

Geotechnical classification of ignimbrite and prediction of engineering behaviour from simple index tests

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ABSTRACT: Ignimbrites are typically weak rocks of low density and high porosity, and undergo considerable softening on saturation. Extensive systems of open, continuous, vertical joints occur in many ignimbrites, while others are effectively non-jointed. Large changes in strength and jointing may occur within a single profile. Two broad categories of ignimbrite are recognised: durable ignimbrites with $I_{d2} \geq 90\%$, and non-durable ignimbrites with $I_{d2} \leq 30\%$. Durable ignimbrites behave as weak rocks for which the rock mass characteristics exert the primary influence upon slope stability and engineering behaviour. Non-durable ignimbrites are typically non-jointed and are the weakest materials; they are classified as soft rocks, and the intact rock characteristics are the dominant control on their behaviour. Second-cycle slake durability index and effective porosity together allow classification of ignimbrites and prediction of likely material characteristics.

1 INTRODUCTION

Ignimbritic materials are widely distributed throughout the Central North Island of New Zealand as a result of Quaternary eruptions from the Taupo Volcanic Zone, together with eruptions from older volcanic centres in the Coromandel region. These materials are increasingly being encountered in engineering investigations, sometimes less than successfully (for example, Anon., 1982, 1983).

Many site-specific investigations of the engineering behaviour of ignimbrites have been undertaken (for example, Maloy and Lowe, 1945; Yamanouchi *et al.*, 1981; Price, 1983; Price *et al.*, 1985; Nappi and Ottaviani, 1986). However, site-specific studies measure only those properties relevant to the particular development and hence data from different studies are not necessarily complementary.

In this paper, the results of a systematic series of measurements of a variety of geotechnical properties of ignimbrite materials are used to develop a simple classification system for ignimbrites which gives a ready indication of the likely engineering behaviour of the materials. Index tests which allow classification of ignimbrites, and hence prediction of their characteristics, are identified.

2 DEFINITION OF IGNIMBRITE

Ignimbrites are well defined from a geological point of view as materials deposited by a pyroclastic flow. This genetic definition provides useful geological information about the origin and likely composition of the material. From an engineering viewpoint however, this definition covers an enormous range of materials which display quite different geomechanical properties.

At one extreme are the hard, jointed materials which form steep bluffs, and which have successfully been used as the foundation rocks for a number of hydro-dam projects, such as the Whakamaru,

Maratai, and Waipapa dams. The definition of ignimbrite also incorporates somewhat softer material which may show excellent columnar jointing, or very soft material that is characterised by few joints, can be dug with a spade and might generally be referred to as "non-welded" or "poorly welded". At the furthest extreme are deposits consisting of essentially individual clasts, such as the Taupo Ignimbrite.

3 GEOMECHANICS

3.1 Intact rock properties

Table 1 presents geomechanical data obtained from a variety of unweathered ignimbrite specimens from the Central North Island, New Zealand. Geomechanical tests were undertaken following the standard procedures recommended by Brown (1981). Where appropriate, measurements were made in both saturated and dry conditions to give the range of likely geomechanical properties over all moisture contents.

Table 1 includes the maximum and minimum measured values for bulk density, porosity, a variety of strength parameters, and the second-cycle slake durability index (the percentage of the original mass remaining after two standard cycles of wetting and drying and mechanical abrasion). Softening values for strength measurements are also given: these are the ratios of dry to saturated strengths.

The following points summarise the geomechanical behaviour of ignimbrite:

(1) Ignimbrites have low bulk densities and high porosities, with a significant proportion of the total porosity accounted for by pores which do not contribute to the effective porosity.

(2) Some ignimbrites are essentially unaffected by the slake durability test, whereas others break down almost completely.

(3) Ignimbrites are weak in both compression and tension; their cohesion is weak, but the angle of internal friction is relatively high and uniform. Saturation leads to considerable softening of the

Table 1: Range of a variety of geomechanical properties of intact ignimbrite specimens (from Moon, 1993a).

	minimum	maximum
bulk density		
saturated, ρ_{sat} (kg m^{-3})	1644 \pm 10	2290 \pm 2
oven-dry, ρ_{dry} (kg m^{-3})	1212 \pm 10	2124 \pm 2
porosity		
effective, η_{eff} (%)	14 \pm 1	43 \pm 1
true, η_{true} (%)	17 \pm 1	51 \pm 2
compressive strength		
saturated, $\sigma_{\text{c,sat}}$ (MN m^{-2})	0.23 \pm 0.01	36 \pm 5
oven-dry, $\sigma_{\text{c,dry}}$ (MN m^{-2})	0.73 \pm 0.07	54 \pm 4
softening factor, $\sigma_{\text{c,soft}}$	1.3	5.9
tensile strength*		
saturated, $\sigma_{\text{t,sat}}$ (MN m^{-2})	0.12 \pm 0.03	7 \pm 2
oven-dry, $\sigma_{\text{t,dry}}$ (MN m^{-2})	1.3 \pm 0.4	71 \pm 0.7
softening factor, $\sigma_{\text{t,soft}}$	1.0	10.8
cohesion		
effective, c' (MN m^{-2})	0.06 \pm 0.01	9.0 \pm 0.5
total, c (MN m^{-2})	0.14 \pm 0.06	13 \pm 2
softening factor, c/c'	1.2	8.4
angle of internal friction		
effective, ϕ' ($^{\circ}$)	31 \pm 4	38 \pm 4
total, ϕ ($^{\circ}$)	27 \pm 5	35 \pm 2
slake durability index		
second-cycle, $I_{\text{d}2}$ (%)	30	99

* Note that reliable tensile strengths could not be obtained for the weakest specimens.

materials, with softening factors of 3 to 5 being common.

(4) Although weak, the strength of ignimbrites is highly variable. Indeed, the materials are characterised by very rapid vertical variations in strength, which can lead to two orders of magnitude change in the measured strengths within one vertical section.

(5) Considerable deformation prior to reaching the peak strength is typical. Fracture surfaces show evidence of crack initiation at inhomogeneities in the rock (crystals and pumice clasts), and propagation through the groundmass between these inhomogeneities.

3.2 Jointing

The primary jointing features in ignimbrites are tension fractures formed during cooling and compaction of the mass. However, classical columnar jointing, such as seen in basalts and other lavas, is surprisingly rare in New Zealand ignimbrites.

Typical columnar jointing in ignimbrites is comprised of very wide, somewhat curved, irregular columns. The margins of these columns are generally marked by narrow zones of joints, rather

than a single, discrete joint plane. Many ignimbrites have horizontal joints superimposed on the columnar jointing pattern; occasionally these are sufficiently well developed that they split the material into a blocky structure.

The other common situation is for the jointing to be so widely spaced that the materials are best treated as non-jointed for practical purposes, although some, approximately vertical joints may exist. In general these joints occur in groups separating truly non-jointed zones of up to 15 m width. Unlike the columnar joints, individual joints in this material are tightly closed.

Finally, many ignimbrites show a more complex jointing pattern. Dominantly vertical jointing exists, but the joints are curved along both horizontal and vertical axes and are more closely spaced than their columnar counterparts. They thus form complex joint blocks, often developing a tabular form, with large, vertical plates running parallel to eroded cliff faces. This complex jointing pattern is believed to represent cooling towards a complex cooling surface following emplacement in a deep, narrow valley.

4 GEOTECHNICAL CLASSIFICATION

Possibly the most significant geotechnical property of ignimbrites on which to base a classification of the materials is the slake durability index. The marked dichotomy in response to a weak slaking process allows a ready subdivision of the materials into two principal groups: non-durable ignimbrites ($I_{\text{d}2} \leq 30\%$), and durable ignimbrites ($I_{\text{d}2} \geq 90\%$). Based on the data described above, the ranges of geotechnical properties associated with these groups are given in Table 2; for most properties the ignimbrites fall into two distinct groups, with no overlap between the ranges given for the two groups.

Although an apparently arbitrary distinction, this classification provides a ready differentiation between ignimbrites which respond to stress in a way generally associated with "normal" rocks (durable ignimbrites), and those non-durable ignimbrites which behave as "soft rocks" - materials which exhibit many properties transitional between engineering rocks and soils (Johnston, 1993). For engineering and slope stability purposes recognising this distinction is critical for the prediction of material behaviour.

4.1 Non-durable ignimbrites

Non-durable ignimbrites are those which break down under a weak slaking process. They are typically low density, highly porous ignimbrites, are very weak in compression, and undergo considerable plastic deformation prior to failure. Softening factors are not strictly related to the durability classification as they tend to vary between individual ignimbrites, but in general the non-durable ignimbrites also undergo the most softening on

Table 2: Geotechnical classification of ignimbrites based on second-cycle slake durability index. Ignimbrites falling into the non-durable category behave as soft rocks where the intact rock properties are an important control on engineering behaviour; in highly durable ignimbrites the rock mass properties of prime importance (from Moon, 1993b).

	non-durable ignimbrites	highly-durable ignimbrites
slake durability		
I_{d2}	$\leq 30 \%$	$\geq 90 \%$
density and porosity		
ρ_{dry}	$\leq 1300 \text{ kg m}^{-3}$	$\geq 1500 \text{ kg m}^{-3}$
ρ_{sat}	$\leq 1700 \text{ kg m}^{-3}$	$\geq 1800 \text{ kg m}^{-3}$
η_{eff}	$\geq 40 \%$	$\leq 35 \%$
η_{true}	$\geq 50 \%$	$\leq 40 \%$
compressive strength		
$\sigma_{c,dry}$	$\leq 5 \text{ MN m}^{-2}$	$\geq 15 \text{ MN m}^{-2}$
$\sigma_{c,sat}$	$\leq 2.5 \text{ MN m}^{-2}$	$\geq 10 \text{ MN m}^{-2}$
$\sigma_{c,soft}$	> 3	≤ 3
tensile strength		
$\sigma_{t,dry}$		$\geq 3 \text{ MN m}^{-2}$
$\sigma_{t,sat}$		$\geq 1 \text{ MN m}^{-2}$
$\sigma_{t,soft}$		≤ 2
shear strength		
c	$\leq 1 \text{ MN m}^{-2}$	$\geq 6 \text{ MN m}^{-2}$
c'	$\leq 0.1 \text{ MN m}^{-2}$	$\geq 2 \text{ MN m}^{-2}$
c_{soft}	$\geq 2 \text{ MN m}^{-2}$	$\leq 3 \text{ MN m}^{-2}$
ϕ, ϕ'	$27 - 38^\circ$	$27 - 38^\circ$
jointing	non-jointed (spacing $\geq 10 \text{ m}$)	very to extremely wide columnar with blocky or complex variants
engineering problems	sensitive materials, piping and gully erosion	high cleft water pressures in jointed rock mass

saturation.

In the field these ignimbrites are non-jointed, as thermal stresses during cooling are released by plastic deformation rather than brittle failure, so joint development is minimal. Intact rock characteristics are thus an important control on slope stability and engineering behaviour, and the materials typically behave as very stiff soils which derive the bulk of their strength from frictional effects between groundmass glass shards.

The relatively high cohesion and the very high angles of internal friction means that these materials can maintain steep slopes for long periods of time (almost vertical artificial cuttings of greater than 40 years age still maintain their initial form). Slope stability analysis (using Culmann wedge and infinite slope analyses) suggests that steep, stable slopes of $\geq 10 \text{ m}$ can readily be supported in these non-durable ignimbrites. Indeed, natural slopes in these materials are steep, and maintain a steep profile as they erode, though gully erosion may be a problem (Yamanouchi *et al.*, 1981).

Conversely however, past engineering experience on similar materials suggests that these non-durable ignimbrites may be susceptible to loss of strength caused by structural changes or elevated pore water

pressures, resulting in sensitive and dispersive behaviour. The failure of the Ruahihi headrace canal was contributed to by seepage of canal water into non-durable ignimbrite, which resulted in piping of this material, elevated pore water pressures in the non-durable ignimbrite and adjacent artificial fill, and eventual rapid breakdown of the ignimbrite structure with associated loss of strength; these characteristics of the material led to major slope failure (Anon., 1982). Likewise, piping in non-durable ignimbrites is seen as an important problem in these materials for engineering purposes in Japan, especially where they overlie jointed, durable ignimbrites (Okamoto *et al.*, 1981), and piping of non-durable ignimbrites and associated pyroclastic fall deposits lying above a jointed, durable ignimbrite, assisted in the development of major leakage into the foundation rocks of the Wheao Power scheme (Anon., 1983).

4.2 Durable ignimbrites

At the other extreme are ignimbrites which are highly resistant to slaking. These ignimbrites have high bulk densities, low porosities, and high strength. They exhibit some elasticity under an applied load, and most closely approach a brittle

failure. Softening factors for strength tend, in general, to be lower than those for the non-durable ignimbrites. The high strength and brittle nature of these materials mean that they develop extensive systems of open, continuous joints during cooling. Their engineering behaviour is thus dominated by the jointing, giving them properties most akin to "normal" rocks in an engineering sense, and making rock mass characteristics of prime importance in terms of slope stability and engineering behaviour.

The most common jointing pattern is the very widely spaced, vertical columnar jointing described previously, though blocky and complex variants may also exist. Overall, the most important aspect of the jointing is the tendency for approximately vertical joint planes to predominate. As a result, in these durable ignimbrites, precipitous faces and narrow gorges represent the normal slope patterns as the materials erode by failure of jointed blocks; dominantly vertical jointing thus results in steep faces. The very wide joint spacing typical of the columnar jointing zone, in particular, produces large blocks which are insensitive to breakdown by the action of water (high slake durability), and these may accumulate as coarse talus at the base of the slopes.

Engineering applications of these materials must recognise the open, continuous nature of the jointing, together with the deformable nature of both the intact rock and the rock mass. Considerable deformation of the country around the Maraetai Dam, for example, was noted by James (1955) following the installation of a grout curtain; this was attributed primarily to closure of the joint apertures (James, 1955). The Arapuni Dam suffered a near toppling failure of a large joint block, upon which the powerhouse was founded, following an increase in cleft water pressure along an open joint plane (Hornell and Werner, 1930; Marshall, 1930), and more recently, the collapse of the headrace canal of the Wheao power scheme occurred after water was allowed to leak into a jointed rock mass (Anon., 1983). Likewise, seepage due to high permeabilities in jointed, durable ignimbrites is quoted as an important problem in these materials for engineering purposes in Japan (Okamoto *et al.*, 1981; Iida *et al.*, 1981).

4.3 Ignimbrites with intermediate characteristics

A few ignimbrites cannot be readily classified as durable or non-durable materials on the basis of the classification given here. This may either be due to their properties being intermediate to the ranges given, or because they have some properties appropriate for each range and hence do not clearly fall into either category. The ignimbrites that cannot be readily classified appear to have undergone some unusual post-depositional alteration processes, such as case-hardening or zeolitization, which have changed their mechanical behaviour.

Consequently, special consideration must be given to ignimbrites which do not readily fall into one of the two main categories. In particular, one or two critical properties, especially the slake durability, may

allow the field expression and slope development of the materials to indicate a highly durable ignimbrite, but if subjected to a change in the stress or groundwater conditions the materials may well behave as non-durable ignimbrites with very low strength. Localised hardening must also be considered when anomalously high durability and strength measurements are obtained.

5 PREDICTION OF IGNIMBRITE BEHAVIOUR

As the original basis for the classification, the second-cycle slake durability provides an excellent index property which allows classification of ignimbrite materials. This test can be readily undertaken with minimal material and very simple laboratory equipment, and in almost all cases it gives a good indication of whether the materials behave as stiff engineering soils which may show sensitive and dispersive behaviour, or whether they can be treated as weak, jointed rocks in an engineering sense. Borehole specimens or material from areas of limited exposure are easily tested for slake durability.

For the few specimens recognised where the slake durability did not readily indicate the overall poor engineering response of the materials, the porosity did indicate that the ignimbrites fell into the non-durable category. Hence, the effective porosity in conjunction with the slake durability provides a reliable means of classifying the materials. This test (from saturation methods described by Brown, 1981) can also be simply carried out using a minimal quantity of material and with little specimen preparation.

6 CONCLUSIONS

Ignimbrites are characteristically weak rocks under all forms of stress, but the strengths vary over a wide range due to the genesis of the materials. This range extends across the boundaries traditionally associated with engineering soils and rocks, thus many ignimbrites fall into the category of soft rocks - materials which show properties transitional between those of soils and rocks.

Second-cycle slake durability index data show a remarkable dichotomy, with some ignimbrites remaining almost completely intact, whilst others undergo almost total breakdown. This provides a ready means of classifying the geotechnical properties of ignimbrites into durable and non-durable ignimbrites. This classification provides a clear distinction between ignimbrites which respond to stress as "normal" rocks (durable ignimbrites) and for which the jointing, or mass characteristics, provide the principal control over engineering behaviour, and "soft" rocks (non-durable ignimbrites), for which the intact rock characteristics are of the greatest concern. Recognition of this distinction is critical for any

engineering application.

Durable ignimbrites characteristically have systems of open, continuous, vertical joints. Access of groundwater into the rock mass is thus an important engineering consideration, as the materials may develop high cleft water pressures; historical failures of structures founded in these ignimbrites have been largely attributable to this mechanism. Non-durable ignimbrites are subject to rapid breakdown of the structure when subjected to changes in the moisture regime or to weak applied loads. These ignimbrites may thus behave sensitively and are susceptible to gully erosion on exposed slopes or piping within the rock material, leading to major failures if uncontrolled.

The slake durability index provides the best indicator of the overall material behaviour for ignimbrites. However, some materials which have undergone case-hardening or other localised induration processes will give spurious results, so the effective porosity should be used in conjunction with the slake durability to classify the materials. These two tests can both be undertaken with a minimum quantity of specimen, and with simple laboratory apparatus.

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