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Direct shear characteristics of rounded pumice gravel and its mixture with marine sand

Yoichi Watabe
Faculty of Engineering, Hokkaido University, Sapporo, Japan, watabe@eng.hokudai.ac.jp

ABSTRACT: A submarine volcano on the Ogasawara Islands, Japan, erupted in August 2021, spewing large quantities of pumice fragments into the Pacific Ocean. The pumice fragments drifted on the ocean currents and became rounded gravel particles due to abrasion, and then the pumice particles drifted ashore, particularly in ports on the west coast of northern Okinawa Island, Japan. Therefore, disposal/effective use of the collected pumice gravel became a major social issue. A series of direct shear tests was conducted for the drifted pumice gravel particles, marine sand, and a mixture of these two types of soil, with parameters of normal stress in the range of 100 – 400 kPa, and shear strength constants and dilation properties were investigated in detail in relation to the effect of particle crush. It was found out that for pumice particles with a large shear resistance angle but with concerns about crushability, filling the pores among pumice particles with small sand particles significantly reduces the impact of particle crushing, which is a weak point of the pumice, and then contributes to an increase in shear strength.

KEYWORDS: Pumice, particle crush, sand, direct shear.

1 INTRODUCTION

The submarine volcano "Fukutoku Okanoba" in the Ogasawara Islands in Japan erupted in August 2021, spewing a large amount of pumice into the Pacific Ocean. The pumice drifted on the ocean currents and became rounded particles due to abrasion, and then, so much pumice particles were washed ashore in various parts of the Nansei Islands, especially in ports on the west coast of the northern Okinawa main island. In ports where water surface was covered by pumice particles, the disposal/effective use of the collected pumice became a major social issue. Therefore, the Okinawa General Bureau, Cabinet Office, Japan, which is responsible for national public works in Okinawa Prefecture, considered making effective use of the pumice as a mixture with marine sand, and published a technical manual for using it for land development based on the results of cone index and plate load test (Okinawa General Bureau, Cabinet Office, 2022). In fact, a mixture of pumice and marine sand was used for land development in the park's green space development on the Awase artificial island in Okinawa.

In order to fundamentally understand the mechanical properties and use them effectively as a soil material, it is key to grasp the mechanical properties based on laboratory soil testing. However, the above-mentioned technical manual does not directly describe shear strength properties. Understanding the mechanical properties of crushable granular materials, as well as their basic mechanical properties as a mixture with silica sand, is extremely important for widely using soil materials such as pumice, which are suddenly generated in large amounts due to volcanic activity. Furthermore, investigating the mechanical properties of a special problematic soil such as drifted pumice particles is of great academic value in the field of soil mechanics.

In this study, a series of direct shear tests (JGS 0560-2020) was conducted on drifted pumice (pumice) as a rounded granular gravel particles with high crushability, marine sand (sand) as a good ground material, and a mixture of these two types of soil materials (mixture), under different normal stress conditions, and the shear strength constants (c and ϕ) and dilation properties were investigated in detail in relation to the effects of particle crushing. In particular, the study focused on the mechanism by which the disadvantage of crushable pumice particles is compensated for by filling the large pores among the pumice particles with small sand particles, improving the pumice with crushable property to be a soil mixture with good mechanical property.

2 SOIL SAMPLE AND TEST CONDITIONS

The drifted pumice examined in this study were washed ashore and collected at the Unten Port in Nakijin Village and Nago City, Okinawa Prefecture, Japan. The internal structure of the pumice particles has a foamed, sponge-like porous structure, and its surface is characterized by a rounded shape due to abrasion while drifting (Figure 1). When the particles are finely crushed, closed voids are destroyed, and the soil particle density increases and approaches the true density. In this study, the density of soil particles crushed to fine particles (0.075 mm or less) was 2.476 Mg/m^3, regarded as the true density.

In the following tests, since the dimensions of the direct shear box were 60 mm in diameter and approximately 20 mm in height, it would be desirable to set the maximum particle size of the pumice smaller. However, as shown in Figure 1, most pumice has a particle size of 5 to 10 mm, and since it is possible that mechanical test results that reveal the high crushability of pumice particles may not be obtained without a certain particle size. Therefore, pumice particles that had been passed through a 9.5 mm sieve were used. Although the minimum particle size was not adjusted, there were few small particles, and the majority were particles of approximately the uniform size in 2.0 to 9.5 mm, which corresponds to gravel particles.

The mixed sand is marine silica sand that was used as a material for the mixture in the pumice landfill in the Awase artificial island of Nakagusuku Bay Port. The samples tested were three types: pumice, sand, and a mixture of pumice and sand in bulk volume ratio of 1:1, and the grain size distribution curves for these three soils are shown in Figure 2. Although the bulk volume ratio for the mixture is 1:1, its grain size

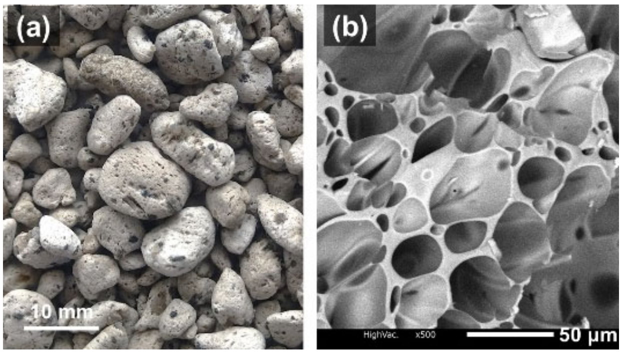

Figure 1. Drifted pumice: (a) Rounded shape particles; (b) SEM image of fracture surface.

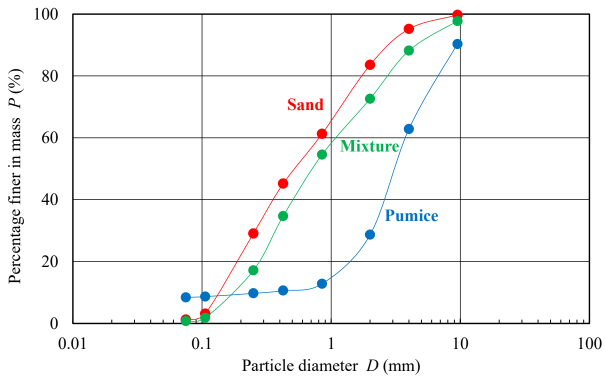

Figure 2. Grain size distribution curves.

distribution curve expressed as mass passing percentage shows that the mass proportion of sand is as much as 80%, and the mass proportion of pumice is less than 20%, because the pumice particles contain many air bubbles (i.e., foamed structure) resulting in a low density.

Specimen and test conditions for the pumice, sand, and mixture for the direct shear tests are shown in Tables 1, 2, and 3, respectively. In the names of the test cases, P stands for pumice, S for sand, PS for a pumice-sand mixture, the letter L following S stands for loose, and D for dense. The numbers following these indicate the normal stress (in kPa) applied before shearing, and were set at 100, 200, and 400 kPa. Additionally, the suffixes a and b identify tests conducted under the same conditions to confirm reproducibility.

The specimen dimensions were 60 mm in diameter and approximately 20 mm in height. For the pumice and mixture, specimens were prepared by packing the pumice particles somewhat densely in the strong box for the direct-shear test so as not to crush them (in reality, the specimens were quite loosely packed). For sand, in addition to specimens in a similarly compacted state (loosely packed state), specimens in a firmly compacted state (densely packed state) were also prepared. After applying a normal stress and confirming that settlement had completed, the clearance between the upper and lower shear boxes was set to 0.2 mm, the loading piston was fixed to be a constant volume condition, and the specimens were sheared at a horizontal displacement rate of 0.2 mm/min up to a horizontal displacement of 7 mm.

3 TEST RESULTS AND DISCUSSION

The (a) relationship between shear stress and horizontal displacement and (b) relationship between shear stress and normal stress (i.e., stress path) obtained from the tests on the pumice, sand, and mixture are shown in Figures 3, 4, and 5, respectively.

The test results for the pumice (Figure 3) show that the higher the normal stress, the higher the yield stress during shear and the greater the horizontal displacement at yield. In all cases, after yielding, the results exhibited strain-hardening behavior in which the shear stress increased with displacement. The relationship was not smooth, but rather jagged, indicating that this is due to particle crushing associated with shear displacement. Overall, the result exhibited strain-hardening behavior, with the stress path moving to the upper right, indicating that a dilation tendency was dominant. However, in the case of a normal stress of 400 kPa, the effects of particle crushing became strong before the dilation tendency became apparent, and a temporary, significant tendency for contraction was observed in the early stages of shearing.

The stress path is shown with points corresponding to horizontal displacements of 1.0, 2.0, 4.0, and 7.0 mm, as well

Table 1. Specimen and test conditions for the pumice.

Test case for pumice	Normal stress σ (kPa)	Water content w (%)	Initial dry density (Mg/m^3)	Dry density at shearing (Mg/m^3)
P100a	100	30.7	0.210	0.221
P100b	100	30.0	0.216	0.227
P200a	200	25.3	0.218	0.235
P200b	200	30.5	0.225	0.244
P400a	400	29.1	0.197	0.223
P400b	400	28.4	0.218	0.249

Table 2. Specimen and test conditions for the sand.

Test case for sand	Normal stress σ (kPa)	Water content w (%)	Initial dry density (Mg/m^3)	Dry density at shearing (Mg/m^3)
SL100a	100	13.0	0.663	0.691
SL100b	100	13.4	0.706	0.744
SL200a	200	10.0	0.699	0.764
SL200b	200	13.6	0.686	0.726
SL400a	400	13.1	0.678	0.723
SL400b	400	13.0	0.646	0.721
SD100	100	14.5	0.862	0.893
SD200	200	11.3	0.813	0.850
SD400	400	14.5	0.754	0.793

Table 3. Specimen and test conditions for the mixture.

Test case for mixture	Normal stress σ (kPa)	Water content w (%)	Initial dry density (Mg/m^3)	Dry density at shearing (Mg/m^3)
PS100a	100	13.9	0.482	0.509
PS100b	100	13.2	0.471	0.502
PS200a	200	13.4	0.498	0.526
PS200b	200	15.3	0.484	0.506
PS400a	400	14.6	0.488	0.524
PS400b	400	15.0	0.499	0.541

as contour lines connecting the points at each displacement. These contour lines can be considered as the failure criterion lines when failure is defined at each displacement. The stress path up to a displacement of 1.0 mm moves upward, so it may be interpreted as elastic behavior before yielding. However, considering that P100 and P200 shown in Figure 3(a) already yielded at a displacement of 1.0 mm, it is considered that the contraction due to particle rearrangement and crushing and the expansion due to dilation are offsetting each other. In the case of a high normal stress of 400 kPa (P400), a significant decrease in normal stress is observed after a displacement of 1 mm in Figure 3(b), and the effect of contraction due to particle crushing is strongly evident. However, normal stress begins to increase after a displacement of 3 to 4 mm, which indicates that the effect of dilation becomes dominant over the effect of particle crushing.

The failure criterion line defined at each displacement point is an upward convex curve, which shows a typical stress-dependent tendency in which the shear resistance angle ϕ decreases as the stress level increases due to particle crushing. When setting the Coulomb's failure criterion line for design purposes, it is necessary to set the apparent cohesion c and the shear resistance angle ϕ according to the target stress level and the displacement level at which failure is defined. The Coulomb's failure criterion line defined at a displacement of 7.0

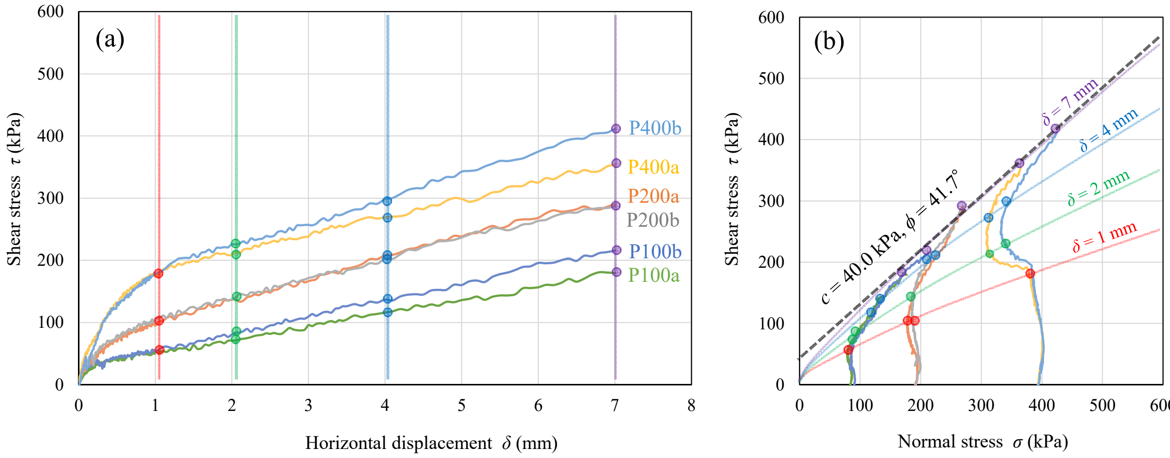

Figure 3. Test results for the pumice: (a) Relationships between shear stress and horizontal displacement; (b) Relationships between shear stress and normal stress (stress paths).

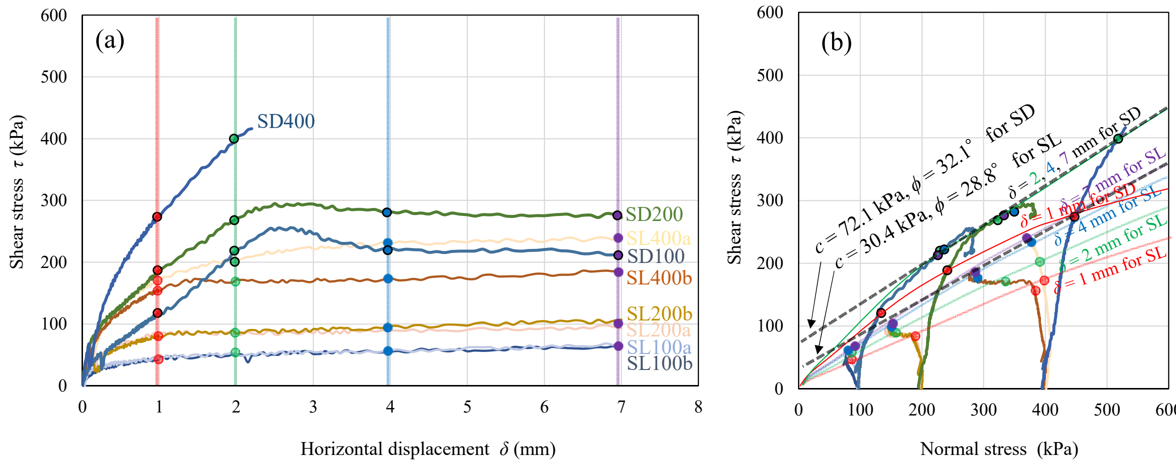

Figure 4. Test results for the sand: (a) Relationships between shear stress and horizontal displacement; (b) Relationships between shear stress and normal stress (stress paths).

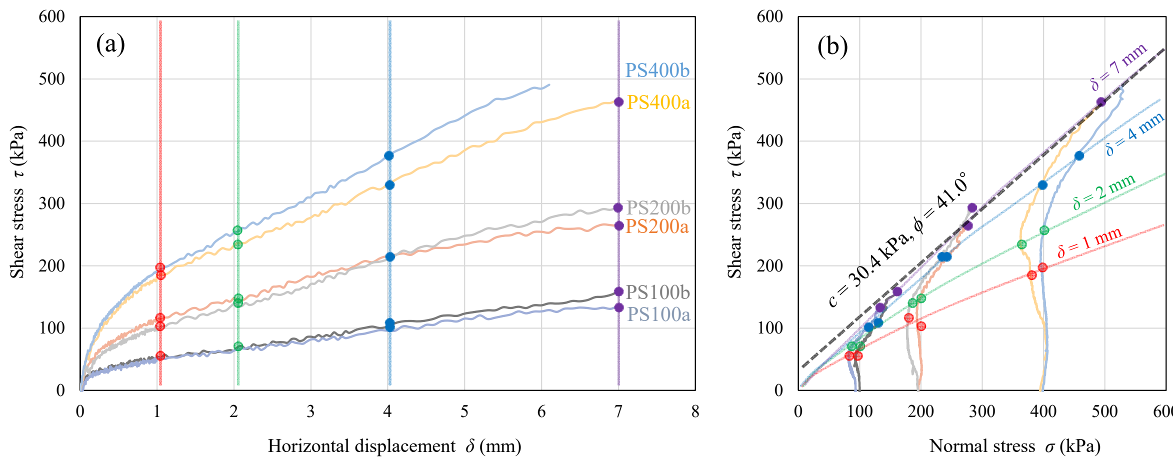

Figure 5. Test results for the mixture: (a) Relationships between shear stress and horizontal displacement; (b) Relationships between shear stress and normal stress (stress paths).

mm is expressed as a straight line with c = 40.0 kPa and ϕ = 41.7°. The apparent c does not represent the cohesion itself but rather appears to have c, representing the intercept because the influence of particle crushing becomes stronger as the stress level increases and the failure criterion becomes an upward convex line.

The test results for the sand (Figure 4) show that for loose packing, the stress path tends to move to the left, which is a tendency for contraction, and this tendency becomes more pronounced as the vertical stress increases. However, for dense packing, the stress path tends to move to the upper right, which is a tendency for dilation, and the shear stress also shows a tendency to decrease slightly after reaching a peak. Looking at the failure criterion lines connecting the points corresponding to horizontal displacements of 1.0, 2.0, 4.0, and 7.0 mm on the stress path, the lines move gradually upward in the tests of loose packing, whereas in the tests of dense packing, the lines converge to a single curve after a horizontal displacement of 2

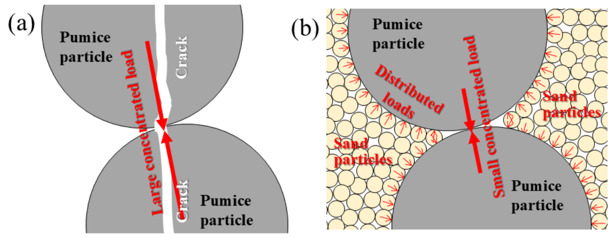

Figure 6. Schematic diagram of contact force between pumice particles: (a) Particle crushing due to high contact force between pumice particles; (b) Stress dispersion on the surface of pumice particles by filling the large pores with small sand particles.

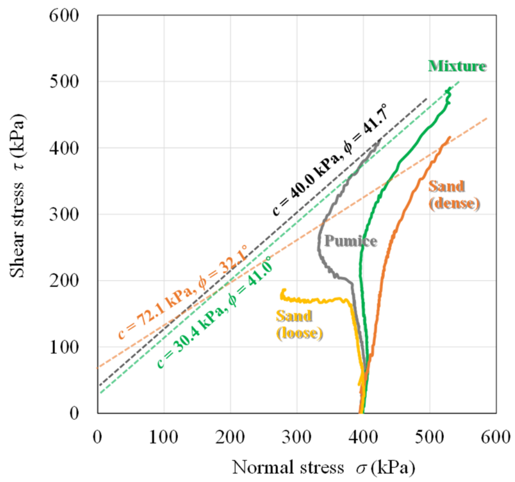

Figure 7. Stress paths obtained in the direct shear tests.

mm. The Coulomb's failure criterion line defined at a displacement of 7.0 mm is expressed by a straight line with c = 30.4 kPa, ϕ = 28.8° for loose packing, and with c = 72.1 kPa, ϕ = 32.1° for dense packing.

The test results for the mixture (Figure 5) tend to be similar to those for the pumice, but the following points are notable. In the case of a low normal stress of 100 kPa (PS100) for the mixture, the shear stress was lower than that of the pumice, but a higher shear stress was obtained than for loose packing of sand. This indicates that pumice particles with a large shear resistance angle ϕ is effective in improving the shear strength of sand. On the other hand, in the case of a high normal stress of 400 kPa (PS400) for the mixture, the shear stress increases compared to that of the pumice, and no sudden contraction due to particle crushing was observed. This indicates that for pumice particles with a large shear resistance angle but with concerns about crushability, filling the pores among pumice particles with small sand particles significantly reduces the impact of particle crushing, which is a weak point of the pumice, and then contributes to an increase in shear strength.

As illustrated in the conceptual diagram in Figure 6, if the soil is filled with only pumice particles, stress is concentrated at the contact points between the pumice particles, making them more susceptible to particle crush. However, if small sand particles are filled into the pores among the large pumice particles, the stress is dispersed homogeneously and the concentrated stress applying to the pumice particles is significantly decreased, making them less likely to be crushed.

Looking at the line connecting the points corresponding to horizontal displacements of 1.0, 2.0, 4.0, and 7.0 mm on the stress path for the mixture, the trend is roughly the same as in the case of the pumice. The Coulomb's failure criterion line defined at a displacement of 7.0 mm is c = 30.4 kPa, ϕ = 41.0°, which is roughly the same as in the case of the pumice.

The stress paths for a normal stress of 400 kPa for four types of soil: the pumice, loosely packed sand, densely packed sand, and mixture are shown in Figure 7. In the case of loosely packed sand, the normal stress decreases due to negative dilatancy, and the stress path moves to the left while the shear stress remains almost constant. In the case of densely packed sand, the stress path moves to the upper right due to positive dilatancy, and the shear stress continues to increase. In the case of pumice, negative dilatancy appears due to particle crushing, and the stress path moves to the left, but as the displacement becomes larger, this changes to positive dilatancy and the stress path moves to the upper right. Behavior characterized by highly crushable particles appears in the early stage, and behavior characterized by large granular particles appears in the later stage. Although the mixture is composed of pumice, which is a highly crushable particle, and loosely packed hard silica sand, it follows a stress path similar to that of densely packed sand. This indicates that the disadvantages of the high friability of the particles and the weakness of the loosely packed sand are offset by a synergistic effect in the mixture, resulting in the soil material exhibiting behavior similar to that of densely packed sand, which is ideal in its mechanical properties.

4 CONCLUSIONS

The pumice treated in this study was derived from the eruption of the submarine volcano "Fukutoku Okanoba" in Ogasawara Islands in Japan. A series of direct shear tests for the drifted pumice, marine sand, and a mixture of these was conducted under normal stresses ranging from 100 to 400 kPa. The new findings from this study are written hereunder:

1) A series of direct shear tests was conducted on rounded pumice particles under a normal stress range of 100 to 400 kPa. The results showed that the overall behavior was a strain-hardening type with a predominant dilation tendency, but that particle crush was a factor when the normal stress was higher than 200 kPa. In addition, because the pumice is highly stress-dependent due to particle crushing, it is necessary to set the shear strength constants according to the stress level and displacement (strain) level.
2) By mixing the pumice with marine silica sand in bulk volume ratio of 1:1, the weak point of pumice due to its crushability (rapid contraction due to shear under high confining pressure) is greatly improved.
3) The mixture of pumice and sand exhibits high shear strength like densely packed sand, even in a loosely packed state.
4) The shear strength of loosely packed sand is greatly improved by mixing pumice.

5 ACKNOWLEDGEMENTS

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