Laboratory-based method to quantify pumice contents of volcanic deposits

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ABSTRACT: Pumice-rich soils originating from volcanic eruptions are deposited in various parts of the world, such as in the central part of North Island, NZ. Since they are often encountered in engineering projects, their geotechnical characterization is very important. One factor which affects the engineering properties of pumice-rich deposits is the amount of pumice sands present in the soil. Pumice sand is characterized by the vesicular make-up of its particles, resulting in their light weight, highly crushable and compressible nature. Currently, other than visual inspection, there is no well-accepted method to quantify the pumice content (*PC*). In this paper, attempts were made to quantify *PC* through the crushability feature of pumice sand. For this purpose, laboratory tests were performed on known mixtures of pure pumice sand and hard-grained sand. The soil mixtures (with known *PC*) were compacted using a modification of the test used to determine the maximum density of sand. The particle size distribution curves before and after compaction were determined, and the degree of particle crushing was quantified using a breakage index, which was found to correlate well with *PC*. The developed procedure was validated by quantifying the *PC* of several pumice-rich samples sourced from various sites in central North Island. SEM images were taken on these samples and their *PC*s were quantified by visually counting the pumice-looking particles; the results agreed quite well with those estimated using the proposed method.

Keywords: volcanic soil; pumice content; particle crushing; minimum density test

1. Introduction

Pumice-rich deposits are found in several areas of the North Island of New Zealand. They originated from a series of volcanic eruptions centered in the Taupo and Rotorua regions, called the "Taupo Volcanic Zone" (see Figure 1). The pumice material has been distributed initially by the explosive power of the eruptions and associated airborne transport; this has been followed by erosion and river transport. Presently, pumice-rich deposits exist mainly as deep sand layers in river valleys and flood plains, but are also found as coarse gravel deposits in hilly areas. Although they do not cover wide areas, their concentration in river valleys and flood plains means they tend to coincide with areas of considerable human activity and development. Thus, they are frequently encountered in engineering projects and their evaluation is a matter of considerable geotechnical interest.

Because of its vesicular nature, pumice sand is lightweight, highly crushable and compressible, rendering it problematic from an engineering and construction viewpoint. Although significant studies have been carried out on many crushable soils, such as carbonate sands and calcareous soils, pumice is a unique material – the particles crush easily under fingernail pressure. It is possibly the most delicate of the suite of crushable soils found at various locations around the world.

As a result of the explosion and subsequent deposition, pumice sands are normally mixed with the in-situ soil in varying amounts. Figure 2 shows photos of undisturbed samples of pumice-rich soils, where it can be seen that the pumice sands can be quite mixed with the other hard-grained components (left photo), or can appear in layers (right photo). In any case, their presence within the soil

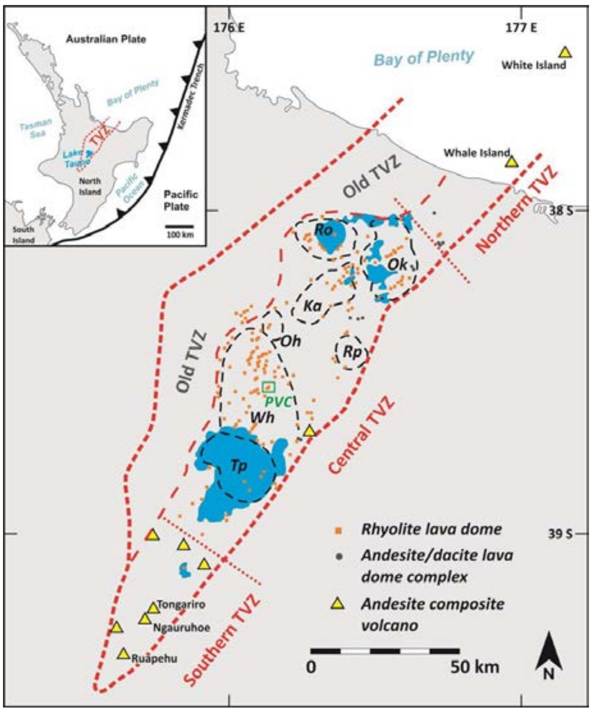


Figure 1. The Taupo Volcanic Zone (TVZ) in the North Island of New Zealand [1].

matrix generally leads then to questions as to whether existing empirical correlations, derived for normal (hard-grained) sands, would be applicable to pumice-rich soils. Intuitively, the response of these soils would depend on the amount of such crushable pumice particles present in the soil. Unfortunately, other than visual inspection of the material, there is no well-accepted method to quantify the proportion of pumice sands present in the soil sample.

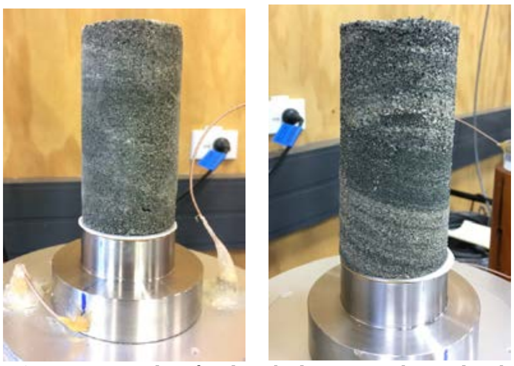


Figure 2. Examples of undisturbed pumice-rich samples obtained from the Waikato Basin in central North Island [2].

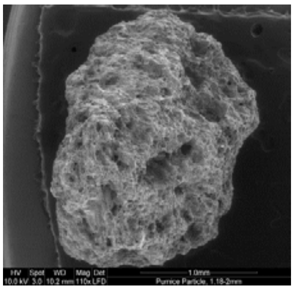
In order to address the need to quantify the pumice content of volcanic soils, a laboratory testing program was carried out focusing on the crushable nature of pumice particles as means of indicating the pumice content.

2. Previous studies on particle crushing of pumice sands

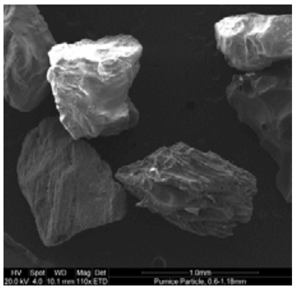
Before discussing the proposed method, it is worth reviewing the previous works conducted by the authors on pure pumice sands, especially those related to their crushing properties.

2.1. Single particle characterization

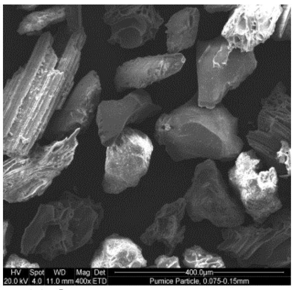
Kikkawa et al. [3-4] and Orense et al. [5] investigated the properties of pumice sands at grain-size (micro) level through particle shape characterization. This was done through scanning electron microscope (SEM) imaging and computed tomography (CT).



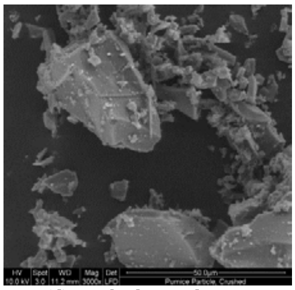
(a) diameter > 2mm



(b) diameter 0.6 – 1.18mm



(c) diameter 0.075 – 0.15mm

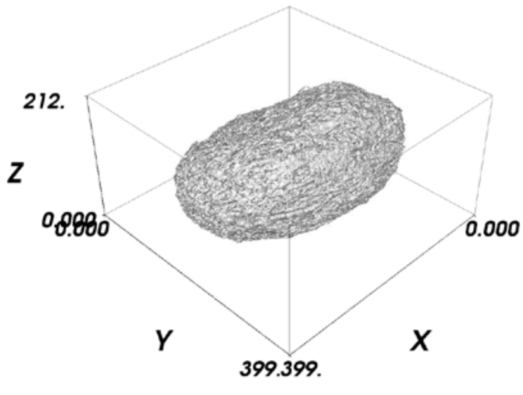


(d) crushed particles

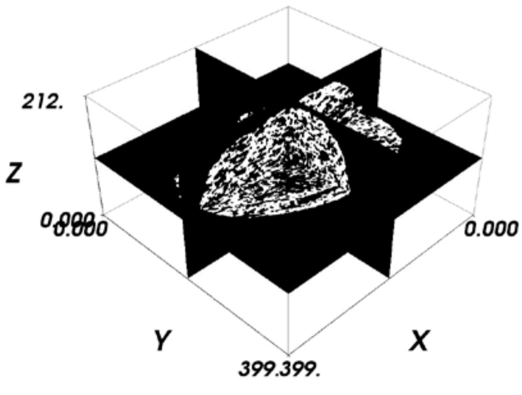
Figure 3. Scanning electron microscope (SEM) images of pumice sands with different sizes [5].

The SEM images, shown in Figure 3, give a clear qualitative indication that pumice sand particles are vesicular and that they have very rough and angular surfaces. Moreover, as the particle size decreases, the shape and surface texture tend to be less uniform and more angular. Especially when the particles are crushed, the surface is more jagged and irregular, and this could lead to more interlocking potential under shear load application.

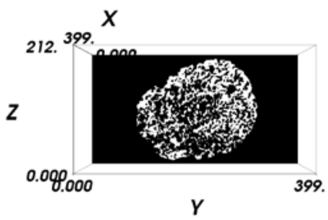
In addition to SEM imaging, many particles of pumice sand were individually scanned using Sky-scan 1172 high-resolution micro CT scanning machine. This was



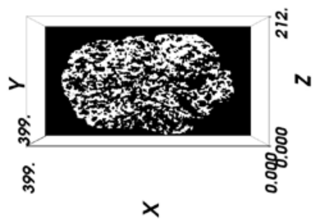
(a) Three-dimensional reconstructed image



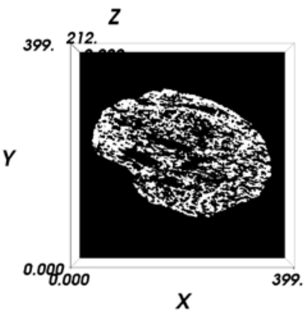
(b) locations of cross-sectional planes



(c) image on *y-z* plane



(d) image on *x-z* plane



(e) image on *x-y* plane

Figure 4. CT images of a pumice particle, showing the cross-sectional images and the reconstructed particle through image analysis [3].

done for the purpose of distinguishing between surface and internal voids, as once particle crushing occurs more internal voids are exposed to the surface, creating a greater number of voids between particles. An example image is shown in Figures 4 where the solid portion of the particle is shown as white color and the black region is the void. Figure 4(a) shows the 3D pumice particle reconstructed using all longitudinal binarized images. Figure 4(b) indicates the locations of the cross-sectional planes while Figures 4(c), 4(d) and 4(e) are the images in the *y-z*, *z-x* and *x-y* cross-sectional planes, respectively.

It can be seen from the figure that almost all the voids open to the exterior of the pumice particle, so that there are more surface voids than internal voids. Using an imaging analysis algorithm, Kikkawa et al. [3-4] attempted to quantify the bulk volume of the particle, the volume of solids and the volume of internal voids. Based on the analysis of many particles of varying sizes, they noted that, in terms of volume, the internal voids are much smaller than surface voids, indicating that most of the internal voids apparent in the cross-sections of the particle are actually connected to the outside surface in 3-dimension.

2.2. Single particle crushing tests

Single particle crushing tests were conducted on pumice particles by Orense et al. [6]. In their tests, a particle was placed in stable direction on the bottom bearing plate and the top plate was lowered at constant speed (0.1 mm/min) to crush it. During the test, axial load and displacement were measured and recorded with a computer.

The tests were performed on 60 pumice sand particles with diameter between 0.6 – 2.5 mm. The samples of pumice grains appear to be of two types: yellow-colored particle (referred as particle A; and light brown-colored particle (referred as particle B). Figure 5 plots the relation between single particle crushing strength (defined as the first peak load, divided by the square of the initial height of the particle). It can be seen that there is a general trend of decreasing strength with increase in particle size. For comparison purposes, the trend for Silica sand is also indicated in the figure, based on tests conducted by Nakata et al. [7]. Note that while the trends are similar, the particle crushing strength of pumice is one order of magnitude less, showing the highly crushable nature of pumice sands.

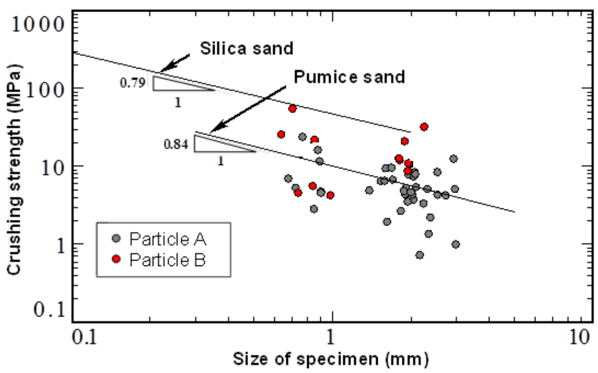
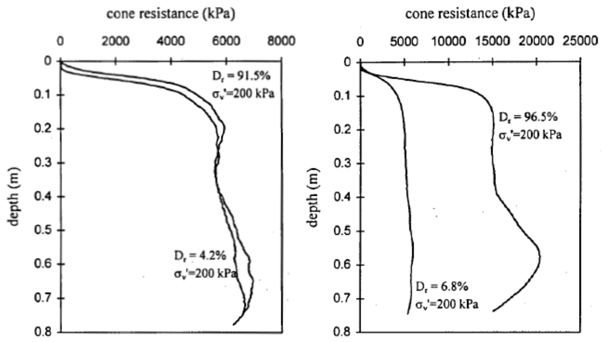


Figure 5. Variation of crushing strength with particle size [6].

2.3. Penetration testing

Penetrometer testing was undertaken on pumice sands by Wesley et al. [8] using a calibration chamber, with results compared to hard-grained quartz sands. Results of the cone penetration tests for both sands are shown in Figure 6, where the quartz behaves as expected of a sand, with large differences in the cone resistance between the loose and dense states under the same vertical effective stress. However, the pumice sand shows unusual behavior, with very little change in cone resistance between the loose and dense states and is only marginally greater than that of the loose quartz specimen.



(a) (b)

Figure 6. Comparison of cone resistance results for: (a) pumice sand; and (b) quartz sand [8].

The reason for this behavior is possibly because the stresses imposed by the penetrometer are so severe that particle breakage forms a new material whose properties are nearly independent of the initial state of the sand. It is also noted that pumice sand cone resistance shows very gentle increase with confining stress as compared to normal (i.e. hard-grained) sands [8]. Thus, conventional relationships between the cone resistance, relative density, and confining stress are not valid for these soils. Therefore, alternative relationships specifically for pumice sands need to be developed.

3. Experimental program

3.1. Material used

During the first stage of the test program, two materials were used: the commercially available (pure) pumice sand and river sand. The pure pumice sand is not a natural deposit but was derived by processing sand from the Waikato River, located near the town of Mercer. The particles were centrifugally separated from the other river sand particles so that the samples consisted essentially of pumice grains. This commercially available material has been used extensively in the Geomechanics Laboratory of the University of Auckland. The river sand, on the other hand, were the leftovers of the separation process; this is refereed herein as Mercer river sand.

Table 1 lists the index properties of these materials, while the corresponding particle size distribution curves are shown in Figure 7. The New Zealand standard NZS4402 [9] for soil testing was followed to determine the specific gravity and minimum dry density of the

Table 1. Index properties of the materials tested (based on NZS 4402)

Material	Origin	Specific gravity	Minimum dry density (g/cm^3)
River sand	Mercer	2.65	1.44
Pure pumice	Mercer	2.09	0.64
NP1	Hamilton	2.53	1.27
NP2	Hamilton	2.50	1.07
NP3	Rangiriri	2.54	0.93
NP4	Huntly	2.45	0.98

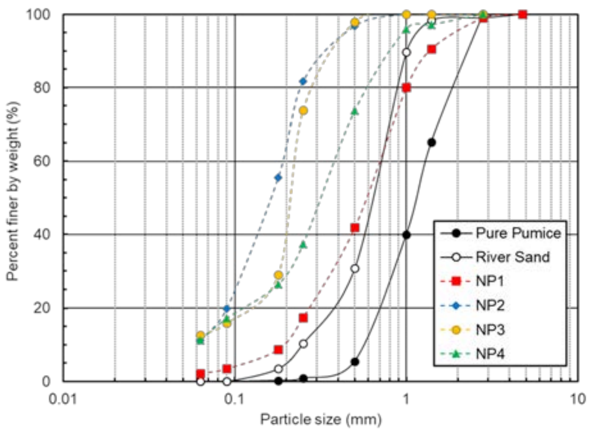


Figure 7. Original particle size distribution curves of the materials tested

materials. Note that similar values of index properties were obtained using the Japanese standard [10].

For the validation stage, four different natural sands containing pumice sands (i.e. mixture of some pumice particles with other hard-grained constituents and with different percentages of non-plastic fines, referred herein as natural pumiceous [NP] sands), were obtained from different site locations within the Waikato Basin in central North Island. Sites NP1 and NP2 were located in Hamilton City while Sites NP3 and NP4 were near the towns of Rangiriri and Huntly, respectively. The materials were sourced at depths of 1.5 m, 2.0 m, 4.5 m and 5.5 m, respectively, for NP1, NP2, NP3 and NP4 sites. Their index properties are also listed in Table 1 and their particle size distribution curves are also depicted in Figure 7.

3.2. Maximum dry density testing

In another study, when investigating the maximum dry density (MDD) of pure pumice and NP sands, Asadi et al. [11] used two different methods, i.e. the procedures outlined in the New Zealand standard and in the Japanese standard.

3.2.1. MDD test based on Japanese standard

In the Japanese standard [10], densification is achieved by tapping the side of the mold with a small hammer with a face approximately 3 cm in diameter and a mass of 200 g. In this method, the soil is poured into a mold with diameter 60 mm and height 40 mm in 10 layers, and for each layer a hammer was used to tap the side of the mold 100 times while rotating the mold. To accommodate more soil for densification at the last two layers, a sleeve was attached to the top of the mold. At the end of compaction the sleeve was removed and the excess soil above the mold trimmed away to give a flat surface. The mass of the soil inside the mold was measured and the MDD calculated.

3.2.2. MDD test based on NZ standard

In the New Zealand standard [9], a mold with diameter 105 mm and height 110 mm is fixed to a vibrating table. A sleeve is attached to the top of the mold to accommodate a surcharge weight producing a pressure of 14 kPa at the top of the dry soil. Subsequently, the dry soil is vibrated with 0.5 mm vertical double amplitude at a frequency of 50 Hz for 10 minutes, then the surcharge weight and sleeve are removed and extra soil above the top of the mold is trimmed away. The soil inside the mold is weighed for the MDD calculation.

3.2.3. Proposed method

At the end of each MDD test for both standards, Asadi et al. [11] determined the particle size distribution (PSD) curves by sieving to check for possible particle crushing. They noted that that because of the crushable nature of the pumice sand components, the use of New Zealand standard resulted in significant amount of particle crushing in these materials and, consequently, it was not possible to get the same result when the test was repeated. On the other hand, the results using Japanese standard showed consistent MDD when repeating the tests due to negligible particle crushing. Thus, the results of MDD tests confirmed that under a specified amount of loading the potential breakage of natural pumiceous sand are different which may be a function of their composition (e.g. pumice content).

As a way forward, they proposed a modified MDD test (based on New Zealand Standard) wherein the ultimate potential breakage of the pumice sands for the given surcharge load could be reached. In the proposed test, the materials to be tested was divided into four parts and placed inside the mold layer by layer, with each layer subjected to 10 minutes of vibration with the 14 kPa surcharge, as specified in the New Zealand standard. Hence, instead of one single layer 110 mm high and vibrated with a surcharge on top, the 4-layer variation of the New Zealand standard procedure as outlined above ensured that all pumice particles within the soil are crushed to reach the ultimate potential breakage.

Asadi et al. [11] hypothesized that the degree of particle crushing a pumice-containing soil would undergo would be proportional to the amount of pumice sand present within the sample.

3.3. Experimental program

In order to examine the procedure outlined above, samples of pure pumice sand and Mercer river sand were mixed at different proportions by weight, i.e. 0%, 25%, 50%, 70%, and 100% pumice sands were mixed with the river sand. The particle size distribution curves of the River sand – pumice mixtures are shown in Figure 8. Then, samples with known pumice contents, *PC*, were

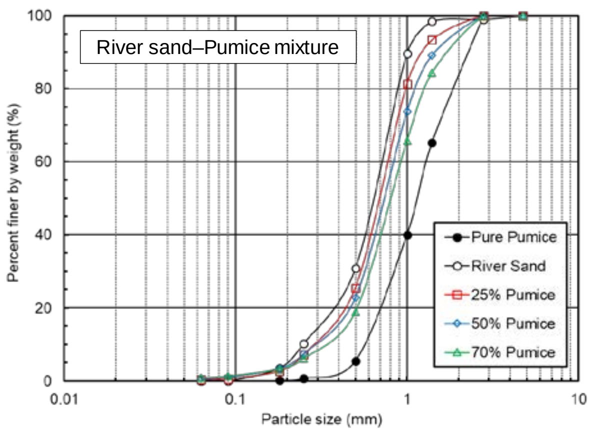


Figure 8. Particle size distribution curves of the River sand-pumice mixtures.

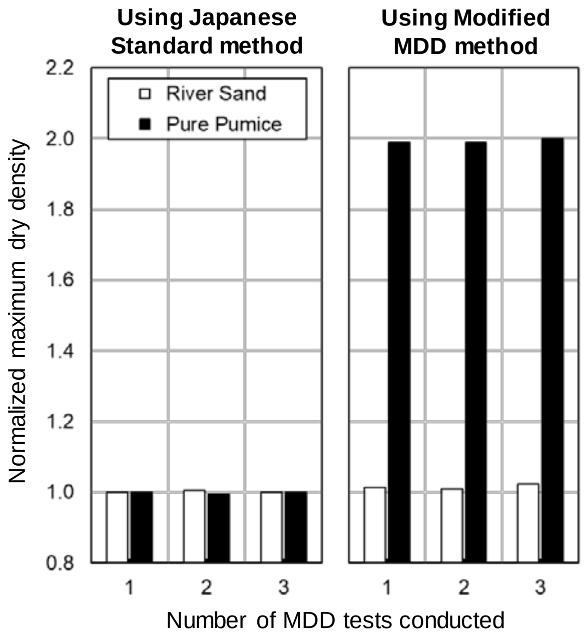


Figure 9. Variation in normalized maximum dry density, MDD, versus the number of MDD tests conducted for pure River sand (PC=0%) and pure pumice (PC=100%).

subjected to both the procedures as outlined in the Japanese standard and the modified MDD test described above to investigate if there is correlation between the known pumice content, PC, and degree of crushing. For each sample, the tests were repeated a number of times to check whether a consistent value of MDD was obtained. In the succeeding tests, the material from the previous tests was reused, with extra material being added as required to fill the mold to the required level. At the end of each test, the materials inside the mold were thoroughly mixed and some material were taken for sieve analysis.

For the purpose of quantifying the degree of crushing, the samples were sieved before and after the test, and their PSD curves compared. Then, the method proposed by Hardin [12] was used to quantify the degree of particle crushing; in this method, the area enclosed by the PSD curves before and after the tests and the line corresponding to 0.063 mm was used to calculate the total breakage B_t. The relative breakage (B_r=B_t/B_{po} where the initial potential breakage B_{po} is the enclosed area between the PSD curves before the tests and the line corresponding to 0.063 mm) was used to allow the ultimate breakage of the materials within the range of the surcharge applied to be compared.

4. Results and Discussion

A comparison between the maximum dry density (MDD) obtained for pure Mercer river sand (PC=0%) and pure pumice sand (PC=100%) using the Japanese standard and the modified MDD test is shown in Figure 9. In the figure, the MDD for the modified test procedure is normalized by the average MDD from the Japanese standard method.

The results of the MDD test using the Japanese standard confirmed that particle crushing did not occur for both samples tested, and the MDD values for each sample were consistent, with < 0.01 (gr/cm^3) variation between repeated tests. Similarly, the modified MDD tests proved that using the procedure as outlined above, particle crushing in sample with PC=0% was negligible (with not much change in MDD) while for sample with PC=100%, particle crushing was quite significant such that the proposed method resulted in MDD values of about twice that of the Japanese standard. More importantly, the variation in the MDD for the three successive tests (where the samples were re-used) was < 0.01 (gr/cm^3), indicating that the ultimate potential breakage of the samples were reached with the method. To illustrate the degree of crushing, the PSD curves before and after the application of the Japanese method and the modified MDD test method in the case of PC=100% sample are shown in Figure 10, while those for the River sand-pumice mixtures are shown separately in Figure 11 for clarity.

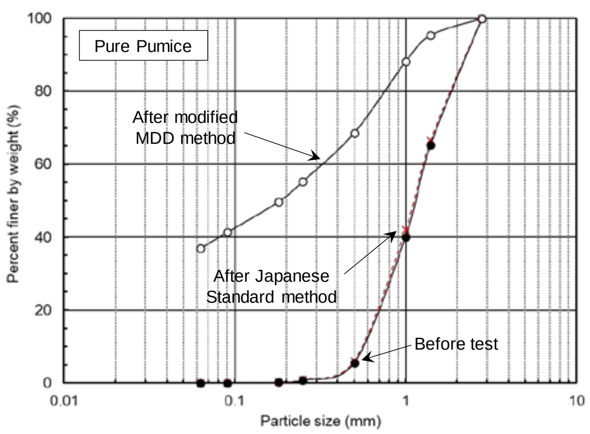


Figure 10. PSD curves of pure pumice sand before test and after the application of Japanese and modified MDD tests.

Based on the PSD curves of all the sand-pumice mixtures before and after the tests, the relative breakage, B_r, for each sample (i.e. PC=0%, 25%, 50%, 70% and 100%) was calculated, and the results are summarized in Table 2. It can be observed that as PC increases, the value of B_r also increases. This trend is to be expected; when subjected to the same surcharge load during the modified MDD testing, the degree of particle crushing experienced by each sample should be proportional to the amount of crushable pumice components present in the sample. This

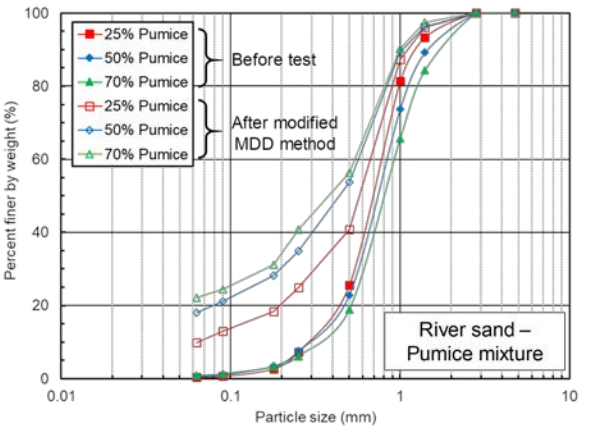


Figure 11. PSD curves of River sand - pumice mixtures before test and after the application of modified MDD tests.

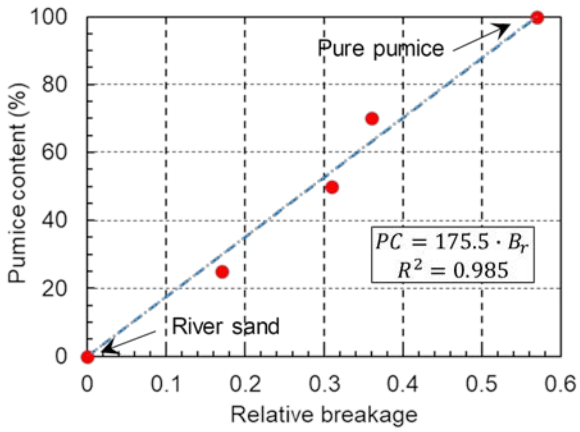


Figure 12. Estimation of pumice content according to the relative breakage

Table 2. Relative breakage at the end of modified MDD tests

Sand	Pumice content (PC), %	Relative breakage, B_r
River sand	0	0
	25	0.17
	50	0.31
	70	0.36
Pure pumice	100	0.57

Table 3. Comparison of estimated *PC* from B_r and from SEM images

Material	Relative breakage, B_r	Estimated *PC* (from chart)	Estimated *PC* (from SEM)
NP1	0.12	21%	18%
NP2	0.18	32%	29%
NP3	0.22	39%	42%
NP4	0.28	49%	53%

hypothesis is true if the non-pumice components (hard-grained sands) did not undergo significant particle crushing under such level of loading, and this was confirmed in the tests.

While the relationship between the amount of crushable pumice particles present (referred to as pumice content) and the level of crushing (i.e. relative breakage was considered as the best index, as it is independent of particle size distribution) is not clear, it is expected that the more crushable pumice components are present, the higher the degree of crushing the sample would experience for the same load; hence, a linear relation between pumice content and relative breakage is not unthinkable (e.g. doubling the pumice content implies twice the level of particle crushing). Thus, the variation of *PC* with B_r is depicted in Figure 12. It is observed that the data points from the tests with various *PC*s lie in close proximity to the proposed linear relation, which is expressed as:

$$PC(\%) = 175.5 \cdot B_r \quad (1)$$

The very high correlation coefficient ($R^2 \approx 0.99$) indicates the validity of a linear relation.

In order to validate the proposed correlation, the same procedure proposed herein was applied to the four NP sands sourced from the Waikato Basin, and the values of B_r at the end of the tests were computed. From these B_r values (obtained after the modified MDD test procedure), the pumice content of the samples were estimated using Eq, (1). These were then compared to the pumice contents reported by Asadi et al. [11] based on visually counting the number of pumice-looking particles with respect to the number of total particles shown in SEM images of the NP samples. Table 3 compares the estimated *PC* from Eq. (1) and the estimated *PC* from the SEM images. It can be observed that there is good agreement between the two sets of values, indicating that the proposed method is an accurate way of estimating the pumice content of pumice-rich soils.

5. Conclusions

In order to quantify the pumice content of volcanic soils, a method is proposed where the MDD procedure outlined in the NZ standard (NZS4402) was modified to ensure ultimate potential breakage of all crushable pumice particles in the soil samples under the 14 kPa applied surcharge was achieved. In this method, the sample was divided into four parts and each part was placed into the mold layer by layer, with each layer subjected to the specified vibration under the surcharge mass.

By comparing the particle size distribution curves of samples with known pumice contents before and after the tests, it was observed that the degree of particle crushing, expressed in terms of Hardin's [12] relative breakage B_r, correlated well with amount of pumice sands present in the samples tested. The proposed method of quantifying pumice content was validated by visually quantifying pumice-looking particles from SEM images of natural pumice-rich samples obtained in Waikato Basin.

The proposed method, which can be easily conducted in a standard geotechnical engineering laboratory, can assist practitioners in quantifying pumice contents of volcanic soils, allowing them to take these into account when determining geotechnical parameters for design.

Acknowledgements

The assistance of geotechnical engineers from Tonkin and Taylor and Opus International Consultants Ltd in facilitating access to the sites and in providing some samples and site details is gratefully acknowledged. The authors would also like to thank Jeff Melster of the University of Auckland for the assistance provided in the laboratory.

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