

Technical Paper

Separation of pumice from soil mixtures

M.E. Stringer

Department of Civil and Natural Resources Engineering, University of Canterbury, Christchurch, New Zealand

Received 17 October 2018; received in revised form 26 April 2019; accepted 28 May 2019

Available online 28 June 2019

Abstract

Pumice-rich deposits are found in a number of locations around the world, and in particular across large areas of the North Island of New Zealand. Pumice grains are commonly described as being lightweight, highly crushable, and vesicular in nature. These characteristics give rise to a unique set of behaviours under loading, and pumice-rich soils are highly problematic in terms of in situ characterisation in large part due to their crushability. The presence of pumice within a soil mixture has the potential to completely alter the stress–strain behaviour of these soils as well as require a different interpretation of results from commonly used site characterisation technique. It is therefore important to be able to determine quantitatively the percentage of pumice within a given soil deposit. This paper proposes a methodology based on a gravity separation of pumice-bearing mixtures with a heavy fluid. The application of the method to artificial mixtures of fine pumice and non-pumiceous sands is shown to be sufficiently accurate for engineering purposes.

© 2019 Production and hosting by Elsevier B.V. on behalf of The Japanese Geotechnical Society.

Keywords: Pumice; Gravity separation; Soil classification; Soil mixtures

1. Introduction

Pumice is a particular type of pyroclastic material, and is described as “a white or pale gray to brown, highly vesicular, silicic or mafic glass foam which will commonly float on water” (Fisher and Schminke, 1984). The vesicular nature of pumiceous soil grains means that they are lightweight (hence larger particles will commonly float), and it is known that these particles have a low crushing strength. Orense et al. (2013) investigated the crushing strength of pumiceous sand grains and showed that while there is significant scatter, the crushing strength of single particles were typically one order of magnitude weaker than a typical silica sand grain, and that the crushing strength of the material reduced with increasing particle size. The relatively low crushing strength of these soil grains makes these soils problematic from a characterisation point of view. In

particular, Wesley et al. (1999) showed that in calibration chamber tests, the cone penetration resistance of commercially available pumice was completely insensitive to the relative density of the soil as shown in Fig. 1. This has significant implications for practicing engineers who routinely rely on the use of such tools to derive engineering properties from correlations to particular parameters.

In addition to the issues associated with the in situ characterisation of pumice-rich soils, the presence of pumiceous material is known to affect the response of a soil, in terms of compression characteristics (Hyodo et al., 1998; Miura et al., 2003), stiffness (Senetakis et al., 2016), stress–strain response (Orense and Pender, 2016, 2013), and liquefaction resistance (Hyodo et al., 1998; Orense and Pender, 2016). Additionally, volcanic materials can evolve significantly due to weathering or freeze–thaw effects, with implications for mechanical strength, cyclic resistance (Matsumura et al., 2015) and slope stability (Ishikawa et al., 2016). These studies indicate that if engineers are to make reasoned decisions regarding the behaviour of a pumice-

Peer review under responsibility of The Japanese Geotechnical Society.

E-mail address: mark.stringer@canterbury.ac.nz

<https://doi.org/10.1016/j.sandf.2019.05.004>

0038-0806/© 2019 Production and hosting by Elsevier B.V. on behalf of The Japanese Geotechnical Society.

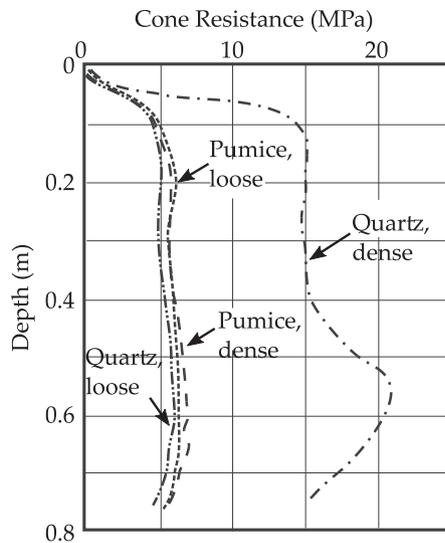


Fig. 1. Calibration chamber testing on pumice and quartzitic sands (Wesley et al., 1999).

bearing soil deposit, then a key property to evaluate is the percentage of pumice in a mixture.

Despite the importance of this parameter, it appears that there are currently few viable techniques that can be carried out in the laboratory. An obvious approach may include “spot-counting” where samples are examined under a microscope to determine the total number of pumiceous soil grains in a small sample. However, this process is generally too time consuming to be a reasonable tool for industry, as well as the issues related to the small numbers of particles being examined and the ability to convert numbers of particles into a percentage by mass or volume. In the absence of specific gravity (G_s) measurements, it is common to assume G_s in the range 2.65–2.7 for normal geotechnical materials, hence it is tempting to estimate the pumice content of a soil mixture based on the average specific gravity, noting that pumice has a low specific gravity due to its internal void structure. However, in the highly variable deposits containing pumiceous materials, G_s of the non-pumiceous component could be significantly different from 2.65. Additionally, Wesley (2001) discussed some of the issues associated with measuring specific gravity (G_s) in volcanic materials. In particular that when following the standard methods (i.e. ASTM D854-14), only part of the volume of gas in the internal voids is replaced with water so that the resulting G_s represents neither the actual mineral density, nor the bulk density of the grains. The G_s of pumiceous soil grains is generally size dependent, increasing with decreasing particle size. Therefore this simplistic method is unable to produce a satisfactory result.

Rogers and Sanderson (1954) described a method for commercial separation of pumice, where material is “jigged” - a process where water is introduced to the bottom of a vessel in a series of pulses, with the pumice being carried out of the vessel in the overflow. Recently, Asadi et al. (2019) attempt to apply the relative breakage index

proposed by Hardin (1985) to estimate the percentage of pumice based on the change in particle size distribution when a soil sample is subjected to a vibratory load in a proctor compaction mold. However, while this latter approach may be closely linked to a parameter of interest to engineers (i.e. the strength of the particles), it is not known how robust the technique is in terms of particle sizes, previous stress history (i.e. previous crushing) and the effect of different particle strengths within the mixture. The determination of pumiceous content within a soil mixture therefore remains a question of interest.

In this paper, the author will present a methodology for determining the amount of pumiceous sands and gravels based on gravity separation, which aims to provide a robust test that can be replicated in a commercial laboratory.

2. Pumice samples in this study

In this paper, pumiceous material has been obtained from a number of sites located on the North Island of New Zealand, with their locations marked on Fig. 2 and noted in Table 1 along with key size properties, their mineral density ($G_{s,sk}$) and their geological formation. Particle size distributions are shown in Fig. 3. The materials from Whakatane and Hamilton were obtained as part of wider research studies looking into the liquefaction resistance of natural pumiceous materials. The Whakatane samples were obtained from a site close to the Whakatane River and represent material which has been redeposited on a bend of the Whakatane river. The samples from two locations in

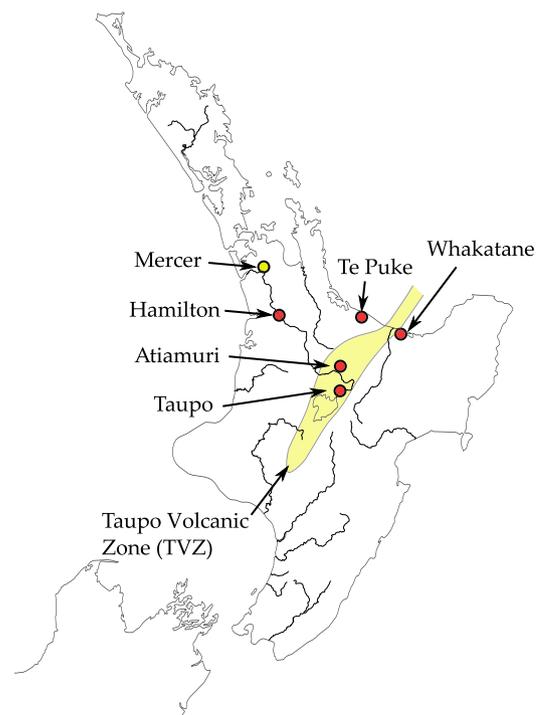


Fig. 2. Location of samples used in this study.

Table 1
 G_s measured on ground pumice material.

Formation	Sample ID (Location)	Location	$G_{s,sk}$	FC (%)	D_{50} (mm)	D_{95} (mm)	Density Separation
Hinuera formation	HAMTR1	Hamilton	2.340	4	0.43	1.31	Y
Tāupo alluvium	HAMGS1	Hamilton	2.309	18	0.19	3.71	N
Tāupo tephra	TPSH1	Tāupo	2.295	0	N/A	N/A	N
Tauranga formation	WH1	Whakatane	2.335	1	0.46	2.16	Y
Tāupo alluvium	C-CMP ^a	Atiamuri	2.395	1.2	0.27	0.55	Y
Tāupo alluvium	C-FMP ^a	Atiamuri	–	12	0.13	0.23	Y
Tauranga formation	C-EGM ^a	Te Puke	2.294	0	4.67	9.21	N
Tāupo alluvium	C-MCR ^{a,b}	Mercer	2.2	0	0.90	2.05	N
Christchurch formation	NBS ^c	Christchurch	2.65	1	0.19	0.29	Y

^a Commercially available product.

^b Solid density from CT-scanning, Orense and Pender (2016).

^c Non-pumiceous beach sand from Christchurch, NZ.

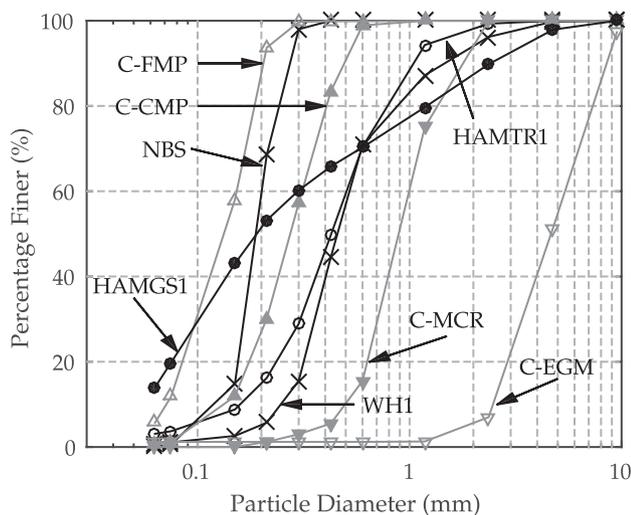


Fig. 3. Particle size distributions of materials used in this study.

Hamilton were obtained from several meters below the ground surface, and represent two very different depositional environments. The material from Tramway Road is taken from the Hinuera formation, while the material at Grantham Street lies within the Tāupo Pumice Alluvium (TPA). The Hinuera formation within the Hamilton Basin is described by Hume et al. (1975) and the sediments are considered part of an alluvial fan created by the ancient braided Waikato River, with material being derived from volcanic eruptions in the central Tāupo Volcanic Zone and deposited between 40,000 and 12,000 BP. The TPA is much younger, and were deposited rapidly when a pumiceous dam created during the Tāupo eruption in 180 AD failed (Manville, 2002).

2.1. Specific gravity of pumiceous materials

The three commonly quoted characteristics of pumice are vesicularity, low unit weights (as a result of internal voids) and crushability. In terms of determining the percentage of pumiceous material in a soil mixture, the low

unit weight of pumice is appealing since it opens up the possibility of natural segregation through sedimentation, or a method based on the specific gravity of a mixture. As previously noted, the specific gravity of pumiceous materials tends to be size dependent, owing to the inability to replace the gas present within the internal voids of the grains with the fluid being used in the standard methods (i.e. using a pycnometer). A similar trend was observed in this study with the natural pumice samples from Whakatane (WH1) and Hamilton (HAMGS1). These results are shown in Fig. 4 with those of Wesley (2001). While both of these samples appeared to be composed of pure pumice, it should be noted that the finest fraction (i.e. less than 75 μm) was significantly darker in colour and may represent a mixture of pumiceous material as well as hard-grained materials (i.e. the specific gravity may be higher in these fine fractions than the solid density of pumice).

In order to measure the mineral density ($G_{s,sk}$ in Table 1), individual gravel sized pumice particles were separated by hand, and then ground using a mortar and pestle, to destroy the internal void structure. Grains were selected from natural materials in Hamilton (both sites), Tāupo and Whakatane, as well as commercially available pumice. The results from these tests are summarised in Table 1 and varied between 2.29 and 2.40. The highest specific gravity

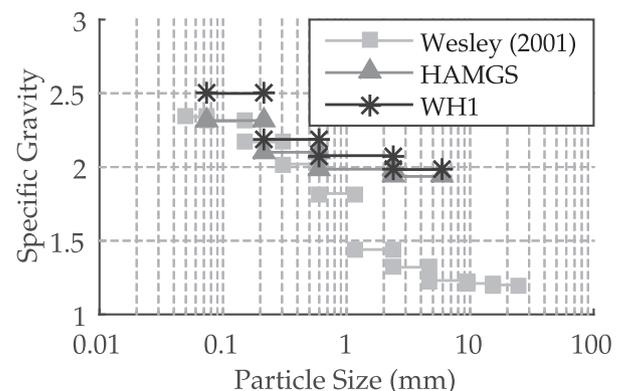


Fig. 4. Specific gravity of pumice particles.

came from the “milled” pumice - a product where naturally mined pumice is ground and then sieved to produce a more uniformly sized product for industrial applications. In this particular material, it was apparent that there was a noticeable amount of two additional components - both having the appearance of crystals and being either black in colour, or transparent and colourless. Similar materials were observed in the gravel sized particles from the sites in Hamilton, and testing on these particles indicated G_s is 2.65–2.67. Hence it is assumed that the higher value of G_s in the milled pumice is a result of the inclusion of these additional crystals. Excluding this result, the G_s of the ground pumiceous materials is 2.35 or less. In addition to the measurements on ground pumiceous material, [Orense and Pender \(2016\)](#) report a solid density (from CT-scanning) of 2.2 g/cm^3 for commercially available pumice grains sourced near the town of Mercer. The values of ground pumice and that of [Orense and Pender \(2016\)](#) are similar to the material density of 2.3 g/cm^3 assumed by [Whitam and Sparks \(1986\)](#) when attempting to estimate the internal void volume of Minoan pumice samples.

2.2. Microstructure of pumiceous soil grains

To better understand the microstructure of these materials, the natural soil from the Grantham street site (HAMGS1) were sorted into size fractions corresponding to fine grained material (i.e. smaller than $75 \mu\text{m}$), fine sand (i.e. $0.075\text{--}0.212 \text{ mm}$), medium sand (i.e. $0.212\text{--}0.6 \text{ mm}$) and coarse sand ($0.6\text{--}2.36 \text{ mm}$) and gravels. These particles were examined using a scanning electron microscope (SEM) and examples are shown in [Fig. 5](#).

The grains in [Fig. 5](#) display some of the commonly observed characteristics of these materials, namely that the surface is extremely irregular as a result of the vesicles. From the largest particles to the smallest particles, the overall characteristics remain similar until the finest materials in [Fig. 5](#), when they started to appear as plates. At the time of taking the SEM photographs, one grain ($\approx 2.2 \text{ mm} \times 1.6 \text{ mm}$) was deliberately split with a scalpel, shown in [Fig. 6](#). Around the area of the cut, there are a number of very small plate like particles on the carbon mounting “dot”, as well as a few fragments on the surface

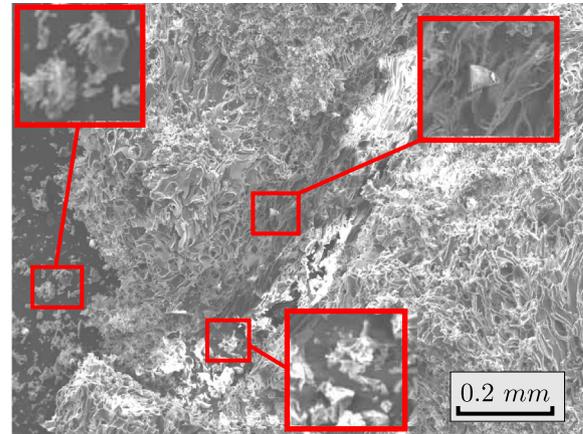


Fig. 6. Split pumice grain. Zoomed view shows fragments of wall structure.

of the cut, two of which are visible in the expanded view. These photos suggest that when the pumice particles are broken to a sufficiently small size (i.e. smaller than $20 \mu\text{m}$), they are mainly composed of broken fragments of the walls between pumice cells.

[Ashby \(1983\)](#) discusses that the strength of a cellular material is significantly lower than the parent material as a result of the fracturing of cell walls. Additionally, it has been shown that the strength of porous ceramics is a function of porosity, with lower porosity materials displaying greater strength (i.e. [Knudsen \(1959\)](#)). [Orense et al. \(2013\)](#) have shown that the crushing strength of pumiceous grains increases with decreasing particle size. It is hypothesised that the low crushing strength of pumiceous soil grains comes as a result of their cellular structure, and that once broken down into platelike fragments the strength of the individual fragments would become significantly larger. Hence if the aim is to identify the effect of pumice content on the engineering properties of a soil (i.e. as a result of the increased compressibility), it may be sufficient to develop a separation technique which concentrates on the coarse silt, sand and gravel sized particles within a soil mixture.

3. Density separation using heavy liquids

Despite the wide range in potential specific gravities of different rocks, the G_s of ground pumice is sufficiently

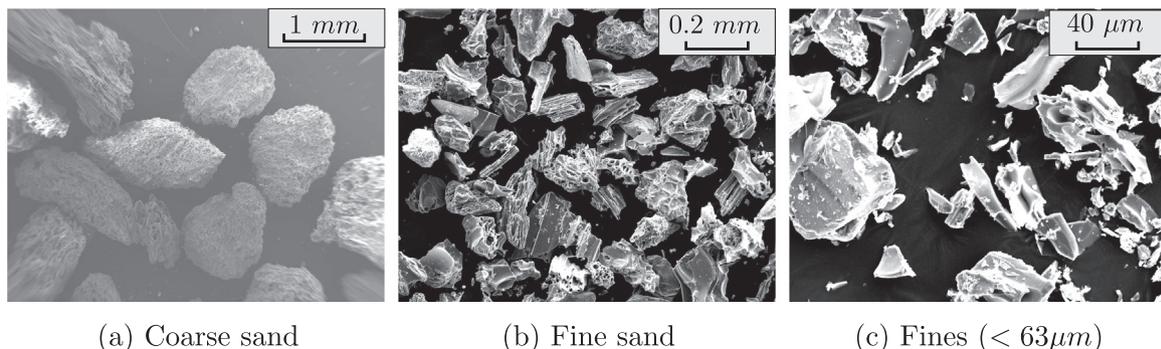


Fig. 5. SEM images of pumiceous grains from Grantham Street, Hamilton.

low that separating the component of pumiceous material from a mixed soil sample remains an attractive approach. In the ideal scenario, the unit weight of the separating fluid would be set just above the mineral density of pumice (i.e. 2.35), and when a soil sample is mixed into the fluid, the pumice component will tend to float (recall also that the G_s of pumice reduces with increasing particle size), while other materials will sink.

Initial approaches considered the use of concentrated brine solutions, however the heavier brines (i.e. Sodium, calcium or zinc bromides) typically have a number of health and safety concerns, making them unsuitable for routine laboratory analysis methods. Attempts were made with lighter brines (i.e. calcium chloride, $G_s \approx 1.4$ at 40% concentration), where the slightly elevated unit weight compared with water might allow separation of similarly sized particles of pumice from other materials due to differences in settling velocity. In this approach, the soils were pre-sieved into different size fractions (by sieving) and then placed in measuring cylinders filled with brine. However, it was found that when soil samples were introduced into the brine solutions, turbulent eddy currents were formed as the soil material settled, which caused a significant proportion of the pumiceous fraction to remain mixed with the non-pumiceous material. Separation of the pumice by “jigging” in a tube filled with calcium chloride brine was attempted using sieved fractions of the soil sample and an example of the resulting separation (medium sand sized particles) is shown in Fig. 7. While some clear sorting has occurred, close inspection revealed that an appreciable amount of pumice remained in the “non-pumiceous” portion and vice versa. This particular experiment had been sieved into size fractions prior to jigging, and it is expected that if the whole sample was tested at the same time, the separation would have been less effective still as a result of the finer non-pumiceous soil grains settling more slowly than the coarser pumiceous grains.

In geological studies, “sink/swim” analyses have been used to separate foraminifera from soil mixtures for many years, traditionally using bromoform as the heavy liquid. The use of bromoform was discontinued when non-toxic aqueous solutions of sodium metatungstate (SPT) became

available, with specific gravities up to 3.1 (Gregory and Johnston, 1987; Munsterman and Kerstholt, 1996). More recently, aqueous solutions of lithium heteropolytungstates (LST) have been used, and as described by Leipe et al. (2018), they have two advantages over SPT: first, they are thermally stable above 60 °C, such that their density can be quickly increased by boiling to evaporate excess water. Second, they have a slightly lower viscosity, meaning separations occur slightly quicker. In this study, an aqueous solution of lithium heteropolytungstate (LST) was used to perform sink/swim analyses on the soil mixtures. It should be noted that LST solutions react with metals to form a dark blue coloured solutions. To avoid this, the experiments are carried out with glassware.

A glass separating cylinder was fabricated at the University of Canterbury, as shown in Fig. 8. The main body of the separating cylinder is approximately 180 mm high and 45 mm inside diameter. A spout is fashioned near the top of the cylinder, with inner diameter 16 mm, while a stopcock is placed at the base. A side arm (extending above the top of the main cylinder body by approximately 35 mm) is placed approximately half-way up the body of the cylinder with an inner diameter of 7 mm. Additionally, a modified glass stirring rod was made where the end of the rod was pressed into a paddle shape.

During the experiments, the density of the LST solution was set at 2.35 kg/l by dissolving concentrated LST solution (supplied at $G_s = 2.85$) with deionised water (DI). The density of the solution was verified using a hydrometer, and at the specific gravity of 2.35, the kinematic viscos-

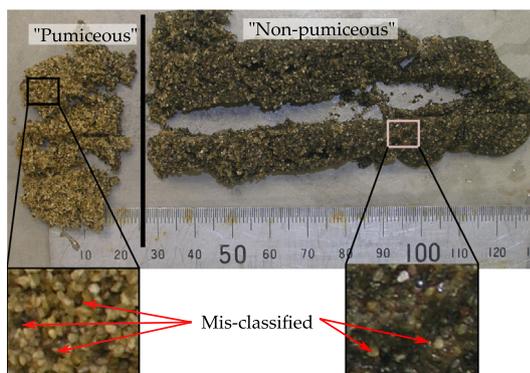


Fig. 7. Separation of pumice by “jigging”.

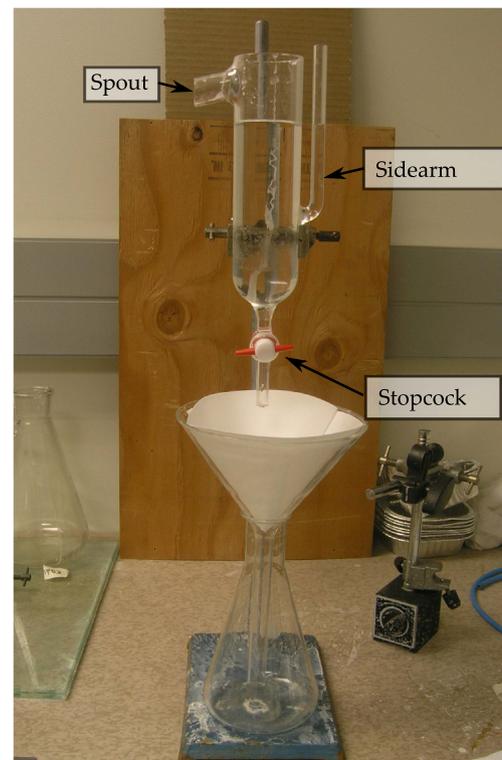


Fig. 8. Glass separating cylinder.

ity was estimated (by measuring the velocity of falling soda glass spheres) as 2.86 cSt. The solution was added to the separating cylinder such that it filled approximately half of the cylinder. At this point, a 25 g or 50 g soil sample was added to the solution, thoroughly mixed using a stirring rod and left for 1 h. The cylinder was then slowly filled via the side arm so that a gap of approximately 1 cm was left below the spout. This second filling allows material which has floated inside the side arm to be washed back in the main chamber. If the soil is prevented from entering the side arm (i.e. placing a porous plastic filter at the base of the side arm, attaching filter paper across the base of the side arm, or redesigning the sidearm geometry) then the second filling stage would not be necessary. At this point, a clear separation of the sunken components and floating components would typically be apparent. It is possible that in the initial separation of the material, some pumice may become trapped in the sinking grains, while some non-pumiceous material may have become trapped in the floating grains. Hence, the raft of pumiceous material and the sunken material were both stirred gently to release any trapped grains. The soil was again allowed to separate for at least 4 h. Photos showing the separation of KM04 are shown in Fig. 9 and the clear separation of material is visible. It should be noted that there is some pumice in the side arm of this experiment. This material can be moved into the main body of the cylinder by the addition of more LST solution through the side arm, or placing a filter at the base of the side arm.

Soil was removed from the device in one of two ways, depending on the perceived grain size of the materials. In cases where the sinking material did not contain gravels, the separation took place by carefully opening the stop-cock and slowly drawing off both fluid and the material

which had sunk. Where the material contained gravel sized particles, it was not possible to draw the soil through the stop-cock, hence additional fluid was added via the side arm to raise the fluid level such that floating material would exit the cylinder via the spout. In the case of larger floating material (i.e. gravel sized pumice grains), the paddle on the end of the modified stirring rod was used to push the large particles into spout, whereafter the flow of fluid would carry the particles out of the spout.

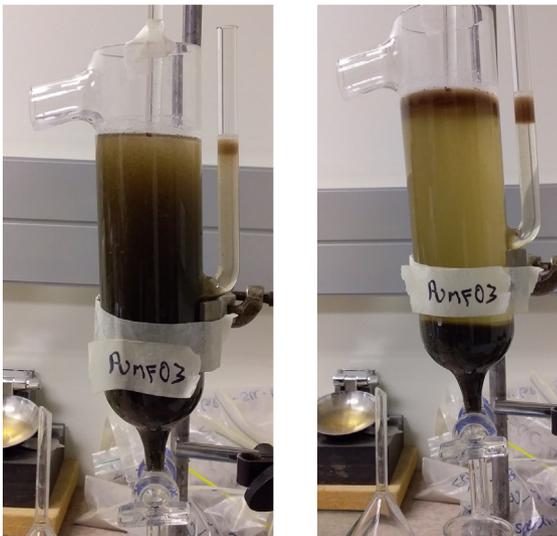
The LST solution used in these experiments is relatively expensive (approximately \$ 1000/l) so that a key element of these tests is the recovery of the LST. Whether the final separation takes place through the spout or stop-cock, the material is captured in a funnel lined with filter paper which has a pore size of 11 μm . The fluid which passes the filter is considered “clean” and can be directly re-used in the next analysis. After storing the “clean” LST fluid, the filter paper and contents are rinsed a further 3 times using DI water. In each rinse, the filter cone is filled, and allowed to completely empty prior to refilling. It should be noted that the rinse water contains an appreciable quantity of LST, hence this solution should be captured, stored and eventually concentrated (i.e. by evaporation in a soil oven) for re-use.

The remaining fluid and either floating or sunk material in the separating cylinder can then be carefully transferred to another filter cone, and treated in a similar way. The rinsed filter papers and soil grains are placed in a beaker and allowed to completely dry in a soil oven for 24 h at 105 °C. The masses of the pumiceous soil grains ($M_{floating}$) and the remaining soil ($M_{sinking}$) can then be obtained and used to obtain the percentage of pumice by mass (P) of the sand and gravel portion using Eq. (1).

$$P = \frac{M_{floating}}{M_{floating} + M_{sinking}} \quad (1)$$

The dilute LST solution from the rinse water is transferred to a large volume beaker (i.e. 5 l) and periodically placed in a conventional soil oven to concentrate the solution so that the G_s is greater than 2.35. At this point the solution can be re-diluted to $G_s = 2.35$ using DI water. In cases where all of the fluid is evaporated, the LST will crystallise, but can be re-dissolved in DI water.

The aim of the filtration is to return the LST to its virgin state. If particles smaller than 11 μm are present within the soil, then they may pass through the filters and begin to contaminate the LST solution. As previously noted, the strength of pumiceous particles increases with reducing size so that pumice “fines” may play a lesser role in affecting the behaviour of a pumice bearing material compared with the larger particles. Hence in this method, it is recommended that the finest soil particles are removed from the sample prior to separation by wet sieving. If a user specifically wishes to retain silt sized particles (or if the soil sample contains a significant proportion of fines), it would be possible to wash the soil sample over a filter paper which is slightly coarser than the final filtration used to recover the LST.



(a) Start

(b) End

Fig. 9. Separation of KM04.

Note that in this paper, the soil samples were not pre-filtered, and there was no noticeable deterioration of the LST from the retention of fine grained material passing through the filter paper.

4. Separation of artificial soil mixtures

To test the efficacy of the method, a series of soil mixtures were created using commercially available milled pumice (C-FMP) and New Brighton sand (NBS). The particle size distributions for these two materials are shown in Fig. 3, while the compositions of the soil mixtures are shown in Table 2. The separation of materials occurs due to the density difference of the materials relative to the fluid density. As shown in Fig. 4, the apparent G_s of the material reduces as particle diameter increases. Stoke's law (Eq. (2)) governs the speed at which particles settle and examination of Eq. (2) indicates that the most challenging situation in terms of separation occurs with small sized particles with the lowest difference in specific gravity relative to the fluid. For this reason, a “fine” grade of milled pumice was selected.

$$v = \frac{2}{9} \frac{\rho_s - \rho_f}{\mu} gR^2 \quad (2)$$

where v : settling velocity, ρ_s : density of solid, ρ_f : density of fluid, μ : dynamic viscosity, g : acceleration due to gravity, R : particle radius.

In order to create a separation of the materials, any pumice in the bottom half of the separating cylinder should have moved to the top half, and vice versa. For the dimensions of the separating cylinder, a clear separation would be observed with a settling distance of 100 mm. Assuming that the solid phase of the pumice particles have a specific gravity of approximately 2.3, then with the kinematic viscosity of 2.9 cSt, it is possible to estimate the smallest particle that will have “separated” in the mixture after a given time. For the tests being described, there would be separation of particles greater than 27 μm after 4 h.

Table 2 summarises the tests on known mixtures, expressing the pumice content as a percentage of the total soil mass. In some cases the final total mass of soil after the experiment is slightly larger than the initial mass. This observation implies that in those tests, there was a limited amount of LST that was not properly filtered out of the material. The amount of pumice being measured is consis-

tently lower than that in the original mixture, and is particularly obvious in the case of KM01, where the mixture was 100% milled pumice. During the separation with KM01, it was apparent that the sinking portion of KM01 was visibly different to the floating portion, appearing as either black crystals or clear, colourless crystals. Careful examination of the raw milled pumice revealed the existence of both components. These crystals (often volcanic quartz) are not uncommon and are found as phenocrysts within pumice grains (Fisher and Schminke, 1984; Hume et al., 1975). In undisturbed sampling carried out by the authors (in Hamilton and Whakatane), these crystals were also observed within the soil samples, often as individual soil grains. It is assumed that these particles would typically be attached to (or incorporated within) a large pumice particle, but that during the milling to reduce the particle sizes, these can become detached, or form a significant proportion of the smaller sand sized grains. The specific gravity of the volcanic glasses/quartz in the undisturbed specimens was 2.65 and hence they would be expected to sink in the LST solution with G_s equal to 2.35. Accepting that the sinking portion of KM01 is composed of these crystal particles, then the starting mass of pumice should be decreased by 16% in each of the tests, and the mass of the non-pumiceous component increased by the corresponding amount. The “corrected” starting pumice content is shown in Table 2 and agreement within 3% is obtained for all of the separated mixtures.

SEM photography was carried out on both the sinking and floating components of the material in KM01, with representative photos shown in Fig. 10. An SEM image of the New Brighton sand is shown for comparison in Fig. 11. On initial inspection it was surprising that the components of KM01 are not more obviously different. However, on close inspection, it is apparent that the grains from the floating component have internal voids which are visible on many of the particle faces, as well as a number of the grains displaying the expected surface vesicularity. In general these features were not apparent on the particles in the sinking component, which appear to have smooth faces, devoid of vesicles. It should be noted that a small number of particles in the sinking component did however have some vesicles, meaning that there is some minor mis-separation. However, within the context of engineering requirements, the accuracy of the method is considered satisfactory.

Table 2
Separation of known mixtures of fine milled pumice (C-FMP) and New Brighton sand (NBS) using LST solution with $G_s = 2.35$.

ID	Mass of soil (g)		Pumice Content (%)			Error (%)
	Initial	Final	Initial	Corrected	Separated	
KM01	25.1	25.3	100	84	84	0
KM02	50.0	49.9	75	63	64	1
KM03	50/0	49.8	50	42	39	-3
KM04	50.0	50.2	25	21	20	-1
KM05	50.0	25.2	0	0	0	0

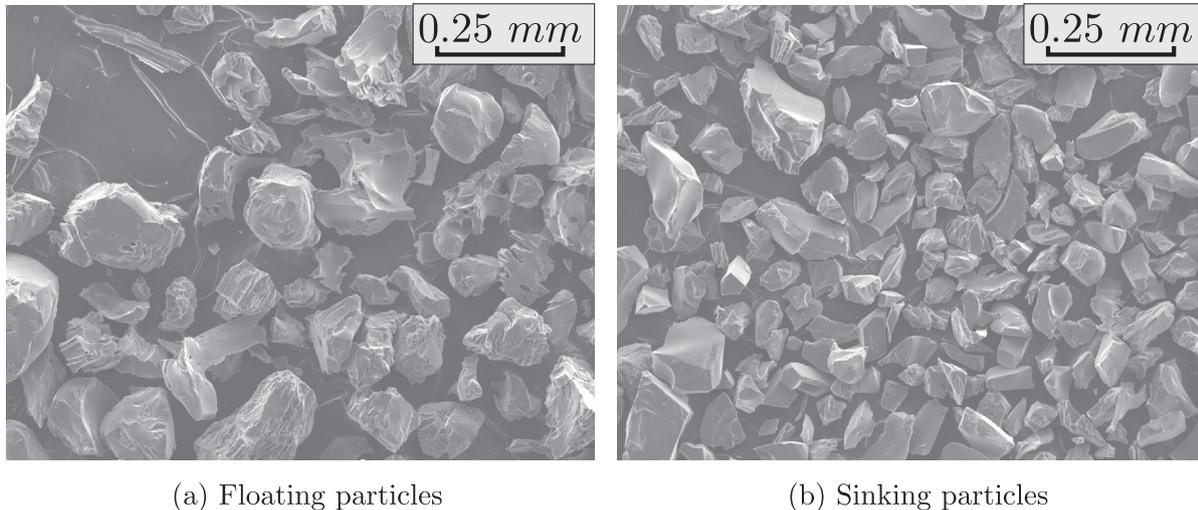


Fig. 10. SEM photographs showing separated components of “milled” pumice” from KM01.

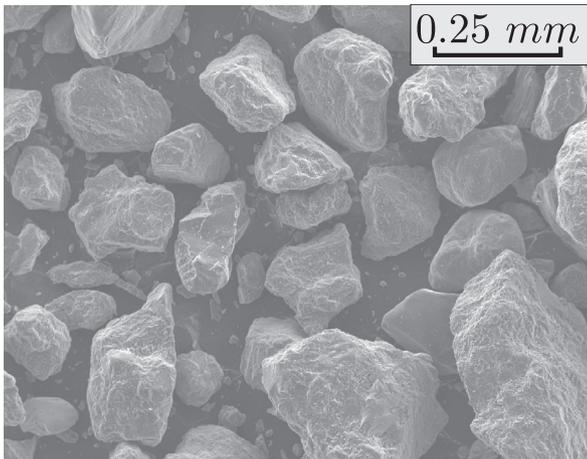


Fig. 11. SEM photograph of New Brighton Sand (non-pumiceous).

A key question to consider is how sensitive the results of the method are to the specific gravity being selected. The decision to use a fluid with G_s equal to 2.35 was based on the specific gravities of ground pumice material listed in Table 1. It is now understood that there can be small crystals of volcanic glass/quartz attached to particles of pumice. If the pure pumice material were to have a specific gravity of approximately 2.30, and the glass/quartz a specific gravity of 2.65, then once a particle has more than about 15% quartz/glass (by mass) and is ground up, it would be expected to have a specific gravity more than 2.35, and would be classified as non-pumiceous. This is oversimplified in the sense that the presence of voids within the particle will have an important effect - if the voids of a particle do not get completely filled with LST, then they will act to reduce the specific gravity of the particle, such that the quartz/glass would need to be a major proportion of the combined particle before it made the particle sink in the LST. It is also the case that in a “typical” pumice particle, the phenocrysts would be expected to take up a small

percentage of the overall volume, such that pumice particles would still have a specific gravity less than 2.35. If the pumice particles get crushed, then it is expected that many of the phenocrysts would also be released, such that they form their own particles, and hence would not be considered pumiceous.

To partially investigate the sensitivity of the separation with the milled pumice to the specific gravity of the fluid, the sinking portion of the soil mixture from KM01 was subjected to additional separations, with the specific gravity being gradually increased each time. These tests (KM01-S1 to KM01-S3 in Table 3) were performed in the same way as before, with the sinking portion being re-used in the next experiment after being dried. From these experiments, it can be seen that as the specific gravity is increased, there is a small amount of additional material which floated, while the majority continued to sink. At $G_s = 2.40$, only an additional 15% of the material which sank at an G_s of 2.35 became floating. This implies that $G_s = 2.35$ is a reasonable choice for this method.

5. Separation of natural materials

In the previous section, artificial mixtures of commercially available “milled” pumice and natural soil from Christchurch (non-pumiceous) were separated using the LST solution. To check the performance of the method for more realistic soil mixtures, an additional set of separations were undertaken using the HAMTR1 and WH1 soil samples. The results of these separations are shown in Table 4, and included three independent tests on the HAMTR1 material. As shown, the tests on the HAMTR1 material show agreement within 2% for the three samples, highlighting the good repeatability of this method.

After performing the separations, a series of SEM photographs were taken on the floating and sinking portions respectively, with representative photographs shown in

Table 3
Separations with increasing fluid G_s .

ID	Fluid G_s	Starting Mass (g)	Separated Mix (g)		Description
			Floating	Sinking	
KM01	2.35	25.1	21.3	4	
KM01-S1	2.40	3.7	0.57	3.13	Sinking fraction of KM01
KM01-S2	2.45	3.1	0.24	2.74	Sinking fraction of KM01-S1
KM01-S3	2.50	2.7	0.25	2.62	Sinking fraction of KM01-S2

Table 4
Separation of natural soil samples.

ID	Location	Depth (m)	Initial Mass (g)	Separated Mix (g)		Pumice (%)	
				Floating	Sinking	P_{11}	P_{75}
HAMTR1	Hamilton	12.5	54.3	18.5	35.9	34.0	34.0
			43.6	14.1	29.1	32.6	32.6
			42.5	14.9	28.3	34.5	34.5
WH1	Whakatane	5.5	50.0	24.1	25.9	47.8	47.8

Note: depths refer to the location of the soil sample below the ground surface.

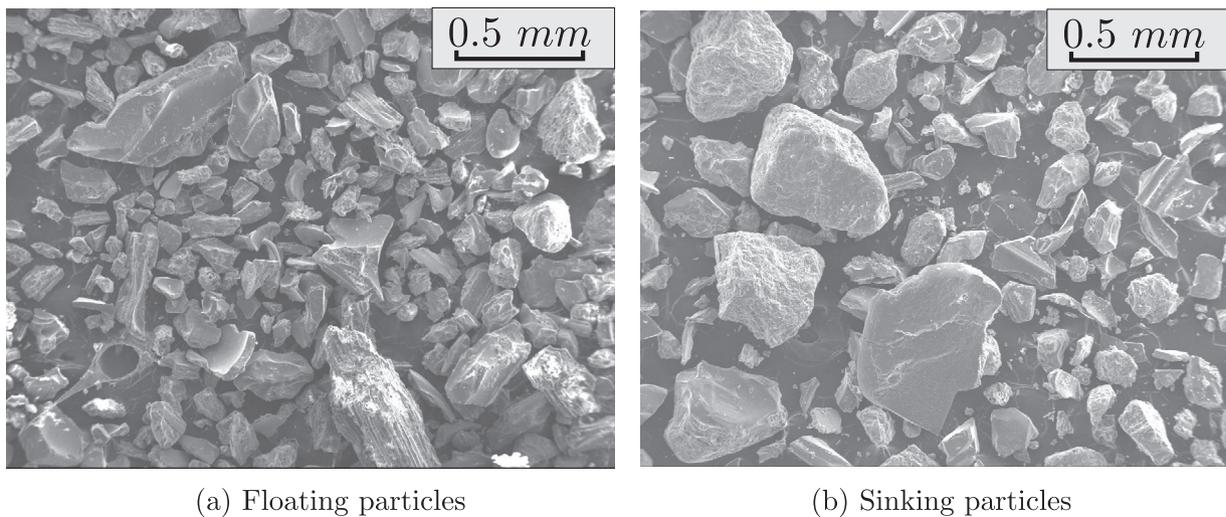


Fig. 12. SEM photographs showing separated components of natural sample from Hamilton site, HAMTR1.

Figs. 12 and 13. Image comparisons must always be qualitative, however it is clear that there are marked differences in the appearances of the grains in the floating and sinking images. In the case of the floating particles, it is observed that there are a number which show the highly vesicular nature previously shown in Fig. 5. There are also particles which don't display the obvious vesicularity, but appear highly curved and plate-like, with many appearing to have features which make the particles appear like the fragments of a broken cellular structure. These particles match the "bubblewall shards" description of Fisher and Schminke (1984). On the other hand, the sinking particles appear to have surface texture similar to the New Brighton sand (i.e. Fig. 11) or to be smooth and lacking the vesicularity displayed by the floating particles. Similar to the artificial mixtures, there appear to be a small number of particles

which might be thought of as being pumiceous but sinking, or non-pumiceous and floating. However, the number of these particles is generally small. The photos therefore appear to show that the separation technique has successfully separated the lightweight pumiceous grains from the main soil sample.

Having successfully separated the pumice material from the soil mixture, it is possible to consider the particle size distributions of the pumiceous and non-pumiceous components, as well as their relative proportions. This however raises an interesting point that should be considered by engineers and researchers alike. Namely, that it is generally assumed that the particle size distributions by mass are equivalent to size distributions by volume. If however, there are significant differences in the specific gravities of the constituent particles, then this equivalence is lost. This

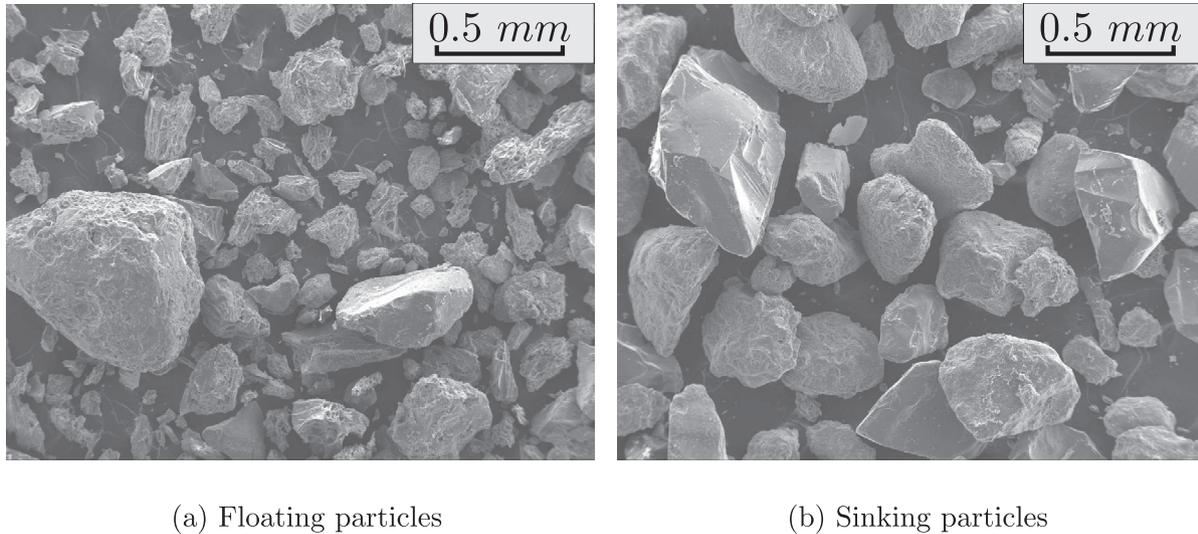


Fig. 13. SEM photographs showing separated components of natural sample from Whakatane site, WH1.

is particularly the case for pumice-rich deposits, and it may be necessary to consider whether proportions by mass are the best basis for comparison.

It is important to recall that in the separation of artificial soil mixtures, it was estimated that after 4 h, only particles greater than 27 μm would be expected to have separated in the cylinder. On the basis of the increasing particle strength with reducing diameter, and the desire to preserve the purity of the LST solution, it was recommended that the materials be wet-sieved or filtered prior to performing the separation. For materials wet-sieved to either 63 μm or 75 μm , it is recommended that the separation time be at least 2 h. For materials filtered to approximately 30 μm , the separation time should be at least 4 h, and materials filtered to 11 μm should have a separation time of 24 h.

When presenting the results, it is essential that users state the diameter of the sieve or filter used in the initial steps, hence the parameter P should be followed by the sieve or filter size in microns (i.e. results on materials filtered to 11 μm would be represented by P_{11} .) Note that for unfiltered materials, the final filtration will be an implicit filter, hence for these tests where the material was not pre-filtered, the appropriate parameter is P_{11} due to the washing of the material over an 11 μm filter paper. Given the prevalence of “fines” in geotechnical engineering practice, it is recommended that the parameter P_{75} be stated for all tests. Users retaining smaller particles than 75 μm may calculate P_{75} by sieving the dried components to determine the percentage of pumice which would have been obtained if wet sieving had been performed with a 75 μm sieve. In the cases of the natural materials tested here, the fines contents of the WH1 sample was 0.8% and 0.6%, while the HAMTR1 sample had fine contents of 4.2% and 4.5% for the pumiceous and non-pumiceous components respectively. The similarity in the fines contents for the pumiceous/non-pumiceous materials meant that there is

no difference between the values of P_{11} and P_{75} in these cases.

It should be noted that over time it is possible for small amounts of fine grained material (i.e. those which weren't fully removed in the wet-sieving or initial filtration stages) to accumulate in the “cleaned” LST. As part of the procedure, the specific gravity of the LST solution is adjusted before separation, such that the separation itself is not affected by these fine particles. However, these very fine grained particles may then be retained in a future soil sample, such that they might begin introduce an error into future analyses. These fine grained particles can be removed by centrifugation followed by careful decanting of the clean liquid. During this process, pumice particles could potentially float, so it is recommended that centrifugation is performed after diluting the LST solution to a specific gravity of a maximum 2.0 so that all particles will sink. The purified LST can then be placed in an oven to increase the specific gravity as required.

The soils tested in this paper were typically dominated by sand and fine gravel sized particles, hence a representative sample can be obtained with relatively small amounts of material (i.e. 50 g for natural soils) due to the binary result of the test. The separation technique described in this paper will work for mixtures containing coarser gravels, however the sample size will need to be increased to ensure a representative value is obtained. If larger samples sizes are being used, then the physical size of the separating device will need to be increased.

Finally, the method has only been tested on New Zealand soils, in a relatively limited number of locations, hence when using this method in a new area, researchers should pay attention to whether there are unexpected components (i.e. mis-classification of the grains) in either the floating or sinking portions of the mixture. Prior to using this technique for the first time in a new area, it is recommended

that users measure the specific gravity on a small sample of hand-separated, crushed pumiceous grains. If the specific gravity of the crushed pumiceous grains is larger than 2.3, then the specific gravity of the LST solution in the analysis should be raised.

6. Conclusions

In this paper, a gravity separation technique using aqueous solutions of LST has been proposed for the quantitative determination of pumice content by mass in the sand and gravel fraction of soil mixtures. A high-level summary of the method is shown in Fig. 14.

The method has been developed for mixtures containing predominantly sand to fine gravel sized particles, but can also be applied to soils containing coarser gravel components. A sample size of 50 g is recommended for sand-fine gravel mixtures, and a repeatability of $\pm 1\%$ was obtained for a natural mixture using this sample mass.

In the development of the method, it was found that the specific gravity of ground pumice samples taken from a number of locations across New Zealand was typically less than 2.35, though the presence of volcanic quartz/glass

within the pumice grains could act to increase the apparent specific gravity. A specific gravity of 2.35 was therefore adopted in this paper, though when the technique is being applied in a new region or to previously untested deposits users may need to adjust the specific gravity to suit local conditions.

The method requires that the samples separate over a period of time, and it is recommended that the final separation take place over a minimum of 2 h for materials washed across a 63 μm or 75 μm sieve. Materials which have been filtered to include particles up to 30 μm should be allowed to separate for at least 4 h, and materials filtered to 11 μm should separate for 24 h. In sieving or filtering the material, the method explicitly estimates the percentage of pumice in the part of the distribution coarser than the finest particles and the P parameter should include the minimum particle size as a subscript. The direct or back-calculated P_{75} parameter should be reported for all tests. For the natural materials tested in this paper, there was no difference between the P_{11} and P_{75} values.

The technique has been applied to a series of known mixtures of commercially available “milled” pumiceous material and non-pumiceous beach sand. After correcting for the presence of the volcanic (quartz) crystals, it was found that the method was able to separate pumiceous material from mixtures of fine sands with an apparent accuracy of around 3%.

The presence of phenocrysts (volcanic quartz) within grains of pumice can increase the specific gravity of the pumice grain, and pumice grains which contain a significant proportion of quartz will not be included within the “pumice” fraction of the soil using the proposed technique. In the artificially milled pumice particles tested, the uniform fine sand particle size accentuated this error and increasing the specific gravity of the LST solution towards 2.65 caused an increasing proportion of these grains to float. SEM photographs of the natural soils collected by the author to date suggest that this is not a major source of error for unprocessed materials.

Confidence in the method has been gained through the examination of SEM photographs of the sinking and floating components of artificial and natural soil mixtures. The photographs showed that the majority of floating particles contain features associated with pumice soil grains (i.e. presence of voids/or ridge features which suggest that the grain previously formed part of a larger pumiceous particle), while photos of the sinking grains tended to be dominated by particles without obvious internal pores or ridge structures, suggesting successful separation of the pumiceous component.

It is expected that this method will be used by practicing engineers as part of routine site characterisation in pumiceous deposits, where existing in situ characterisation techniques (such as the CPT) may require different interpretation depending on the pumice content.

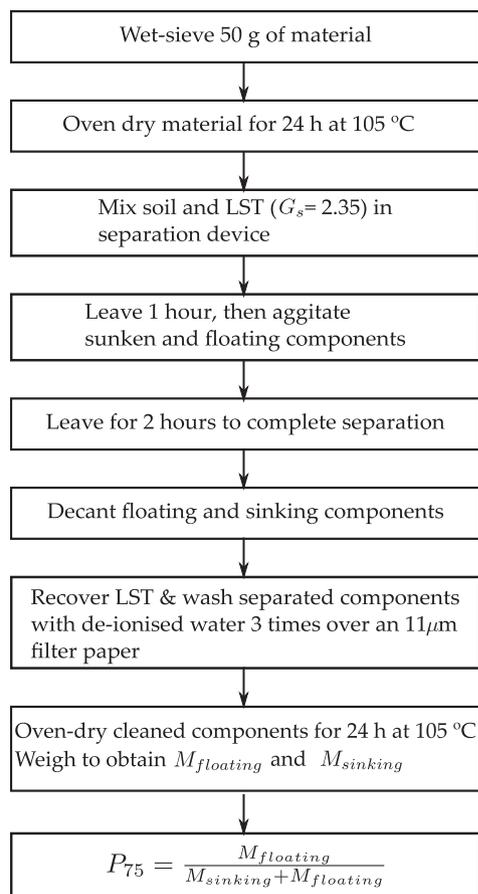


Fig. 14. High-level summary of proposed method for determining pumice content by mass.

Acknowledgements

The author would like to acknowledge the technical staff at the University of Canterbury, and in particular Rob McGregor for fabricating the separating cylinder, and Chris Grimshaw for discussions and demonstration regarding the use of heavy liquids in geology. Additionally, the author would like to thank Prof. Cubrinovski, Assn. Prof. Orense and the reviewers of this paper for their helpful suggestions and advice.

This project was partially supported by QuakeCoRE, a New Zealand Tertiary Education Commission-funded Centre. This is QuakeCoRE publication number 0333. Additional support was provided by the University of Canterbury.

References

- Asadi, M., Orense, R.P., Asadi, M., Pender, M.J., 2019. Maximum dry density test to quantify pumice content in natural soils. *Soils Found.* 59 (2), 532–543.
- Ashby, M.F., 1983. Mechanical properties of cellular solids. *Metall. Trans., A, Phys. Metall. Mater. Sci.* 14 A (9), 1755–1769.
- ASTM, 2014. Standard test methods for specific gravity of soil solids by water pycnometer. D854-14. West Conshohocken, PA.
- Fisher, R., Schminke, H., 1984. *Pyroclastic Rocks*. Springer-Verlag, Berlin Heidelberg, Germany.
- Gregory, M.R., Johnston, K.A., 1987. A nontoxic substitute for hazardous heavy liquids - aqueous sodium polytungstate ($3\text{Na}_2\text{WO}_4 \cdot 9\text{WO}_3 \cdot \text{H}_2\text{O}$) Solution. *NZ J. Geol. Geophys.* 30 (3), 317–320.
- Hardin, B.O., 1985. Crushing of soil particles. *J. Geotech. Eng.-ASCE* 111 (10), 1177–1192.
- Hume, T.M., Sherwood, A.M., Nelson, C.S., 1975. Alluvial sedimentology of the upper pleistocene hinuera formation, hamilton basin, New Zealand. *J. Roy. Soc. New Zealand* 5 (4), 421–462.
- Hyodo, M., Hyde, A.F.L., Aramaki, N., 1998. Liquefaction of crushable soils. *Géotechnique* 48 (4), 527–543.
- Ishikawa, T., Tokoro, T., Miura, S., 2016. Influence of freeze–thaw action on hydraulic behavior of unsaturated volcanic coarse-grained soils. *Soils Found.* 56 (5), 790–804.
- Knudsen, F.P., 1959. Dependence of mechanical strength of brittle polycrystalline specimens on porosity and grain size. *J. Am. Ceram. Soc.* 42 (8), 376–387.
- Leipe, C., Kobe, F., Müller, S., 2018. Testing the performance of sodium polytungstate and lithium heteropolytungstate as non-toxic dense media for pollen extraction from lake and peat sediment samples. *Quatern. Int.*
- Manville, V., 2002. Sedimentary and geomorphic responses to ignimbrite emplacement: Readjustment of the Waikato River after the AD 181 Taupo Eruption, New Zealand. *J. Geol.* 110 (5), 519–541.
- Matsumura, S., Miura, S., Yokohama, S., Kawamura, S., 2015. Cyclic deformation-strength evaluation of compacted volcanic soil subjected to freeze-thaw sequence. *Soils Found.* 55 (1), 86–98.
- Miura, S., Yagi, K., Asonuma, T., 2003. Deformation-strength evaluation of crushable volcanic soils by laboratory and in-situ testing. *Soils Found.* 43 (4), 47–57.
- Munsterman, D., Kerstholt, S., 1996. Sodium polytungstate, a new non-toxic alternative to bromoform in heavy liquid separation. *Rev. Palaeobot. Palynol.* 91 (1–4), 417–422.
- Orense, R.P., Pender, M.J., 2016. From micro to macro: An investigation of the geomechanical behaviour of pumice sand. *Volcanic Rocks Soils*, 45–62.
- Orense, R.P., Pender, M.J., Hyodo, M., Nakata, Y., 2013. Micro-mechanical properties of crushable pumice sands. *Géotech. Lett.* 3, 67–71.
- Rogers, J., Sanderson, F., 1954. The separation of pumice from sand. *NZ Eng.* 9 (4), 106–109.
- Senetakis, K., Anastasiadis, A., Pitilakis, K., 2013. Normalized shear modulus reduction and damping ratio curves of quartz sand and rhyolitic crushed rock. *Soils Found.* 53 (6), 879–893.
- Senetakis, K., Madhusudhan, B.N., Anastasiadis, A., 2016. Wave propagation attenuation and threshold strains of fully saturated soils with intraparticle voids. *J. Mater. Civ. Eng.* 28 (2).
- Wesley, L.D., 2001. Determination of specific gravity and void ratio of pumice materials. *Geotech. Test. J.* 24 (4), 418–422.
- Wesley, L.D., Meyer, V., Prantoto, S., Pender, M.J., Larkin, T.J., Duske, G., 1999. Engineering properties of a pumice sand. In: Vitharana, N., Colman, R. (Eds.), . In: 8th ANZ Conference on Geomechanics, vol. 2. Australian Geomechanics Society, Hobart, Australia, pp. 901–907.
- Whitam, A., Sparks, R., 1986. Pumice. *Bull. Vulcanol.* 48, 209–223.