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Geotechnical properties of liquefied pumiceous layers in lakes

Propriétés geotechniques de couches ponceuses liquéfiées dans des lacs

Jordanka Chaneva, Max O. Kluger, Vicki G. Moon & David J. Lowe
School of Science/Te Aka Mātuatua, University of Waikato, New Zealand, jc409@students.waikato.ac.nz

Rolando P. Orense
Department of Civil and Environmental Engineering, University of Auckland, New Zealand

ABSTRACT: Earthquake failures in volcanic-ash soils are relatively common, considering their physical nature and the fact that such deposits tend to occur in areas with high seismicity in which the volcanism, responsible for their emplacement, shares some tectonic-related origin. However, experimental and empirical data related to geotechnical properties and mechanical behavior of volcanic-ash soils are still quite limited compared to those for hard-grained soils. Moreover, the limited data largely focus on pumiceous sands, whereas pumiceous silts have not been significantly investigated to date. This study summarizes relevant geotechnical properties of volcanic-ash layers preserved in lake sediments in the Hamilton lowlands in North Island, New Zealand. These highly pumiceous layers are hypothesized to have liquefied within the past 20,000 years, based on paleo-liquefaction features observed in some of the lakes. The layers that are liquefaction susceptible were identified. Additionally, the pumiceous layers were characterized by means of specific gravity, fines content, and pumice content. Finally, the characteristic void ratios (i.e., e_{min}, e_{max}) of five samples were analyzed. Pumiceous silts exhibit higher characteristic void ratios than those for hard-grained soils.

RÉSUMÉ : Les glissements de terrains dans les sols de cendres volcaniques sont des phénomènes communs, étant donné leur nature et le fait que ces dépôts ont tendance à apparaitre dans des zones hautement sismiques, puisque le volcanisme à l'origine de leur formation repose sur les mêmes procédés tectoniques que ceux qui causent les tremblements de terre. A ce jour, les données expérimentales et empiriques liées aux propriétés géotechniques et leur comportement mécanique sont limitées par rapport à celles des sols à grains durs. De plus, les données disponibles sont spécifiques aux sables ponceux, tandis que les silts ponceux n'ont pas encore été étudiés. Cet article résume les propriétés géotechniques pour certaines couches de cendres volcaniques présentes dans les sédiments lacustres autour d'Hamilton (Nouvelle-Zélande). Ces couches ponceuses sont supposées avoir été liquéfiées par le passé, basé sur des observations caractéristiques de la paléo-liquéfaction observés à certains endroits. Leur caractérisation géotechnique est une étape cruciale pour estimer leur potentiel de liquéfaction et ainsi évaluer les anciens tremblements de terre qui ont pu engendrer ces formations. En outre, les propriétés géotechniques de ces limons ponceux vont contribuer à la base de données mondiale de résistance à la liquéfaction de ces sols.

KEYWORDS: geotechnical properties, pumice, liquefaction, lacustrine volcanic-ash deposits

1 INTRODUCTION

Earthquake failure (e.g., liquefaction, landslides) of volcanic-ash soils has been observed in the recent past, including in Japan, South and North America, and New Zealand (Ishihara et al., 1986; Pender et al., 1987; Bommer and Rodríguez, 2002; Orense et al., 2002; Uzuoka et al., 2005). Yet, experimental and empirical data related to relevant geotechnical properties and their mechanical behavior are still quite limited compared to those obtained on hard-grained quartzitic soils. Moreover, the limited data are largely focused on pumiceous sands (Hyodo et al., 1998; Wesley et al., 1999; Pender et al., 2006; Orense et al., 2012), whereas pumiceous silts have not been sufficiently investigated to date (Rolo et al., 2004). Existing studies often label these vesicular sands as 'problematic' because of their crushability, compression characteristics, liquefaction resistance, etc. These soil properties are highly dependent on the grain size and pumice content (Hyodo et al., 1998; Miura et al., 2003; Orense et al., 2012). Related research also shows that geotechnical properties (e.g., particle density) of these soils strongly depend on the laboratory method adopted, mainly because of their vesicularity (Wesley 2001, Pender et al., 2006). This means that, unlike quartzitic soils, where, e.g., the specific gravity is considered constant (Gs = 2.65–2.67) and independent of the method used, the determination of geotechnical properties of pumiceous soil mixtures is challenging. Their problematic nature makes these soils challenging in conventional engineering liquefaction studies. This is because both the laboratory and in-situ methods that are commonly used for liquefaction potential estimation can induce particle crushing, thus affecting the assessment (Orense et al., 2012; Asadi et al., 2018; Orense et al., 2020). It has been hypothesized that pumice content is the key property that needs to be evaluated prior to a relevant geotechnical study in areas with volcanic-ash soils (Orense, 2020; Stringer, 2019).

This study summarizes relevant geotechnical properties of numerous volcanic-ash samples. Volcanic ash is also referred to hereafter as tephra. The tephra samples were taken from layers of known age preserved in lake sediments in the Hamilton lowlands in North Island, New Zealand. Many of the layers are highly pumiceous and show paleo-liquefaction features in some lakes (Kluger et al., under review). Their characterization and liquefaction susceptibility assessment are crucial first steps in assessing their liquefaction potential from which the timing and occurrence of past earthquakes in the lowlands could be estimated. The geotechnical properties of the mainly pumiceous silts reported in this study will be a valuable addition to the existing pumice sand database. Specifically, it was aimed at answering the question of how geotechnical properties of silty pumiceous soil mixtures change with pumice content. In this directive, the dependence of specific gravity on the pumice content was explored. Additionally, the potential trend between the pumice content and the characteristic void ratios (e_{min}, e_{max}), was also discussed. These dependences contribute into guiding researchers and engineers to the most optimal solution for determining the pumice content in a soil mixture.

2 STUDY AREA

The Hamilton lowlands lie within the pre-Quaternary tectonically-formed Hamilton Basin. Volcanic-ash layers deposited from numerous eruptions from active rhyolitic (silica-rich) volcanic centres and andesitic volcanoes in central and western North Island are found in lakes in the lowlands (Figure 1) (Lowe, 1988). Around 30 lakes in total, each ~20,000 years old and underlain and impounded by volcanogenic alluvium (Green and Lowe, 1985), lie scattered amidst the faults in the lowlands. Designated as having a low to moderate seismic risk (Stirling et al., 2012), the Hamilton lowlands, until recently, also lacked any known active faults (Edbrooke, 2005; Langridge et al., 2016). The recently identified faults, as well as the evidence of past seismic activity from paleo-liquefaction studies, supported the hypothesis of potential liquefaction features found in the lacustrine volcanic-ash layers in the area (Kleyburg et al., 2015; Moon and Lange, 2017; Van Dissen et al., 2021).

This study focuses on volcanic-ash samples retrieved from seven lakes: Areare, Kainui, Rotokauri, Waiwhakareke, Rotokaeo, Rotoroa, and Ngaroto (Figure 1).

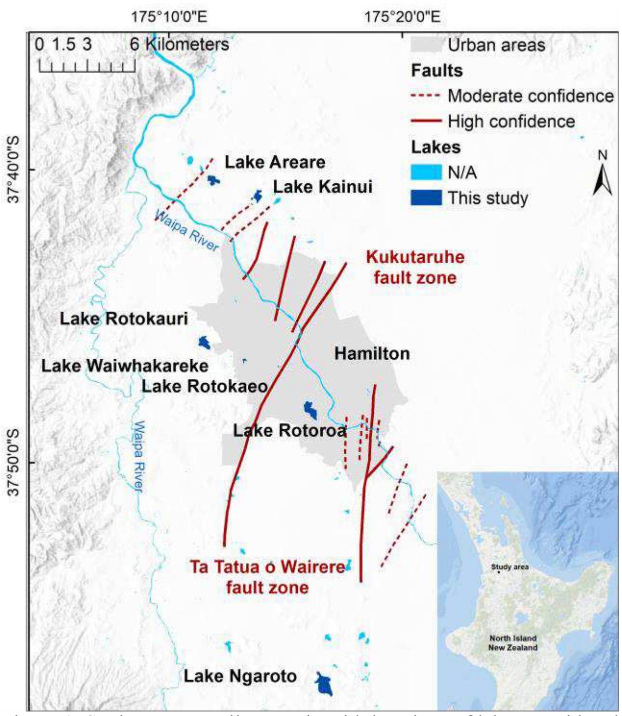

Figure 1. Study area: Hamilton Basin with locations of lakes considered in this study (dark blue) and faults (red lines)

3 MATERIALS AND METHODS

The focus of this paper is four rhyolitic pumiceous tephra layers: Tuhua (Tu), Mamaku (Ma), Waiohau (Wh), and Rotorua (Rr). The tephra layers, each between ~2 and ~8 cm thick (Kluger et al., under review), were sampled from a number of ~1.5 m-long piston cores collected at six lakes (Figure 1). The layers occurred at different depths in the lake sediments ranging from 0.5 m to 2.0 m (Lowe, 1988; Kluger et al., under review) and mainly comprised volcanic glass (in the form of glass shards and glassy pumice fragments) and minor crystals (Figure 2) (Lowe, 1988). They showed differences in composition in terms of grain size and pumice content in the different lakes (Lowe, 1988).

Because the layers were relatively thin (2–8 cm), it was not possible to analyze all the relevant physical and geotechnical properties from the small volumes provided by the cored samples. Therefore, additional onshore in situ block sampling was undertaken at Lake Areare (Figure 1), where lowered lake levels facilitated easy access to near-surface deposits of Tu and Ma tephra layers. This sampling provided sufficient material to characterize the pumiceous tephra layers more comprehensively by Atterberg limits and characteristic void ratios.

In total, 45 individual samples were taken from cores and block samples, comprising 17 samples of Tu, 11 samples of Ma, 17 samples of Rr, and four samples of Wh. For each of the 45 samples, particle density (thus, specific gravity, *Gs*) and grain-size distribution analyses were performed. The particle density of the samples was obtained following ASTM-D5550-14 (ASTM, 2014) using a Quantachrome Ultrapyc 1000 nitrogen-filled gas pycnometer. Potential influences of the method used to determine particle density (Bielders et al., 1990; Wesley, 2001) is not further discussed in this study.

The particle-size distribution was determined on small-volume samples by means of laser diffraction analysis (LDA) using a Malvern Mastersizer 3000.

Scanning electron microscopy (SEM) and X-ray diffraction (XRD) analysis were undertaken using a Hitachi S-4700 FE SEM and a Panalytical Empyrean Series 2 XRD, respectively. Both measurements were performed on a number of representative samples from each tephra in order to examine their pumice content and clay mineralogy.

Quantification of pumice content based on counting individual particles under the SEM has been used before (Asadi et al., 2019). This approach has been referred to as time consuming and not fully representative of large soil volumes as a relatively small number of particles are commonly examined (Stringer, 2019). The present study, however, dealt with thin layers on which most of the laboratory tests (i.e., particle density, grain-size distribution) were already made using small quantities. Therefore, it was considered that estimating pumice content from the number of pumiceous particles in SEM images is the most effective approach. The pumice content was estimated using a point-counting method (Frolov and Maling, 1969). In this method, five SEM images of representative pumice clusters were chosen for each sample and were counted systematically on crossing points (> 200 points per sample) of rectangular grids. The pumice content (*PC*) was calculated from Eq. 1.

$$PC = \frac{N_{\text{A.pumice}}}{N_{\text{A.total}}} * 100\% \quad (1)$$

where $N_{A,pumice}$ is the number of crossing points that lay over a particle with pumiceous features (i.e., being vesicular) and $N_{A,total}$ is the total number of crossing points classified for a specific tephra sample.

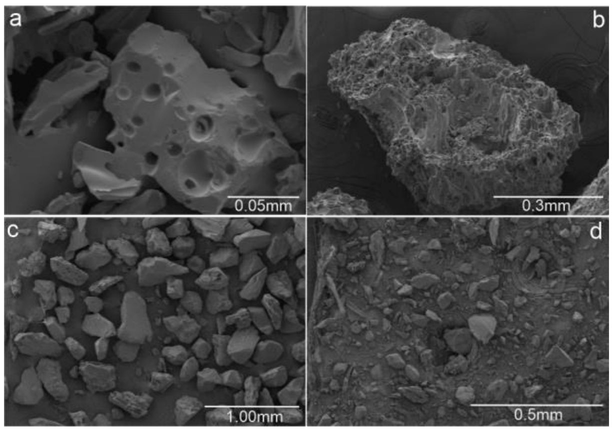

Figure 2 (a) and (b): SEM images of particles in Rr tephra, Lake Kainui; (c) and (d) SEM images of mainly glass shards and pumice particles in Ma tephra, Lake Areare

Dominant clay minerals in selected silty samples were determined qualitatively by XRD. Samples were prepared following standard methods based on Lowe and Nelson (1983) and Whitton and Churchman (1987). Mineral identifications were based mainly on clay mineral identification diagrams formulated by USGS (2001).

The minimum and maximum dry densities (thus, maximum and minimum void ratios, respectively) as well as Atterberg limits were determined on samples retrieved from the onshore location at Lake Areare. The minimum and maximum densities of five samples (three Ma and two Tu) were determined following the Japanese standard method (JGS0161-2009) modified by Mijic et al. (2021). The JGS procedure has been proven to cause negligible particle crushing in natural pumiceous soils found in the North Island of New Zealand (Asadi et al., 2019). The silty samples from the onshore blocks from lake Areare (Table 1) were tested for their liquid and plastic limits following ASTM-D4318-17e1 (ASTM, 2017).

4 LIQUEFACTION SUSCEPTIBILITY

The grain-size distribution curves of all samples retrieved from the seven lakes are presented in Figure 3. Blue solid curves denote Rr tephra samples taken from different lakes, whereas orange dashed curves denote Ma tephra from onshore Lake Areare that comprised three thin layers of different grain-size distributions. The *FC* (fines content, particles %<0.075 mm) for all these samples ranged from ~10% to 99%. The silty samples from the lakes contained up to ~10% clay-sized particles (<0.002 mm). According to the Unified Soil Classification System-USCS (ASTM-D-2487), the samples were classified as silts, sandy silts (37 samples) or silty sands (eight samples).

Each tephra (Tu, Ma, Wh, Rr) exhibited different grain-size compositions when comparing deposits in different lakes. For example, Rr tephra was found to be silty in lakes Waiwhakareke and Ngaroto, yet it was found to be sandy in lakes Kainui and Rotoroa (Figure 3). The thickness and interlayering within each tephra layer also varied between lakes. Some tephra layers comprised a homogeneous silt unit, whereas others comprised a number of thin, well distinguishable internal layers of different grain size (e.g., Ma tephra from Lake Areare: Figure 3). Additional information about thicknesses of the different tephras in the lakes are reported in Kluger et al. (under review).

The geological conditions (such as age and origin) and the grain-size composition are an important preliminary check for the liquefaction susceptibility of soils. In this regard, there is a general agreement that young Holocene sands, non-plastic silts and gravels, and their mixtures, are susceptible to liquefaction.

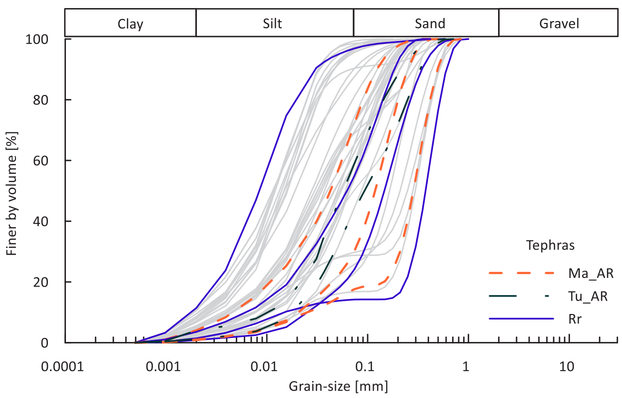

Figure 3. Grain-size distribution curves of all samples (grey curves). The highlighted curves are referred to in the text

The geological and compositional characteristics are not enough when it comes to characterizing fine soils that contain clay-sized particles because of the many significant differences in undrained behavior of sands versus clays. Plasticity characterization is considered the conclusive method when it comes to liquefaction susceptibility of fine-grained soils (Boulanger and Idriss, 2006; Bray and Sancio, 2006).

The silty samples from the onshore blocks from Lake Areare (Table 1) were tested as non-plastic (ASTM-D4318-17e1, 2017), which confirms their liquefaction susceptibility.

Table 1. Grain-size characteristics for silty onshore samples from Lake Areare

Sample	Lake	D_{50} [mm]	*FC* [%]	*CC* [%]
Tu	Areare	0.06	59	4
Ma	Areare	0.04	72	6

For the purpose of extending the non-plastic classification to the layers in the lakes, XRD analysis on the clay-sized portion of some selected samples (containing 8–10% clay-sized particles, referred to as *CC*) was performed.

Three of six samples tested by XRD did not comprise any clay minerals (Table 2). These samples were therefore considered to be non-plastic and, thus, liquefaction susceptible. The remaining three samples showed evidence of low-activity clay minerals (e.g., halloysite). Therefore, no final conclusion could be drawn whether or not these three samples are susceptible to liquefaction.

Table 2. Minerals and glass in clay-sized fraction of selected samples

Sample	Lake	*FC* [%]	*CC* [%]	Minerals/glass
Tu	Rotokaeo	97	8	Glass >> mica
Tu	Rotokauri	99	9	Glass
Ma	Kainui	87	7	Glass >> 1.0 nm halloysite
Rr	Kainui	87	10	Glass >> 1.0 nm halloysite
Rr	Rotokauri	98	10	Glass
Rr	Ngaroto	95	10	Glass >> 0.7 nm halloysite

5 SPECIFIC GRAVITY

The relationship between specific gravity and fines content is presented in Figure 4. The specific gravity values range from 2.10 to 2.68 for tephras with fines content from ~14 to 99%. For comparison purposes, data for Toyoura sand (quarzitic, hard-grained sand), Shirasu sand (pumiceous sand), pure pumice sand (commercially available), and the Tierra Bianca silt (volcanic-ash silt) were plotted as well.

Specific representative samples were selected in order to investigate the relationship between the pumice content and the specific gravity. Figure 5 plots the specific gravity vs. pumice content of ten samples, including four of the onshore block samples from Lake Areare.

In general, the first observation from the results (Figure 4) is that the specific gravity of pumiceous soils depends on fines content. As the content of fine particles increases, the specific gravity values increase as well. All data points lie in the range between the value for pure pumice sand (Asadi et al., 2019) and that for the representative hard-grained Toyoura sand.

The increase of specific gravity with increasing fines content is especially evident in the Tu and Rr trendlines (blue dash-dotted and dark green solid line, respectively). Additionally, it could be observed that the trendline of Tu tephra was systematically higher than those derived for the other tephras tested in this study. This is most probably a result of small differences in glass shard major elemental compositions, with Tu notably enriched in Fe (FeO_t~6 wt%) compared to Rr (~1 wt%) (Lowe, 1988; Lowe et al., 2008). Subscript *t* denotes total Fe expressed as FeO.

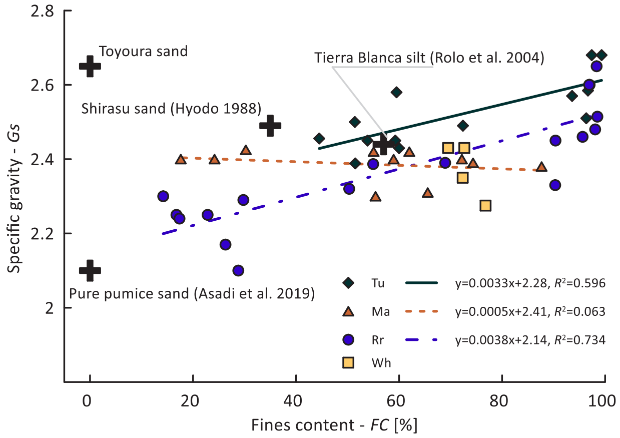

Figure 4. Specific gravity (*Gs*) vs. fines content (*FC*) graph for the four tephra samples (Tu, Ma, Rr, Wh) from different lakes compared with values of relevant sands/silt in published literature.

An interesting exception in the relationship between specific gravity and fines content is the trendline for Ma tephra, where specific gravity is seemingly independent of the fines content. All specific gravity values are close to 2.4 (ranging from 2.30 to 2.43), resulting in an almost flat trendline. It is inferred that this could be a result of a potential lesser (if not completely lacking) content of internal voids within the pumiceous particles, as the values tend towards a specific gravity of 2.4, which is the specific gravity typical of volcanic glass shards. Moreover, in the case of Ma tephra, the specific gravity also seems to be less sensitive to the pumice content in comparison with that of the other two tephras (Tu and Rr) (Figure 5). This indicates that an isolated tephra with these characteristics will still probably be crushable (having pumiceous particles varying from 30 to 50%), yet it would not contribute to a trendline that would assist in deriving pumice content from *Gs* values. This observation may support pumice content estimation methods that are based on the crushability characteristics of pumiceous soil mixtures rather than of those based on weight properties. Nevertheless, the fitted line in Figure 5 (which corresponds to a value of 2.64 for 0% pumice content) supports possible *Gs*-*PC* correlations, which could be used as an indicator for the pumice content of a soil mixture based on the specific gravity value (determined in an identical way – i.e., via gas pycnometer).

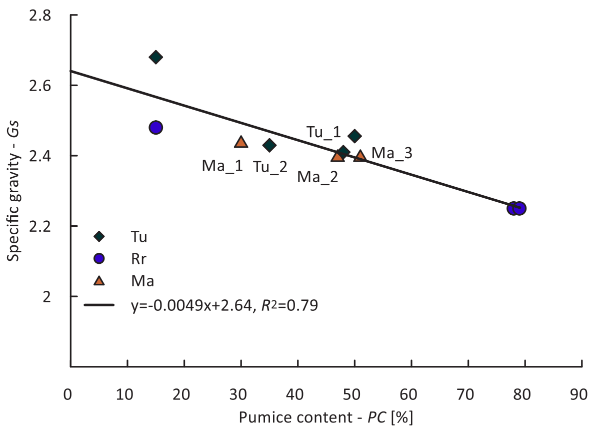

Figure 5. Specific gravity (*Gs*) vs. pumice content (*PC*) for ten selected samples of tephras (Tu, Rr, Ma) from the lakes

6 CHARACTERISTIC VOID RATIOS

Characteristic void ratios of Tu and Ma tephra samples collected from the block samples at Lake Areare, as well as the trendlines and data point zone from Cubrinovski and Ishihara (2002), are presented in Figures 6 and 7.

Cubrinovski and Ishihara (2002) found that the void ratio range (e_{max}-e_{min}) embodies the combined effects of mean grain size, grain-size distribution, fines content, and grain shape. Note that the characteristic void ratios in this study were determined using the same procedure as that used by Cubrinovski and Ishihara (2002), but modified for small quantities of soil.

By using a large database of more than 300 soil samples, Cubrinovski and Ishihara (2002) established correlations between the characteristic void ratios and the material properties mentioned above (Figures 6 and 7).

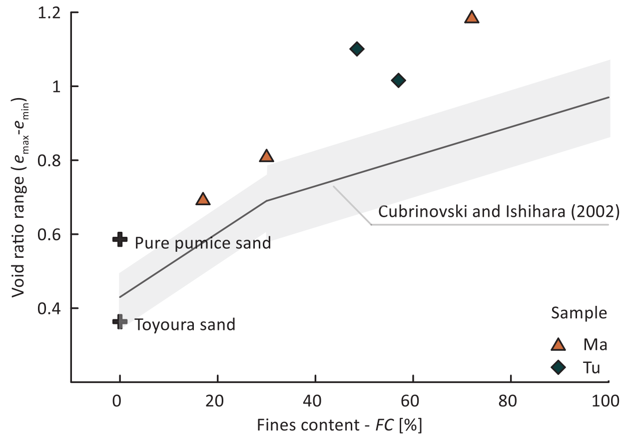

Figure 6. Void ratio range (e_{max}-e_{min}) vs. fines content (*FC*) graph for the two tephras (Ma, Tu) sampled onshore at Lake Areare compared to trendlines and values found in published literature

These correlations are widely recognized when it comes to hard-grained soils, yet as their database did not include pumiceous soils, it is of particular interest to examine whether this trend extends to volcanic-ash materials as well.

In their study, Cubrinovski and Ishihara (2002) found that, there was less scatter and better correlation between the void ratio range and the fines content of sandy soil samples with less than 30% fines, but in general, the void ratio range increases with the increase in fines content (Figure 6). The five pumiceous samples from the present study show the same trend when observing the fines content. Moreover, the silty samples also show higher offsets from the trendline when compared to the sandy ones, which also indicates that they are in accordance with the results of Cubrinovski and Ishihara's study mentioned above.

The five tephra samples, as well as the pure pumice sand (Asadi et al., 2019), have higher maximum void ratios compared to those of the hard-grained Toyoura sand (Table 3), meaning in the loosest state (minimum density), the voids-to-solid volume ratio is much higher for the same fines content, which is expected as the pumice particles contain voids. The minimum void ratios also follow this trend but not to the same extent in general. As a result, the data points plot above the void ratio range vs. fines content trendline (Figure 6). This indicates that the difference between the characteristic void ratio values is generally high for pumiceous soils, which may result in higher compressibility because of the bigger range of potential void ratio values (between e_{max} and e_{min}). More research needs to be conducted in order to further analyze and interpret if that is indeed the case.

Table 3. Characteristic void ratios and pumice content for Tu and Ma samples, Lake Areare (onshore samples), and relevant void ratios from literature

Sample	Lake/Ref	D_{50} *[mm]*	*FC* *[%]*	*PC* *[%]*	e_{min}	e_{max}
Tu_1	Areare	0.09	44	48±14	1.047	2.148
Tu_2	Areare	0.06	59	35±11	1.152	2.168
Ma_1	Areare	0.04	72	30±10	0.881	2.069
Ma_2	Areare	0.3	18	47±10	0.817	1.513
Ma_3	Areare	0.13	30	51±11	0.705	1.518
Toyoura sand	(Zlatovic, 1994)	0.17	0	100	0.616	0.988
Pumice sand	(Asadi et al., 2019)	1.3	0	0	1.679	2.266

The mutual effects of fines content, mean grain size, and particle shape on the void ratio range are presented in Figure 7 (Cubrinovski and Ishihara, 2002). The five tephra samples from our study generally seem to fit in the trends of the grain size and the fines content, with the exception of the Ma_2 and Ma_3.

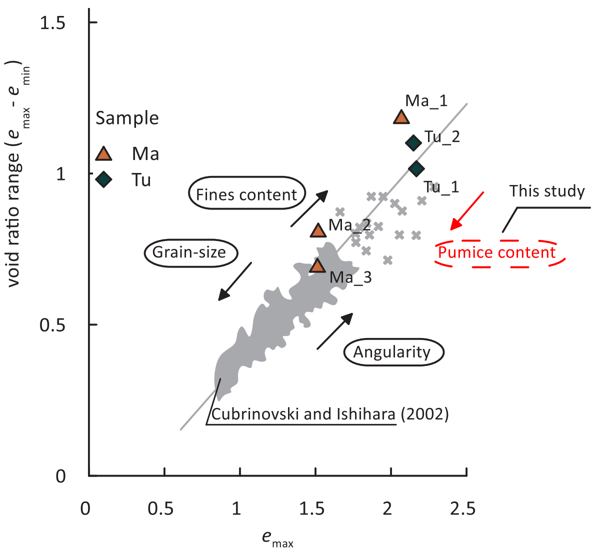

Figure 7. Void ratio range (e_{max}-e_{min}) vs. maximum void ratio (e_{max}) for the two volcanic-ash samples, Lake Areare compared with the values from Cubrinovski and Ishihara, (2002)

Ma_2 has lower fines content and higher D_{50} than Ma_3 (Table 3), despite plotting above Ma_3. In other words, Ma_2 should have lower characteristic void ratios, or more voids in these two states (minimum and maximum densities achieved in laboratory conditions), so that it would be in accordance with the trendline. A possible reason for this might be because Ma_3 has higher pumice content than Ma_2, thus resulting in a higher minimum void ratio on account of the voids in the pumice (Table 3).

Moreover, if we observe how the five tephra data points plot in the graph, a trend by means of the effect of pumice content can be observed. This would indicate the pumice content may have an effect on the void ratio range values. The observation is not based on enough data to be conclusive but it does inspire the idea for further research in defining to what extent is the pumice content relevant in the characteristic void ratio trendlines for pumiceous soil mixtures.

7 CONCLUSIONS

Geotechnical properties of up to 45 pumiceous volcanic-ash samples were presented in this paper, with the purpose of characterizing their liquefaction susceptibility as well as assessing the dependence of the void ratios and specific gravity on the pumice content. The main findings can be summarized as follows:

(1) The tephra layers found in lakes in the Hamilton lowlands can be categorized into two groups: (*i*) liquefaction susceptible sands, silty sands, and silts with no clay minerals; and (*ii*) samples with a potential but unconfirmed liquefaction susceptibility: silts that contain more than 5% clay-sized particles (in the form of clay minerals).

(2) In general, the specific gravity increased as the fines content increased. An exception to this trend was noted for one of the tephras (Ma). It was hypothesized that this exception could be due to a significantly lower (if not completely lacking) presence of internal voids in the pumiceous particles of this tephra that are non-penetrable by the gas in the gas pycnometer.

(3) Soils with higher pumice content (*PC*) showed lower values of specific gravity (*Gs*), indicating that the effect of pumice content could be exploited to derive *Gs*–*PC* correlations, which could potentially be used in practice to determine the pumice content from a known value of specific gravity.

(4) The five pumiceous samples from Lake Areare were found to have relatively higher characteristic void ratios compared with values for hard-grained soils. It was found that they fit reasonably well into relevant void ratio range trends derived for hard-grained soils. Further research with a larger database is needed for a more conclusive result.

8 ACKNOWLEDGEMENTS

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