Ref.5).

In this paper it is shown how a similar grading system is applicable to a particular site in Wellington. This visual grading is confirmed for the more weathered material by the standard classification tests used in soil mechanics and also by the range of values for the mechanical properties. In addition reasonable relations exist between the void ratio of the weathered material and the values for the mechanical properties.

II.- SAMPLING, DESCRIPTION AND GRADING OF THE MATERIAL

Continuous 4" diameter undisturbed samples were taken with a triple tube rotary core barrel. In this barrel, designed by Northey (Ref.6), the sample was not retained in the usual split liner but in a series of copper rings 4" I.D. and 2" or 4" long held in a split liner. Up to 32" of core could be recovered per run. With this barrel it was possible to obtain good quality undisturbed samples of the wide variety of material at the site. After sampling the core was wrapped in thick plastic sheeting and stored in a humid room in an attempt to maintain the in-situ moisture content. Presumably the material is saturated in-situ, but it is likely that there is a decrease in the degree of saturation associated with the stress relief on sampling. At present these cores provide the only means available of examining the material at the site.

The material was logged visually and could be divided into four groups ranging from completely weathered greywacke in the form of a red highly plastic clay to a moderately weathered material. In all the classification schemes discussed in references 1 to 4 the unweathered material has been termed grade I and the same idea of assigning the lower grade numbers to the least weathered material is followed here. An attempt is made to follow the classification system of Fookes and Horswill (Ref.4) for the weathering of hard rocks explained in reference 4 and the details of which are given in Table I. Following this system it seems that the least weathered material found at the site corresponds to Fookes's and Horswill's grade III and the most weathered to their grade

VI. The details of the four grades of weathered greywacke are set out below:

Grade VI. Dark red, stiff to very stiff homogeneous highly plastic clay; structure of parent rock no longer apparent although there are areas of grey, less weathered material; on drying slightly mottled texture evident.

Grade V. Very similar colour and texture to Grade IV but weathering more advanced; joints in parent material clearly marked; in some cases sandy texture of original rock not so evident as in Grade IV material; Grade V material easily crumbled to sandy silt under light finger pressure.

soil

Grade IV. Light yellow-brown material; broken down to silty sand with moderate to firm finger pressure; occasional much harder lumps; original rock fabric still evident in the undisturbed material by virtue of the black manganese dioxide along joint planes during weathering; spacing of joints variable, ranging upward from ½" and orientation random.

Grade III. Dense, brown, moderately weathered, very closely jointed material. Typical size of pieces ranges from ½" upwards; separate pieces break under moderate hammer blow, brown colour extends through the broken pieces but diminishes towards centre.

The material in all four of these grades is weathered greywacke. Because the original rock fabric is still clearly discernable in grades III to V they are residual weathered materials. The exact origin of the grade VI material is not clear. At present it does seem that although it is derived from greywacke it was probably transposed to the site. The degree of weathering before this transposition is uncertain. As explained by Te Punga (Ref.7) greywacke weathered to a red colour is not uncommon around the Wellington area and it has been suggested that a different weathering mechanism might be responsible for this colour.

It was possible to perform the usual soil mechanics classification tests on grades IV, V and VI but grade III was more in the gravel range and so the bulk of the discussion from here is confined to the more weathered material. These tests showed that a characteristic range of values for the index properties is associated with each grade.

Particle size distribution curves provided the first confirmation of the grading scheme. Some typical curves for grades IV, V and VI are plotted in Fig.1. This shows that the weathering process increases the proportion of fine grained material present. On the basis of these particle size distribution curves the diagram has been divided into regions characteristic of each grade. One difficulty encountered in determining the particle size distribution curves for residual soils is the tendency for the coarser fraction to keep breaking down during the sieving process. In this case the sieving time was kept to a standard 15 minutes thus at least ensuring that any such effect was uniform throughout the results discussed here. An effort was also made to ensure that the pretreatment of the material was always the same. Before sieving and washing it was

TABLE I

CHARACTERISTICS OF THE CLASSIFICATION SCHEME FOR THE WEATHERING OF HARD ROCK BY FOOKES AND HORSWILL

Term	Grade	Rocks
True residual soil	VI	Rock is discoloured and completely changed to soil with original fabric completely destroyed.
Completely weathered	V	Rock discoloured and externally changed to a soil, but original fabric mainly preserved; properties of the soil depend partly on nature of parent rock.
Highly weathered	IV	Rock discoloured; discontinuities may be open and fabric of rock near to discontinuities altered; alteration penetrates deeply inwards, lithorelicts still present.
Moderately weathered	III	Rock discoloured; discontinuities may be open and surfaces have greater discolouration with alteration penetrating inwards; intact rock noticeably weaker, as determined in the field, than fresh rock.
Slightly weathered	II	Rock slightly discoloured; discontinuities may be open and have slightly discoloured surfaces; intact rock not, as determined in the field, weaker than fresh rock.
Fresh	I	Parent rock shows no discolouration, loss of strength or any other effects due to weathering.

crumbled under gentle finger pressure. Thus even if there may be some doubt about the "true" grading curve those discussed here are adequate for comparative purposes.

Plasticity tests gave a similar picture. As with the particle size analysis an attempt was made to keep the pretreatment of the material before the tests consistent. The material that passed the number 36 sieve was wetted up to well above the liquid limit and the separate points for the liquid limit and plastic limits were then reached by a continuous sequence of gradual drying, cycles of wetting and drying being carefully avoided. The values of the plasticity index (I_p) are plotted against the liquid limit (w_L) in Fig.2 and it can be seen that the points are spread along a narrow band, the regions of this diagram occupied by the various grades are shown. In Table II characteristic ranges of values for the classification test results are tabulated. This table includes values for the specific gravity (G) of the soil particles and the range of void ratios that seem to be associated with each grade.

Table II indicates that although there is some overlapping between the grades there is a range of values associated with each. A similar conclusion is reached when the values for the various mechanical properties are examined, these are tabulated in Table III.

Table III illustrates that there is a characteristic range of values for the various properties in each grade even though there is some overlapping at the transition from one grade to

TABLE II

INDEX PROPERTIES FOR GRADES IV TO VI WEATHERED GREYWACKE

Grade	Liquid Limit (%) (w_L)	Plasticity Index (%) (I_p)	% Passing 200 Sieve	% Finer than 2 microns	Specific Gravity (G)	Void Ratio (e)
IV	35	10	25-55	15	2.70-2.69	0.30-0.55
V	34-60	8-35	55-80	15-40	2.70-2.69	0.50-0.85
VI	60-100	>30	>80	40-60	2.74	0.75-1.40

TABLE III

MECHANICAL PROPERTIES FOR GRADES IV TO VI WEATHERED GREYWACKE

Grade	Coef.of Perm. (K) cm/sec.	Comp. Index (C_c)	Preconsol. Pressure (p_c) tons/ft^2	Angle of Int.Friction ϕ
IV	10^{-7}	0.1	>20	>35
V	4×10^{-6}-1×10^{-8}	0.1-0.35	24-10	35-15
VI	3×10^{-8}-5×10^{-9}	0.30-0.70	<10	<15

the next. The table also indicates the major limitation of the grading scheme. Each grade has a characteristic range of properties but the spread of values within a given grade can be fairly wide. For example, the compression index, C_c, may range between 0.70 and 0.30 for grade VI material. This suggests that for practical application some better means of estimating likely values would be useful. In the following sections of this paper the results of each of the individual types of test are discussed and it is shown that the void ratio of the material provides a more useful way of assessing the likely range of values for a given property.

III.- PERMEABILITY TESTS

Nineteen permeability tests were performed on samples of grades IV, V and VI material. Each sample was trimmed into a consolidation ring the inner surface of which had been smeared with silicone grease. The prepared sample was mounted with a porous stone at one end and connected to a supply of de-aired water at the other and placed in a constant temperature bath set at 20°C. The test set up was such that any tendency for the sample to swell on exposure to water was prevented. No attempt was made to ensure that the samples were fully saturated at testing but the calculated degree of saturation (S_r) indicated that all the material tested for permeability and also for consolidation and strength was either fully saturated or nearly so.

Falling head tests were done each of which was allowed to proceed for about two weeks. After several days the measured permeability settled down to a steady value and these are plotted against the void ratio in Fig.3. There is a fair amount of scatter in this diagram but it does show that as the void ratio increases there is a tendency for the permeability to decrease. This is probably a consequence of the increase in the proportion of clay sized particles during the weathering process.

IV.- CONSOLIDATION TESTS

A series of consolidation tests was performed and some typical results are plotted in Fig.4. The consolidometer used was capable of applying stresses up to 133 tons/ft^2 to a 3" diameter sample. The use of such high loads was necessary because of the high values of preconsolidation pressure exhibited by all grades of this material. Fig.4 shows that there is a considerable increase in the compressibility of the weathered greywacke from grades IV through to VI. This is shown more clearly in Fig.5 where the values of the compression index C_c, have been plotted against void ratio. This diagram shows that there is a surprisingly good correlation between the compression index and the void ratio.

The e, log p curves were determined with the usual load increment ratio of unity. The load increments were applied and the settlement plotted on a log time scale. This indicated that the primary consolidation phase for the tests on almost all of the material, the exception being some grade VI material, was complete in less than 10 minutes. The initial settlement on the application of the load occurred so quickly that it was not possible to plot the initial linear part of the settlement, log(time) curve for all the grade IV and most of the grade V material. Because of this there can be no comparison of c_v values for the various grades.

The preconsolidation pressure, p_c, for each of the consolidation tests was determined by the Casagrande construction and the results are plotted against void ratio in Fig.6. This shows that once again there is a fairly well defined relation between this parameter and the void ratio. In this case the amount of scatter is somewhat greater than that for the curve of C_c against void ratio but part of the problem here is probably related to the difficulty in determining the magnitude of the preconsolidation pressure. On the e, log p curves for this weathered greywacke it is not easy to decide on the point with the minimum radius of curvature. To get a more realistic estimate for this two values were determined - apparent upper and lower limits for p_c. The points plotted in Fig.6 are the average of these values, the range at each point was about 2 or 3 tons/ft^2. The preconsolidation pressures plotted in Fig.6 are about 2 to 8 times the present overburden pressure on the material.

The samples tested were of two sizes. The majority were trimmed into conventional 3" diameter by ¾" high consolidation rings, these results are drawn as round dots in Fig.6. Before trimming the inner surface of the rings was smeared with silicone grease. The remainder of the samples were tested without being removed from the 4" diameter, 2" high copper sampling rings and these results are plotted as squares. In both cases a floating ring type of consolidometer was used. Fig.5 and Fig.6 show that there is no significant difference between the results

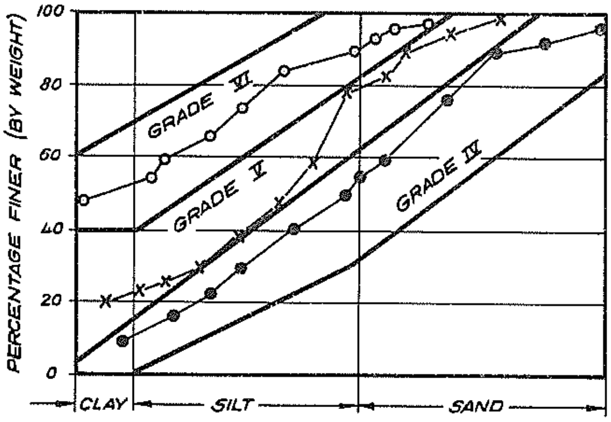

FIG.1 PARTICLE SIZE DISTRIBUTION CURVES

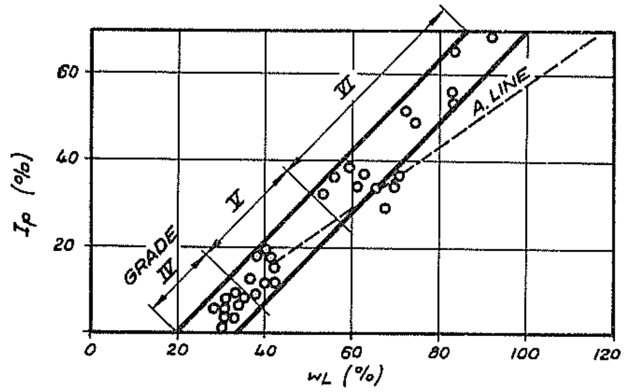

FIG.2 PLASTICITY CHART

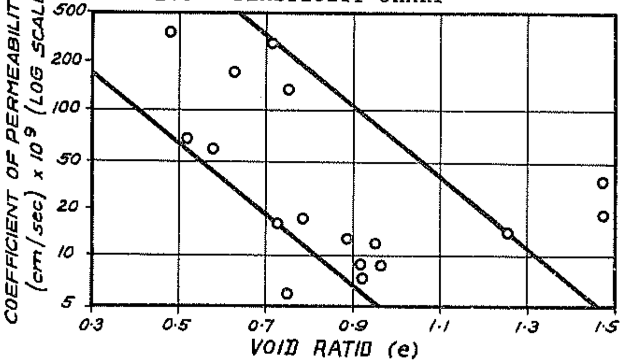

FIG.3 PERMEABILITY VALUES

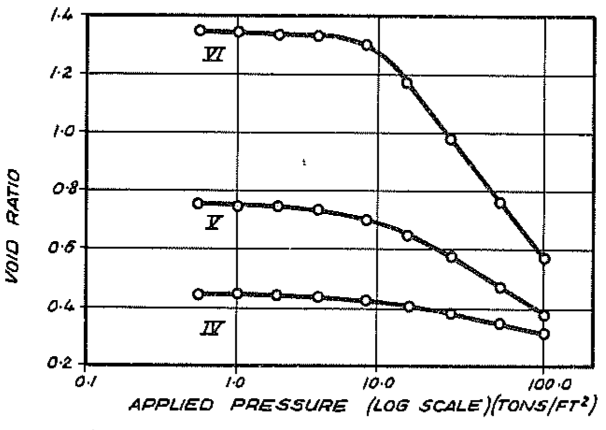

FIG.4 TYPICAL CONSOLIDATION CURVES

obtained from the two sizes of sample holders despite the difference in height to diameter ratios and the treatment of the inner surface.

Before moving onto the discussion of the triaxial test results the significance of large values obtained for the preconsolidation pressure requires comment. The usual explanation for preconsolidation is that at some time in the past history of the soil stresses of the order of the preconsolidation pressure have been applied to the material and subsequently removed. The material "remembers" this and it is reflected in the shape of the e, log p curve. However in the present case it seems to the writer that previous loading of the magnitude required is most unlikely.

It is known that when a material is loaded in a consolidometer at stresses less than the preconsolidation pressure the deformation is approximately recoverable whereas substantial irrecoverable deformation occurs, no doubt with interparticle movement and rearrangement, at higher stresses. When the applied stress approaches the preconsolidation pressure there is a definite change in curvature of the e log p curve. It is suggested here that this change in curvature as p_c is approached will be exhibited by any granular material that is found under stress conditions of magnitude such that only recoverable deformations are possible. In other words it seems to the writer that the so called "preconsolidation pressure" is merely a measure of the stresses that must be applied to the material before the onset of any substantial irrecoverable deformation on loading in a consolidometer.

The behaviour of weathered greywacke discussed in this paper is suggested as an example where the existence of an apparent preconsolidation pressure considerably greater than the existing overburden pressure may not be the result of the previous loading history. Rather it is thought to be a consequence of the weathering process. Initially the unweathered rock is very dense and as the weathering process proceeds the void ratio increases, each change of void ratio giving a material with slightly different consolidation properties. However at each stage of the weathering the resulting material is still comparatively dense and so large pressures have to be applied before there is any irrecoverable change of void ratio. As the void ratio increases the stress required to cause this irrecoverable deformation would be expected to decrease as suggested by Fig.6.

V.- TRIAXIAL TEST RESULTS

A number of consolidated undrained triaxial tests were performed and the resulting effective angle of internal friction is plotted against the initial void ratio of the material in Fig.7. The failure criterion used in determining ϕ' was the peak value of the principal effective stress ratio and a strain rate of 0.1%/minute was applied to all the samples. Once again it is seen that there is a reasonable relation between this parameter and the void ratio of the material. Three of the sixteen points plotted fall well outside the suggested band, at this point the reason for this is not clear. In Fig.8 the values of the effective cohesion intercepts obtained from these undrained

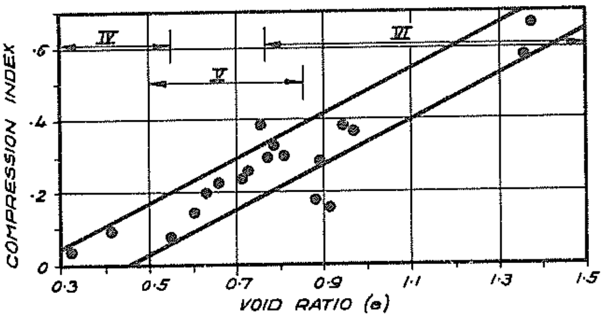

FIG.5 VALUES OF COMPRESSION INDEX

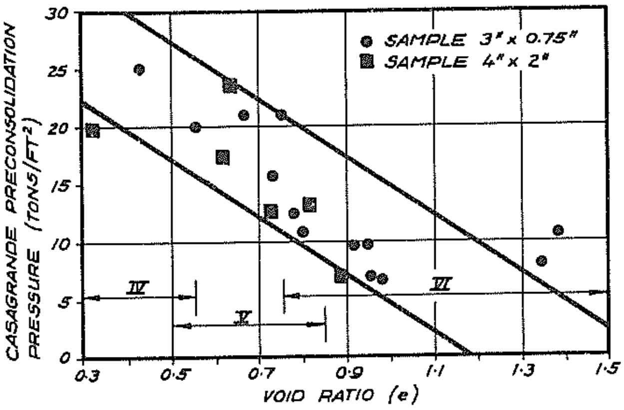

FIG.6 PRECONSOLIDATION PRESSURES

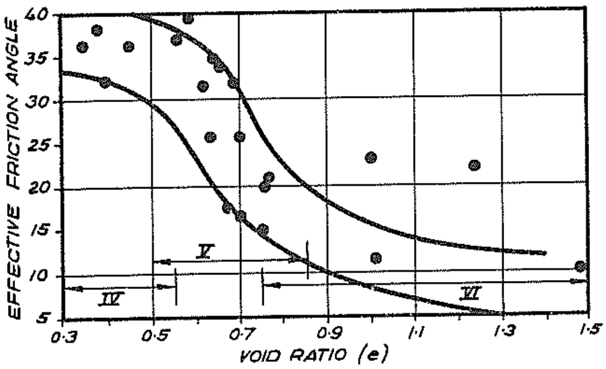

FIG.7 EFFECTIVE ANGLES OF INTERNAL FRICTION

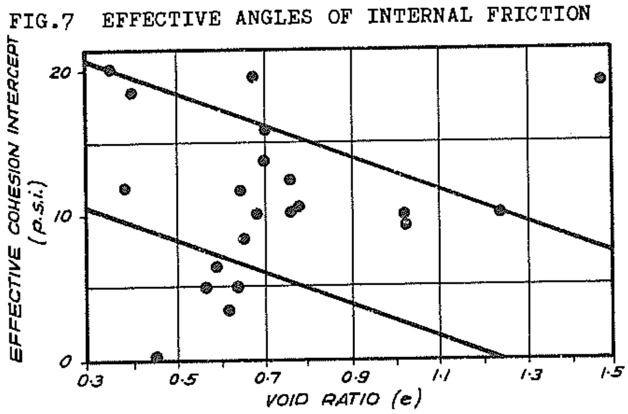

FIG.8 VALUES OF EFFECTIVE COHESION

triaxial series have been plotted against void ratio. The majority of the points fall into a fairly broad band which suggests that as the void ratio increases there is a general decrease in the effective cohesion intercept. Most of the pairs of values for c' and ø' were obtained from a triaxial series consisting of tests on 5 separate samples consolidated before testing at cell pressures ranging from 5 psi to 120 psi. Although the values of c' and ø' have been associated with one particular void ratio in Figs.7 and 8 there was in fact a range of values for the calculated void ratios of the samples tested in each triaxial series. Typically these variations ranged from 0.03 to 0.10 over the five samples for a given series. Variations of this order did not seem to have a significant effect on the graph for which the shear strength parameters were determined.

The majority of the triaxial samples failed by the formation of slip planes that became evident at about the same axial strain as the peak value of the principal effective stress ratio was reached. Despite the joint planes in the original greywacke still being evident in grades IV and V material only a very small number of the total number of samples tested actually failed along one of these planes.

Apart from the usual precautions of careful setting up and filling the cell base and pore pressure transducer with de-aired water no special effort was made to ensure full saturation of the sample and pore pressure measuring system for most of the triaxial tests. The calculated degrees of saturation suggested that the material was either fully saturated or within a few percent of saturation in most cases. Unfortunately the indirect procedure involved in calculating the degree of saturation is very prone to the cumulative effects of small errors and so it is only possible to specify the degree of saturation to within a few percent. Thus the exact degree of saturation of the samples tested remains uncertain but it seems probable that most of the samples were not quite fully saturated. The importance of this was investigated by a few series of tests conducted on samples saturated by the application of back pressure. Another effect was also investigated. Some of the triaxial results were obtained on samples 3" high by 1½" in diameter with porous stones at each end while others were determined from tests on samples 4" high and 4" in diameter with the free ends developed by Rowe and Barden (Ref.8). In these there were two 0.012" thick rubber disks between the sample and each end platen. Silicone grease was smeared on the end platens and between the rubber disks before testing and the disks were also cut radially and circumferentially to reduce any restraint preventing free expansion of the sample. In Fig.9 the result of a triaxial series conducted on 12 samples of grade V material is plotted. The points were determined from tests on back pressure saturated and unsaturated samples some of which were 3" x 1½" and the others 4" x 4". The back pressures used varied between 60 and 90 psi and saturation was checked by measuring the speed with which the pore pressure transducer responded to successive 5 psi increments in cell pressure. In all cases the reading from the pore pressure transducer reached a steady value in less than 10 seconds which is taken as evidence of saturation. Fig.9 in which the twelve points are plotted suggests values of c' and ∅' determined are not dependent on the sample size or the samples not being quite fully saturated. The initial void ratios for these twelve samples were in the range 0.64 ± 0.05. However it was noted that the form of the stress paths determined from samples with back pressure saturation was slightly different from those without the saturation. Thus any accurate consideration of stress paths or pore pressure parameters requires that measures must be taken to ensure that the sample and pore pressure measurement system are fully saturated.

It was also noted that the initial part of the stress-strain curve (principal effective stress difference v axial strain) was linear for these undrained tests. When the curves were corrected for initial bedding errors it was possible to determine the tangent modulus for the initial parts of these stress-strain curves. The corrected stress-strain curves were linear for the first one per cent or so of axial deformation. The tangent modulus values calculated from the slope of these curves are plotted against the effective consolidation pressure in Fig.10 for the same twelve samples that have already been discussed above. From this it is seen that there is an approximately linear relation between the tangent modulus value and the pressure under which the sample was consolidated. In addition Fig.10 suggests that the values measured for the tangent modulus are not particularly sensitive to the sample size or to the sample not being quite fully saturated. Similar linear relations were obtained for triaxial series on material with other initial void ratios. As the void ratio decreases the values for the tangent modulus increase. Similar behaviour was observed by Lumb (Ref.9) for the secant modulus measured from drained tests on residual soil from Hong Kong.

It must be noted that this initial linearity of the stress-strain curve does not mean that the material can be regarded as elastic. The fact that the modulus value is not independent of the applied stresses and that the deformation along the initial linear part of the stress-strain curve is not fully recoverable demonstrates this.

Examination of the stress conditions at the onset of the nonlinear part of the stress-strain curves reveals that the curves are linear until the stress path has almost reached the failure line. For samples consolidated at cell pressures up to about 30 psi the stress conditions at the onset of nonlinearity were very close to the failure line and at higher consolidation pressures a little below the line, the distance increasing with consolidation pressure. If this aspect of the behaviour is confirmed for drained tests a pseudo-elastic procedure would probably be suitable for predicting the settlement of the material under foundation loads.

VI.- CONCLUSIONS

This work on the properties of weathered greywacke found at a particular site in Wellington has shown that it is possible to relate the index and mechanical properties for the various materials to a scheme for classifying the weathering of hard rocks. For each grade there are characteristic ranges of values for the various properties. It has also indicated the limitation of such a procedure in that for a particular grade the range of values for a property can be fairly wide.

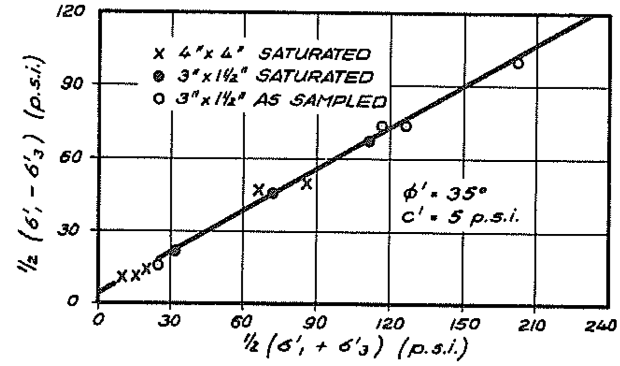

FIG.9 FAILURE POINTS FOR SPECIAL TRIAXIAL SERIES

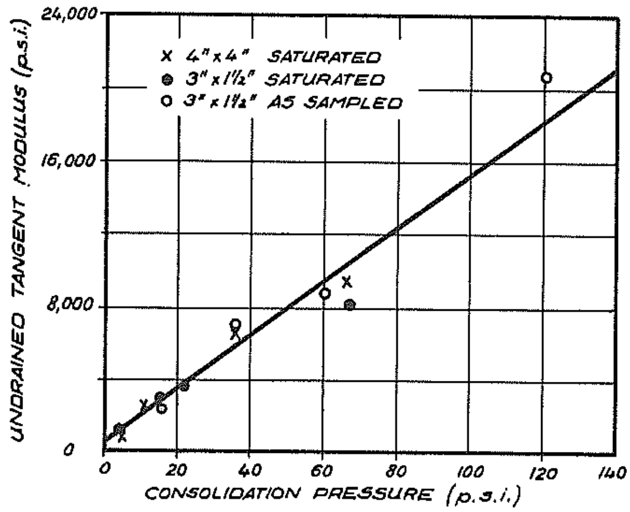

FIG.10 VALUES OF THE UNDRAINED TANGENT MODULUS

Figures 3, 5, 6, 7 and 8 indicate that the magnitudes of the various mechanical properties for the weathered material are related to the void ratio of the material. Despite a certain amount of scatter among the points plotted, as is to be expected with a natural deposit, these diagrams do indicate a fairly uniform trend as the void ratio changes. This means that although in soil mechanics terms the weathering process results in a whole spectrum of materials with differing properties the current void ratio of the material gives a reasonable indication of the likely range for the values of the various properties for this particular weathered greywacke.

The majority of samples were tested at the degree of saturation after sampling and no specific procedure was used to ensure full saturation. A limited number of triaxial series with back pressure saturation indicated that the measurement of the effective angle of internal friction, the effective cohesion intercept and the tangent modulus is not particularly sensitive to the sample being a few per cent short of full saturation.

VII.- ACKNOWLEDGEMENTS

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