Numerical analysis of the effects of vesicle distribution characteristics on the engineering properties of volcanic rocks

Pallewela Liyanage, Piyal wasantha, Heng, Zhen and Xu, T (2023) Numerical analysis of the effects of vesicle distribution characteristics on the engineering properties of volcanic rocks. Journal of Rock Mechanics and Geotechnical Engineering, 15 (12). pp. 3094-3104. ISSN 1674-7755

Journal of Rock Mechanics and Geotechnical Engineering 15 (2023) 3094–3104

Contents lists available at ScienceDirect

Journal of Rock Mechanics and Geotechnical Engineering

journal homepage: www.jrmge.cn

Full Length Article

Numerical analysis of the effects of vesicle distribution characteristics on the engineering properties of volcanic rocks

P.L.P. Wasantha [a,b,*], Z. Heng [c], T. Xu [c]

[a] College of Sport, Health and Engineering, Victoria University, Melbourne, VIC, 3011, Australia
[b] Institute for Sustainable Industries and Liveable Cities, Victoria University, Melbourne, VIC, 3011, Australia
[c] Center for Rock Instability and Seismicity Research, Northeastern University, Shenyang, 110819, China

ARTICLE INFO

Article history:
Received 27 November 2022
Received in revised form
27 May 2023
Accepted 9 July 2023
Available online 22 August 2023

Keywords:
Vesicular rocks
Porosity
Vesicle size and distribution
Numerical simulation
Mechanical characteristics

ABSTRACT

Vesicles can be of different sizes and shapes and can be randomly distributed within vesicular volcanic rocks. This study investigates the variation of engineering properties of vesicular rocks due to the changes in vesicle distribution characteristics for different cases of bulk porosity and vesicle diameter using a systematic numerical simulation program using the finite element method-based rock failure process analysis (RFPA) software. Models with uniform-size vesicles and combinations of different proportions of different-sized vesicles were considered to resemble natural vesicular rocks more closely, and ten different random vesicle distributions were tested for each case. Increasing bulk porosity decreased the uniaxial compressive strength (UCS) and elastic modulus of the specimens, and the specimens with the lowest bulk porosity showed the greatest range of UCS values in the case of uniform-size vesicles. The effect of vesicle diameter on UCS showed an unsystematic response which was understood to be a result of different vesicle distribution patterns, some of which facilitated a shear failure. Specimens with multiple-size vesicles in different proportions revealed that the variation of UCS due to vesicle distribution characteristics is minimum when the bulk porosity is equally shared by different size vesicles. In addition, when the proportion of smaller-sized vesicles is higher, UCS showed an increase compared to that of the equal proportion of different size vesicles case at low porosities, but a decrease at higher porosities. Variation of elastic modulus showed minor, unsystematic fluctuations as a function of vesicle diameter and different proportions of different-sized vesicles, and the range for different vesicle distribution patterns was narrow in general. Overall, the findings of this study recommend cautious use of the engineering properties determined through a limited number of laboratory tests on vesicular rocks.

1. Introduction

Depressurisation associated with magma ascending causes abundant bubble nucleation and growth in the melt, which is commonly known as magma vesiculation. The vesiculation process has key controls on the eruption process and physical and geological characteristics of volcanoes (Toramaru, 1989; Navon and Lyakhovsky, 1998; Gondé et al., 2011). The bubbles that fail to escape from the melt during solidification are preserved in volcanic rocks in the form of vesicles. In general, the porosity of volcanic rocks resulting from vesicles is higher in moderate-to fast-ascending magma as the outgassing has only a little time, whereas slow-ascending magma permits greater outgassing leading to low porosity (Heap et al., 2014a).

The size, number (or number density), and shape of vesicles in volcanic rocks are a manifestation of magma ascend conditions and associated vesiculation attributes. The resulting porosities of volcanic rocks and magma could range from as low as almost 0% to as high as almost 100%, and the vesicle sizes can be a few tens of microns to a few mm in diameter (Kueppers et al., 2005; Wright et al., 2009; Heap et al., 2014a). Fig. 1 shows a vesicular basalt core specimen obtained from a site west of Melbourne, Victoria, Australia, showing different sizes and shapes of natural vesicles. Several techniques have been used in the literature to obtain the

* Corresponding author. College of Sport, Health and Engineering, Victoria University, Melbourne, VIC, 3011, Australia.
E-mail address: wasantha.pallewelaliyanage@vu.edu.au (P.L.P. Wasantha).

Peer review under responsibility of Institute of Rock and Soil Mechanics, Chinese Academy of Sciences.

https://doi.org/10.1016/j.jrmge.2023.07.005
1674-7755

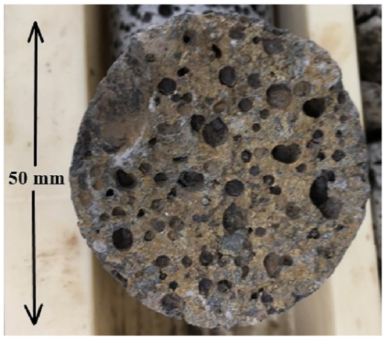

Fig. 1. A vesicular basalt core specimen from the west of Melbourne, Victoria, Australia, showing different sizes and shapes of vesicles.

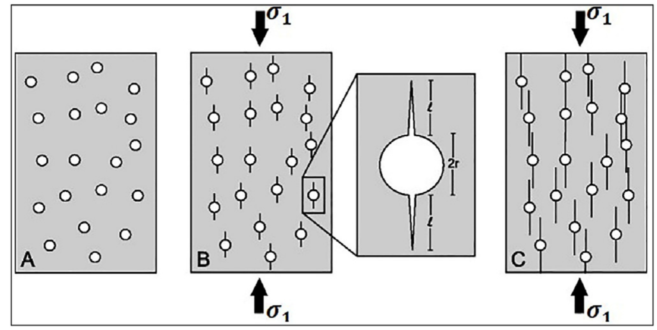

Fig. 2. The pore-emanating crack model of Sammis and Ashby (1986) for a 2D elastic medium populated with circular pores of a uniform radius r (modified after Heap et al., 2014a).

pore size distribution of rock. These include the fluid displacement method, water vapour adsorption/desorption isotherm, mercury intrusion porosimetry, image analysis, nitrogen absorption, small angle X-ray scattering, scanning electron microscopy, helium pycnometer, air porosimetry and resin impregnation (Kate and Gokhale, 2006). Numerous previous studies have attempted to correlate the measured size, number, and shape of vesicles with the mechanisms of volcanic eruptions and processes of subsequent solidification and rock formation (e.g. Blower et al., 2001; Moitra et al., 2013; Polacci et al., 2006; Proussevitch et al., 2007; Shea et al., 2010; Moitra et al., 2013). Besides, the heterogeneous nature of rock masses complicates the mechanical behaviour of rocks under applied stress and influences short- and long-term stability. Discontinuities within rock masses, such as pores or vesicles, cracks, joints, and bedding, can significantly affect the engineering properties of strong rocks (Wasantha et al., 2014; Abdollahipour et al., 2016; Haeri et al., 2020; Liu et al., 2022). Therefore, the vesicles and their characteristics, such as size/diameter, shape, density/bulk porosity, inevitably influence the micromechanics, damage evolution and macroscopic failure of volcanic rocks leading to marked variations in their engineering behaviour (Heap and Violay, 2021). This knowledge is essential for the safe design of rock structures on or within volcanic rocks. In addition, low porous volcanic rocks are used as construction materials, e.g. basalt as coarse aggregates in concrete and as a pavement subbase material. Therefore reliable estimation of their engineering properties, as dictated by the presence of vesicles, is essential for the designs of such applications.

Mechanical properties of rocks, such as uniaxial compressive strength (UCS) and elastic modulus, are of critical importance to the safe design of rock structures (Cemiloglu et al., 2023). Porosity is one of the parameters that exert a first-order control on the physical and mechanical properties of rocks, including volcanic rocks (Ji et al., 2006, 2019; Yu et al., 2016; Heap and Violay, 2021; Ng and Santamarina, 2022). The pore-emanating crack model of Sammis and Ashby (1986), which was developed based on fracture mechanics and beam theory, describes the micromechanics of macroscopic failure of a two-dimensional (2D) elastic medium populated with circular pores/vesicles of uniform radius 'r' (Fig. 2). As the external compressive stress increases, the pores act as stress concentrators and microcracks emanate from the pores parallel to the applied stress direction, followed by the interaction and coalescence of separate microcracks leading to the macroscopic failure. An analytical approximation of the pore-emanating crack model was derived by Zhu et al. (2010) to estimate the UCS, σ_{UCS} (Eq. (1)). It should be noted that Eq. (1) assumes the vesicles are circular, of uniform radius and initially disconnected.

$$\sigma_{UCS} = \frac{1.325}{\phi^{0.414}} \frac{K_{IC}}{\sqrt{\pi r}} \tag{1}$$

where K_{IC} is the critical stress intensity factor, and ϕ is the bulk sample porosity.

Weakening (i.e. a decrease in mechanical properties such as compressive strength, elastic modulus, and stiffness) of rocks with increasing porosity is expected as the increased void space means a weakened rock skeleton, and the results of numerous previous experimental and numerical studies agree with that (e.g. Al-Harthi et al., 1999; Baud et al., 2014; Heap et al., 2014b; Schaefer et al., 2015; Wong and Peng, 2020; Ng and Santamarina, 2022). In addition to the bulk porosity, the pore diameter is known to decrease the compressive strength and the elastic modulus of rocks (Vasseur et al., 2013; Heap et al., 2014a; Wasantha et al., 2020; Wong and Peng, 2020). Considering the combined effect of porosity and pore diameter, Heap et al. (2014a) found that the role of vesicle diameter in dictating the rock strength is prominent at lower porosities and is less pronounced at porosities above 15% using the 2D rock failure process analysis code (RFPA^{2D}). In the case of multiple sizes of circular vesicles, both Heap et al. (2014a) and Zhang et al. (2018) reported a greater influence of larger vesicles on macroscopic failure and compressive strength. In other words, a rock with a greater proportion of smaller vesicles is stronger than a rock with the same porosity that contains a greater proportion of larger vesicles. While many analytical and numerical studies simplified the vesicle shape to circular to minimise its associated numerical complications, some studies investigated the effect of vesicle shape on the mechanical properties and observed a significant control of vesicle shape on rock mechanical properties. Griffiths et al. (2017) used RFPA^{2D} with elliptical vesicles and found that the effect of vesicle aspect ratio on the strength and stiffness of rocks is vesicle angle dependent, and both UCS and elastic modulus decrease as the vesicle angle, measured from the loading direction, is increased from 0° to 90°. Unsurprisingly, the influence of the vesicle angle diminishes as the vesicle aspect ratio reaches unity, as a vesicle with a unit aspect ratio represents a circular vesicle. The experimental study using vesicular basalt and the accompanying numerical simulations of Bubeck et al. (2017) also observed a significant influence of vesicle shape and orientation on the compressive strength of vesicular rocks.

The locations of the vesicles within the rocks or the vesicle distribution pattern is another factor that affects the engineering properties of vesicular rocks but has scarcely been studied in the literature. The numerical simulations of Zhang et al. (2018) using the universal distinct element code (UDEC) considered a rock sample with a single vesicle, and after changing its location in the sample, they observed that the UCS is significantly lower when the pore is located closer to the edges of the specimen. When the vesicle was located near the centre of the model, the UCS was minimally affected. Fakhimi and Gharahbagh (2011) used a 2D hybrid discrete-finite element program to study the effect of vesicle size and vesicle distribution and observed a significant scatter of UCS, elastic modulus, and crack initiation stress after randomly changing the locations of uniform-size vesicles but keeping the vesicle size and porosity unchanged. The UCS and elastic modulus variations of volcanic rocks as a function of porosity collated by Heap and Violay (2021), based on the published data in the literature, show a greater scatter of UCS and elastic modulus at lower porosity levels (Fig. 3), which could potentially be attributed to the more significant effect of pore distribution patterns at lower porosities.

The mechanical properties of rocks in general engineering practice are determined using a limited number of laboratory tests (1–3 replicates in most cases). In the case of vesicular rocks, these properties could vary significantly based on the vesicle distribution characteristics such that the results of a limited number of tests can be misleading. Therefore, understanding the potential degree of deviation of those properties due to vesicle distribution characteristics from those results is imperative for safe designs of engineering structures, which is inadequate. This study uses the elastic damage mechanics-based RFPA^{2D} code to qualitatively and quantitatively investigate the effects of vesicle distribution characteristics on the engineering properties of vesicular volcanic rocks. In particular, we focus on rocks with various distribution patterns of both uniform- and multiple-size circular vesicles. This enables a more realistic evaluation of the engineering properties of vesicular volcanic rocks and a better understanding of the potential deviations of those properties to more reliably characterise vesicular rocks. The following sections detail and discuss the methods and results.

2. Numerical simulation procedure

The 2D finite element method (FEM)-based code RFPA^{2D}, which can simulate the damage and failure evolution process of quasi-brittle materials (e.g. rock), is used in this study. RFPA^{2D} has been used for various rock mechanics and rock engineering applications in the literature, e.g. failure process of heterogeneous rocks (Wang et al., 2012; Xu et al., 2013), slope stability analyses (Li et al., 2006), dynamic rock failure (Zhu et al., 2012), seismicity in rock failure (Tang et al., 1996), and rock failure in mining engineering (Ma et al., 2016). These previous studies detail the analysis method, governing equations, and constitutive models that the software is based on.

We first simulated and validated an intact numerical model of 20 mm × 40 mm that consisted of 80,000 square-shaped (0.1 mm × 0.1 mm) elements. We used the same mesoscopic physical and mechanical properties of Heap et al. (2014a), as shown in Table 1. These properties are representative of a model with 0% porosity and 100% homogeneity (i.e. no micro- or macro-scale discontinuities). However, natural rocks are often heterogeneous due to the presence of various forms of discontinuities, and this is reflected in RFPA^{2D} using the Weibull probability density function (Weibull, 1951) that assigns compressive (σ_c) and tensile strength (σ_t), and elastic modulus (E_0) to the elements in the model (Eq. (2)).

$$x(u) = \frac{m}{u_0}\left(\frac{u}{u_0}\right)^{m-1} \exp\left[-\left(\frac{u}{u_0}\right)^{m}\right] \tag{2}$$

where x is either σ_c, σ_t or E_0; u is the scale parameter of an individual element; u_0 is the scale parameter of the average element; and m is the Weibull shape parameter (homogeneity index), which describes the degree of heterogeneity in numerical specimens. In general, lower m values represent a greater level of heterogeneity and vice versa (Xu et al., 2012, 2013). We used $m = 3$ and kept it unchanged in all simulations. The UCS of the intact model specimen with $m = 3$ was found to be 553 MPa, which is close to the experimentally observed UCS of ~600 MPa for borosilicate glass in Vasseur et al. (2013). This validates the choice of mesoscopic physical and mechanical properties shown in Table 1 and the homogeneity index ($m = 3$), as also concluded by Heap et al. (2014a, 2016). However, it should be noted that this UCS of the intact model is higher than that of most of the commonly observed intact volcanic rocks (Fig. 3a). The intact numerical specimen, failure mechanism, and the corresponding axial stress-strain curve are shown in Fig. 4.

Table 1
The mesoscopic physical and mechanical properties used for the RFPA^{2D} model specimens. These values are the same as those used in Heap et al. (2014a, 2015, 2016).

Parameter	Unit	Value
Homogeneity index, m		3
Mean UCS	MPa	2300
Mean elastic modulus	GPa	100
Poisson's ratio		0.25
Ratio of compressive to tensile strength		10
Frictional angle	°	30

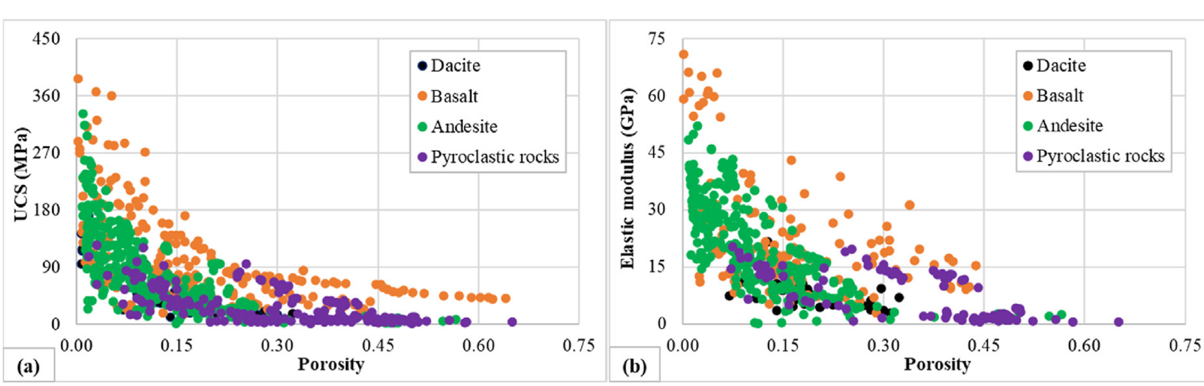

Fig. 3. (a) UCS, and (b) elastic modulus versus porosity for volcanic rocks based on the results of previous studies (the graphs were plotted using the supplementary data of Heap and Violay (2021), and the original references are cited in Heap and Violay (2021)).

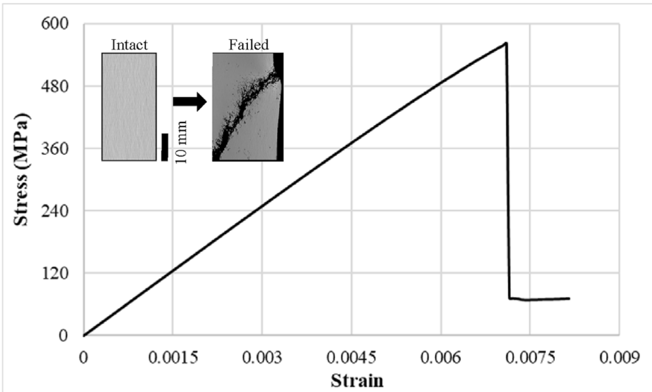

Fig. 4. Axial stress versus strain variation for the intact numerical specimen of 20 mm × 40 mm (the intact specimen and its failure mechanism are also shown in the graph).

Then the simulation scheme considered numerical specimens with embedded vesicles. We introduced circular vesicles to numerical specimens that generated bulk porosities of 2%, 5%, and 8%. Three different diameters (1 mm, 2 mm, and 3 mm) were considered for the vesicles, which are more common sizes of vesicles. In addition to the specimens with vesicles of uniform diameter, specimens containing vesicles of multiple diameters were also simulated. In this case, different porosity proportions of vesicles from each diameter were considered, i.e. 1:1:1, 1:1:2, 1:2:1, and 2:1:1 ratios of 1 mm:2 mm:3 mm diameter vesicles to produce bulk porosities of 2%, 5%, and 8%. More importantly, for each of these different cases of porosity, diameter, and size ratio (21 cases altogether), ten different random vesicle distributions were simulated to investigate the variation of engineering properties resulting from different vesicle distribution patterns. Fig. 5 shows example numerical samples for the cases of (1 mm, 2% and uniform diameter), (3 mm, 8% and uniform diameter), (2% and 1:1:2 diameter ratio), (5% and 1:2:1 diameter ratio), and (8% and 2:1:1 diameter ratio). Fig. 5 also shows the ten different cases of vesicle distribution patterns used for 5% and 1:2:1 size ratio case.

3. Results

3.1. Uniform-size vesicles

UCS and elastic modulus of the simulated models with uniform-size vesicles were determined. The heatmaps of Fig. 6 show their variations (averages of 10 different models in each case) for varying vesicle diameters and bulk porosities.

As expected, the UCS decreases with increasing bulk porosity and increasing vesicle diameter for a given porosity, in agreement with the results of numerous previous studies discussed before. A more pronounced effect of bulk porosity on the UCS than that of vesicle diameter can be observed in Fig. 6a within the considered ranges of porosity and vesicle diameter. Fig. 6a also shows a gradual decrease in UCS with both increasing vesicle diameter and bulk porosity, as displayed by the gradual change in colour of the heatmap, except for the case of 5% at 2 mm and 3 mm diameters. This anomaly at 5% porosity is attributed to the effect of different failure mechanisms of specimens as dictated by their randomised vesicle arrangements; a particular vesicle arrangement may facilitate macroscopic failure leading to a lower UCS, while another vesicle arrangement may have the opposite effect, although the vesicle diameter is higher. Fig. 7 shows the initial vesicle arrangement and damage evolution leading to the failure of two example specimens with 2 mm diameter and 3 mm diameter cases for 5% porosity. As shown in Fig. 7, shear failure is facilitated by diagonally aligned 2 mm vesicles leading to lower UCS, compared to the more splitting-type failure of the specimen with 3 mm diameter vesicles. Therefore, it shows that despite testing ten different vesicle arrangements for each case, the averages of UCS demonstrate anomalies in the expected trends. This suggests the importance of the vesicle distribution pattern on the mechanical properties of vesicular rocks, where unpredicted behaviours are also likely.

Elastic modulus variation in Fig. 6b closely follows the trend of UCS variation with increasing bulk porosity. However, elastic modulus shows neither systematic nor significant variation with increasing vesicle diameter within its considered range. This suggests that the vesicle diameter within the considered range has minimally affected the elastic modulus. A similar observation was made by Heap et al. (2014a), where the elastic modulus was nearly unchanged for the cases of vesicle diameters above 0.3 mm after their study, considering vesicles with diameters in the range of 0.1–1 mm.

Fig. 8 shows the range of UCS and elastic modulus values (maximum and minimum values) observed for ten different vesicle arrangements under each case of uniform-size vesicles, along with their average values. Fig. 8a generally suggests that the range of UCS is lower for higher bulk porosities. In other words, the impact of the vesicle distribution pattern on UCS is less significant at higher bulk porosities. The specimens become increasingly indistinctive for different distribution patterns as the number of vesicles increases at higher bulk porosities leading to less scattered UCS, which describes the reason for this. However, the range of UCS does not show any systematic variation with increasing vesicle diameter within the considered range of diameters. The ranges of elastic modulus in Fig. 8b indicate a relatively minor scatter around the mean value. The strikingly greater range is in the 8% bulk porosity and 2 mm diameter case, and that for 2 mm and 3 mm at 5% porosity is also notable. It was observed that these relatively larger ranges are a result of very few models in each case that showed significantly low elastic modulus as dictated by its vesicle distribution pattern favourable to a macroscopic shear failure by breaking fewer elements, while the vast majority conformed to a narrow range similar to other cases. The role of the vesicle distribution pattern in governing the mechanical behaviour of vesicular rocks is highlighted by this too.

The heatmaps of standard deviations for UCS and elastic modulus are shown in Fig. 9. The less scatter of UCS with increasing porosity can be generally observed in Fig. 9a except for the case of 2 mm diameter. However, the effect of vesicle diameter shows a sporadic distribution of standard deviation. According to Fig. 9b, the standard deviations of elastic modulus are relatively smaller and unsystematically varied with the bulk porosity and vesicle diameter. As described before, the observed anomalies are attributed to the different failure mechanisms caused by different patterns of vesicle distributions.

3.2. Combinations of different size vesicles

The variations of UCS and elastic modulus of models with combinations of different-sized vesicles were determined (porosity ratios of 1 mm: 2 mm: 3 mm = 1:1:1, 1:1:2, 1:2:1 and 2:1:1 that produce three different bulk porosities, 2%, 5% and 8%). Fig. 10 shows the average values of UCS and elastic modulus of 10 different specimens for each simulated scenario.

In all cases of bulk porosities, UCS decreased from equal proportions of all three diameters case (i.e. 1:1:1) to the case with a greater proportion of larger vesicles (i.e. 1:1:2). The introduction of more larger vesicles is expected to decrease the UCS according to

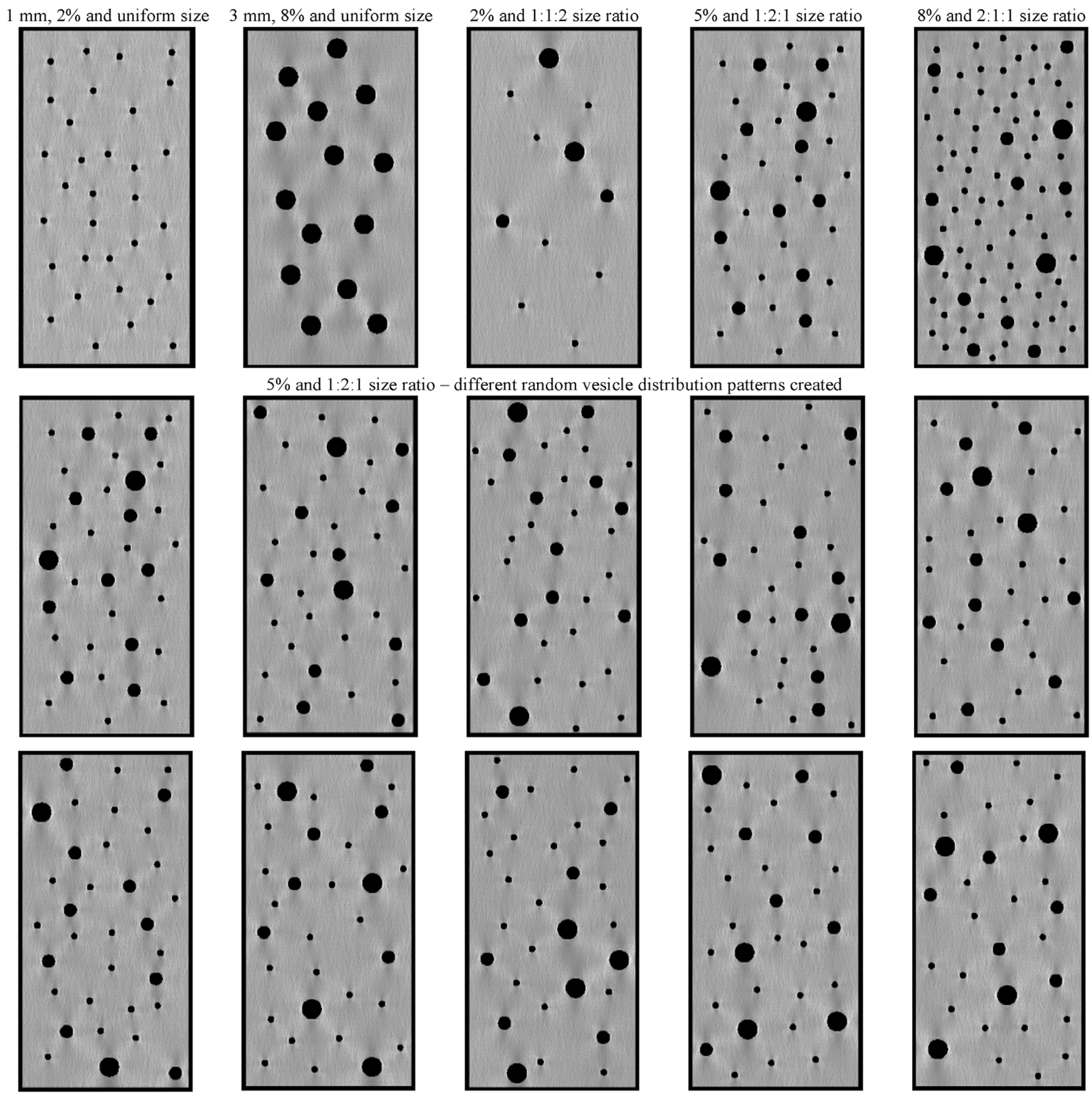

Fig. 5. Example numerical specimens for various combinations of vesicles.

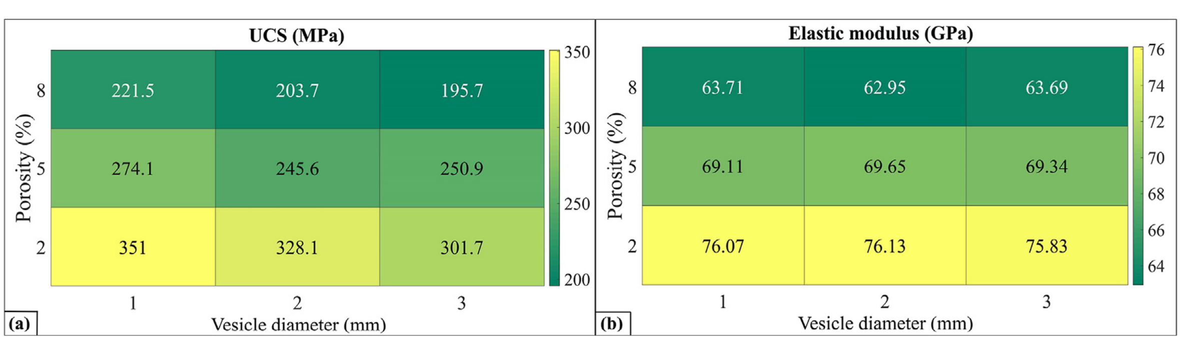

Fig. 6. Variations of (a) average UCS and (b) average elastic modulus against vesicle diameter for different bulk porosities for the case of uniform vesicle size.

Equation (1). In addition, the decrease in UCS is more pronounced at 2% bulk porosity, indicating the relatively more dominant role that larger vesicles play at lower porosities. The progressive fracturing and damage evolution behaviour of 1:1:1 and 1:1:2 cases for 2% bulk porosity, as shown in Fig. 11, indicates that 3 mm vesicles have decisively involved in the final failure of specimens in the case of 1:1:2 diameter ratio leading to lower UCS values.

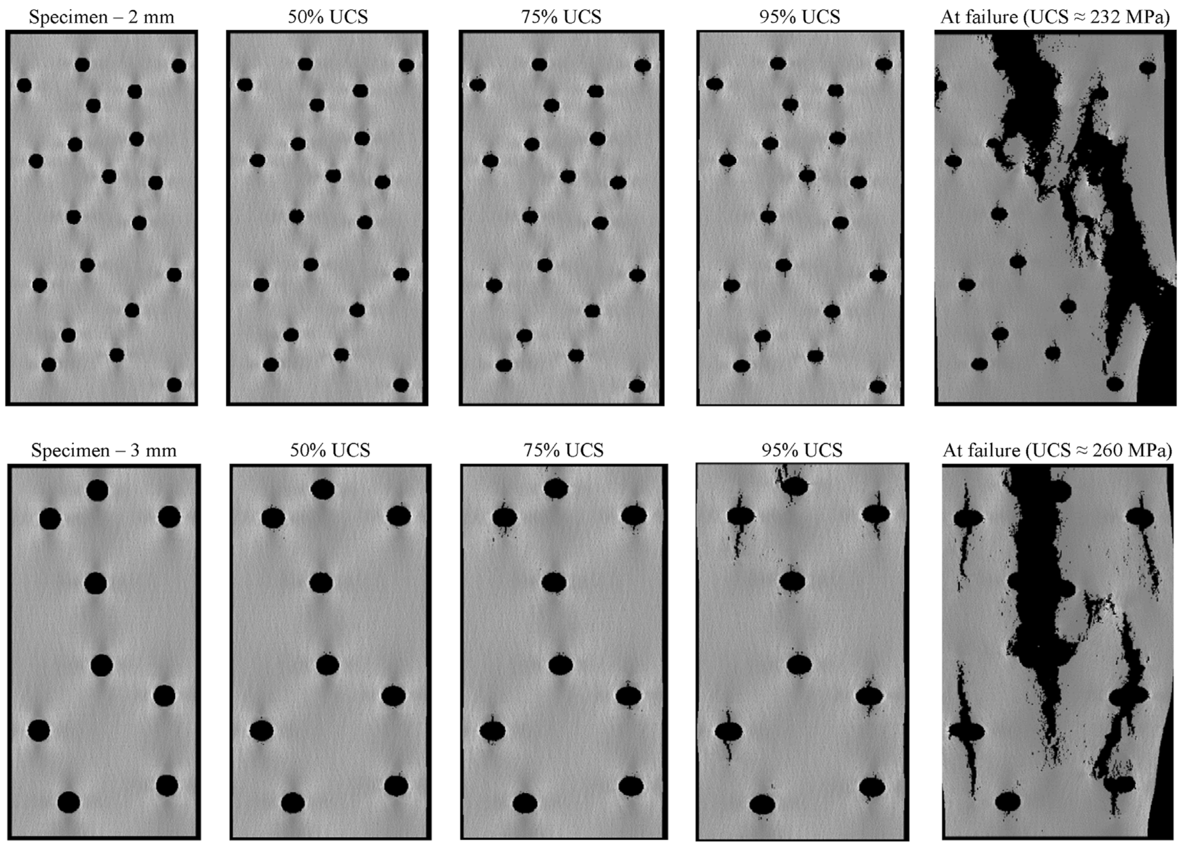

Fig. 7. Progressive fracturing and damage evolution characteristics of specimens having 2 mm and 3 mm diameter vesicles with a bulk porosity of 5% in each case.

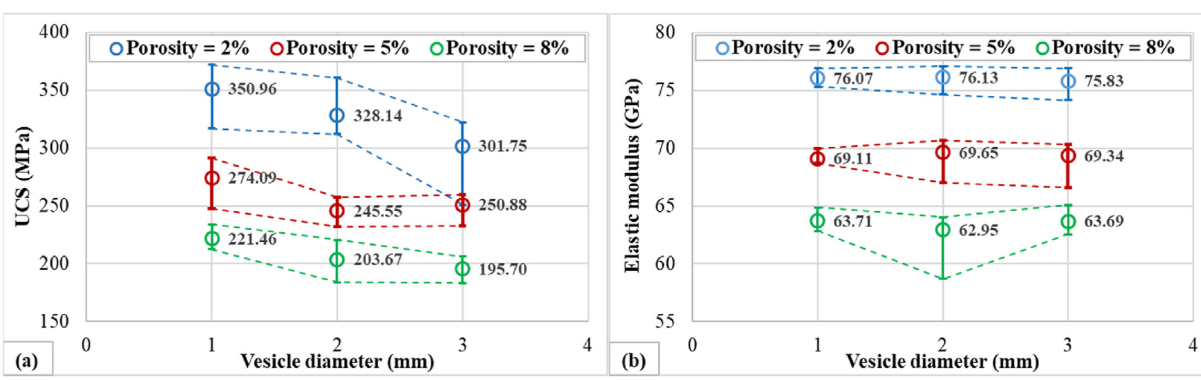

Fig. 8. (a) Average UCS versus vesicle diameter, and (b) average elastic modulus versus vesicle diameter for different bulk porosities. The error bars indicate the range between maximum and minimum values.

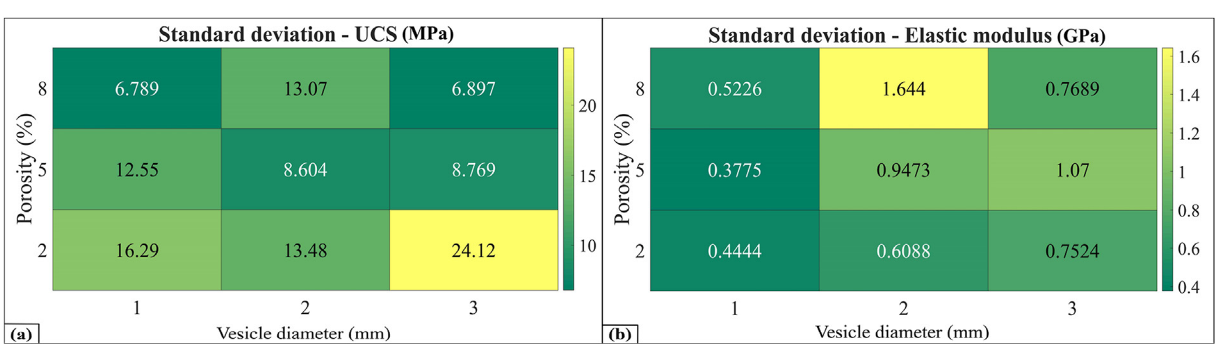

Fig. 9. Standard deviations of (a) UCS and (b) elastic modulus for the cases of different porosities and vesicle diameters for specimens with uniform-size vesicles.

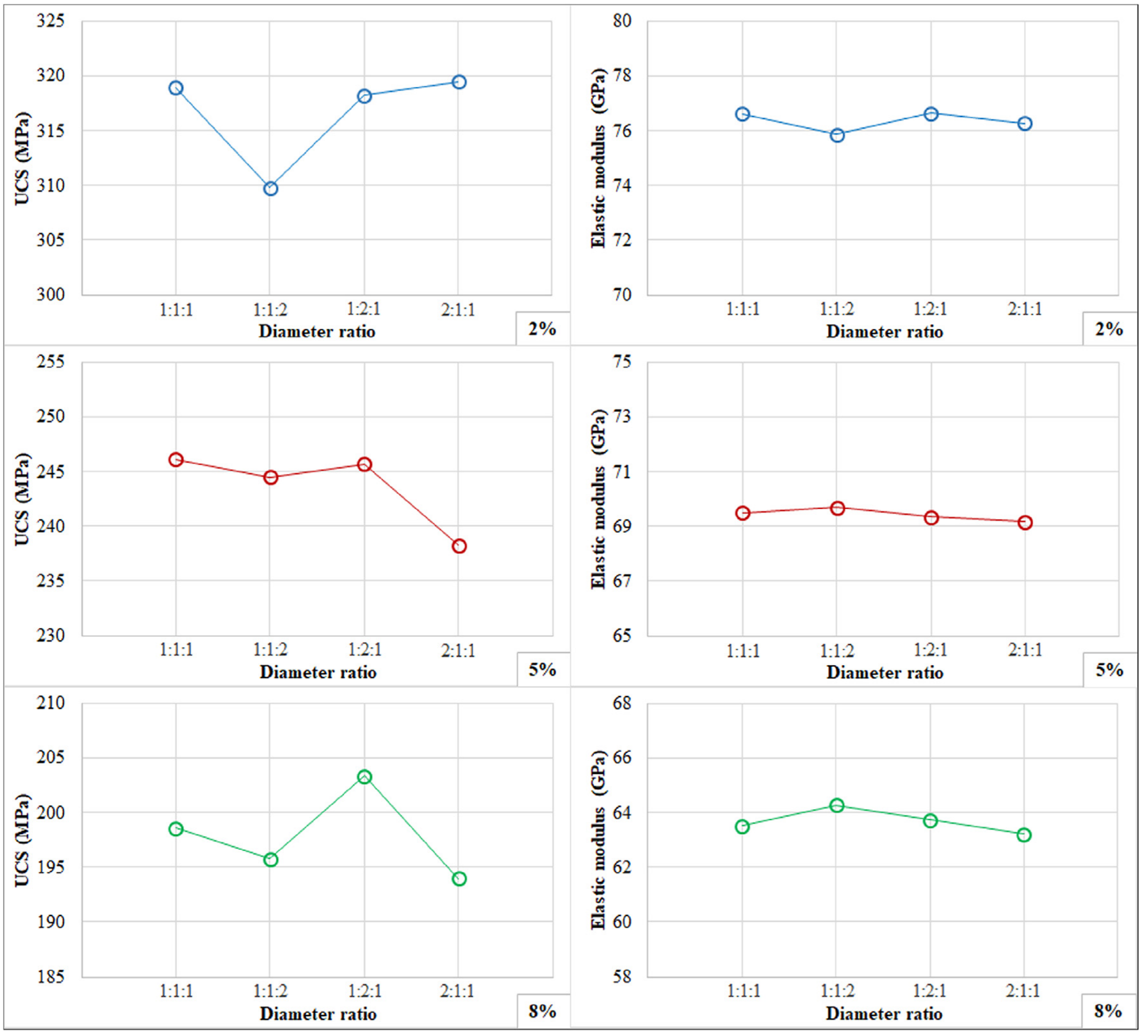

Fig. 10. Average UCS and elastic modulus for combinations of different vesicle sizes at bulk porosities of 2%, 5% and 8% (porosity ratios are 1 mm:2 mm:3 mm = 1:1:1, 1:1:2, 1:2:1 and 2:1:1).

The increase in the 2 mm diameter vesicle proportion shows a less profound effect irrespective of the bulk porosity (Fig. 10). However, the increase in the 1 mm diameter vesicle proportion has markedly lowered the UCS for both 5% and 8% bulk porosity cases from that of the case of equal proportions of all three diameters. This was identified as an effect of the introduced higher number of smaller vesicles compared to the 1:1:1 case, which bridges the gap between larger vesicles to assist a macroscopic shear failure. The progressive fracturing and damage evolution patterns for the cases of 1:1:1 and 2:1:1 at 5% bulk porosity in Fig. 12 show these different characteristics dictated by the relative proportion of vesicle sizes.

The elastic modulus is minimally impacted by the varying proportion of different-sized vesicles, as shown in Fig. 10. The trivial and unsystematic effect of vesicle diameter on elastic modulus was observed in the case of uniform-size vesicles in the present study and some previous studies as described before. The same behaviour is observed here for different proportions of varying-size vesicles.

Fig. 13 shows the ranges of UCS and elastic modulus for the cases with different proportions of varying-size vesicles and different bulk porosities. One important observation from Fig. 13a suggests that the scatter of UCS is generally minimum when the bulk porosity is equally shared by varying-size vesicles. In addition, when the proportion of larger vesicles is higher (i.e. 1:1:2 case), the range of UCS is consistent across all bulk porosities, and the deviation from the average to the maximum and minimum is approximately equal. This is attributed to the relatively more dominant role larger vesicles play on the failure mechanisms and strength of the specimens. The elastic modulus shows a relatively smaller range of maximum and minimum values (Fig. 13b).

4. Discussion

Vesicles of different sizes and shapes markedly affect the mechanical properties of vesicular rocks. In addition to the bulk porosity and size of vesicles, the vesicle distribution characteristics can have significant controls on the mechanical properties of a given vesicular rock, as suggested by many previous studies (e.g. Fakhimi and Gharahbagh, 2011; Heap et al., 2014a; Zhang et al.,

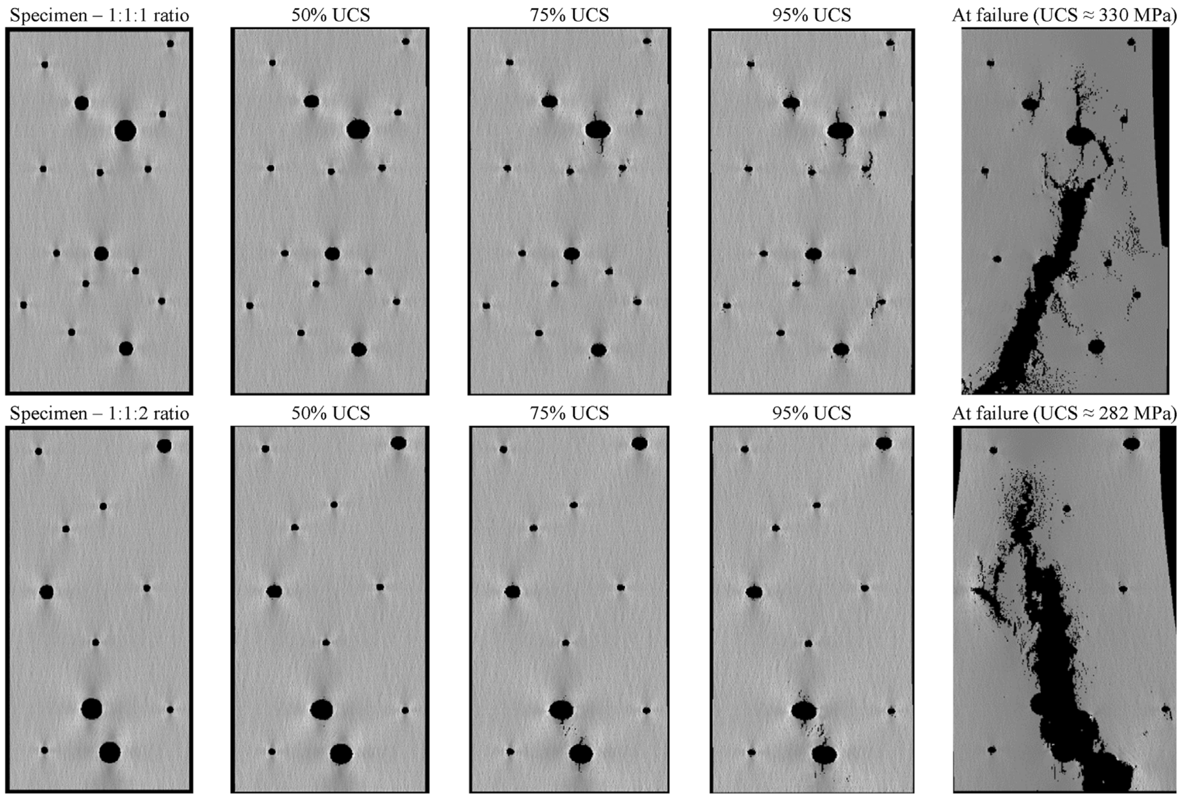

Fig. 11. Progressive fracturing and damage evolution behaviour of the specimens for the cases of 1:1:1 and 1:1:2 diameter ratio of 1 mm:2 mm:3 mm diameter vesicles with a bulk porosity of 2% in each case.

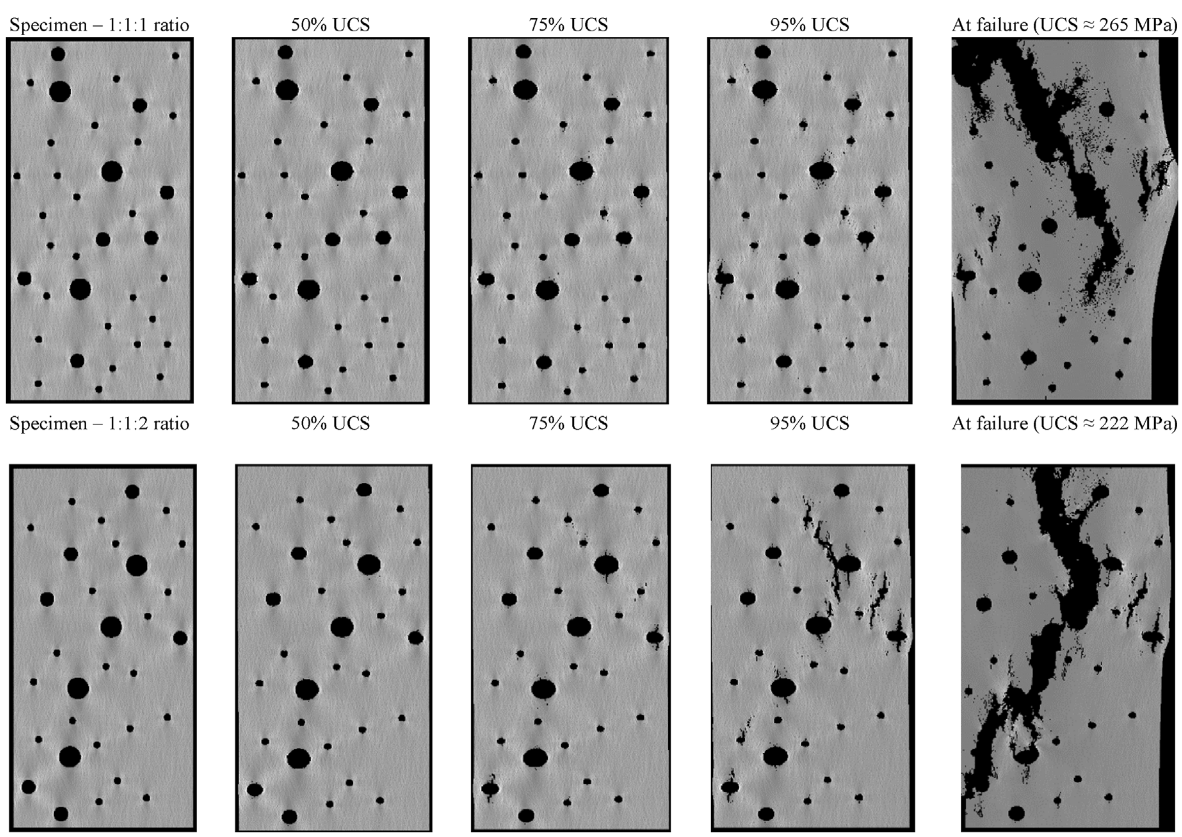

Fig. 12. Progressive fracturing and damage evolution behaviour of the specimens for the cases of 1:1:1 and 2:1:1 ratio of 1 mm:2 mm:3 mm diameter vesicles with a bulk porosity of 5% in each case.

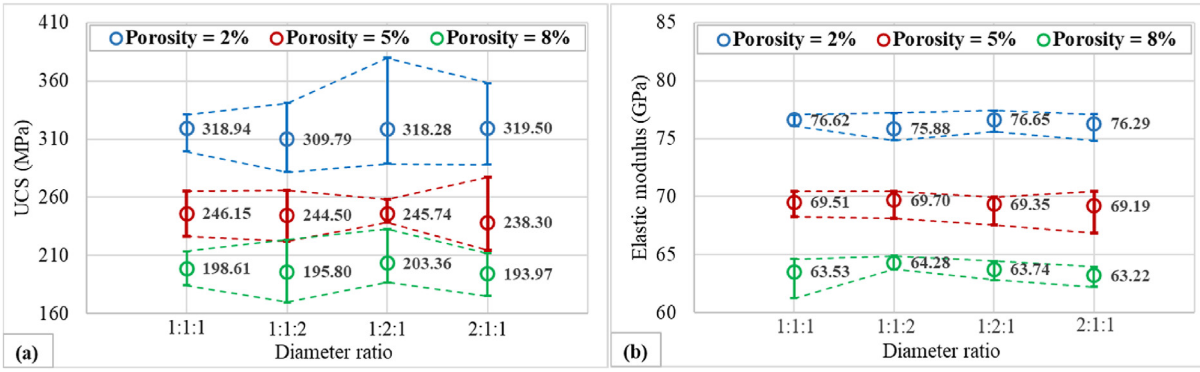

Fig. 13. Variations of (a) UCS and (b) elastic modulus for different proportions of different size vesicles and different bulk porosities. The error bars indicate the range between maximum and minimum values.

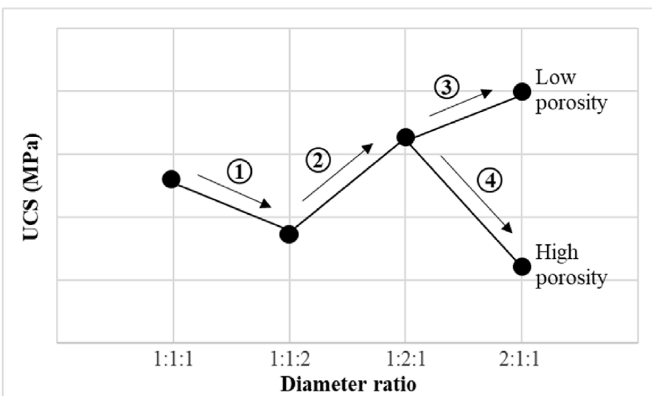

Fig. 14. The general trends of UCS variation versus vesicle diameter ratio.

2018). Therefore, understanding the potential degree of deviation from an average/mean value due to the vesicle distribution patterns is critical for practising engineers/designers. This leads to a more comprehensive stability assessment of infrastructure designs and a reduced degree of uncertainty.

Increasing bulk porosity was observed to decrease the UCS as expected. The range of UCS is greater at low porosities due to the greater distinctiveness of vesicle distribution patterns. This is in agreement with the results of previous studies compiled by (Heap and Violay 2021), as shown in Fig. 3. In general, larger vesicles tend to decrease the UCS according to the pore-emanating crack model and Equation (1) discussed before. However, our results revealed exceptions caused by the vesicle distribution pattern. For example, at 5% bulk porosity, the average UCS of specimens with 3 mm diameter vesicles showed a greater average UCS than that of the 2 mm diameter case. The failure mechanisms indicated that the vesicle arrangements in support of shear failure by breaking fewer elements lead to lower UCS, although the vesicles are relatively smaller, causing the discrepancy.

Vesicular rocks may contain a mixture of different size vesicles in different proportions (Fig. 1). The UCS of specimens with different-sized vesicles with varying proportions showed interesting behaviours (Fig. 13). The irregular variations of Fig. 13 are a result of multiple interacting factors. These include vesicle distribution characteristics, vesicle diameter and bulk porosity. An increase in the proportion of the largest vesicles decreased the UCS from that of the equal proportion state (① of Fig. 14). In general, the larger vesicles in a mixture of different-sized vesicles are more influential on UCS, particularly at low porosities. An increase in the proportion of smallest vesicles displayed different behaviours for low and high bulk porosities – at lower bulk porosities, it caused an increase of UCS due to the reduced number of larger vesicles (③ of Fig. 14), whereas, at higher bulk porosities, the greater presence of smaller vesicles bridged the gaps between larger vesicles to induce a shear failure leading to lower UCS values (④ of Fig. 14). In addition, the results of the present study show that the UCS generally varies within a relatively narrow range if the rock comprises an approximately equal proportion of different size vesicles, regardless of the bulk porosity. In contrast, the other combinations of different size vesicle proportions showed UCS values within a greater range, and it is more pronounced at lower bulk porosities.

Overall, the UCS results of limited tests on vesicular rocks must be used with caution, particularly for low-porosity rocks, and testing as many replicates as possible is recommended. Interestingly, the elastic modulus varied within a narrow range in the vast majority of the cases of vesicles studied in this study, suggesting relatively higher confidence in using the results of laboratory tests for elastic modulus.

It should be noted that the models used in this study had relatively lower bulk porosities, and the observed behaviours may not stand for vesicular rocks with higher bulk porosities. In addition, the vesicles were geometrically simplified to a circular shape and were completely disconnected from each other initially, which may not be the case for some vesicular rocks. Furthermore, the presence of only vesicles was considered in the models disregarding the presence of other types of macro-scale discontinuities (e.g. joints, fractures, faults), which can affect the damage evolution, failure mechanisms and mechanical properties when combined with vesicles.

5. Conclusions

A systematic numerical simulation program was used to reveal some critical insights into the effects of vesicle distribution characteristics on the engineering properties of vesicular rocks. Ten different vesicle distribution patterns were considered for each case of bulk porosity, vesicle diameter and combinations of different proportions of different-sized vesicles. The following conclusions were derived based on the results:

(1) An increase in bulk porosity decreased both the UCS and elastic modulus of specimens, irrespective of the size of the vesicles. The vesicle distribution was found to play a major role at lower porosities in the specimens with uniform-size vesicles where the UCS varied within a greater range. The failure mechanisms of specimens were found to be influenced by the vesicle distribution patterns, which caused counter-intuitive trends of UCS variation against vesicle diameter.
(2) Specimens with combinations of different-sized vesicles in different proportions showed that the variation of UCS is minimum when the bulk porosity is equally shared by different-sized vesicles. In addition, the results revealed that the UCS is higher when the mixture of different-sized vesicles is dominated by smaller vesicles than that when the proportion of different-sized vesicles is equal in the mixture at low porosities, while, at higher porosities, the UCS was found to be lower than the equal proportion case. A greater proportion of larger vesicles was observed to decrease the UCS from that when the vesicle mixture has equal proportions of all vesicle sizes. Elastic modulus showed only minor and unsystematic variations against vesicle diameter in the case of uniform-size vesicles and against different proportions of different-sized vesicles in the case of combinations of different-sized vesicles in different proportions. Furthermore, the elastic modulus variation was observed to be within a narrow range in general for different vesicle distribution patterns.
(3) Overall, the results of this study highlight the important role of vesicle distribution characteristics in controlling the mechanical properties of vesicular rocks and stress the need for practitioners to cautiously use the engineering properties of vesicular rocks determined through limited laboratory tests.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Abdollahipour, A., Marji, M.F., Bafghi, A.Y., Gholamnejad, J., 2016. Time-dependent crack propagation in a poroelastic medium using a fully coupled hydromechanical displacement discontinuity method. Int. J. Fract. 199 (1), 71–87.
Al-Harthi, A.A., Al-Amri, R.M., Shehata, W.M., 1999. The porosity and engineering properties of vesicular basalt in Saudi Arabia. Eng. Geol. 54 (3), 313–320.
Baud, P., Wong, T-f., Zhu, W., 2014. Effects of porosity and crack density on the compressive strength of rocks. Int. J. Rock Mech. Min. Sci. 67, 202–211.
Blower, J.D., Keating, J.P., Mader, H.M., Phillips, J.C., 2001. Inferring volcanic degassing processes from vesicle size distributions. Geophys. Res. Lett. 28 (2), 347–350.
Bubeck, A., Walker, R.J., Healy, D., Dobbs, M., Holwell, D.A., 2017. Pore geometry as a control on rock strength. Earth Planet Sci. Lett. 457, 38–48.
Cemiloglu, A., Zhu, L., Arslan, S., Xu, J., yuan, X., Azarafza, M., Derakhshani, R., 2023. Support Vector Machine (SVM) application for uniaxial compression strength (UCS) prediction: a case study for Maragheh limestone. Appl. Sci. 13 (4), 2217.
Fakhimi, A., Gharahbagh, A.E., 2011. Discrete element analysis of the effect of pore size and pore distribution on the mechanical behavior of rock. Int. J. Rock Mech. Min. Sci. 48 (1), 77–85.
Gondé, C., Martel, C., Pichavant, M., Bureau, H., 2011. In situ bubble vesiculation in silicic magmas. Am. Mineral. 96 (1), 111–124.
Griffiths, L., Heap, M.J., Xu, T., Chen, C.-F., Baud, P., 2017. The influence of pore geometry and orientation on the strength and stiffness of porous rock. J. Struct. Geol. 96, 149–160.
Haeri, H., Sarfarazi, V., Ebneabbasi, P., Nazari maram, A., Shahbazian, A., Fatehi Marji, M., Mohamadi, A.R., 2020. XFEM and experimental simulation of failure mechanism of non-persistent joints in mortar under compression. Construct. Build. Mater. 236, 117500.
Heap, M.J., Xu, T., Chen, C-f., 2014a. The influence of porosity and vesicle size on the brittle strength of volcanic rocks and magma. Bull. Volcanol. 76 (9), 856.
Heap, M.J., Xu, T., Kushnir, A.R.L., Kennedy, B.M., Chen, C-f., 2015. Fracture of magma containing overpressurised pores. J. Volcanol. 301, 180–190.
Heap, M.J., Wadsworth, F.B., Xu, T., Chen, C-f., Tang, C., 2016. The strength of heterogeneous volcanic rocks: a 2D approximation. J. Volcanol. Geoth. Res. 319, 1–11.
Heap, M.J., Lavallee, Y., Petrakova, L., Baud, P., Reuschle, T., Varley, N.R., Dingwell, D.B., 2014b. Microstructural controls on the physical and mechanical properties of edifice-forming andesites at Volcán de Colima, Mexico. J. Geophys. Res. 119 (4), 2925–2963.
Heap, M.J., Violay, M.E.S., 2021. The mechanical behaviour and failure modes of volcanic rocks: a review. Bull. Volcanol. 83 (5), 33.
Ji, S., Gu, Q., Xia, B., 2006. Porosity dependence of mechanical properties of solid materials. J. Mater. Sci. 41 (6), 1757–1768.
Ji, S., Wang, Q., Li, L., 2019. Seismic velocities, Poisson's ratios and potential auxetic behavior of volcanic rocks. Tectonophysics 766, 270–282.
Kate, J.M., Gokhale, C.S., 2006. A simple method to estimate complete pore size distribution of rocks. Eng. Geol. 84 (1), 48–69.
Kueppers, U., Scheu, B., Spieler, O., Dingwell, D.B., 2005. Field-based density measurements as tool to identify preeruption dome structure: set-up and first results from Unzen volcano, Japan. J. Volcanol. Geoth. Res. 141 (1), 65–75.
Li, L.C., Tang, C.A., Li, C.W., Zhu, W.C., 2006. Slope stability analysis by SRM-based rock failure process analysis (RFPA). Geomechanics Geoengin. 1 (1), 51–62.
Liu, Z., Zhang, C., Zhang, C., Wang, H., Zhou, H., Zhou, B., 2022. Effects of amygdale heterogeneity and sample size on the mechanical properties of basalt. J. Rock Mech. Geotech. Eng. 14 (1), 93–107.
Ma, T., Wang, L., Suorineni, F.T., Tang, C., 2016. Numerical analysis on failure modes and mechanisms of mine pillars under shear loading. Shock Vib. 2016, 6195482.
Moitra, P., Gonnermann, H.M., Houghton, B.F., Giachetti, T., 2013. Relating vesicle shapes in pyroclasts to eruption styles. Bull. Volcanol. 75 (2), 691.
Navon, O., Lyakhovsky, V., 1998. Vesiculation processes in silicic magmas. Geol. Soc. London Spec. Publ. 145 (1), 27.
Ng, K., Santamarina, J.C., 2022. Mechanical and hydraulic properties of carbonate rock: the critical role of porosity. J. Rock Mech. Geotech. Eng. 15 (4), 814–825.
Polacci, M., Baker, D.R., Mancini, L., Tromba, G., Zanini, F., 2006. Three-dimensional investigation of volcanic textures by X-ray microtomography and implications for conduit processes. Geophys. Res. Lett. 33 (13).
Proussevitch, A.A., Sahagian, D.L., Tsentalovich, E.P., 2007. Statistical analysis of bubble and crystal size distributions: formulations and procedures. J. Volcanol. Geoth. Res. 164 (3), 95–111.
Sammis, C.G., Ashby, M.F., 1986. The failure of brittle porous solids under compressive stress states. Acta Metall. 34 (3), 511–526.
Schaefer, L.N., Kendrick, J.E., Oommen, T., Lavallee, Y., Chigna, G., 2015. Geomechanical rock properties of a basaltic volcano. Front. Earth Sci. 3.
Shea, T., Houghton, B.F., Gurioli, L., Cashman, K.V., Hammer, J.E., Hobden, B., 2010. Textural studies of vesicles in volcanic rocks: an integrated methodology. J. Volcanol. Geoth. Res. 190 (3), 271–289.
Tang, C., Kaiser, P.K., Yang, G., 1996. Numerical Simulation of Seismicity in Rock Failure. 2nd North American Rock Mechanics Symposium. ARMA-96-1833.
Toramaru, A., 1989. Vesiculation process and bubble size distributions in ascending magmas with constant velocities. J. Geophys. Res. Solid Earth 94 (B12), 17523–17542.
Vasseur, J., Wadsworth, F.B., Lavallee, Y., Hess, K.-U., Dingwell, D.B., 2013. Volcanic sintering: timescales of viscous densification and strength recovery. Geophys. Res. Lett. 40 (21), 5658–5664.
Wang, S.Y., Sloan, S.W., Sheng, D.C., Tang, C.A., 2012. Numerical analysis of the failure process around a circular opening in rock. Comput. Geotech. 39, 8–16.
Wasantha, P.L.P., Ranjith, P.G., Viete, D.R., 2014. Effect of joint orientation on the hydromechanical behavior of singly jointed sandstone experiencing undrained loading. J. Geophys. Res. Solid Earth 119 (3), 1701–1717.
Wasantha, P.L.P., Bing, D., Yang, S.Q., Xu, T., 2020. Numerical modelling of the crack-pore interaction and damage evolution behaviour of rocklike materials with pre-existing cracks and pores. Int. J. Damage Mech. 30 (5), 720–738.
Weibull, W., 1951. A statistical distribution function of wide applicability. J. Appl. Mech. 18 (3), 293–297.
Wong, L.N.Y., Peng, J., 2020. Numerical investigation of micro-cracking behavior of brittle rock containing a pore-like flaw under uniaxial compression. Int. J. Damage Mech. 29 (10), 1543–1568.

Wright, H.M.N., Cashman, K.V., Gottesfeld, E.H., Roberts, J.J., 2009. Pore structure of volcanic clasts: measurements of permeability and electrical conductivity. Earth Planet Sci. Lett. 280 (1), 93–104.
Xu, T., Ranjith, P.G., Wasantha, P.L.P., Zhao, J., Tang, C.A., Zhu, W.C., 2013. Influence of the geometry of partially-spanning joints on mechanical properties of rock in uniaxial compression. Eng. Geol. 167, 134–147.
Xu, T., Tang, C.A., Zhao, J., Li, L., Heap, M.J., 2012. Modelling the time-dependent rheological behaviour of heterogeneous brittle rocks. Geophys. J. Int. 189 (3), 1781–1796.
Yu, C., Ji, S., Li, Q., 2016. Effects of porosity on seismic velocities, elastic moduli and Poisson's ratios of solid materials and rocks. J. Rock Mech. Geotech. Eng. 8 (1), 35–49.
Zhang, C., Tu, S., Bai, Q., 2018. Evaluation of pore size and distribution impacts on uniaxial compressive strength of lithophysal rock. Arabian J. Sci. Eng. 43 (3), 1235–1246.
Zhu, W., Baud, P., Wong, T-f., 2010. Micromechanics of cataclastic pore collapse in limestone. J. Geophys. Res. Solid Earth 115 (B4).
Zhu, W.C., Bai, Y., Li, X.B., Niu, L.L., 2012. Numerical simulation on rock failure under combined static and dynamic loading during SHPB tests. Int. J. Impact Eng. 49, 142–157.

P.L.P. Wasantha obtained his BSc degree in Civil and Environmental Engineering from the University of Ruhuna, Sri Lanka and his PhD in Geotechnical Engineering from Monash University, Australia. He then joined the Technical University of Bergakademie Freiberg, Germany, as a Postdoctoral Research Fellow after receiving a prestigious Humboldt Early-Career Researcher Award. Wasantha then moved to the University of Oxford, the United Kingdom, to continue as a Postdoctoral Researcher before joining Victoria University, Melbourne, Australia, as a lecturer in Geotechnical engineering in 2017, where he is currently a Senior Lecturer. His research interests include (1) experimental investigations on the thermo-hydro-mechanical (THM) behaviours of rocks and rock joints; (2) hydraulic fracturing and induced seismicity; (3) impacts of fire exposure on rock behaviour; and (4) foundations on reactive soils. Wasantha has published over 50 journal articles and presented at several international conferences.