Compaction Properties of Bay of Plenty Volcanic Soils, New Zealand

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1 INTRODUCTION

The extraordinary physical properties of soils of volcanic origin were significant in the construction of a 3.3 km earthlined headworks canal for the 20 MW Ruahihi hydro-electric power project. The scheme is the final stage of hydro-electric development on the Wairoa River for the Tauranga Joint Generation Committee.

Soils at the site were found to have high natural water content, high plasticity, high sensitivity and low bulk density. These physical properties gave rise to problems during earthworks construction; namely, difficulties in excavation and compaction. These problems have since been attributed to the presence of the clay mineral allophane; similar difficulties have been reported by Northey and Schafer (1974). Perhaps the most perplexing property is that the soils undergo irreversible changes on drying. Hence compaction control values were found to be dependent on the treatment of the soils before testing.

This paper describes the engineering characteristics of the soils encountered at the site and the work carried out to establish parameters for compaction control. A range of laboratory tests were carried out to investigate the effects of pre-treatment of the soils encountered.

2 THE CANAL

The canal passes through rugged topography, traversing ridges and deeply incised river gorges necessitating cuts of 40 m depth and embankments of up to 15 m in height. At the downstream end, the canal is constructed on the top of a narrow ridge and structural fills are required on either side for stability. The canal is 8 m deep with 1 on 2 side slopes (in both cut and fills) and has a 4.5 m wide invert. The flow under maximum operating conditions is 28 cumecs. Earthworks design required the utilisation of all 2 million cubic metres of cut material.

3 GEOLOGICAL SETTING

The dominant feature of the project area is a broad plateau (the north-western margin of the Mamaku Plateau) that has been deeply incised by the Wairoa River and its tributaries. The ignimbrite forming the basement in the region is the middle Pleistocene Waiteariki Ignimbrite. Overlying the ignimbrite is a massive grey pumice breccia. This pyroclastic flow material was extensively eroded and redeposited within small lakes and rivers giving rise to highly variable and discontinuous lacustrine/alluvial sedimentary units. A further ignimbrite flow overlying the pumice breccia has been deeply weathered into a cream to reddish-brown silty clay. The present topography mantles the upper surface of these deposits.

Two sequences of volcanic tephras form a covering deposit 2 - 4 m thick, over the whole region. The older tephras are the highly weathered andesite Hamilton ash beds (approx. 0.3 my) while the younger tephras range in age from 41,000 years (Rotoehu Ash) to the present.

4 WEATHERING OF ALLOPHANE SOILS

Allophane soils are products of weathering of parent volcanic material. Fieldes (1966) has shown that the occurrence of allophane in soils is favoured by conditions that lead to the formation and persistence of random structural hydrous alumnosilicates such as:

i) Weathering of basic silicate material.
ii) Weathering of glasses in rhyolitic and andesitic volcanic ashes.
iii) Weathering of feldspars.

This weathering produces disordered structures with no discernible regular arrangement. The materials known collectively as allophanes appear under X-Ray diffraction as disordered fluffy formless substances termed gels.

Fieldes (1966) and Fieldes and Furkert (1966) state that the properties of these gels depend upon the extent to which dehydration has progressed. In their hydrous condition the allophane consists of gel-like fragments of alumnosilicates held together by random cross-linking at a small number of points. Large amounts of water are often enclosed in the open structure and these allophanic substances are termined hydrogels. Upon dehydration progressive isometric shrinkage occurs as increasing condensation and cross-linking leads to more compact structures termed xerogels. This process is largely irreversible and air drying of these fine grained cohesive soils tends to produce non-plastic silty sands. The effect of this irreversible drying is discussed further in Sections 5 and 6.

Fieldes and Furkert (1966) report great differences in the physical properties of allophane soils that are permanently wet and those which have been dried. This is very marked at the Ruahihi site where the surface ash is more friable due to periodic wetting and drying while the lower ignimbrites, which are permanently beneath the ground water level, exhibit a characteristic greasy consistency due to the presence of hydrogels.

Mineralogical analyses have been undertaken by the Geological Survey of the DSIR on typical samples of both soils (see Table 1). The absence of recognisable volcanic glass in samples P26 and P27 is probably the result of more intense weathering of these soils and is consistent with the relative quantities of allophane and halloysite present. Fieldes (1955) distinguishes between the various forms of allophane and indicates that with increasing age clays derived from the weathering of parent volcanic material pass through a typical sequence allophane B → allophane AB → allophane A → meta-halloysite → kaolinite. This mechanism is consistent with the data contained in Table 1. Other minerals recorded in small amounts were quartz, plagioclase feldspar, cristobalite, illite and gibbsite.

TABLE 1

MINERALOGICAL ANALYSIS

Sample	Glass	Allophane	Halloysite
P17 Ash	Present	Abundant	Minor
P18 Ash	Present	Abundant	Minor
P20 WI	Present	Abundant	Minor
P26 WI*	-	Abundant	Common
P27 WI	-	Common	Abundant

*Weathered Ignimbrite

5 CLASSIFICATION TESTS

5.1 Atterberg Limits

A number of Atterberg Limit tests have been performed on soils recovered during the preliminary investigations and subsequently during construction (see Table 2). These tests were performed on materials which had not been subjected to drying before testing and the data relate only to samples on which liquid and plastic limit tests were performed. Many other water content tests have been performed and values in the ash as high as 221% have been measured.

TABLE 2

ATTERBERG LIMIT VALUES

Material	Index	Average	Range
Brown Ash	ω (%)	63	45-85
	LL (%)	85	64-115
	PL (%)	67	42-97
	PI	18	7-37
	< 75 µm (%)	56	32-84
Weathered Ignimbrite	ω (%)	86	36-240
	LL(%)	83	44-170
	PL(%)	68	31-130
	PI	15	2-57
	< 75 µm (%)	58	45-72

Note: ω = natural water content

5.2 Presence of Allophane

The test for presence of allophane as described in Test 13 NZS 4402P Pt 1: 1976 has been carried out on a number of samples. In general the test results indicate that few samples contain less than 5% allophane, while approximately equal numbers of tests show allophane contents in the range 5% - 7% or exceeding 7%.

5.3 Particle Size Distribution

A number of wet sieve tests were carried out according to Test 9A of NZS 4402P Pt 1: 1976 to investigate the effect of pre-treatment by drying back from the natural water content. Samples were washed through a nest of sieves down to the 63 µm sieve. For this comparative work the hydrometer test was not carried out.

Test results presented in Figure 1 show a marked change in particle size distribution depending upon whether the soils have been maintained at their natural water content before testing or pre-treated by drying.

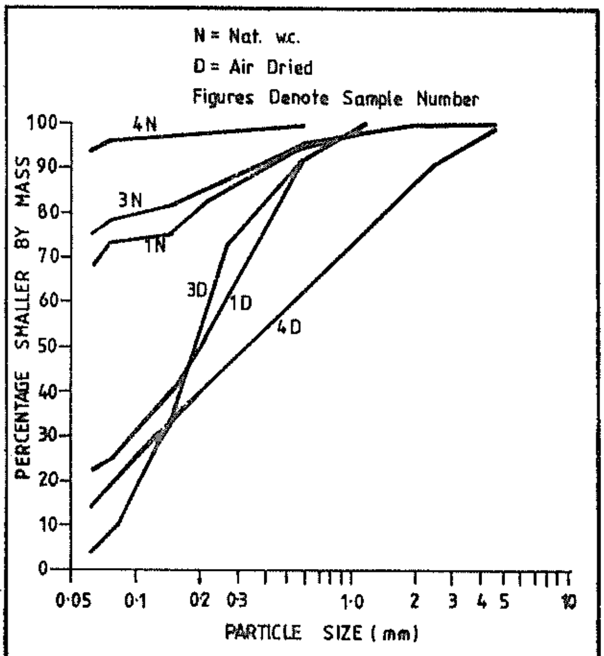


FIG. 1 PARTICLE SIZE DISTRIBUTION

6 COMPACTION CHARACTERISTICS

The physical properties of the *in-situ* soils have been described briefly in the preceding sections. In essence, the soils exist at relatively high water contents with high void ratios and low bulk densities.

Substantial drying of the soils is necessary to produce satisfactory earthfill materials. Table 3 presents average data compiled from laboratory compaction testing during construction. The ash had to be dried from an average water content of 63% to an optimum value of 46% while the weathered ignimbrite from 96% to 52% to achieve maximum dry densities of 1.09 and 1.06 tonnes/m^3 respectively.

The characteristic irreversible changes brought about by drying the allophane soils were significant in establishing the compaction properties of the soils at Ruahihi. Test results were found to be very dependent on the pre-treatment of the soils. In many cases, if specimens for compaction testing were prepared by drying back from their natural water contents, an ill-defined relationship between water content and maximum dry density was found with no clearly defined optimum water content

TABLE 3

Soil Type	Property	Average	Range
Volcanic Ash	ω (%) ρ_d (t/m^3) OWC (%)	63 1.09 46	36-123 0.83-1.55 23-66
Weathered Ignimbrite	ω (%) ρ_d (t/m^3) OWC (%)	96 1.06 52	33-178 0.72-1.42 32-88

ω = Natural water content
ρ_d = Maximum dry density
OWC = Optimum water content

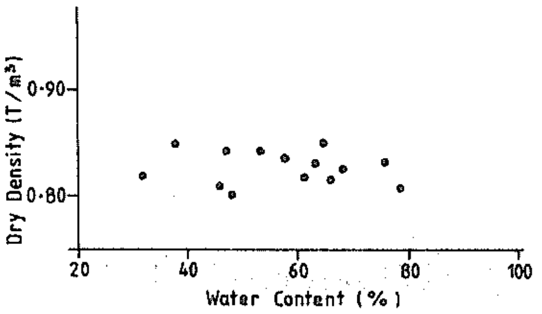


FIG. 2: SAMPLE P18: COMPACTION

as shown in Figure 2.

Wesley (1973) reported that optimum water contents of two allophane soils found in Indonesia were not well defined if the soils were prepared in this manner. He also showed that if the soils were air dried to various water contents and then prepared for compaction by wetting up from those intermediate values, any value of optimum water content and maximum dry density could be obtained. An illustration of Wesley's data is given in Figure 3 where decreasing initial water contents result in decreasing optimum water contents and increasing maximum dry densities.

Curve	Pretreatment
A	Natural Water Content
B	Air-dried to 65%
C	Air-dried
D	Oven-dried

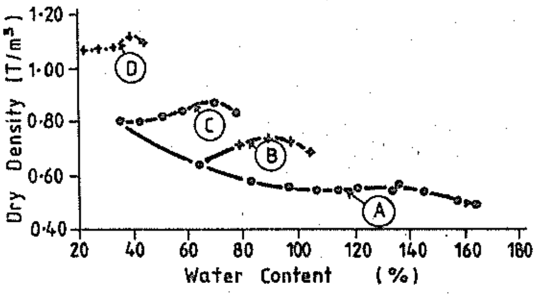


FIG. 3: COMPACTION CURVES FOR ALLOPHANE SOILS (from WESLEY 1979)

Frost (1967) has reviewed the behaviour of a number of tropical soils and examined the behaviour of some soils found in Papua New Guinea. His work showed that soils containing allophane, halloysite and gibbsite, exhibit irreversible changes in normal air drying which can significantly affect the engineering properties of the soils.

The same trends have been observed in the ash and ignimbrite soils found at Ruahihi. In one particular case (shown graphically in Figure 4), three samples were allowed to partially dry in the field during earthworks operations. Sample E was then subjected to complete air drying in the laboratory before preparation of specimens by wetting up and curing. Samples F and G were prepared by wetting up from the partially dry state. Sample E, which has been air dried, shows a significantly higher maximum dry density and lower optimum water content than samples F or G.

Curve	I W C* %	O W C %	ρ_d (Max.) T/m^3
E	<5	45·5	1·07
F	64·5	57·5	0·98
G	75·3	[illegible]·0	0·93

* initial water content

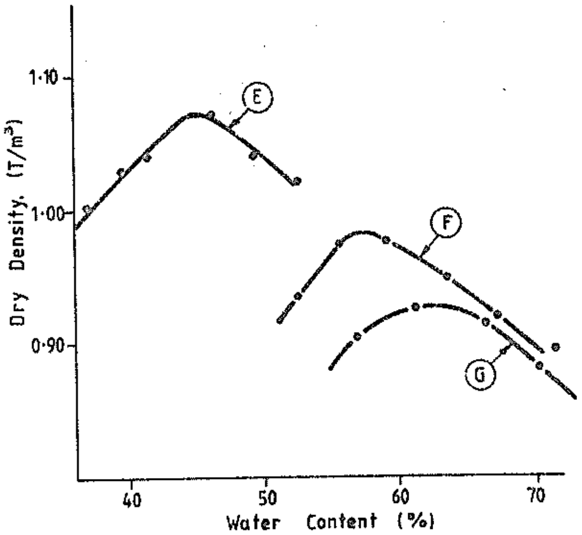


FIG. 4 COMPACTION CURVES AT DIFFERENT INITIAL WATER CONTENTS

Further studies were undertaken to investigate the effects of drying and curing in the pre-treatment of soil for compaction testing. The drying effect described above was investigated by comparing pre-treatments according to two standard test methods. The draft New Zealand Standard (DZ 4402P Pt. 2:1978, Tests 14 and 15) precludes a drying and wetting cycle prior to compaction. This is in recognition of the changes allophane soils can undergo when subjected to cyclic drying and wetting. In this standard test method specimens are prepared by drying back or wetting up from the "as received" water content with no other cyclic changes in water content. This method is referred to hereafter as the <u>drying back method</u>.

On the other hand Test 12 of BS 1377: 1975 allows complete air drying of the soil in certain circumstances and the specimens are further prepared by wetting up to the required water contents. This method is referred to hereafter as the air drying method.

Figure 5 presents data from compaction tests on sample P29, a weathered ignimbrite. Compaction tests using the 2.5 kg rammer have been carried out using both the drying back and air drying methods. The effects of curing have also been investigated. Samples H and I were prepared by drying back. Sample H was compacted immediately after drying, whilst sample I was cured for 24 hours after drying before compaction. The difference between the two curves is negligible and is to be expected as the drying process in this case was slow and curing took place essentially as the sample was drying.

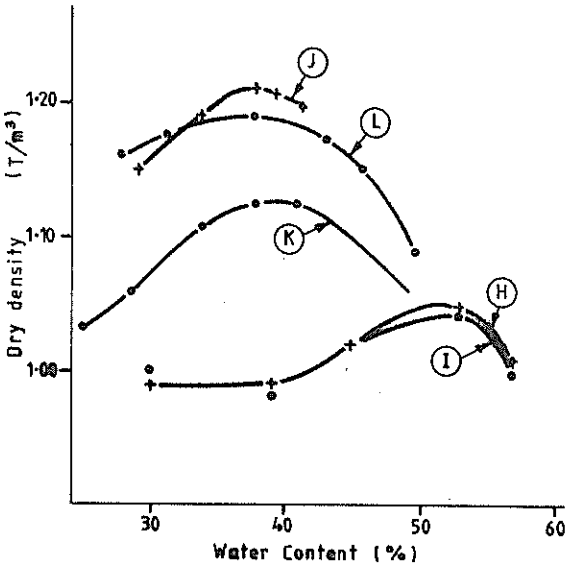
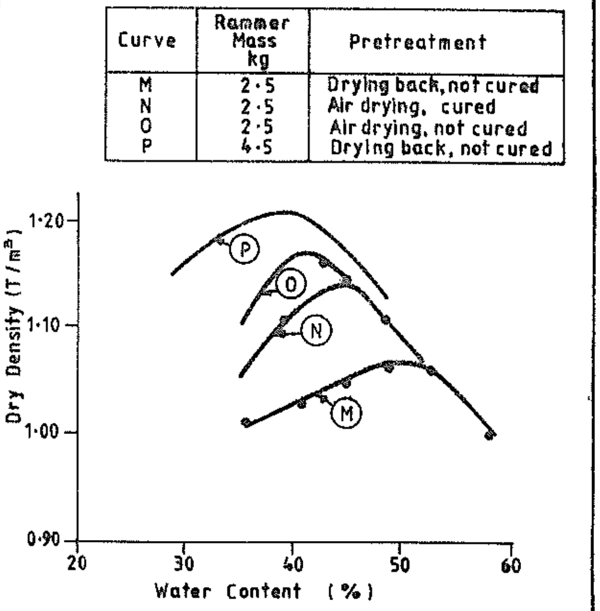


FIG 5: SAMPLE P 29: COMPACTION

Further tests were carried out by complete air drying, wetting up and then compacting immediately or curing prior to compaction. The resulting curves labelled J and K in Figure 5 show the non-cured specimens, J,gave a substantially higher dry density and lower optimum water content than the cured specimens, K.

Figure 5 also shows the curve L, for specimens prepared by drying back from the natural water content and compacting with the 4.5 kg rammer without curing. The increased energy of compaction is reflected in a higher maximum dry density and lower optimum water content than specimens prepared in the same manner but compacted according to the 2.5 kg rammer method.

Similar series of tests carried out on sample P38 are shown in Figure 6 and the trends above are again evident.



Curve	Rammer Mass kg	Pretreatment
M	2·5	Drying back, not cured
N	2·5	Air drying, cured
O	2·5	Air drying, not cured
P	4·5	Drying back, not cured

FIG. 6: SAMPLE P 38 COMPACTION

7 COMPACTION CONTROL

The most widely used and accepted method of earthfill compaction control is based on the comparison of the dry density and water content of the field compacted soil with the laboratory determined values of maximum dry density and optimum water content. A certain proportion of the maximum dry density must be achieved in the fill and the water content of the soil must lie within a specified range, which usually encompasses the optimum water content.

The main shortcomings of such a method for use in highly variable soils is that each time a new soil type is exposed in the cut or borrow area, a new laboratory compaction curve must be obtained, which could result in unacceptable time delays in the earth works.

Other methods of compaction control were considered at the time the earthworks specification was prepared. Control based on minimum shear strength and maximum air voids criteria such as reported by Pickens (1978) has certain advantages. Perhaps the main advantage of the method is that even in soils of variable compaction characteristics the need to establish compaction curves for each material type is eliminated. The air voids determination depends mainly on the field dry density and is insensitive to small variations in the solid density of soil particles.

This latter parameter was assessed during investigations and is checked from time to time during construction. At Ruahihi however, even values of solid density of soil particles were found to vary widely. This would have necessitated providing new values of solid density of soil particles for each soil type and hence the advantage of the method over the conventional dry density/water content method of control would have been largely negated.

A control method based on the 'compaction ratio', where field densities are compared with the laboratory density of the soil compacted at the field water content (an attempt to negate the irreversible changes on drying) was rejected because of its lack of general acceptance.

The specification for compaction control of the earthworks contracts at Ruahihi was written to BS 1377: 1967, as the draft New Zealand Standard (DZ 4402: Part II: 1978) was not published at that stage. Preliminary compaction testing of the soils adhered strictly to Test 11 BS 1377: 1967. To obtain consistent results the following procedures were adhered to as allowed with the BS test method:

a) the soil was air-dried to zero water content;
b) sub-samples for compaction testing were wet up to the required water contents;
c) sub-samples were cured for a minimum of 16 hours prior to testing;
d) the soil was not re-used;
e) at least 300 g mass of each compacted specimen was taken for water content determination.

This practice has been adhered to for all construction phase testing. It is recognised that the air drying method (not allowed by Test 14, DZ 4402, Pt. 2: 1978) changes many of the physical properties of the soil, but it is considered that this change is somewhat irrelevant to the question of compaction control as the laboratory testing merely sets the standard against which values achieved in the earthfill are compared. In addition, the values of maximum dry density and optimum water content achieved by the air drying method are conservative when compared with values obtained by drying back.

8 CONCLUSIONS

The irreversible changes allophane soils undergo on drying from their natural water contents were significant in establishing the compaction properties of volcanic soils encountered at a site in the Bay of Plenty. In many cases if specimens for compaction testing were prepared by drying back or wetting up from the natural water content, an ill-defined relationship between water content and maximum dry density was found with no clearly defined optimum water content.

To overcome this problem, and to establish unique values for compaction control, specimens were prepared for compaction testing by complete air drying prior to wetting up and curing before compaction. It has been shown that air drying to intermediate water contents, between the natural and air dried states, results in a range of compaction curves lying under the zero air voids line with no clearly defined maximum dry density or optimum water content.

The method evolved for determination of the dry density/water content relationship at the Ruahihi site is as follows:

- air dry soil completely and pass through 19 mm sieve;
- wet up to range of desired water contents and cure for 16 hours minimum in sealed containers;
- compact without re-using the soil.

It was found that the most practical method of compaction control was the comparison of water contents and dry densities of the field compacted soil (using the core cutter method) with laboratory determined values of maximum dry density and optimum water content. The main shortcoming of this method is the time delay in preparing a compaction curve when new soils are exposed in borrow areas. However, by maintaining close control on earthworks operations it has been possible to foresee changes in material types in sufficient time to avoid delays in obtaining control values from the laboratory.

9 ACKNOWLEDGEMENTS

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