Mechanical Behaviour of a Residual Soil from Ignimbrite Rock of São Miguel Island - Azores

Luís Andrade Pais ¹, P. E. Maia Carvalho ¹, Ferreira Gomes ¹, Victor Cavaleiro ¹, Ana Malheiro ²

¹ University of Beira Interior, GeoBioTec, Covilhã, Portugal
² LREG – Regional Laboratory of Engineering and Geology, Azores, Portugal

ljap@ubi.pt

Abstract. Azores consists of nine islands and several islets, located in the North Atlantic to 1600 km from Continental Portugal and is distributed between latitudes 36° 55' to 39° 43' N and longitude 24° 46' to 31° 16' W. Azores archipelago is in a convergence zone of a series of dynamic tectonic structures, that are responsible for seismicity and volcanism, geological and petrological of these islands. The island of São Miguel, an eastern group, in addition to other petrology’s in its geology, has ignimbrite, which is a pyroclastic rock with a dacitic or rhyolitic composition, resulting from the deposition of materials in semi-melting at high temperatures from a pyroclastic flow. At the site of Água D’Alto, the residual soil sample resulting from the ignimbrite alteration was taken and was evaluated with the interest of studying its application or use as construction material. The soil was subjected to physical and chemical classification test, compressibility, and stress-strain behaviour. This material shows good mechanical characteristics, although its chemism is potentially corrosive.

1. Introduction

Azores archipelago consists of 9 islands, located in the North Atlantic, 1600 km away from Continental Portugal. The distribution in the Atlantic allows the islands to be grouped into the Western group (Flores and Corvo), the Central group (Faial, Pico, São Jorge, Graciosa and Terceira) and the Eastern group (São Miguel and Santa Maria and the islets of Ants). These Islands are lined according to a general NW-SE orientation, over 600km.

Azores archipelago is in a convergence zone of a series of dynamic tectonic structures, which are responsible for seismicity and volcanism and define the geomorphological, geological, petrographic and chemical characteristics. The tectonic structures that stand out are the mid-Atlantic ridge, the Terceira rift, the North fracture zone of Azores, the eastern fracture zone, and the western fracture zone. The mid Atlantic ridge is a distensile structure that goes from North to South Atlantic, it is seismically active and is intersected by general trend E-W transforming faults that interrupt its continuity. This structure establishes the boundary between the American plate in the west, and the Eurasian and African plates in the east [1] [2]. Azores archipelago is in this triple junction, and the islands are distributed between the North American plate and the Eurasian plate, as can be seen in figure 1. The fracture zone in the East of Azores, the Azores-Gibraltar fracture, represents the West segment of one of the most important fracture zones in the terrestrial globe.
The island of São Miguel is the largest in the archipelago with an area of 747 km$^2$ (figure 2), and the geomorphology is conditioned by the volcanism that corresponds to an important stratovolcano or composite volcano and some secondary volcanoes with alignment of the NW-SE to WE fractures with the top of some volcanic cones occupied by lakes. Generically, the stratigraphic complexes are constituted by lava flows and pyroclastic deposits that originate stratigraphic sequences according to the sequence of the volcanic episodes. Deposits of dacitic or rhyolitic composition.

The volcanic products resulting from the central volcano of the region Povoação and are densely covered by materials emitted by the central volcano of Furnas, located to the west, predominantly ignimbrites [3]. The pyroclastic deposits, with thick coverage, gaining some cementation during the loading time which turns it into a soft rock. At the site of Água D’Alto, the sample of residual soil results from the ignimbrite alteration that was taken and was evaluated with the interest of studying its application or use as construction material. The soil was subjected to physical and chemical classification test, compressibility, and stress-strain behaviour. The series of oedometer tests and undrained triaxial compression tests (CU) are used to estimate the compressibility parameters and the stress-strain and strength rupture behaviour.
2. Natural soils identification and classification

The particle size distribution, liquid limits and particle density were used to the physical characterization of soils. Soil identification tests was carried out following a British Standards protocols [4]. Ignimbrite residual soil sample from Azores belongs to SM – SP group with clay activity normal to low, that means, with low-expansive clay, according to ASTM classification [6]. Grain size distribution is presented in figure 3.

![Grain size curves of tested soils](image)

**Figure 3.** Grain size curves of tested soils

Table 1 shows the grain size, physical characteristics, and the limits of consistency of Água D’Alto sample. The liquidity limit values, and the low plasticity index reflects the presence of low expansive clays.

| Sample          | Effective size | Liquid limit | Plasticity index | Clay activity |
|-----------------|----------------|--------------|------------------|---------------|
| Água D’Alto_Azores | 0.006          | 46           | 10               | very low      |

* The defloculant used in the test is hexametaphosphate.

The chemical (X-Ray) tests show the presence of Halite (NaCl), generally occurs with other evaporite deposit minerals, such as sulphates, halides and borates, the presence of halloysite is an aluminosilicate clay mineral with the empirical formula [Al2Si2O5(OH)4]2H2O, typically forms by hydrothermal alteration of aluminon-silicate minerals and anorthoclase [(NaK)Si3AlO8]. The mineral anorthoclase is a crystalline solid solution in the alkali feldspar series, in which the sodium-aluminium silicate member exists in larger proportion (see figure 4).
The presence of sulphates causes the tested soil to be corrosive as can be seen in figure 5, where the reaction with the operator's skin is seen.

3. Compressibility behaviour

On series of one-dimensional consolidation (oedometer) tests were carried out under a $K_0$ condition with null radial strain on saturated (Água D’Alto_Azores: Wet) and unsaturated (Água D’Alto_Azores: Dry) specimens to verify the capacity of collapse, by using the cell of 63 mm diameter and 20 mm height. The groups of specimens for oedometer tests were prepared with similar physical parameters. The initial increment of 1.2 kPa and the maximum vertical effective stress of 3067 kPa were used in this work. The following increment was the double of the previous stress made 24 hours prior.

From the oedometer test at the dry specimen it is observed an increase of virtual preconsolidation stress ($\sigma'_{p*}$) for the soils influenced by the developed suction. The wet sample has a preconsolidation
stress less than dry and is explained by the rupture of original structure of the original pyroclastic rock. So is better to call the specimen virtually intact and take a virtual preconsolidation stress with a correct concept because these processes are different of the consolidation on sedimentary layers (table 2 and figure 6).

**Table 2.** One-dimensional consolidation test result of Água D’Alto_ Azores sample – wet and dry condition test

| Sample                  | \( \nu_0 \) (-) | \( \sigma_p(*) \) (kPa) |
|-------------------------|------------------|------------------------|
| Água D’Alto_Azores_dry  | 2.930            | 60                     |
| Água D’Alto_Azores_wet  | 3.038            | 140                    |

**Figure 6.** One dimensional consolidation test result of Água D’Alto_ Azores sample – wet and dry condition test

### 4. Shear stress behaviour

On series of consolidated undrained triaxial compression tests (CU) with pore water pressure and axial strain measurements were carried out on Água D’Alto_Azores sample. The testing conditions are shown summarized in Table 3.

**Table 3.** Testing conditions for undrained tests on saturated specimens of samples from Azores

| Sample                  | \( P_0 \) (kPa) | \( \gamma_d \) (kN/m\(^3\)) | \( \nu_0 \) (-) |
|-------------------------|----------------|-----------------|----------------|
| Água D’Alto_Azores      | 70             | 9.2             | 2.918          |
|                         | 150            | 9.7             | 2.770          |
|                         | 300            | 9.5             | 2.821          |

The specimens placed on the triaxial cell were saturated (\( B=\Delta u/\Delta \sigma_3 > 97\% \); \( \Delta u \), pore pressure and \( \Delta \sigma_3 \), cell pressure variation) and consolidated for different confinement stress or different initial mean effective stress. The saturation of each sample was ensured by water flow followed by application of back pressure (figure 7).
After saturation and isotropic consolidation to different initial mean effective stress, CU shearing test were carried out at axial strain rate of 35%/min. The results of the tests for the undrained triaxial compression showed that the sample tends contracts. As it is shown in Figure 8, the stress-strain results. The magnitude of the drop for $p'_{0}=70$ to 300 kPa in CU test was attributed to the contractive tendency of the specimen.

The stress-strain-strength behaviour of soils is described by a set of parameters that are defined in a failure moment. Corresponding parameters were used to the maximum value of shear stress $t_{\text{peak}} = (\sigma_1 - \sigma_3) / 2$, to axial extensions exceeding 4%, to estimate the envelope corresponding to the maximum shear strength. There were also considered the values obtained in the failure of specimens for axial deformation exceeding 23%, to estimate the envelope in its ultimate limit state or minimum $t_{\text{min}} = (\sigma_1 - \sigma_3) / 2$. Figure 9 shows the failure envelope for the maximum shear stress ($t_{\text{peak}}$) and the ultimate limit state ($t_{\text{min}}$) in the shear stress versus mean effective stress space ($t : s'$), for $p'_{0} = 70, 150$ and 300 kPa.

The sample of ignimbrite residual soil with low relative density, in the test conditions, only a line is obtained of the type $t = a + s' t g a'$ in the space $t : s'$. Envelop failure for maximum shear strength
\[(t_{\text{peak}} = 0.5674s' + 0.976; \phi'_{\text{peak}} = 34.6^0; c' \approx 0 \text{ kPa})\] for residual or minimum strength \[(t_{\text{min}} = 0.5699s' + 0.640; \phi'_{\text{min}} = 34.7^0; c' \approx 0 \text{ kPa})\] are similar and that passes in the origin, as shown in figure 9. These lines define the critical/stable state (CSL) and are intrinsic property of the soil. The intrinsic behaviour is defined for the state in which the initial structural properties (fabric and bonding) and the physical ones of the soil have no influence in its mechanical behaviour.

The cohesion is null due to transformation of the fabric and is linked to the collapse of the minerals in minor and rigid particles, which can be in accordance with the purely frictional behaviour.

![Figure 9](image)

**Figure 9.** Consolidated undrained triaxial compression tests (CU) of Água D’Alto sample: shear strength versus mean effective stress space

Yet stress path for \(p'_0 = 300 \text{ kPa}\) reached the structural collapse for extensions close to the maximum stress strength. Probably we are in a compressible zone and softening by deformation below a zone of instability in relation to liquefaction.

5. Conclusions

This examination of data from physical, triaxial and oedometer tests on Água D’Alto samples has revealed:

1. Particle size distribution and Consistency test showed that Ignimbrite residual soil belongs to the SM – SP group with clay activity normal to low, that means, with low-expansive clay, denouncing the presence of kaolinite mineral. The chemical (X-Ray) tests show the presence of Halite (NaCl), the presence of halloysite is an aluminosilicate clay mineral and Anorthoclase \([\text{NaK}]_3\text{Si}_3\text{Al}_8\).

2. From the oedometer test at the dry specimen it is observed an increase of virtual preconsolidation stress \((\sigma'_p=140 \text{ kPa})\) for the soils influenced by the developed suction. The wet sample has a preconsolidation stress less \((\sigma'_p=65 \text{ kPa})\) than dry and is explained by the rupture of original structure of the original pyroclastic rock.

3. Envelop failure for maximum shear strength \((t_{\text{peak}} = 0.5674s' + 0.976; \phi'_{\text{peak}} = 34.6^0; c' \approx 0 \text{ kPa})\) and for residual or minimum strength \((t_{\text{min}} = 0.5699s' + 0.640; \phi'_{\text{min}} = 34.7^0; c' \approx 0 \text{ kPa})\) are similar and passes in the origin. These lines define the critical/stable state (CSL) and are intrinsic property of the soil. The cohesion is null due to transformation of the fabric and is
linked to the collapse of the minerals in minor and rigid particles, which can be in accordance with the purely frictional behaviour. Yet stress path for $p'_{0} = 300$ kPa reached the structural collapse for extensions close to the maximum stress strength. Probably associated with a zone of instability in relation to liquefaction.

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