

Mechanical behaviour of unsaturated undisturbed black volcanic ash soil under static and cyclic loading

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Abstract. The mechanical behaviour of unsaturated undisturbed black volcanic ash soils was investigated using a constant volume direct shear apparatus. A series of static and cyclic tests were conducted under unsaturated and saturated samples. The cyclic test under two patterns were adopted. First type of pattern, cyclic one-sided shearing was applied. For the second type, two-sided shearing was conducted. For further understanding of the chemical content and microstructure, X-Ray Fluorescence analysis (XRF) and Scanning Electron Microscope (SEM) were evaluated. It was found that, under static shearing, the unsaturated sample exhibits a higher apparent cohesion and friction angle in comparison to the saturated sample. The normalized vertical stress under one-sided cyclic shearing in both overconsolidated and normally consolidated samples rapidly reduced at the beginning of shearing. This might be attributed to increase of the pore water pressure during shearing. Furthermore, there is a significant difference between the normalized shear stress under cyclic one-sided and two-sided shearing. For the two-sided cyclic shearing test, the normalized shear stress value is higher than the one-sided cyclic shearing test. In addition, the normalized shear stress under unsaturated condition is significantly larger. This can be related to the suction forces to the total strength of soils. The main chemical content of the black volcanic ash soil is allophane. Further, the microstructure of the black volcanic ash changes due to shearing. For the overconsolidated sample, particles of soil more severe damage than normally consolidated sample.

1 Introduction

Black volcanic ash soil, known as Kuro-boku soil in Japan, is a problematic type of soil [1, 2]. Kuro-boku (organic cohesive volcanic ash soil) is typical allophanous volcanic ash soil which has high natural moisture content varying from 65-140% [3]. Distribution of black volcanic ash soil covers approximately 31% of the total area of Japan, mainly within the volcanic zones [4].

Black volcanic ash soils are generally found near the slope surfaces above the groundwater table which is generally unsaturated. The unsaturated zone is part of the subsurface attending from the ground surface and the groundwater. The soil within this zone imposes a degree of saturation less than 100%.

The soils under unsaturated condition have higher resistance in comparison with the saturated condition. But under heavy rainfall events, the pore water pressure increases leading to loss of shear strength and slope instability may occur.

In 2016, Kumamoto earthquake triggered many slope failures around the Aso area. In general, the slope surface in the Aso area consists of volcanic ash soil and commonly overconsolidated due to the environmental effects. The black volcanic ash soils and orange-colored pumice deposits are the most common types of soils that experienced failure in the Aso area. The key factor in

slope failures was to be the shear strength of the volcanic soils before and after the earthquake [5].

Many researchers have studied the volcanic ash soil in Kumamoto slope failures, especially the orange-colored pumice [6-9]. They investigated the shear strength by a series of static and cyclic triaxial tests. However, small attention was given to the shear strength and characteristic of the black volcanic ash soil.

In this paper, the shear strength and characteristic of black volcanic ash soil was evaluated. A series of static and cyclic tests using the constant volume direct shear box were performed. Also, for further understanding of the microstructure and chemical content of the black volcanic ash soil, X-Ray Fluorescence analysis (XRF) and Scanning Electron Microscope (SEM) has been done.

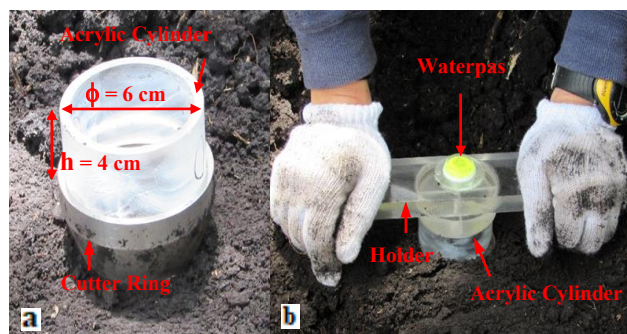


Fig. 1. Sampling setup. a) Acrylic cylinder b) Sampling.

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In order to enhance understanding of the black volcanic ash soil behaviour same as natural condition, undisturbed samples were collected and focused on overconsolidated area. Furthermore, to consider the effect of changing the moisture content under precipitation events, saturated samples were tested.

2 Methodology and Materials

2.1 Sampling methodology

The newly developed undisturbed sampling methodology for the black volcanic ash soil is illustrated in Figure 1a. Sampling was carried out using 6 cm in diameter and 4 cm in height acrylic cylindrical moulds. Before sampling, the inner of the acrylic mould and the cutter ring were lubricated using grease oil. In order to avoid plants and roots, sample were collected 10-20 cm below the ground surface. The mould attached to the cutter ring were pushed using a plate into the ground as illustrated in Figure 1b. After that the samples surfaces were trim using spatula. In order to keep the moisture content same as the natural condition, samples were kept and covered by plastic bags.

2.2 Materials and sampling locations

Tests were conducted using undisturbed samples. After Kumamoto earthquake 2016 many slope failures around Aso area occurred. Samples were collected at the middle and the top of the slope failure zone at the boundaries as illustrated in Figure 2. Samples were collected 1.5 m, from the original surface next to the failures zone boundaries and the cross-section mainly showed the black volcanic ash.

The physical properties of the black volcanic ash are listed in Table 1. It can be seen the organic matter content range from 22.9 % - 28.2 %. The particle size distribution curve is shown in Figure 3. The median grain size D_{50} is approximately 0.012 mm. Based on that, the black volcanic ash soil can be classified as volcanic cohesive soil type II (VH₂) according to the JGS standards.

The consolidation test results of the black volcanic ash under various degree of saturation as indicated in Figure 4. The yield stress in the unsaturated undisturbed sample was 105 kN/m² in average. Based on the consolidation test results, the black volcanic ash used in this research is considered as overconsolidated soil. Where the sampling depth is around 1.5 m, thus overburden pressure less than 105 kPa.

2.3 Methodology

In order to examine the shear strength properties of the black volcanic ash soil, a series of constant volume direct shear box tests were carried out considering both unsaturated and saturated samples. During shearing, the specimen volume was maintained constant or not allowed to change in volume. A schematic diagram of direct shear box test is illustrated in Figure 5. The box is divided into upper and lower parts. While the bottom fixed and the top

movable. 2 cm in height circular sample were prepared for test. In a static test for overconsolidated sample, 10 and 50 kPa vertical stress was applied. On the other hand, for normally consolidated sample 200 kPa vertical stress was adopted. Before the shearing start, specimens were consolidated under the designated vertical stress each condition for 1 hour. Then, sheared with the undrained condition up to 7 mm at a shear rate of 0.2 mm/min according to the JGS standards.

In order to examine the shear strength of the black volcanic ash soil under the earthquake shakes, a series of cyclic direct shear box test using both unsaturated and saturated samples was carried out. The cyclic test under two pattern with displacement 1 mm were adopted. First type of pattern, cyclic one-sided shearing was applied. Where shearing was started from 0.5 mm to 1 mm, from 1 mm moving back to 0 mm and again to 0.5 mm. The total of displacement for one cycle was 2 mm. On the other hand, for the second type of pattern two-sided shearing was conducted. Where shearing was started from 0 mm to 0.5 mm, then from 0.5 mm moving back to -0.5 mm and again to 0 mm. The total of displacement for one cycle was also 2 mm. For each pattern, a total number of cyclic was 10 times. Then, the shearing was terminated when the displacement reached 7 mm. Based on that, the cumulative displacement for both pattern for one times test was 27 mm. A schematic diagram adopted pattern is shown Figure 6. The 50 kPa vertical stress was applied for the overconsolidated sample and 200 kPa for the normally consolidated sample was used. The initial suction before shearing [10] is shown in Table 2.

Table 1. Physical properties of the black volcanic ash.

Physical properties	Black volcanic ash
Water content (%)	111-159
Dry density, ρ_d (g/cm ³)	0.56-0.58
Wet density, ρ_t (g/cm ³)	1.18-1.25
Specific gravity	2.28-2.34
Liquid limit (%)	154-214
Plastic limit (%)	112-139
Organic matter (%)	22.9-28.2

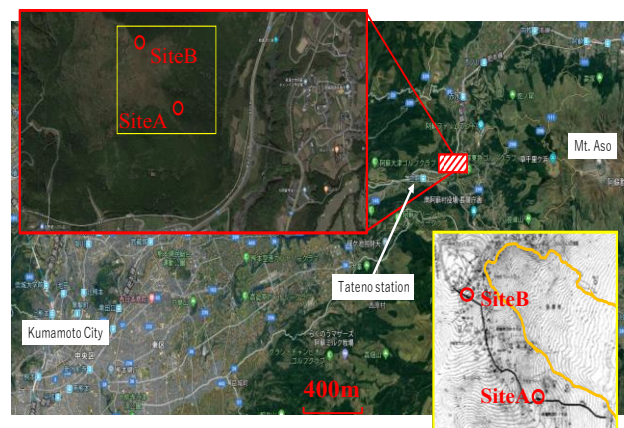


Fig. 2. Sampling location of the black volcanic ash.

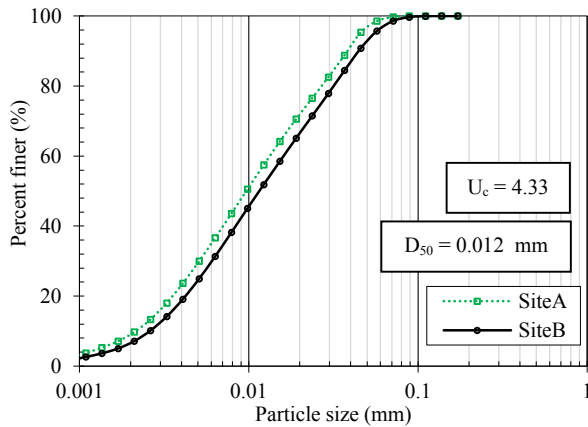


Fig. 3. Particle size distribution of the black volcanic ash.

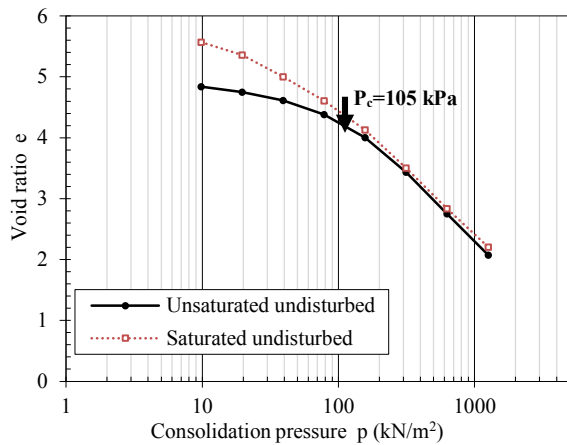


Fig. 4. Consolidation test of the black volcanic ash.

3 Test results and discussion

3.1 Static shearing behaviour

The relationship between the shear displacement and the shear stress is shown in Figure 7. It can be seen in unsaturated condition, for the normally consolidated sample the shear stress converges to a constant value with a shear displacement of 1.5 mm. While, for the overconsolidated sample, the shear stress dramatically increases and converges to a constant value at shear displacement about 0.5 mm.

The relationship between the vertical and shear stress for the unsaturated and saturated sample is illustrated in Figure 8. It can be observed that for the normally consolidated condition, the vertical stress increases dramatically till achieving the peak shear stress. Then, slightly decreases regardless of the saturation condition. On the other hand, for the overconsolidated condition both vertical stress and shear stress increases without distinct peak value. The observed behaviour is similar to the clayey soil behaviour under undrained triaxial test [11]. For the overconsolidated condition, the monotonical increases in the vertical stress can be justified to be a result of the pore water pressure reduction under shearing. On the other hand, for the

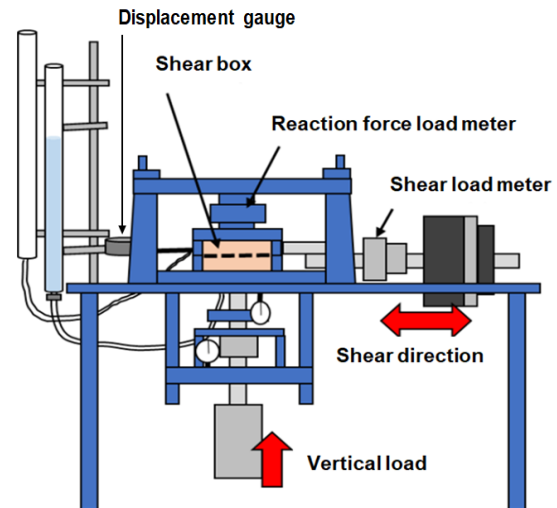


Fig. 5. Schematic diagram of direct shear box test.

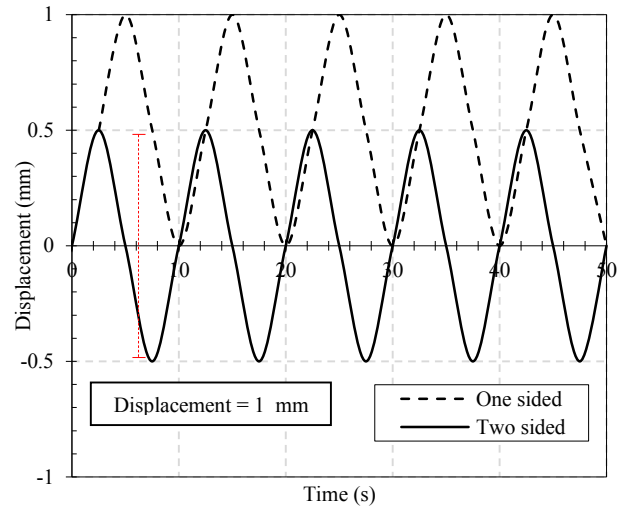


Fig. 6. Schematic of (one-sided and two-sided) cyclic loading.

Table 2. Test program for static and cyclic.

Test ID	Sample	Void Ratio (e ₀)	S _{r0} (%)	Initial Suction* (kN/m ²)	Vertical stress (kN/m ²)
Static test					
S01	Unsaturated	4.70	65.5	100	10
S02	Unsaturated	5.16	68.0	100	50
S03	Unsaturated	4.95	72.5	97	200
S04	Saturated	4.60	99.7	0.1	10
S05	Saturated	4.77	99.3	0.1	50
S06	Saturated	4.72	100	0.1	200
One-sided cyclic					
C101	Unsaturated	4.03	67.8	100	50
C102	Unsaturated	4.01	69.5	100	200
C103	Saturated	4.41	99.5	0.1	50
C104	Saturated	4.45	96.8	0.2	200
Two-sided cyclic					
C201	Unsaturated	4.73	74.1	97	50
C202	Unsaturated	4.96	82.9	8	200
C203	Saturated	4.43	100	0.1	50
C204	Saturated	4.77	100	0.1	200

* Initial suction before shearing

normally consolidated condition increases in the pore water pressure during shearing leads to decreasing of the vertical stress.

The apparent cohesion decreases from 24.6 kN/m² under unsaturated condition to 13 kN/m² for saturated condition. In addition the apparent friction angle slightly reduced from 35.5° under unsaturated condition to 35.1° for saturated condition. This tendency agrees very well with the results obtained by Bai and Atsumi [12, 13]. Finally it can be concluded that the shear strength strongly depend on soil water content, within translate into suction force which contributed to the total shear strength of the soil.

An empirical relationship of the overconsolidation ratio and the shear stress ratio was developed [14]. The relationship for the black volcanic ash soil is shown in Figure 9. The line represents an empirical model, while the scatter represents the experimental data. For OCR = 1 the shear stress ratio was 0.55, and the shear stress ratio increases as the increasing number of OCR. These obtained results are in well agreement with the kaolin clay behaviour [15].

3.2 Cyclic shearing (one-sided and two-sided) behaviour

The stress path of the cyclic one-sided shearing illustrated in Figure 10. It can be seen that the vertical stress significantly decreases in both overconsolidated and normally consolidated samples. Furthermore, in order to clearly understand the vertical stress reduction trend, the cumulative shear displacement and the normalized vertical stress were plotted as indicated in Figure 11. In general, the normalized vertical stress decreases by increasing the number of cyclic. When the normalized vertical stress decreases, it is mean affects the shear strength of soil [16]. The normalized vertical stress reduction might be attributed to increase of the pore water pressure during shearing. It must be noted that for both normally consolidated condition and overconsolidated condition, the normalized vertical stress exhibited similar reduction tendency and value. The normalized vertical stress decreases rapidly at the beginning of shearing. However, for the overconsolidated condition the normalized vertical stress decreases till reaching 0.65. Excluding the saturated normally consolidated sample, all samples converge to almost constant normalized vertical stress ratio when reaching 12 mm the cumulative shear displacement. After reaching a total cumulative displacement 20 mm, the shearing continue to 7 mm under static condition. It can be observed the normalized vertical stress significantly increases in the overconsolidated area but can not converge to the initial condition. On the other hand, in the normally consolidated area decreases till the end of shearing.

The relationship between the shear displacement and normalized shear stress in the overconsolidated area illustrated in Figure 12. There is a significant difference between cyclic one-sided and two-sided shearing. On the cyclic one-sided shearing the test results indicated that

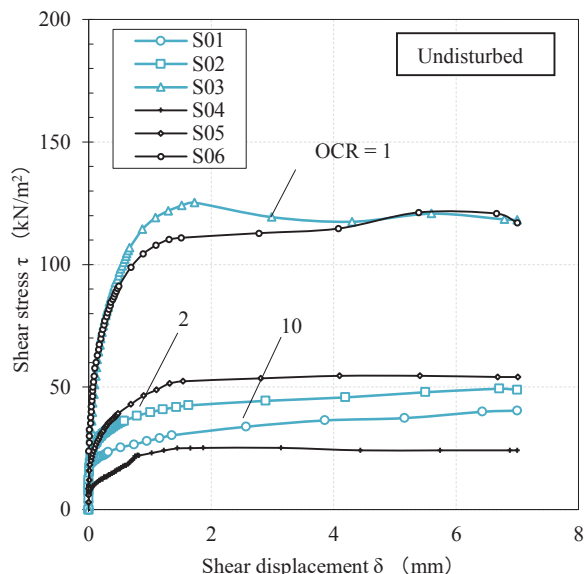


Fig.7. Relationship of shear stress and shear displacement

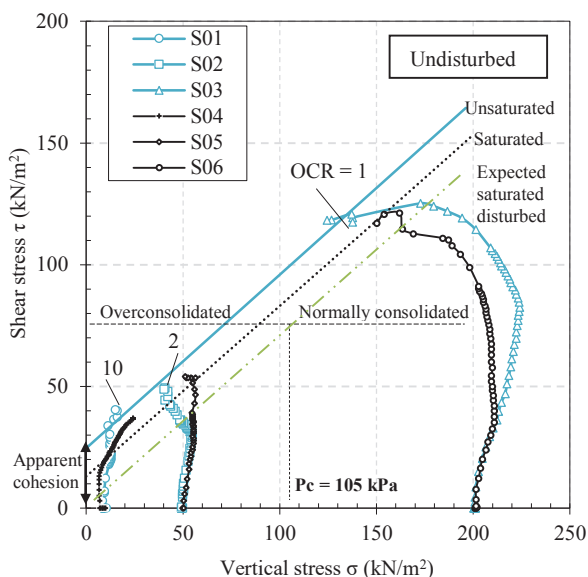


Fig. 8. Stress path static test unsaturated and saturated sample

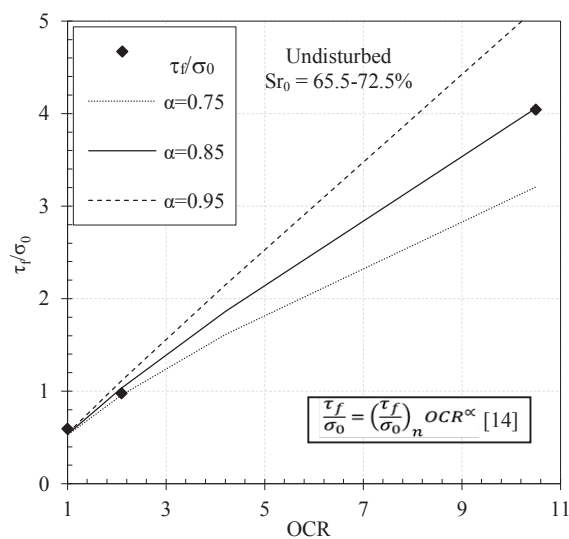


Fig. 9. Relationship of normalized shear stress at the end of shearing and overconsolidation ratio.

the normalized shear stress decreases since the first of cyclic load. This can be attributed to reduction normalized vertical stress during shearing. These results are in well agreement with the Takanodai pumice under cyclic loading using direct shear box test [17]. On the other hand for the two-sided cyclic shearing test, the normalized shear stress value is higher than the one-sided cyclic shearing test. It can be observed that the normalized shear stress value increases with the increasing number of cyclic till reaching the maximum value at the 10th cycles (final cycles). This might be justified to be a result increasing of frictional resistance of soils. The obtained results also are in good agreement with two-sided cyclic test direct shear box test results obtained by Cabalar [18] which reported that increasing of the normalized shear stress with the number of cycles for strain controlled test. Finally, It can be concluded that the cyclic shearing pattern and direction significantly affect the normalized vertical stress and shear stress of soil.

Furthermore, it can be observed the normalized shear stress of unsaturated condition, it is significantly larger. The obtained results are in good agreement with the shearing behaviour in the static shearing. This can be related to the suction forces to the total strength of soils.

3.3 Chemical Content and Microstructure

The chemical content of black volcanic ash soil results SiO₂, Al₂O₃, Fe₂O₃ accounts for as high as about 93%. It is known that these three are the main components of substances called allophane. Single particles of allophane are much smaller than other clay minerals and are extremely porous. In black volcanic ash soil, aggregate formation is further accumulated due to the bonding action of humus, therefore the soil structure become more porous. The chemical content of the black volcanic ash soil is listed in Table 3.

In order to assess the influence of the microstructure on the shear strength behaviour of black volcanic ash soil, Scanning Electron Microscopy (SEM) was carried out for the overconsolidated and normally consolidated samples. The SEM test results after the shearing are illustrated in Figure 13.

It can be seen that the microstructure of black volcanic ash soil significantly changes due to shearing. Where shearing changes the structure by breaking down the particles or the aggregate assemblage. For the overconsolidated sample, particles of soil more severe damage than the normally consolidated sample. It can be justified that the soil particles tend to move away from each other due to shearing. These results are in agreement with the final structure of soil after shearing affected by stress history [19].

Table 3. The chemical content of black volcanic ash soil

SiO ₂ (%)	Al ₂ O ₃ (%)	Fe ₂ O ₃ (%)	CaO (%)	TiO ₂ (%)	K ₂ O (%)	SO ₃ , P ₂ O ₅ ,V ₂ O ₅ , S _r O,ZnO, C _r 2O ₃ , MnO, MgO, ZrO ₂ , Br (%)
50.2	28.7	14.4	2.1	1.8	1.0	1.0

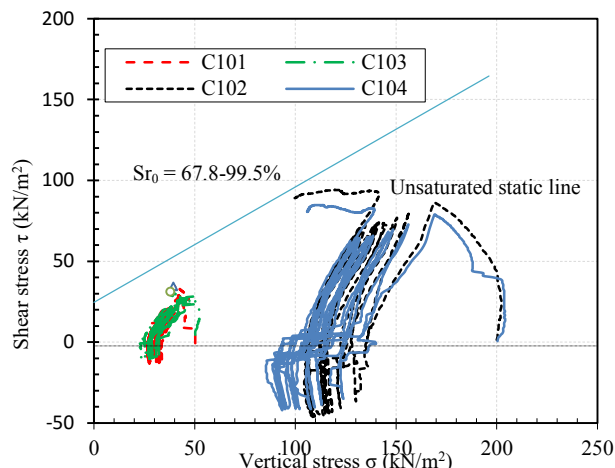


Fig. 10. Stress path of cyclic one-sided shearing under constant volume test

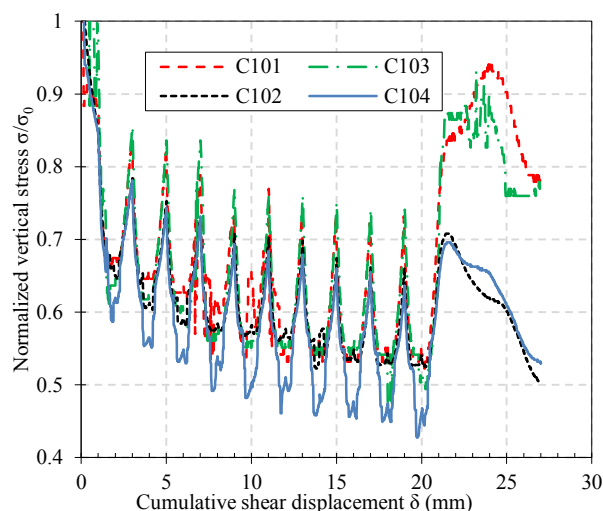


Fig. 11. Relationship between the vertical stress ratio and cumulative shear displacement one-sided shearing

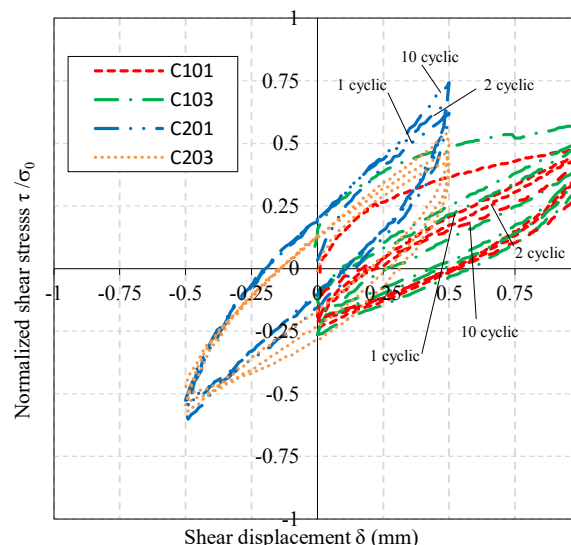


Fig. 12. Cyclic shear stress - displacement behaviour under one-sided and two-sided shearing for the overconsolidated area

4 Conclusions

Through this paper, the mechanical behaviour of unsaturated undisturbed black volcanic ash soils was

investigated using a constant volume direct shear box apparatus. A series of static and cyclic tests were conducted. Also, X-ray fluorescence analysis and Scanning Electron Microscope (SEM) has been done. The main conclusions are as follows:

1. Under static shearing, unsaturated sample exhibits a higher the apparent cohesion and friction angle in comparison to the saturated sample condition.
2. The normalized vertical stress under one-sided cyclic shearing in both overconsolidated and the normally consolidated samples rapidly reduced at the beginning of shearing.
3. The normalized shear stress of the unsaturated undisturbed sample was found to be larger than that of the saturated sample under both one-sided and two-sided cyclic shearing. This can be attributed to the influence of the matric suction contribution in the total shear strength of soils.
4. The chemical content of black volcanic ash soil results SiO_2 , Al_2O_3 , Fe_2O_3 accounts for as high as about 93%. It is known that these three are the main components of a substances called allophane.
5. Shearing changes the microstructure by breaking down the particles. For the overconsolidated sample, particles of soil more severe damage than the normally consolidated sample from SEM results.

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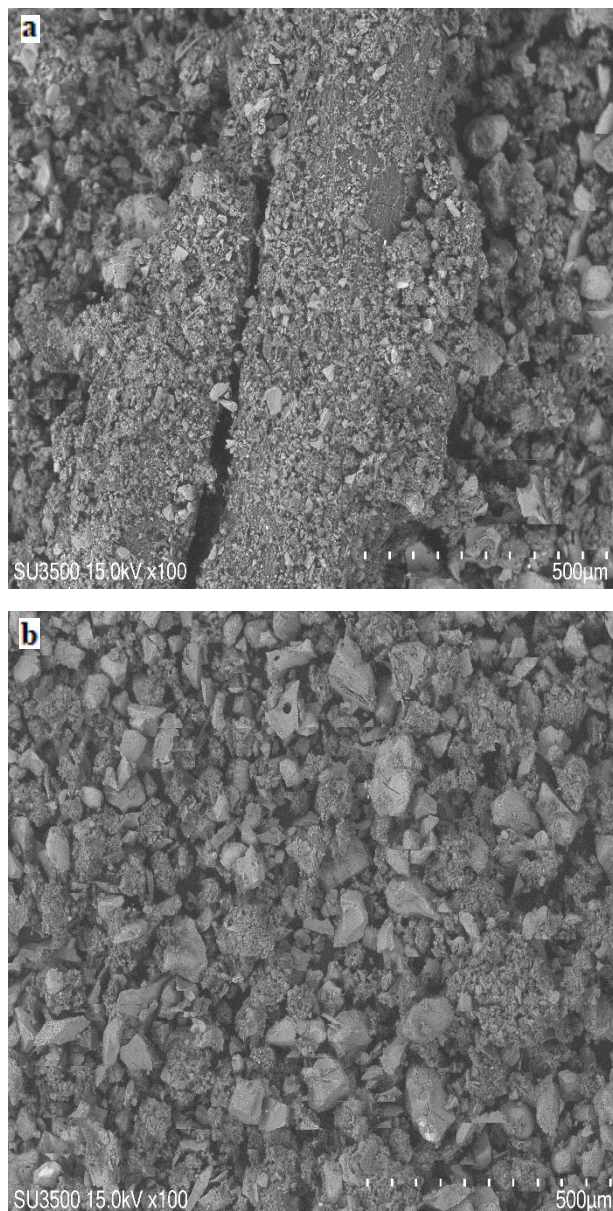


Fig. 13. SEM results of black volcanic ash soil. a) After shearing in the overconsolidated sample. b) After shearing in the normally consolidated sample.