MICROSTRUCTURAL CHARACTERISTICS OF VOLCANIC SOIL IN THE ASO CALDERA RELATED TO THE LANDSLIDE TRIGGERED BY THE 2016 KUMAMOTO EARTHQUAKE

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ABSTRACT

Volcanic soil is recognized for being problematic and hazardous because of its inherent structural and cementation properties. During the 2016 Kumamoto earthquake, a massive landslide occurred on the gentle slope near the Aso Volcanological Laboratory, Kyushu, Japan. Several volcanic soil deposits have been found scattered on the landslide site, along with significant damage to infrastructure, houses, public spaces and the natural environment. Therefore, it is important to understand the mechanism of the landslide by investigating microstructural characteristics of the volcanic soils. The volcanic soils are characterized in this study using scanning electron microscopy, x-ray diffraction and x-ray fluorescence. Scanning electron microscopy analysis is used to investigate the soil fabric characteristics while x-ray diffraction and x-ray fluorescence results are used to determine the mineral and chemical contents of the soil, respectively. Scanning electron microscopy is also used to investigate the landslide mechanism using soil subjected to liquefaction. It is concluded that the deposits have a vesicular structure composed of crushable materials, and the deposits were liquefied, resulting in landslide, because of breakdown of the soil structure during the Kumamoto earthquake.

Keywords: Volcanic soil; Earthquake; Liquefaction; Microscopy; Landslide

1. INTRODUCTION

Earthquakes in Japan have historically resulted in extensive geotechnical damage in areas consisting of volcanic soil (Hazarika et al. 2018; Miyagi et al. 2011; Kazama et al. 2012; Sassa 2005). The volcanic soil has unusual properties that depend on its mineral content, chemical content, microstructure and the porosity of the fabrics, as well as the interlocking and cementation of its particles. These properties are essential when trying to define the weathering history associated with the mechanical soil behavior, as reported by Sumartini et al. (2017). These authors identified volcanic soil as a material with low specific gravity, low plasticity and high porosity. Compositionally, the soil is dominated by plagioclase, and has a fabric consisting of crystal flakes.

On 14–16 April 2016, a series of earthquakes, referred to as the 2016 Kumamoto earthquake, struck Kumamoto Prefecture of Kyushu Island, Japan. According to the U.S. Geological Survey (USGS), the foreshock earthquake occurred at 21:26 JST on 14 April 2016 at an epicentral depth of ~11 km at a magnitude ($M_w$) of 6.5. The main shock struck at 01:25 JST on 16 April at an epicentral depth of ~10 km at an $M_w$ of 7. The Geospatial Information Authority of Japan (GSI) reported that the source of the

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2016 Kumamoto earthquake was the activity of the Hinagu and Futagawa faults. These two faults experienced more than 2 m of strike-slip displacement at shallow depth (Fig. 1). The earthquake triggered widespread landslides in Kumamoto and surrounds (Fig. 2). The most massive landslides concentrated in the Mount Aso area, within a 64 km radius of the epicenter.

One of the landslides, referred to here as the Aso Volcanological Laboratory landslide (Fig. 3), occurred on a gentle slope. It swept away houses and damaged roads, natural and public areas. The geological characteristics of the landslide have been defined by Song et al. (2017). These authors reported that the slope is composed of Kusasenrigahama volcanic pumice tephra beds (referred to as Orange soil in this paper). Sumartini et al. (2017) stated that the geotechnical behavior of the slide was related to mineralogical, chemical and microstructural characteristics of the Orange soil deposit, which is scattered along with other deposits on the scarp of the slope. However, studies on microstructure of the volcanic soil, and the mineralogical and chemical compositions of all volcaniclastic deposits of the slope, have yet to be conducted. This study presents a series of scanning electron microscopy (SEM), x-ray diffraction (XRD) and x-ray fluorescence (XRF) analyses on these deposits. Furthermore, SEM analysis of the Orange soil before and after liquefaction is used to determine the landslide mechanism.

Figure 1. Map showing the seismic displacement of the Futagawa and Hinagu faults, and the values of $M_w$ experienced during the Kumamoto earthquake (sourced from the GSI).

Figure 2. Map showing the landslide distribution by size within a 64 km radius of the Aso caldera (Sourced from GSI).
Thus, the microstructure, chemical, mineralogical and geotechnical characteristics are investigated and reported, as well as their correlation with the Aso Volcanological Laboratory landslide.

2. LANDSLIDE GEOLOGY

The study area is located near the Aso Volcanological Laboratory of Kyoto University. The slope of this area is composed of various tephras (Fig. 3). According to Kochi et al. (2017), the inclination of the slope is about 10–15° which is consistent with the value of 12° found by Song et al. (2017). The various soil deposits originate from the temporal variation in volcanic activity of Kyushu Island.
Table 1. Origin and resistivity of the volcanic soil deposit of the Aso Volcanological Laboratory Landslide (Kochi et al., 2017).

<table>
<thead>
<tr>
<th>Deposit</th>
<th>Origin</th>
<th>Age (cal ka)</th>
<th>Resistivity (Ωm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black soil</td>
<td>Organic (OL)</td>
<td>10-present</td>
<td>160-320</td>
</tr>
<tr>
<td>Brown soil</td>
<td>Aso Central Cone Pumice (AC)</td>
<td>7.3-10</td>
<td>160-320</td>
</tr>
<tr>
<td>Dark brown soil</td>
<td>Kikai Akahoya Ash (K-Ah)</td>
<td>7.3</td>
<td>160-320</td>
</tr>
<tr>
<td>Light brown and grayish soil with sand</td>
<td>Otogase Lava Pumice (Otp)</td>
<td>29-7.3</td>
<td>160-320</td>
</tr>
<tr>
<td>Light brown soil</td>
<td>Aira Tn (Atm)</td>
<td>29</td>
<td>160-320</td>
</tr>
<tr>
<td>Orange soil</td>
<td>Kusasenrigahama Pumice (Kpfa)</td>
<td>31</td>
<td>≤100</td>
</tr>
<tr>
<td>Blackish soil</td>
<td>Takanoobane Lava Pumice (Tp)</td>
<td>51±5</td>
<td>160-640</td>
</tr>
</tbody>
</table>

Sumartini et al. (2017) drew up a schematic profile of the slope, as shown in Fig. 4. These authors noted that the slope is composed of volcaniclastic deposits with distinct colors. They also identified seven volcanic deposits in the volcaniclastic sequence. All the deposits, except the Blackish soil deposit, failed during the earthquake. Kochi et al. (2017) reported that the deposits originated from different places, and also reported their ages and resistivity (Table 1). The lowest resistivity was found in the Orange soil deposits which originated from Kusasenrigahama pumice (Kpfa), and the highest was found in the Blackish soil deposits which originated from Takanoobane lava pumice (Tp).

3. MATERIALS AND TEST METHODS

Samples were taken from the upper side of the landslide site, as shown in Fig. 3, and were obtained from each deposit within the slope profile (Fig. 4). The samples were prepared under air-dried conditions to maintain the natural state of the soil for SEM, XRD and XRF analyses. The SEM analyses were conducted using a Superscan SS-550S instrument (Shimadzu Corp., Kyoto, Japan). The SEM analysis allows for the microscopic investigation of the typical structure and intact bonding of the grains of the volcanic soil. Furthermore, SEM analysis was performed on samples before and after being subjected to cyclic loading to identify the microstructural characteristics of the landslide material. Such analysis has been conducted by Sumartini et al. (2017) using undrained cyclic triaxial tests at a cyclic stress ratio of 0.426.

XRF analysis was conducted using an EDX-7000/EDX-8000 instrument (Shimadzu Corp., Kyoto, Japan) to identify the chemical content of the volcanic soil. The mineral characterization involved the qualitative identification of crystalline compounds in volcanic soil using XRD analysis. The quantification of crystalline phases and amorphous content was performed using Rietveld quantification analysis. A computer-automated diffractometer (Rigaku Corp.) was used, along with Bragg Brentano Geometry. Diffractometry was conducted at 40 kV and 30 mA. Data were collected in the range of 2θ values between 10–60° with a step size of 0.02° and counting time of 2° per minute. XRD patterns were analyzed with PDXL software (Rigaku Corp.). Among the special features likely to be encountered in a technical paper are equations, figures, tables, and references. This section will show how to deal with these features.

4. RESULTS AND INTERPRETATION

4.1 Microstructural Characteristics

The results of SEM analysis reveal that the grain structure of the soil is quite unclear (Figs. 5–9 and
10) except the sand-containing soil, as shown in Figs. 7 and 10. The structure of the soils is vesicular and is composed of stacked crystal flakes (Fig. 5). The structure of the Black soil has a large number of pores and small crystal flakes. The Brown soil and Light brown soil have similar structures, and both tend to have larger crystal flakes than the Black soil. The Light brown and grayish soil and the Blackish soil also have similar structures. The Orange soil has the largest crystal flake sizes compared with the other five soils. Additionally, the Orange soil structure has a visible lack of inter-particle bonding compared with the other five soils. Although all the soil structures are composed of the crystal flakes, the distribution of the crystal flakes is varied. The flakes can be classified into two types as shown in Fig. 11. The first is referred to as the petal-type (Fig. 11a), and is defined by the elliptical form of the flakes. The second is referred to as the flower type, and is defined by a circular form of flakes (Fig. 11b).

Figure 5. Representative SEM image of the Black soil showing the porous structure with small crystal flakes.

Figure 6. Representative SEM image of the structure of the Brown soil showing relatively large crystal flakes.

Figure 7. Representative SEM image of the structure of the Light brown and grayish soil with sand, showing relatively small crystal flakes.
Figure 8. Representative SEM image of the Light brown soil structure with relatively large crystal flakes.

Figure 9. Representative SEM image of the Orange soil showing a lack of inter-particle bonding in its structure. The Orange soil has the largest crystal flakes of the soils investigated.

Figure 10. Representative SEM image of the Blackish soil, showing the porous structure and relatively large crystal flakes.

Figure 11. Idealized crystal flake structures found in the deposits of the Aso Volcanological Laboratory Landslide. (a) Petal-type structure and (b) Flower type structure.
4.2 Mineral and Chemical Contents

The mineral and chemical contents of the soil deposits are presented in Tables 2 and 3, respectively. Table 2 shows that all the soils, except the Black soil, contain feldspar. Feldspar is a relatively brittle mineral that can be easily crushed under suitable conditions. The Orange soil contains the highest...
feldspar content, followed by the Light brown soil, the Brown soil, the Light brown and grayish soil with sand, the Blackish soil and the Black soil. The presence of feldspar is also related to the appearance of the soil: the brighter the soil color, the higher the feldspar content is.

The results in Table 3 show that all of the soils consist predominantly of SiO$_2$, Al$_2$O$_3$ and Fe$_2$O$_3$. Other than Black soil, all the soils have similar concentrations of chemical substances. There are notable differences in SiO$_2$, Al$_2$O$_3$ and Fe$_2$O$_3$. The Black soil has considerably more Fe$_2$O$_3$; about 1.9 to 2.7 times more than the other five soils. The Black soil has the lowest SiO$_2$ (44.864%) and Al$_2$O$_3$ (28.283%) concentrations of the samples investigated.

The concentration of alkalis and alkali earth metals are presented in Fig. 12. The soils have similar alkali earth metal contents, approximately 2/3 of the Light brown soil content. However, the percentage of alkali metals varies between all the soils, with lower concentrations than the alkali earth metals. The ratio of SiO$_2$/Al$_2$O$_3$ of the soils varies from 1.36 to 1.77 (Fig. 13). The Orange soil has the lowest SiO$_2$/Al$_2$O$_3$ ratio compared with the other soils, and the Light brown and grayish soil with sand has the highest ratio.
4.3 Cyclic Loading Effect on Soil fabric

Sumartini et al. (2017) investigated the response of the Orange soil to cyclic loading using an undrained triaxial test, as shown in Fig. 14. The results show that the Orange soil at a cyclic stress ratio of 0.426 liquefies at 128 cycles. Thus, although the Orange soil has low susceptibility to cyclic

Figure 14. Response of undisturbed Orange soil samples to undrained cyclic triaxial test (CSR = 0.426, σc' = 60 kPa): (a) effective stress path, (b) shear stress vs. shear strain, and (c) pore water pressure ratio vs. number of cycles (Sumartini et al., 2017).

Figure 15. Orange soil fabric before cyclic loading, showing a structure of stacked crystal flakes.

Figure 16. Orange soil fabric after cyclic loading, showing reduction in crystal flake size and loss of structure.
loading, liquefaction still occurred. Moreover, Sumartini et al. (2017) reported that the Orange soil liquefies in less than 20 cycles when shear stress exceeds confining pressure. Figs. 15 and 16 show SEM analysis results of the Orange soil structure before and after the liquefaction tests, respectively. Fig. 15 shows that the soil structure is composed of a stack of the crystal flakes and is highly porous. In comparison, Fig. 16 shows that the soil structure is visibly broken, and the crystal flake size has been reduced.

5. DISCUSSION

5.1 Correlation of Microstructure with Mineral and Chemical Characteristics

The SEM results show that all the soils have similar microstructural characteristics, referred to here as crystal flake structures, although each of the structures differ in terms of pore distribution and flake type. The soil structures have been eroded because of groundwater flow, and thus it can be assumed that the higher the pore size, the longer the duration of weathering experienced.

The mineral contents (Table 2) show that the soils are dominated by feldspar (43–97%), except in the Black soil. Such a range is considered wider than the Aso III ash-flow, which has a feldspar content in the 55.8–85.7% range (Lipman 1967). In the parent rock, feldspar is the primary aluminum-bearing mineral, which was decomposed during weathering (Patterson 1971). The SiO₂ content is in the 44.864–53.923% range, which is lower than the values found in the Aso III ash-flow (59.03–70.58%) (Lipman 1967). The alumina concentrations in the soils are relatively high, with values more than half of the silica concentrations, suggesting that the deposits were weathered for a long time, given that alumina typically increases in concentration as Al replaces Si during weathering (Patterson 1971). The high concentration of alumina indicates the occurrence of nodules, and Al can also be conveyed into the weathered deposits by groundwater, although much of the Al is likely from a residual source (Patterson 1971).

Low concentrations of alkali metal and alkali earth metals also provides an indication of prolonged weathering, given that their solubility typically leads to their removal during weathering (Patterson 1971). Consequently, and in reference to Fig. 13, it can be assumed that the Orange soil deposits underwent prolonged weathering and reduction in soil hardness. Soil hardness decreases from Black soil to Blackish soil, Light brown soil, Brown soil, and finally Light brown and grayish soil with sand.

5.2 Correlation of Microstructure with Compositional and Mechanical Characteristics of the Landslide

The results of cyclic testing show that liquefaction occurred because of destruction of the soil structure in relation to decreased effective stress and increased number of cycles. This phenomenon is visible in the results of SEM analysis (Figs. 15 and 16). These results correlate with field observations, in which it is evident that the Orange soil deposit is found scattered along the scarp of the landslide site. All the deposits overlying the Blackish soil failed during the earthquake and although the Orange soil deposit has high resistance to liquefaction, the landslide still occurred, most likely because of the high magnitude of the earthquake (Sumartini et al. 2017). Thus, it is considered that the earthquake caused destruction of the soil structure, leading to collapse of the Orange soil deposits and ultimately all the deposits above it.

The strength of the deposits can be reflected in the alkali and alkali earth metal concentrations (Patterson 1971). Thus, the chemical characteristics of the Blackish soil and the Orange soil (Fig. 13) are used as the boundary with which to evaluate the potential for the deposits to slide as a result of earthquakes. According to Fig. 13, the alkali earth metal concentrations of Orange soil are similar to other deposits, except for the Light brown soil. Otherwise, the alkali concentration is variable in each deposit, and the Orange soil has the lowest concentration compared with the other deposits. Consequently, in this case, the potential landslide is evaluated based on alkali concentration, and it can
therefore be concluded that Black soil and Orange soil have potential to fail during earthquakes.

6. CONCLUSIONS

This study has successfully defined the microstructural characteristics of the soils investigated and explained the relationship between these characteristics and the occurrence of the Kumamoto landslide. The following conclusions can be drawn:

1) The six volcanic soils investigated share the similar features. The structures of each soil deposit are vesicular, although void distribution is variable.

2) SEM analysis reveals that the materials have two typical crystal flake shapes. The unique flake structures can be used as defining features of the volcanic soil of the Aso caldera.

3) XRD and XRF analysis reveals that all of the deposits, except the Black soil, are predominated by feldspar and high alumina content, which explains the vesicular structure of the deposits.

4) The results also indicate that the deposits with similar physical appearance have similar chemical, mineralogical and microstructural characteristics. Based on the three analytical techniques, the microstructural characteristics of the soils can be defined as being composed of brittle material in a vesicular structure.

Considering the microstructural characteristics of the soil deposits, and their alkali concentration, the Orange soil and the Black soil are considered to have the highest susceptibility to failure compared with the other four deposits. Furthermore, SEM analysis of the Orange soil before and after liquefaction shows that the deposit liquefied during the earthquake because of breakage of the soil structure. Thus, all of the deposits in the landslide site, with the exception of the Blackish soil, were found to have collapsed during the earthquake.

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8. REFERENCES


