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Influence of Particle Size and Moisture on the Compression Behaviour of D-G-S

Tae-Gew Ham[1, *], Jin-Hwan Lim[1], Man-Bok Ha[2]

[1]Depterment of Civil Engineering, Kunsan National University, Gunsan, Republic of Korea

[2]Depterment of Civil Engineering, Gyeongsang National University, Jinju, Republic of Korea

Email address:
hamtg@naver.com (Tae-Gew H.), banibini@hanmail.com (Jin-Hwan L.), doro3000@hanmail.net (Man-Bok H.)

[*]Corresponding author

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Abstract: Most studies in geotechnical engineering have focused on soil behavior under low pressures, low stress levels which are typically encountered in many geotechnical projects. But high stresses can lead to particle breakage of even the strongest soil minerals. In addition, many weak-grained soils, such as decomposed granites, carbonate sands, and volcanic ashes, are also crushable and compressible under normal working loads. Hardin stated the degree to which particles are crushed during shearing depends on many factors, such as particle-size distribution, state of effective stress and effective stress path, void ratio, particle hardness, and presence or absence of water. However, these studies have focused mainly on dry particles and the influence of water on the crushing properties of particles has not been sufficiently studied. It is important to mention that characterization of the behavior of D-G-S (decomposed granite soil) is important because this material is commonly used for construction in many engineering projects in Japan and Korea. Therefore, in this patter in order to investigate the influence of particle size and moisture on compression characteristics of D-G-S, single-particle crushing and one-dimensional compression tests were carried out on three types of D-G-S as well as on quartz-rich silica sand under both dry and wet conditions. Results showed that it can be seen that there is a relationship that the crushing strength decreases as the particle size increases. this result was clarified that the same result can be obtained not only in Silica but also in D-G-S. and the initial crushing strength of a single particle was reduced and strength variability increased due to the weakening effects induced by the presence of water. Moreover, it was observed that the one-dimensional compression behavior of decomposed granite soil was related to the initial crushing strength. Finally, the magnitude of initial crushing strength was also affected by the degree of weathering of the soil.

Keywords: Weathering, Particle Size, Moisture, Crushing, Compression, Granular Material

1. Introduction

Most studies in geotechnical engineering have focused on soil behavior under low pressures, i.e., low stress levels which are typically encountered in many geotechnical projects. At such stress range, tests Terzaghi [2] have shown that natural sands do not undergo significant particle crushing. Nevertheless, researchers have also investigated the high-pressure behavior of particulate materials, specially in relation to the construction of large-scale rock-fill dam Sowers [3] and on the bearing capacity of piles in sand layer [4, 5]. Such high stresses can lead to particle breakage of even the strongest soil minerals. In addition, many weak-grained soils, such as decomposed granites, carbonate sands, and volcanic ashes, are also crushable and compressible under normal working loads. High pressure one-dimensional (1D) consolidation tests on soils have been performed by many researchers [6-10] from which particle breakage in soil specimens subjected to shear tresses was investigated.

Hardin [1] stated the degree to which particles are crushed during shearing depends on many factors, such as particle-size distribution, state of effective stress and effective stress path, void ratio, particle hardness, and presence or absence of water.

One of the early studies made on the role of moisture on crushing and compressibility of sand was performed by Lee [11] They conducted triaxial and creep tests on dry and wet specimens of Antioch sand and based on the results, they hypothesized that the presence of mineral cracks is necessary for the sensitive behavior of granular soils. That is, if a soil particle has surface fissures, moisture enters these cracks, and the moisture surface tension greatly increases the stress in the particle which helps to fracture the particle at a lower applied stress than with dry particles. As a result, they concluded that moisture sensitivity is likely to be greatest in granular soils whose particles either contain cracks or are susceptible to the formation of fine cracks as a result of loading, such as soils derived from weathered rocks. By investigating the influence of moisture content on the shear strength of sandy ground, Miura [12] confirmed that the degree of particles crushing increased with soaking of particles under moisture. However, the quantitative effect of degree of weathering, mineral composition, and soaking on particle crushing of decomposed granite soil has not been studied yet. It is important to mention that characterization of the behavior of decomposed granite soil is important because this material is commonly used for construction in many engineering projects in Japan and Korea.

In this study, single-particle crushing tests and 1D compression tests were conducted on three types of D-G-S (decomposed granite soils) in dry and wet conditions to investigate the influence of moisture on their compressive characteristics in terms of particle crushing strength. For comparison purposes, similar tests were conducted on silica sand. By understanding the effect of moisture induced changes in the particle strength on the compression characteristics of D-G-S (decomposed granite soil), useful information can be obtained regarding their physical and mechanical properties. This information is important for the prediction of flooding induced settlement of engineering structures constructed with or on these types of soils.

2. Basic Properties of D-G-S

In this study, three types of D-G-S of different degrees of weathering were used. These soil samples were obtained from Songdo (Incheon, Korea), Ube (Yamaguchi, Japan), and Matsue (Shimane, Japan) and these are referred to as SD, UBE, and MA, respectively, in this paper. Only the particles passing through the 2-mm sieve were employed. For comparison purposes, Mikawa silica sand, which has relatively higher particle strength and whose particle size ranged from 0.18 to 2.0 mm, was also tested; this is simply referred to as silica hereinafter. Table 1 presents the physical properties of the four soil samples based on Japanese Geotechnical Society standard (Japanese Geotechnical Society 2000).

Based on their study, Matsuo [13] concluded that specimens having higher degree of weathering have relatively higher natural moisture contents, and that specific surface area, ignition loss, and absorption rate can be effective indices for the evaluation of weathering of granite soil. The applicability of the above finding was verified by Murata [14] and Yasufuku [4]. In this study, the degree of weathering of the granite soil samples was evaluated using ignition loss which is a relatively easier parameter to evaluate. Ignition loss was measured in compliance with JIS A 1226 (Japanese Geotechnical Society 2000). The specimens, which were predried in an oven at 110°C beforehand, were placed inside a furnace and baked at 750°C for 1 h to measure the difference in mass before and after ignition. Figure 1 shows the drying oven used for the test. The results are listed in Table 1 where it can be seen that ignition loss increases in the following order: silica, MA, UBE, and SD; this shows that among the samples tested, the SD sample has undergone the most severe weathering.

Figure 1. *Drying furnace used.*

Table 1. *Physical properties of soils used.*

Sample	d_{50} (mm)	ρ_s (g/cm^3)	e_{max}	e_{min}	Igintion loss (%)	w_{opt}	ρ_{dmax} (g/cm^3)
UBE	0.509	2.649	1.31	0.81	3.99	15.0	1.79
MA	0.600	2.690	1.17	0.64	1.76	14.2	1.82
SD	0.394	2.698	1.44	0.89	5.29	16.0	1.73
Silica	0.736	2.650	0.93	0.58	1.18	-	-

3. Single Particle Crushing Test

3.1. Apparatus and Testing Procedure

Single-particle crushing tests were conducted on the particles which constitute the soil samples. Using the test apparatus shown in Figure 2, a particle was placed in stable direction on the bottom bearing plate and the top plate was lowered at constant speed (0.1mm/min) to crush it. During the test, axial load and displacement were measured and recorded with a computer.

In the study, single-particle crushing tests were conducted on particles of each soil sample containing each of the minerals (i.e., quartz, feldspar, and mica). For each mineral, 30 or more particles having diameters equal to the mean diameter d50 of the soil sample were tested, both in dry and wet conditions, to investigate the influence of moisture on the single-particle crushing strength. Moreover, in order to observe the pattern of particle crushing, similar tests were conducted under the same condition as above with larger particles of silica and of SD, whose diameter was 1.0-1.5 mm (equivalent to the d90 of the soil). Note that "dry" particles were air-dried as shown in Figure 3 (a), while "wet" particles were soaked in moisture for 1 week and therefore the periphery of the grain was filled with moisture, as shown in Figure 3 (b). The 1-week soaking period was adopted because this represents typical flooding duration soil structures are subjected to. More powerful saturation methods (such as soaking time longer than 1 week) may produce other effects and this may be considered in future research.

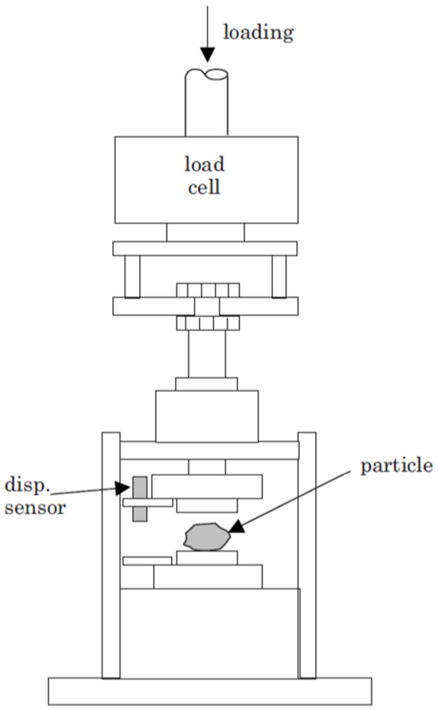


Figure 2. *Apparatus used for single-particle crushing test.*

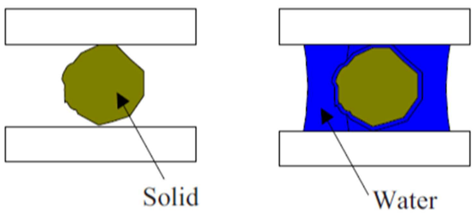


Figure 3. *Schematic diagram showing dry and wet particles in single-particle crushing test: (a) dry condition, (b) wet condition.*

3.2. The Results

Figure 4 shows the relationship between the single particle crushing strength σ_{fm} and the average particle size d_0 of each sample. Here, d_0 is obtained by measuring the distance between the upper plate and the lower plate when the particles touch the upper plate in each single particle crushing test.

From the results of experiments conducted using UBE with different particle sizes, it can be seen that there is a relationship that the crushing strength decreases as the particle size increases. This result is the result of a test conducted by Kato [7] using three types of silica sand with different particle sizes. These results are similar to those of [15, 16, 17] and others on the dimensional effect of crushing strength. In addition, as shown by the line in Figure 4, if the materials are the same, it can be seen that the crushing strength σ_{fm} has a unique relationship with the particle size.

Figure 5 shows representative results of tests performed on SD particle (with diameter of 1.0-1.5 mm) containing quartz, feldspar, and mica, respectively. The results are expressed in terms of the relation between stress σ and the normalized change in height $\delta h/h_0$ which represents the reduction of particle diameter due to crushing. Results for dry particles are represented by open points, while those for wet particles are shown by shaded points.

Figure 6 shows the relation between ignition loss of the specimens and the average first crushing strengths in dry and wet conditions, taking their mineral compositions into consideration. Also included in the figure is the plot of the average first crushing strengths in wet condition [$\sigma_{cm\text{-}all}$(wet)] normalized by that in dry condition [$\sigma_{cm\text{-}all}$(dry)]. Here, the $\sigma_{cm\text{-}all}$(wet) /$\sigma_{cm\text{-}all}$(dry) represents the reduction ratio of the average first crushing strength due to water, taking the mineral compositions into consideration. From the figure, a good correlation can be observed between large ignition loss and low average first crushing strengths in decomposed granite soil in both dry and wet conditions. In all specimens, the average first crushing strengths in wet condition were less than those in dry condition. Looking closely at ($\sigma_{cm\text{-}all}$(wet) /$\sigma_{cm\text{-}all}$(dry), which represents the degree of reduction of the average first crushing strength due to the presence of water, the values were 0.90, 0.82, 0.77, and 0.69 for silica, MA, UBE, and SD, respectively. Therefore, it can be concluded that taking mineral composition into consideration, the decrease in the average first crushing strength due to the presence of water is influenced by the value of ignition loss, which in turn is a function of the degree of weathering of the soil particle.

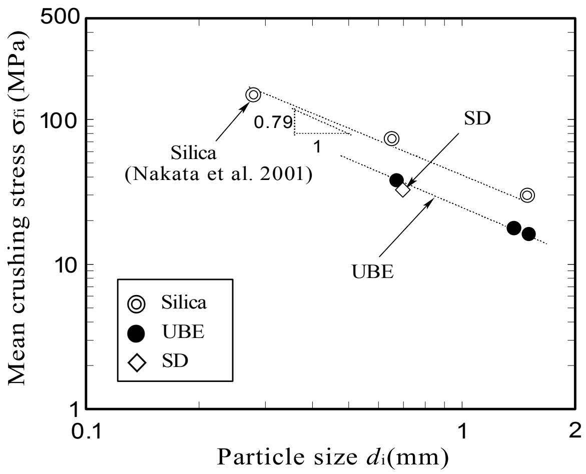


Figure 4. *Relation between Mean crushing stress σ_{fi} and Paticle size d_i.*

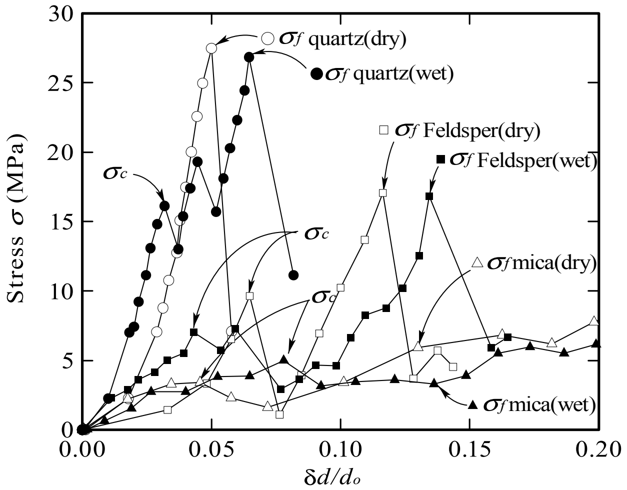


Figure 5. Relation between stress σ and $\delta h/h_0$ for SD soil.

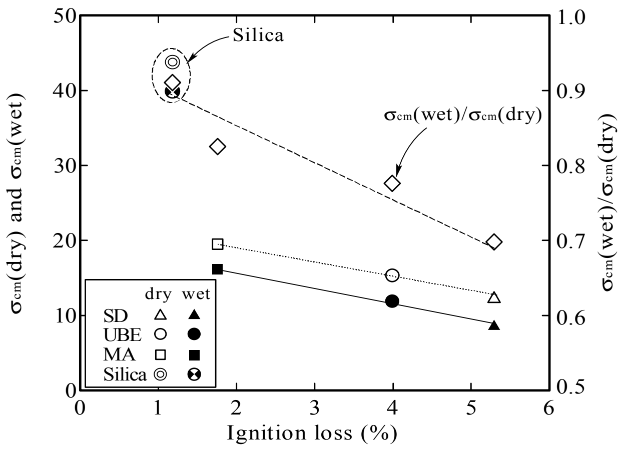


Figure 6. Relation between ignition loss, average first crushing strengths of soils in dry and wet conditions (taking into account their mineral compositions), and average first crushing strengths in wet condition normalized to that in dry condition.

Table 2. Average First Crushing Strengths (σ_{cm}) of Specimens Having Sizes Equivalent to d_{50}.

Sample		σ_{cm}(dry) (MPa)	$\sigma_{cm\text{-}all}$(dry) (MPa)	$\sigma_{cm\text{-}all}$(wet) (MPa)	$\sigma_{cm\text{-}all}$(wet) (MPa)
	Quart	19.06		12.75	
UBE	Feldspar	5.50	12.35	4.40	8.55
	Colored mineral	1.72		1.65	
	Quart	22.10		17.01	
MA	Feldspar	10.15	15.34	8.45	11.89
	Colored mineral	4.26		1.12	
	Quart	32.62		23.53	
SD	Feldspar	15.44	17.97	14.00	14.47
	Colored mineral	2.03		1.097	
Silica	Quart		43.89		39.86

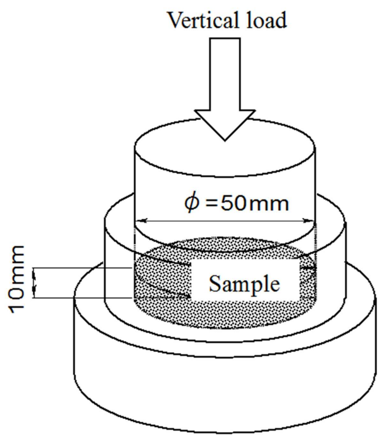


Figure 7. 1D consolidation test equipment.

4. 1D Compression Characteristics

4.1. Apparatus and Testing Procedure

In the 1D compression test, specimens were prepared in a 10-mmhigh, 50-mm diameter ring at a preset density, and compressed by a vertical load at a constant strain rate of 0.1 mm/min (Figure 7). Dry and wet specimens were tested up to the maximum load of 90 MPa to investigate the influence of water on their 1D compression characteristics. In the tests, the dry specimens were prepared from air-dried soil samples and placed in the ring by tamping method to achieve a relative density Dr=90%. In contrast, wet specimens were prepared by adding water to the dry soils to achieve a saturation ratio Sr=100% and then placed in the ring by tamping method with the same compaction energy as the wet specimens.

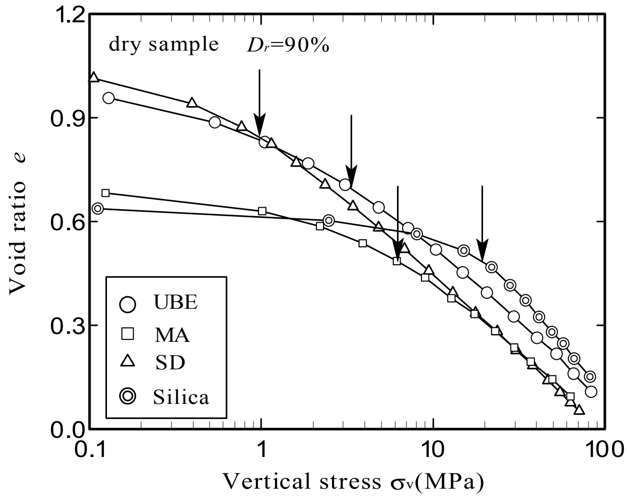
Except for silica sand where the initial void ratios for dry and wet samples are similar (e_0=0.66), the aforementioned procedure did not produce similar initial void ratios for the decomposed granite soils. The preparation method for wet samples generally produced specimens having smaller void ratios, with UBE soil having e_0=0.95 and 0.71 for dry and wet samples, respectively. Similar results were obtained for MA (dry: e_0=0.68; wet: e_0=0.58) and SD (dry: e_0=1.01; wet: e0=0.87) samples.

4.2. Test Result and Discussion

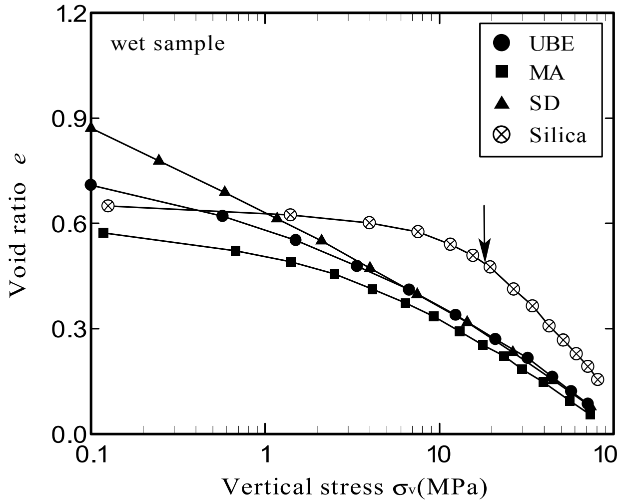
The results of 1D consolidation test on all dry samples are plotted in Figure 8 (a) for all samples in terms of the void ratio e and vertical stress σ_v. The arrows in the figure indicate the yield stress estimated using Casagrande's method. Note that the yield stress (or yield point) is related to the threshold stress for particle crushing when subjected to 1D consolidation. It is clear from the figure that although silica sand has yield stress of about 20MPa, the three D-G-S show lower yield stresses in the following decreasing order: MA, UBE, and SD. This seems to be of the same order as increasing ignition loss, as indicated in Table 1. Figure 8 (b) on the other hand shows the results for wet samples. For silica sand, the yield stress of the wet sample is similar to that of dry sample (20MPa). In contrast, unlike the dry sample which clearly showed yielding, SD wet sample has almost linear e-log σ_v plot. The other decomposed granite soils, MA and UBE, showed almost similar response and no obvious yield stress can be obtained using Casagrande's method. Thus, it is possible that the changing compression slope for dry specimens (i.e., the yield point) is the result of interlocking which prevents the specimen from undergoing greater deformation before crushing is initiated. In the presence of water, however, it is possible that wet specimens do not experience interlocking due to interface lubrication in addition to lower crushing strengths.

In order to quantify particle crushing numerically, several methods have been proposed. Miura [10] introduced the increase in specific surface area of the soil particles as a measure to describe the amount of particle crushing quantitatively. In this study, the amount of crushed particles was quantitatively expressed using the amount of increase in specific surface area proposed by Miura [10].

In order to investigate the difference in the amount of particle crushing during the 1D compression test due to flooding, the experiment was terminated at a vertical stress of 1MPa, and the amount of increase in specific surface area was investigated. The results are shown in Figure 9. From the Figure 9, it can be seen that the increase in specific surface area of Silica hardly increased in both air-dried and wet states, while that of the three D-G-S increased remarkably. Furthermore, comparing the amount of increase in specific surface area between air-dried and wet states, the three D-G-S shows a higher amount of increase in specific surface area in the wet state than in the air-dried state. These results mean that the D-G-S soil particles are samples in which the particle strength decreases and the probability of particle crushing increases due to flooding even in the aggregate.



(a) dry sample



(b) wet sample

Figure 8. *Results of 1D consolidation test.*

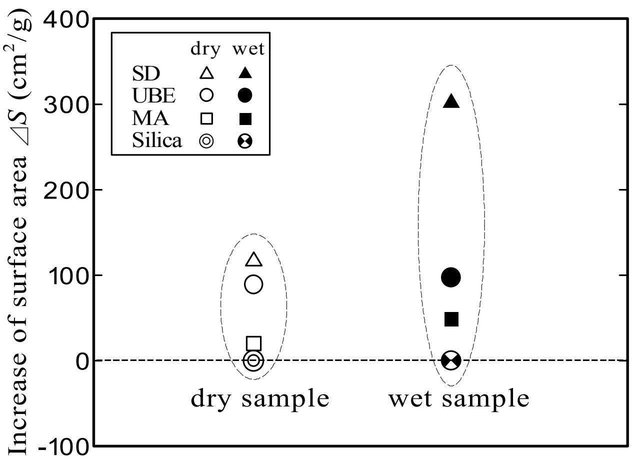


Figure 9. *Amount of Increase in specific surface area at vertical stress of 1MPa during one-dimensional compression test.*

Figure 10 shows the results of the 1D compression tests conducted with dry and wet specimens, in terms of the relation between axial strain (ε_a) and vertical stress (σ_v). It can be seen that silica shows practically the same curve in both dry and wet conditions. This is to be expected since the e-log σ_v plots are similar for both conditions, as shown in Figure 8 On the other hand, the three types of D-G-S have almost identical compression characteristics in dry condition; however, all soil specimens show larger compressibility in wet condition. It can also be seen that the compression characteristics vary significantly with the type of soil. At vertical stress σ_v=20MPa, the axial strains (ε_a) of silica, MA, UBE, and SD in wet condition were 11.3, 21.65, 26.18, and 32.73%, respectively. Thus, compressibility increases in the following order: silica, MA, UBE, and SD, which is the same order as that of increasing ignition loss as indicated in Table 1. The trend in compressibility is also apparent from the slopes of the e-log σ_v plots shown in Figure 8.

In the 1D compression test presented herein, the degrees of saturation of the specimens in dry and wet conditions were almost 0 and 100%, respectively. Considering that the kaolinite fraction of the specimens, i.e., the component with suction properties, are very small (<1% by weight), it can be surmised that for all practical purposes the effect of suction in the tests presented herein can be neglected. Thus, aside from suction, there were other factors which caused the increase in compressibility of the soil as water content was increased. One possible reason was the crushing characteristics of the particle, and this was investigated herein.

4.3. Particle Crushing Particle Crushing During 1D Compression

1D Figure 10 shows the relations between the axial strain (ε_a) and vertical stress (σ_v) of silica and MA in semilogarithmic scale, as well as the relations between the vertical stress and surface area increase. In the experiments, ΔS was obtained for multiple samples subjected to different vertical stresses, i.e., a test was suspended when the target vertical stress was reached and sieve analysis was conducted to determine the change in surface area. In the figure, ΔS was obtained at the following levels of vertical stresses: σ_v=0.5, 3, 9, and 30MPa. For comparison purposes, the test results on Toyoura sand based on isotropic compression test Miura [10] are also indicated in the Figure It can be observed from the figure that the surface area of dry silica sand increases when the vertical stress exceeds 10MPa, showing almost the same results as that observed for Toyoura sand. For both dry and wet MA samples, the surface area increases from 0.5MPa, indicating that the particles are fractured at very low stress levels. Comparing dry and wet specimens, the increase in the surface area of the wet specimens is 2, 1.2, 1.9, and 1.0 times that of the corresponding dry samples at vertical stresses of 0.5, 3, 10, and 20MPa, respectively.

Miura [12] pointed out that water strongly promotes particle fracture, and this was confirmed in the tests presented herein. As shown by the results of 1D compression tests, it can be surmised that the increase in compressibility of MA by soaking is caused by the increase in the particle crushing associated with the decrease in particle strength.

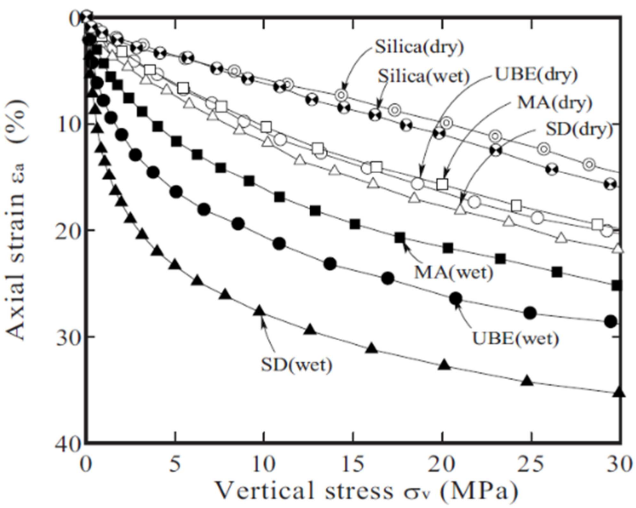


Figure 10. *Relation between axial strain (ε_a) and vertical stress (σ_v).*

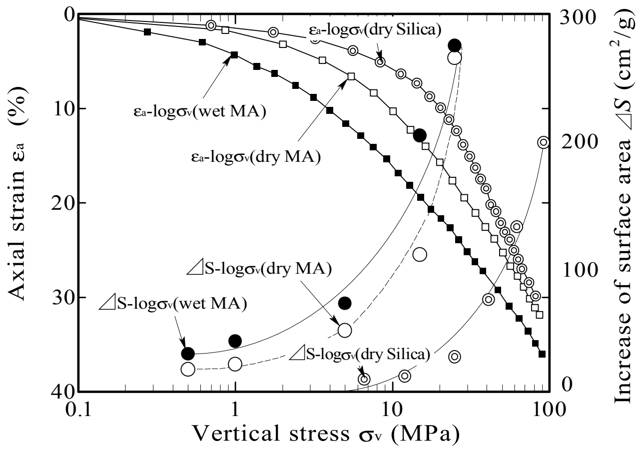


Figure 11. *Relation between vertical stress(σ_v), axial strain(ε_a), and surface area increase.*

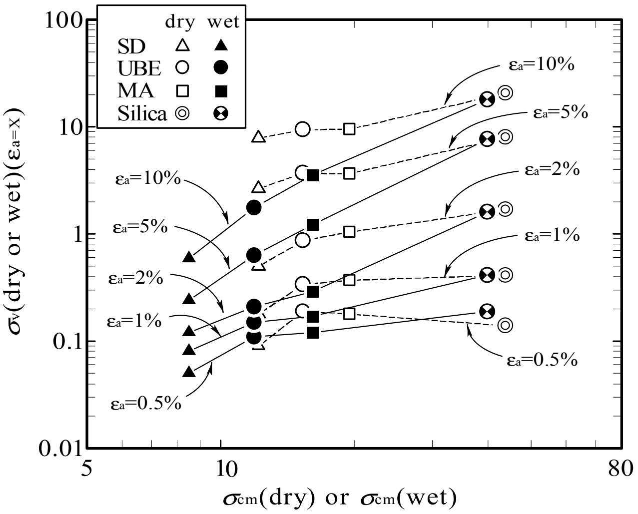


Figure 12. *Relation between the average first crushing strengths in wet condition considering mineral composition and vertical stresses (σ_v) corresponding to certain levels of axial strain.*

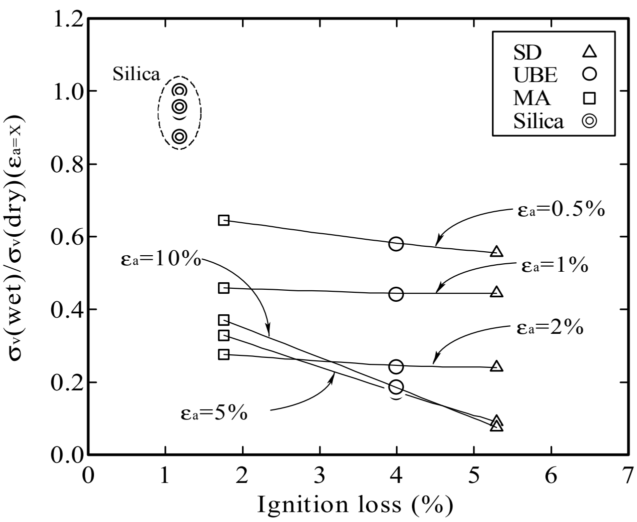


Figure 13. *Relation between ignition loss and the vertical stress in wet condition normalized by the vertical stress in dry condition corresponding to a certain axial strain.*

4.4. Relation Between Single Particle Crushing and 1D Compression Characteristics

In order to explore further the effects of water on single-particle strength, the relation between particle crushing and compression characteristics are investigated in detail. Figure 11 shows the relation in logarithmic scale between the average first crushing strengths ($\sigma_{cm\text{-}all}$) of the d_{50} particles presented in Table 2 and the vertical stress $(\sigma_v)_{\varepsilon a=X}$, corresponding to certain levels of axial strain (i.e., X=0.5, 1.5, 3, 5, and 10%) obtained from 1D compression tests on samples in dry and wet conditions, as shown in Figure 9. From the figure, it can be seen that an almost linear relationship exists between the average first crushing strength ($\sigma_{cm\text{-}all}$) calculated by taking the mineral compositions of the specimens into consideration and the vertical stress $(\sigma_v)_{\varepsilon a=X}$ corresponding to certain values of axial strain, although the slope of the line is larger in wet state than in dry condition.

Finally, the relation between 1D compression characteristics and degree of weathering is examined. The relation between ignition loss and the vertical stress in wet condition normalized by the vertical stress in dry condition corresponding to a certain level of axial strain, designated as $(\sigma_v)_{\varepsilon a=X}$(wet)/$(\sigma_v)_{\varepsilon a=X}$(dry), is illustrated in Figure 12. The parameter $(\sigma_v)_{\varepsilon a=X}$(wet)/$(\sigma_v)_{\varepsilon a=X}$(dry) rep-resents the rate of reduction of the vertical stress corresponding to a certain axial strain caused by the presence of water in 1D compression test. In the figure, the value of $(\sigma_v)_{\varepsilon a=X}$(wet)/$(\sigma_v)_{\varepsilon a=X}$(dry) at axial strains of 0.5 and 1.5% remains practically the same regardless of the type of decomposed granite soil. This is to be expected because at these low strain levels, the compression of the specimen is caused not by particle breakage but by particle deformation (elastic and plastic) and rearrangement. However, at larger axial strains of 3.0, 5.0, and 10% where particle crushing is occurring, specimens with larger ignition loss (or larger degree of weathering) show greater reduction.

The above observations indicate that the degree of increase in compressibility due to soaking in 1D compression depends on the average first crushing strength property of the soil. Moreover, a larger increase in compressibility is expected in severely weathered granite soil. These observations have serious implications on the magnitude of flooding-induced settlements of embankments made of or on decomposed granite soil.

5. Conclusions

In this study, single-particle crushing tests and 1D compression tests were conducted to investigate the effect of Particle size and moisture on the compressibility of D-G-S. The main conclusions obtain from this study are summarized below.

1. From the results of experiments conducted using UBE with different particle sizes, it can be seen that there is a relationship that the crushing strength decreases as the particle size increases. From the experimental results, it was clarified that the same result can be obtained not only in Silica but also in D-G-S.
2. For all D-G-S, the average first crushing strength calculated by considering mineral composition was lower in wet condition than in dry condition. The degree of reduction was larger in more severely weathered granite soil.
3. The major cause of the increase in compressibility in moisture submerged MA soil in the 1D compression test was the increase in particle crushing due to the weakening of particle strength.
4. The degree of increase in compressibility of D-G-S as a result of moisture submergence depended on the average first crushing strength properties which is influenced by the severity of weathering.

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