

THE EFFECTS OF HYDROTHERMAL ALTERATION ON MECHANICAL ROCK PROPERTIES OF THE ANDESITE BRECCIA AND TAHORAKURI FORMATION FROM THE NGATAMARIKI GEOTHERMAL FIELD, NEW ZEALAND AND EMPIRICAL RELATIONS BETWEEN ROCK STRENGTH AND PHYSICAL PROPERTIES

Latasha Wyering¹, Marlene Villeneuve¹ and Irene Wallis²

¹Department of Geological Sciences, University of Canterbury, P O Box 4800, Christchurch 8140, New Zealand

² Mighty River Power, 283 Vaughan Road, P O Box 245, Rotorua 3040, New Zealand

latasha.wyering@pg.canterbury.ac.nz

Keywords: *Mechanical, physical, rock properties, petrological, point load, uniaxial compressive, hydrothermal alteration, empirical relationships.*

ABSTRACT

This paper describes the adopted testing methodology and preliminary results of a study assessing the relationship between hydrothermal alteration and the physical and mechanical rock properties of two key units (Andesite Breccia and Tahorakuri Formation) from the Ngatamariki geothermal field. These results are valuable for geotechnical mechanical characterisation of hydrothermally altered rocks from geothermal reservoirs, and are relevant to drilling optimization, wellbore stability studies and geomechanical modeling.

The Ngatamariki geothermal field is located approximately 25 km northeast of Lake Taupo. Ngatamariki at present has had seven wells drilled, four in the 1980's and three since 2005. Drilling of development wells is currently underway. Core samples collected from these units were tested in-situ and in the laboratory, and the physical rock properties were compared to the alteration assemblage to assess the relationship.

To characterise physical and mechanical rock properties of the Andesite Breccia and Tahorakuri Formation, plugs from intact core were prepared for non-destructive and destructive laboratory experiments. In addition to strength testing parameters, the physical rock properties analysed included porosity, density, P and S wave velocities. The hydrothermal alteration assemblage of the Andesite Breccia and Tahorakuri Formation was characterised using petrography and existing geological reports.

We compared existing empirical relationships established primarily by the petrochemical industry to convert physical properties measured by wireline geophysics to mechanical rock strength. The results show neither of the empirical equations applied here matched the measured UCS.

Once the relationship between hydrothermal alteration and rock strength has been established for a number of formations, we will assess drilling performance data so as to investigate the relationship between drilling performance and rock properties in a hydrothermally altered environment. The improved understanding of rock mechanics in a geothermal environment will support the construction of geomechanical models in improve understanding of structural permeability in geothermal reservoirs.

1. INTRODUCTION

Tools that predict rock properties are essential for reservoir development, management and prospect evaluation during exploration because there is commonly very sparse or no borehole-based rock property data (Ameen et al., 2009; Tamrakar et al., 2007). Rock properties can be defined in two categories, physical (porosity, density, P & S wave velocity) or mechanical (uniaxial compressive strength, point load index, triaxial etc...) – with point load strength index and uniaxial compressive strength being two of the most commonly applied (Karpuz & Pasamehmetoglu, 1997). Many researchers and industry practitioners have sought a quick and easy way to estimate the physical and mechanical properties of different lithologies using empirical relationships (Yagiz, 2008; Entwistle et al., 2005; Koncagu & Santi, 1999; Sharma & Singh, 2007; Lutz et al., 2010). Cobanoglu & Celik (2008) estimated uniaxial compressive strength (UCS) from point load strength index, Schmidt hammer index, and P-wave velocity in sandstone, limestone and cement mortar. They found that an empirical relationship only occurred between the point load index and Schmidt hammer for UCS in their researched lithologies. Dincer et al. (2004) found a positive correlation between UCS, Schmidt hammer index and the Young's modulus of an andesite and basalt. The downfall of these empirical relationships is that they are only applicable to the particular lithologies being studied, and do not necessarily correlate for all rock types.

The influence of secondary mineralization on the strength and durability of rock is of particular interest to the geothermal industry because few rocks in this kind of reservoir are fresh. Various petrographic and weathering indices have been proposed (Tugrul & Zarif, 1999). Studies identifying the impact of petrological characteristics have found that mineralogical and textural characteristics influence the mechanical and physical properties of rocks (Rigopoulos et al., 2010; Tugrul & Zarif 1999). Rigopoulos et al. (2010) found that alteration products generally result in mechanically weaker rock. However, the results also indicate that the dolerites used in this study retain their strength and durability due to the low proportions of soft minerals and microcracks, along with the preservation of their igneous textures. Thin section microscopy has been used to measure indices that are strongly influencing the strength of sandstone. These indices included percentage of voids, strong over weak contacts and packing density (Tamrakar et al. 2007). While investigating the influence of the textural characteristics on the engineering properties of granites, Tugrul & Zarif (1999) found that textural characteristics in the granite influenced rock strength more than mineralogy. In the Desert Peak geothermal field,

Nevada, observations of rock strength while undertaking a well stimulation study found that siliceous lithologies had higher rock strengths than argillaceous lithologies. The argillaceous lithologies had initial higher porosities, but the siliceous lithology was expected to produce a higher permeability after stimulation due to its brittle nature (Lutz et al. 2010). Finally, a study of four hundred carbonate plug samples from a gas reservoir field in Ghawar, Saudi Arabia, showed that rock mechanical parameters are primarily a function of porosity and, to a lesser degree, mineralogy texture and pore fabric (Ameen et al., 2009).

Many of the aforementioned papers have developed an empirical relationship of some description between physical and mineralogical properties. However, the relationships developed using sandstones, dolerites, etc. cannot be applied ubiquitously to all lithologies. Furthermore, many previous studies have demonstrated that a variation in the mineral and textural nature of rock significantly influences the rock strength. It follows that in a geothermal context, where rock lithologies often contain secondary mineralization, empirical relationships cannot be developed.

The Ngatamariki geothermal field is situated approximately 25 km northeast of Lake Taupo (Figure 1) and is one of many high temperature fields located in the Taupo Volcanic Zone (TVZ; Boseley et al., 2010; Clearwater et al., 2012). Drilling is currently underway there for an 82 MW Ormat Binary plant due to be commissioned in 2013. Physical and mechanical rock property laboratory tests were conducted on selected core samples collected from six wells: NM1 through NM5, and NM7. Our analysis evaluated two lithological units, the Ngatamariki Andesite Breccia (NM 7) and Tahorakuri Formation (NM 1-5) stratigraphically located at depths of 2179 – 2184 mD and 1224 – 1350 mD respectively (Figure 2). Physical and mechanical rock properties are generally fundamental information for drilling engineering purposes and geomechanical modeling. Petrological analysis accompanied the laboratory work to describe the thin sections cut from the samples drilled from NM 1-5 and 7.

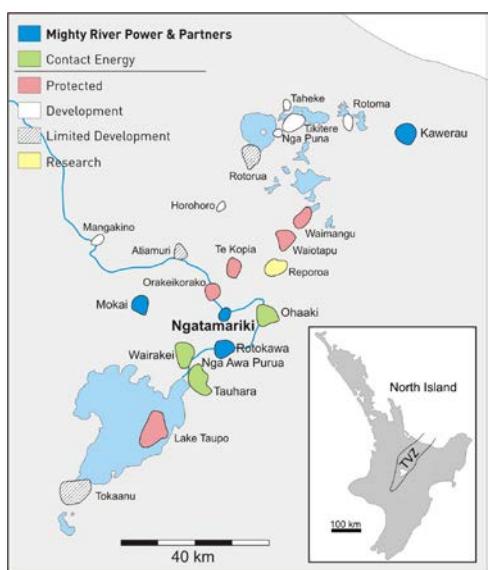


Figure 1: Map showing the location of Ngatamariki and other high temperature geothermal fields in the Taupo Volcanic Zone.

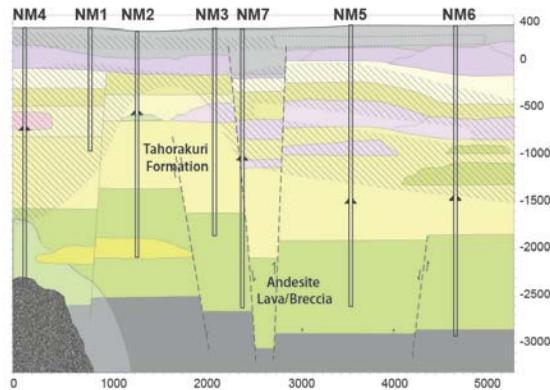


Figure 2: Geologic cross-section of the Ngatamariki geothermal field with wells and the smectite clay alteration zone (hatched area). Formations of note for this study are the Tahorakuri Formation (yellow) and Andesite Lava/Breccia (green). Figure adapted from Boseley et al. (2010).

2. METHODOLOGY

A number of laboratory analyses have been undertaken on the core samples including measuring compressional (P) and shear (S) wave velocities, porosity, density, rock strength and describing the petrographic nature of the rock. Repeat measurements with slightly varied processes were conducted in a number of cases to determine the impact of these processes on the final result.

2.1 Compressional and Shear Wave Velocities

The velocity of ultrasonic pulses travelling through a solid material depends on the density and elastic properties of the material (Sharma & Singh, 2007). These in turn depend on the rock mass properties (e.g., density, porosity, material strength), which are in turn influenced by weathering and alteration zones (Kahraman, 2007). Empirically derived equations, such as the Gardner Equation (Gardner, 1974), have been used in the petrochemical industry to convert sonic velocities collected by wireline geophysics to porosity. These equations were developed using experimental determination of porosity and sonic velocity on the same samples and describing the relationships. We have been unable to locate published exponents for the Gardner Equation specifically for silicic volcanics. Furthermore, there appears to be no other equations developed specifically for the lithologies we are assessing here (see Chang et al. 2006 review) and it is unlikely that any take into account secondary mineralization.

Unconfined sonic velocity measurements were conducted on all the Tahorakuri Formation and Andesite Breccia plugs. We did the tests in three different states (air-dried, oven-dried and saturated) to assess the effect water content has on the results. Good acoustic coupling between the platens and the rock surface is necessary to ensure accuracy of transit time measurement, so petroleum jelly was used as a coupling agent in this study. The plates were pressed to either end of the rock sample using a uniaxial loading frame with an average force of 5-10 kN. This further ensured a good connection between the plates and rock surface.

First, the samples were air-dried at room temperature in the atmosphere over a period of 24-48 hours. After weighing the samples, ultrasonic testing was completed. The sample

was set up with the platens in a uniaxial loading frame, and the height (mm), diameter (mm), mass (g) and density (g/mm^3) were input into the software C.A.T.S. The P wave was sent through the rock sample and the first arrival was manually picked and P wave velocity calculated (m/s). The testing was then repeated in S wave mode. The selected P and S wave velocities were used to derive the dynamic Poisson's ratio, Young's, Bulk and Shear moduli for each sample. This test process was then repeated for the samples after (1) oven drying at 105°C for 24 hours and (2) saturation in a vacuum chamber with deionised water for 24 hours. Every test was repeated 3-5 times in each saturation state to produce a range of average P and S wave velocities.

2.2 Porosity and Density

Porosity and density testing was determined using the saturation and caliper techniques (IRSM, 1974-2006). This method dry and saturated weight of the samples and involves measuring the length and diameter of the cores to determine the bulk volume (V), such that:

$$V (\text{m}^3) = \left(\frac{\text{Diameter (m)}}{2} \right)^2 \times \pi \times \text{length (m)}$$

The samples were oven dried for 24 hours and weighed before being saturated in a vacuum tank filled with deionised water for a period of 24 hours with the weight measured and recorded to determine the M_{sat} . From this data the pore volume (V_p) was calculated, such that:

$$V_p (\text{m}^3) = \frac{\left(\frac{M_{\text{sat}} - M_s}{\text{Water density}} \right)}{1000}$$

The bulk volume and pore volume were then used to calculate the porosity (n) of the sample using:

$$n (\%) = \left(\frac{100V_p}{V} \right)$$

The dry and saturated densities of the samples were also calculated from the recorded M_s and M_{sat} :

$$\text{Dry Density} \left(\frac{\text{kg}}{\text{m}^3} \right) = \frac{\left(\frac{M_s}{1000} \right)}{V}$$

$$\text{Saturated Density} \left(\frac{\text{kg}}{\text{m}^3} \right) = \frac{\left(\frac{M_{\text{sat}}}{1000} \right)}{V}$$

2.3 Strength testing

Due to time constraints, we have only conducted strength testing on the Andesite Breccia for this study. Future work includes extending this data set.

2.3.1 Point load strength

Point load strength index was conducted using the IRSM (1974-2006) standard on eleven Andesite Breccia samples. The test procedure involved the diametral test and irregular lump tests. The samples were inserted in the test machine and platens closed. The failure load was recorded. The tests were then classed as valid or invalid based on the failure mechanism that occurred.

2.3.2 Uniaxial compressive strength and Triaxial

Five uniaxial compressive strength tests were conducted using the ASTM (2010) standard. The samples used had a length/diameter ratio of 2.0-2.2. Electrical

resistance strain gauges measured sample deformation; one in the axial direction and another in the lateral direction.

2.4 Petrological analysis

The Andesite Breccia and Tahorakuri Formation have experienced hydrothermal alteration and, as mentioned above, secondary mineralization has a significant impact on rock strength.

We have, therefore, described the petrography of the Tahorakuri Formation and Andesite Breccia using our own thin section examination and existing geological reports (Rae et al., 2009; Chambefort & Bignall; 2011). Petrographic analysis included microcracks, veins and original textures. Mineral occurrence was classified as abundant when the sample was comprised of >50% of that mineral species, common when <50-20%, minor when <20-5%) and finally rare occurrence is <5% (following Chambefort & Bignall, 2011). We then ranked the minerals by decreasing order of abundance from i.e. 1, 2, 3.

We have developed a preliminary method to produce an alteration strength index (I_d), to facilitate comparison between observed alteration mineralogy and rock properties:

$$I_d = \left(\frac{S_m S_{nf}}{S_{ai}} \right) + 50$$

S_m is a representative value based on the hardness of the minerals and the relative proportion of these minerals contained in each sample. S_{nf} is a number between zero and one assigned to each sample which represents the presence of microfractures observed in the thin section and/or natural planes of weakness within the bulk rock. S_{ai} is a quantitative term used to express the overall degree of alteration within the sample. S_m was multiplied by S_{nf} so that a rock with more natural weaknesses receives a lower strength index value. The result was then divided by S_{ai} so that rocks which contain a greater proportion of unaltered material have a higher index value.

3. LABORATORY RESULTS

3.1 PETROLOGICAL DESCRIPTION

Andesite Breccia

NM 7 2180 – 2182 mD: The Andesite Breccia core recovered from NM 7 is an intensely altered pale green to dark green clast supported breccia. The breccia contains clasts of greywacke, granite, andesitic lava, rhyolite lava and siltstone. The matrix is altered to epidote, chlorite, quartz, illite, calcite, pyrite and titanium oxide (Chambefort & Bignall, 2011). The main alteration assemblage of the rock consists of epidote, chlorite and quartz, with minor calcite, pyrite, albite, adularia, and titanium oxide. The breccia contains small veins and veinlets (<1-2 mm) with calcite, epidote, and quartz fills (Figure 3).

Tahorakuri Formation

NM 1 1305.5 mD: Tahorakuri Formation core removed from NM1 is a strongly altered light greenish grey-white ignimbrite, with softer matrix in parts. The ignimbrite is crystal rich (plagioclase, ferromagnesian and quartz) and has been altered to predominately illite and fine-grained quartz with pyrite in the matrix (Chambefort & Bignall, 2011). Pyrite is common and dispersed throughout the core.

The crystals have been altered to quartz, calcite, albite and pyrite. Veins run through the core and mainly contain fills of quartz, pyrite and some rare smaller calcite (Figure 4).

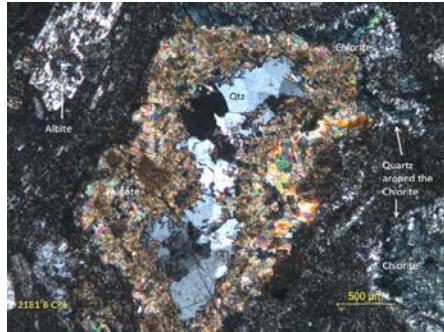


Figure 3: Photomicrographs using cross-polarized light of NM7.

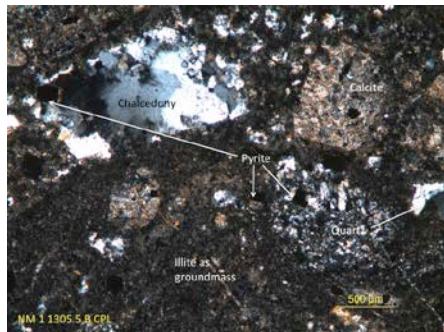


Figure 4: Photomicrographs using cross-polarized light of NM1.

NM2 1350 mD: The Tahorakuri Formation core recovered from NM2 is a strongly altered greyish grey-white ignimbrite with hints of green (likely chlorite alteration). The alteration assemblage includes abundant clay alteration with some rare chlorite (Chambefort & Bignall, 2011). The ignimbrite is crystal poor, with plagioclase as a primary mineral. The plagioclase has been altered to albite and adularia with patches of wairakite surrounded by clinozoisite, pyrite and titanium oxide. The sample has small discontinuous calcite and clay veinlets. This unit is similar to NM 1 (Figure 5).



Figure 5: Photomicrographs using cross-polarized light of NM2.

NM3 1350 mD: Tahorakuri Formation from NM 3 is an intensely altered light grey ignimbrite (?) with sections of soft matrix. Primary minerals that were identified were feldspar and rare ferromagnesian. The ignimbrite is nearly completely altered to clay, quartz, pyrite, titanium oxide and

rare albite. Quartz occurs as a fine-grained matrix or in veins with pyrite. Other veinlets fills include clay or pure quartz. There were many cross cutting veins/veinlets (Figure 6).

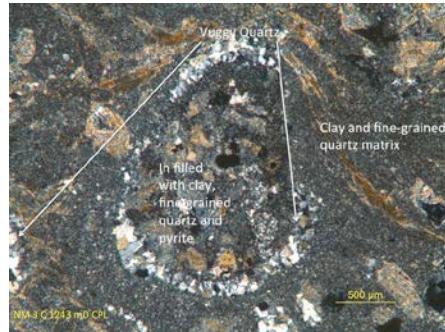


Figure 6: Photomicrographs using cross-polarized light of NM 3.

NM4 1243 mD: Volcanic Breccia recovered from NM4, originally believed to part of the Tahorakuri Formation is an intensely altered, light grey breccia with abundant cream-whiteish clay. Rare primary quartz crystals were present (Chambefort & Bignall, 2011). Alteration assemblage comprises illite and quartz. Quartz – pyrite veinlets (<2 mm) were common throughout the core sample (Figure 7).

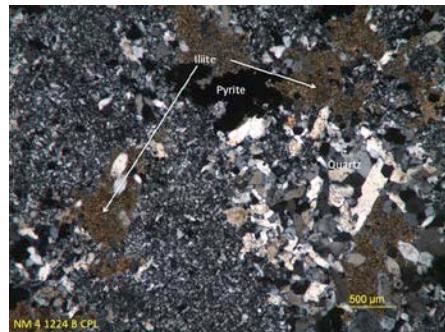


Figure 7: Photomicrographs using cross-polarized light of NM 4.

NM 5 1775-1776 mD: Tahorakuri Formation Ignimbrite. Strongly altered with greenish grey-white colour. Primary minerals include plagioclase, ferromagnesian and quartz. Albite, calcite, adularia, chlorite, illite, pyrite and rare titanium oxide secondary minerals have replaced the primary minerals. Veinlets in the core consist of calcite and rare (<0.2-0.3 mm) illite (Figure 8).

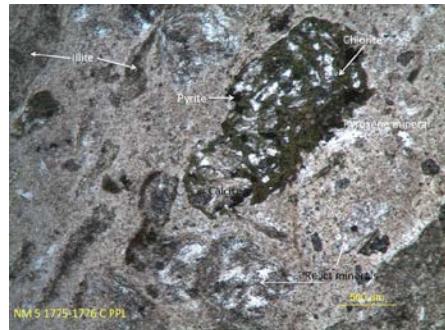


Figure 8: Photomicrographs using polarized light of NM 5.

3.2 POROSITY AND DENSITY

The porosity and density of the Andesite Breccia has a small variation with the porosity value ranging from 1.48 – 2.27%. The dry density ranged from 2616 - 2701 kg/m³ between the samples, while the saturated density ranged from 2633 – 2717 kg/m³. The Tahorakuri Formation had a greater variation in the results with the porosity ranging from 4.7 – 20.28%. The dry density ranged from 2084 – 2479 kg/m³ and the saturated density ranged from 2282 – 2557 kg/m³. Figure 9 demonstrates the porosity and density for the samples with the Tahorakuri Formation having a greater difference in porosity between wells while the Andesite Breccia is less diverse.

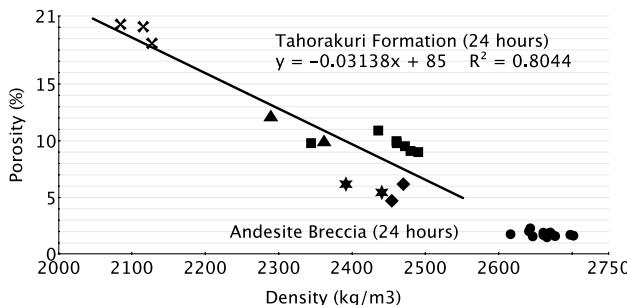


Figure 9: Porosity vs. density plot for the Andesite Breccia and Tahorakuri Formation. Tahorakuri Formation, NM 1 = Diamonds, NM2 = Cross, NM 3 = Squares, NM 4 = Stars and NM 5 = Triangles.

3.3 COMPRESSIVE AND SHEAR WAVE VELOCITIES

As expected, P and S wave velocities measured for the Andesite Breccia and Tahorakuri Formation varied between the states of saturation. Andesite Breccia was quite homogenous, while the Tahorakuri Formation varied between the different wells the samples originated from (Table 1). Figure 10 demonstrates that the V_P increases with saturation while the V_S waves remained the same in the Tahorakuri Formation while the V_P and V_S waves were both influenced by the saturation state in the Andesite Breccia. We recommend that future sonic velocity experiments are undertaken with saturated samples, as these are most likely to reflect reservoir conditions.

Table 1: Variation in the V_P and V_S wave data for the two lithologies in the different states of saturation.

Saturation state	Andesite Breccia		Tahorakuri Formation	
	V _P (m/s)	V _S (m/s)	V _P (m/s)	V _S (m/s)
AD	4104- 4454	2423- 2631	3155- 4625	1578- 2407
OD	4101- 4466	2347- 2686	3192- 4593	1644- 2229
S	4494- 4871	2523- 2743	3439- 4700	1651- 2297

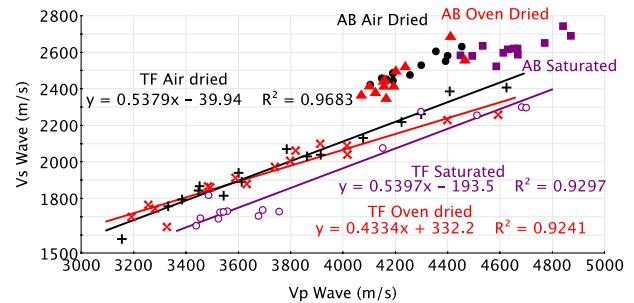


Figure 10: V_P vs. V_S wave for the Andesite Breccia (squares, circles, triangles) and the Tahorakuri Formation (stars, cross, hollow).

Measured velocities are less varied for the low porosity Andesite Breccia than for the higher porosity Tahorakuri Formation because the influence of air or water in the pore spaces is less significant when there are fewer of them. Saturated samples have higher velocities than dry samples because waves travel through air slower than they do through water. P and S wave velocity wireline logs recently run in Ngatamariki (c.f., Wallis et al. this volume) measured P and S wave velocities in ignimbrite from the Tahorakuri Formation are 2950-4875 m/s and 1500-2850 m/s respectively. The results of our laboratory velocity measurements on Tahorakuri Formation fall within this range.

3.4 STRENGTH TESTING

Point load strength

The point load strength conducted on the Andesite Breccia ranged between 1.57 – 6.82 MPa (Table 2). Samples 2 and 4 had lower strength due to natural weakness planes that could be seen propagating through the sample and would have reduced the intact strength of the rock.

Table 2: Results of the point load testing on Andesite Breccia.

Sample Number	Peak Load (kN)	I _{s(50)} (MPa)
1	11.88	6.82
2	2.72	1.57
3	10.08	5.77
4	4.13	2.36
5	5.97	3.42
6	6.21	3.56
7	5.83	3.33
8	8.23	4.70
9	7.48	4.29
10	11.62	3.76
11	12.81	3.95

3.4.1 UNIAXIAL COMPRESSIVE STRENGTH

The uniaxial compressive strength (UCS) tests were conducted on five Andesite Breccia samples and results ranged from 37 to 188 MPa. NM 5-7 failed at a low peak load when compared to the other samples tested because of a large fracture (existing plane of weakness) propagating through the sample. The sample failed on this plane rather than forming a new fracture through the intact core. The four other samples failed initially in a spalling manner before fracturing right down the middle of the sample. NM 7-2 had the highest strength at 188 MPa and this sample failed by shattering into large pieces rather than forming a

single fracture. The measured UCS was compared to two empirical equations in Chang et al, 2006 that involve deriving the UCS from compressional wave velocities and density with the results displayed in Table 4.

Table 3: Results of the uniaxial compressive strength test for the Andesite Breccia.

Sample ID	Peak Load (kN)	Strength (MPa)
NM 7-2	232	188
NM 7-5	46	37
NM 7-7	139	174
NM 7-9	184	127
NM 7-10	156	113

Table 4: Measured UCS for the five Andesite Breccia samples and the UCS strengths derived from empirical equations.

Sample ID	Measured	Eq. 1	Eq. 2
NM7-2	188	112	57
NM7-5	37	124	71
NM7-7	113	114	60
NM7-9	174	112	58
NM7-10	127	115	60

4. COMPARISON BETWEEN THE ALTERATION STRENGTH INDEX AND MECHANICAL ROCK PROPERTIES

The results from the point load strength test and UCS were compared to the alteration strength index (I_d). Results of this comparison show a strong relationship with a R^2 value of 0.69 for the point load and 0.58 for UCS. NM 7-5 has been labeled in the UCS results as the failure is not representative of the intact rock strength. Figures 11 and 12 show that as the alteration strength index increased so too did the strength of the rock.

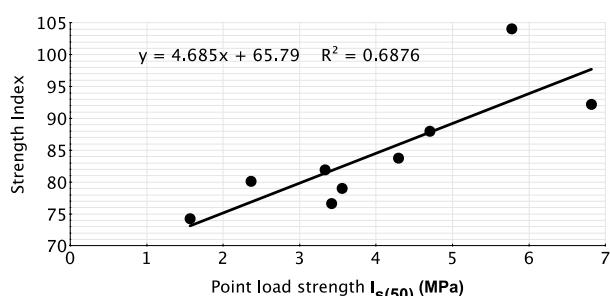


Figure 11: Andesite breccia alteration strength index versus point load strength.

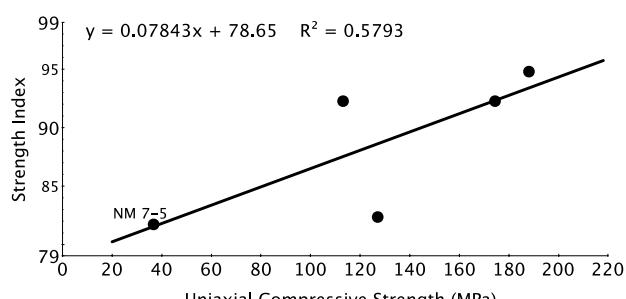


Figure 12: Andesite Breccia alteration strength index versus UCS. NM 7-5 is labeled to illustrate where it fits with the remaining data.

5. DISCUSSION

In this study we have quantified the physical properties and strength of the Andesite Breccia and Tahorakuri Formation from the Ngatamariki geothermal field. At this stage few correlations can be derived from the testing of the Andesite Breccia because all subsamples come from the same 1 m length of core. In contrast, results from the Tahorakuri Formation provides the opportunity to develop strong relationships because we have samples from a number of wells that capture some of the variation of this formation.

The porosity calculations completed in this study are effective porosity. Figure 10 illustrates the relationship between the sonic wave velocities showing that the saturated samples had a faster velocity than the dry samples. Wyllie et al. 1958 indicated that the velocity of fluid saturated rock was dependent on the ratio between the velocity of the rock and the velocity of the pore fluid. This is because the V_p wave travels faster in water (1,485 m/s) than air (300 m/s) which produces a faster arrival time for the compressional wave in the saturated samples. Figure 13 shows the relationship between V_p (dry and saturated) against porosity. The relationship shows that saturation impacted the compressional wave even though the porosity is as low as 1% or as high as 20%. Nur & Simmons (1969) found that a remarkable velocity change could occur even in compact rock having only a minute amount of porosity. This is because the compressional wave velocity in water or air is less than the compressional velocity in the mineral skeleton (Lama & Vutukuri, 1978).

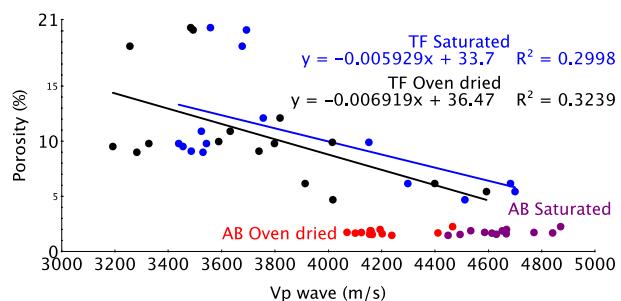


Figure 13: Relationship between V_p wave and Porosity for the Tahorakuri Formation (Blue = saturated, Black = Dry) and Andesite Breccia (Purple = saturated, red = dry).

Strength to porosity, density or petrography relationships for a specific rock formation are developed based on laboratory tests on rock core from a given field or lithology. However, when there are limited core samples, industry practitioners commonly apply empirical strength relations to geophysical wireline data. Chang et al. (2006) reviewed thirty-two empirical relationships for sedimentary rocks where physical rock properties were derived from geophysical wireline tools, such as sonic velocity, internal coefficient of friction, density or porosity to derive mechanical rock properties. We selected two equations from this review that utilize sonic velocity to demonstrate that empirical relationships derived for sedimentary environments, particularly ones without secondary mineralization, may not be applicable to volcanic terrains hosting geothermal systems.

Equation 1 (Freyburg, 1972: as cited in Chang et al., 2006):

$$0.035V_p - 31.5$$

Equation 2 (Moos et al., 1999: as cited in Chang et al., 2006):

$$1.745 \times 10^{-9} \rho V_p^2 - 21$$

Where, V_p is velocity of the compressional wave in (m/s) and ρ is the density in kg/m³.

We compared the UCS results for the Andesite Breccia to the calculated UCS using the above listed equations.

Figure 14 and table 4 shows that neither of the empirical equations applied here matched the measured UCS. In summary, the measured UCS was more variable than those derived from sonic velocities using equations 1 and 2. Equation 1, which was developed for sandstone of unspecified type, matched closer in most cases than equation 2 which was developed for coarse grained sandstones and conglomerates. In sample NM7-5 the measured UCS was significantly lower due to the test failure occurring along a pre-existing plane of weakness. There empirical relationships are developed for intact (i.e., un-fractured) rock. It follows that none of the relationships would have yielded a comparable result for this low strength.

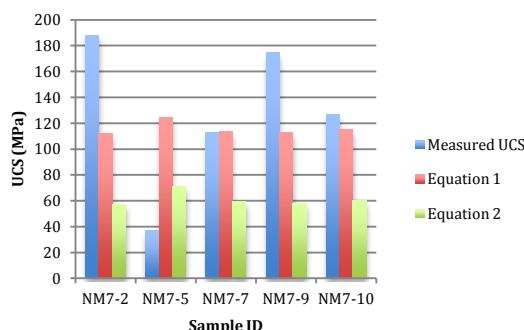


Figure 14: Measured UCS compared with the UCS derived from empirical relationships in equations 1 and 2.

The alteration strength index used to plot petrological analysis against mechanical rock properties showed a reasonable correlation with R^2 values higher than 0.55 for both point load and UCS results. Further work will be conducted on this equation to refine the factors used to determine the alteration strength index. The further work will include researching factors that impact the strength of samples.

We will also extend the data set presented here to more samples of the Andesite Breccia and Tahorakuri Formation, as well as other units from Ngatamariki. These results will then be compiled with wireline and drilling data collected during the current development to (1) develop empirical relationships that can be applied to wireline geophysics collected in volcanic terrains with secondary mineralization and (2) develop an understanding of rock properties that impact drilling performance.

6. CONCLUSIONS

Physical rock property testing, along with petrological analysis were undertaken on Andesite Breccia and Tahorakuri Formation from the Ngatamariki geothermal field. Rock strength testing (point load and UCS) were undertaken on the Andesite Breccia from NM7. The results were evaluated and the following conclusions obtained:

- The sample set available for the Tahorakuri Formation has a greater variety of physical properties than the Andesite Breccia because the former is sourced from five different wells across the field. This accounts for the variety of mineralogy and physical properties observed.
- This variety has allowed us to observe the variation in the density and porosity of the Tahorakuri Formation across the wells, in addition to range of compressional and shear waves velocities.
- Extension of the Andesite Breccia sample set is expected to yield the same result. Despite the limited sample distribution, one clear trend was observed for the Andesite Breccia. Even though it has a low porosity, saturating the sample still increases the velocity of the compressional waves.
- The presence of natural fractures decreases the strength of the sample. NM 7-5 failed along a fracture during testing instead of in the intact core resulting in a low measured UCS of only 37 MPa.
- We developed a simple index to quantify the impact of alteration on rock strength and found a general correlation ($R^2 > 0.58$) between this strength alteration index and measured rock strength. Further work will be undertaken to refine this index.
- Comparison between measured UCS for the Andesite Breccia samples against UCS derived from equations developed for sandstones and conglomerates based on empirical relationships did not show a strong correlation. This was not a surprising result and reinforced the importance of developing relationships that can be applied to geothermal systems hosted in volcanic terrains.

ACKNOWLEDGEMENTS

Mighty River Power and Tauhara North #2 Trust, thank you for your help, co-operation and support for this project. Also thank you to the technical staff at the University of Canterbury who have helped me to complete laboratory testing to the correct standards.

REFERENCES

ATSM International, D 7012-10 Standard Test Method for Compressive Strength and Elastic Moduli of Intact Rock Core Specimens under Varying States of Stress and Temperatures. *Annual book of ATSM standards*. Vol. 04-09. (2010)

Ameen, M., Smart, B.G.D, Somerville, J.Mc, Hammilton, S., Naji, N.A.: Predicting rock mechanical properties of carbonate from wireline logs (A case study: Arab-D reservoir, Ghawar field, Saudi Arabia). *Marine and Petroleum Geology*. pp. 430-444. (2009).

Boseley, C., Grant, M.A., Burnell, J., Ricketts, B.: Ngatamariki Project Update. *Proc. GRC Annual Meeting*. California, USA. pp. 24-27 (2010).

Boseley, C., Cumming, W., Urzua-Monsalve, L., Powell, T., Grant, M.: A resource conceptual model for the Ngatamariki Geothermal field Based on recent exploration well drilling and 3D MT resistivity imaging. *Proc. World Geothermal Congree 2010*. Bali, Indonesia. (2010).

Brotheridge, J.M.A., Browne, P.R.L., Hochstein, M.P.: The Ngatamariki Geothermal field, NZ: Surface manifestations – Past and Present. *Proc. 17th NZ Geothermal Workshop*. (1995).

Chambefort, I and Bignall, G.: Petrographic review of stratigraphic units of the Ngatamariki geothermal field. *GNS Science consultancy report*. (2011).

Chang, C., Zoback, M.D., Khaksar, A.: Empirical relations between rock strength and physical properties in sedimentary rock. *Petroleum science and Engineering*. pp. 223-237. (2006).

Clearwater, J., Burnell, J., Azwar, L.: Modelling the Ngatamariki Geothermal system. *Proc 37th workshop on geothermal reservoir engineering*. Stanford – California, USA. pp. 1-7. (2012).

Cobanoglu, I and Celik, S.B.: Estimation of uniaxial compressive strength from point load strength, Schmidt hardness and P-Wave velocity. *Bull. Eng. Geol. Environ.* pp. 491-498. (2008).

Dincer, I., Acar, A., Cobanoglu, I., Uras, Y.: Correlation between Schmidt hardness, uniaxial compressive strength and young's modulus for andesite, basalts and tuffs. *Bull. Eng. Geol. Environ.* pp. 141-148 (2004).

Entwistle, D., Hobbs, P., Jones, L., Gunn, D., Raines, M.G.: The relationship between effective porosity, uniaxial compressive strength and sonic velocity of intact Borrowdale volcanic group core samples from Sellafield. *Geotechnical and Geological Engineering*. pp. 793-809. (2005).

Freyberg, E., Der Untere und mittlere Buntsandstein SW-Thuringen in seinen gesteintechnischen Eigenschaften. *Ber. Dtsch. Ges. Geol. Wiss.*, A; Berlin 176, pp. 911-919 (1972)

Gardner, G.H.F., Gardner, L.W., Gregory, A.R.: Formation velocity and density – the diagnostic basics for stratigraphic traps. *Geophysics*. pp. 770-780. (1974).

ISRM, The complete ISRM suggested methods for rock characterization, testing and monitoring: 1974-2006. *Turkish National group*. pp 121-132. (2007).

Kahraman, S.: The correlations between the saturated and dry P-Wave velocity of rocks. *Ultrasonics*. pp.341-348. (2007).

Karpuz, C and Paamehmetoglu, A.: Field characterisation of weathered Ankara andesites. *Engineering Geology*. pp. 1-17. (1997).

Koncagul, E.C and Santi, P.M.: Predicting the unconfined compressive strength of the Breathitt shale using slake durability, shore hardness and rock structural properties. *Rock mechanics and mining sciences*. pp. 139-153. (1999).

Lama, R.D., Vutukuri, V.S.: Handbook on Mechanical Properties of rocks, Vol. 2. *Trans Tech Publications*. Clausthal, Germany. (1978).

Lutz, S.J., Hickman, S., Davatzes, N., Zemach, E., Drakos, P., Robertson-Tait, A.: Rock mechanical testing and petrological analysis in support of well stimulation activities at the desert peak geothermal field, Nevada. *Proc. 37th workshop on geothermal reservoir engineering*. Stanford-California, USA. pp. 1-11. (2010).

Moos, D., Zoback, M.D., Bailey, L.: Feasibility study of the stability of openhole materials, Cook Inlet, Alaska. *1999 SPE Min-Continent Operations Symposium*: Oklahoma City, Oklahoma, 21-31 March. SPE 52186. (1999)

Nur, A and Simmons, G.: The effects of saturation on velocity in low porosity rocks. *Earth planet. Sci. Lett.*

Rae, A.J., Ramirez, L.E., Boseley, C.: Geology of geothermal Well NM7, Ngatamariki Geothermal field. *GNS Science consultancy Report*. (2009).

Rigopoulos, I., Tsikouras, B., Pomonis, P., Hatzipanagiotou.: The influence of lateration on the engineering properties of dolerites: The examples from the Pindos and Vourinos ophiolites (northern Greece). *Rock mechanics and mining sciences*. pp.69-80. (2010).

Sharma, P.K and Singh, T.N.: A correlation between P-Wave velocity, slake durability index and uniaxial compressive strength. *Bull. Eng. Geol. Environ.* pp. 17-22. (2007).

Tamrakar, N., Yokota, S., Sherestha, S.: Relationship among mechanical, physical and petrological properties of siwalik sandstones, Central Nepal Sub-Himalayas. *Engineering geology*. pp. 105-123. (2007).

Tugrul, A and Zarif, I.H.: Correlation of mineralogical and textural characteristics with engineering properties of selected granitic rocks from Turkey. *Engineering geology*. pp. 303-317. (1999).

Wyllie, M.R.J., Gregory, A.R., Gardner, G.H.F.: An experimental investigation of factors affecting elastic wave velocities in porous media. *Geophysics*. pp.459-493. (1958).

Yagiz, A.: Predicting uniaxial compressive strength modulus of elasticity and index properties of rock using the Schmidt hammer. *Bull. Eng. Geol. Environ.* pp. 55-63. (2008).