# *Part I*
# *Characterization of volcanic formations*

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# Geomechanical characterization of volcanic materials in Tenerife

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ABSTRACT: The increasing development of infrastructures and building in Canary Islands has revealed the importance of the geotechnical studies and investigations to evaluate the geological materials properties. However, in volcanic islands the studies on rocks and soils characteristics and properties under the geotechnical point of view are very scarce. In this study, carried out mainly in Tenerife, the volcanic materials have been characterized from field survey, bibliographical references and expertise judgement. The main objective has been the data collection from the available sources in order to characterize and evaluate the geomechanical properties of these materials. Besides, it has been carried out an exhaustive bibliographical data collection. Geotechnical properties of lava flows, tuffs, ignimbrites, agglomerates, pyroclastic deposits and volcanic soils is presented, as well as the main problems related to engineering applications.

## 1 INTRODUCTION

This paper includes the description and characterization of the volcanic materials of Tenerife Island, mainly from field data, bibliographical data collection, including the analysis of geotechnical and research projects and studies, and expertise judgment. The main objective is the collection of the available data, from different sources, in order to carry out an assessment of the geomechanical properties of the volcanic materials, and the main geological-geotechnical implications.

The increasing development of infrastructures and constructive activities in the Canary Islands, has pointed out the importance of the geotechnical studies and the investigations on the properties of volcanic rocks and soils, as well as the geomechanical behaviour in engineering applications: foundations, slope stability, underground excavations, etc.

Methodological procedure has included the following tasks:

- Bibliographical collection of physical and mechanical properties of volcanic materials and formations all over the world.
- Analysis of the data collected and assessment of the representative values.
- Field geomechanical characterization of rock masses.
- Description of the types of rock masses and their geomechanical classification.
- Geotechnical description of pyroclastic deposits and volcanic soils.
- Resume of the geotechnical properties of rock masses and soils and the main geotechnical problems for engineering applications.

As a result of this study, a database has been prepared with more than 400 data mainly from bibliographical collection (González de Vallejo et al., 2006).

## 2 GEOLOGICAL DESCRIPTION OF THE VOLCANIC FORMATIONS

### 2.1 *Basaltic lava flows, trachytes and phonolites*

Lava flow is a volcanic extrusive product resulting from the flow of lava on the surface until it cools or the volcanic emission stops. The morphology, length and thickness of the deposit depend, among others, on the magma's composition and topography.

Differential cooling process related with the progression of viscous basaltic lava flow results on the formation of clinker layers. Between two lava flows, a reddish soil layer (*almagre*) as results of heating, can be formed. Columnar jointing affecting the central part of the flow is generally observed.

### 2.2 *Dykes and other intrusive structures*

Dykes can be generally defined as discordant magmatic intrusion along faults, fractures or fissures. Thus, they are planar structures, generally vertical or sub-vertical. Usually dykes group into families with similar tectonic strikes.

If the magmatic intrusion is horizontal and usually concordant with the neighbouring formations it is called *sill*.

Plugs are the filling up of volcanic conduits, namely of scoria cones, usually present a cylindrical shape and can be affected also by columnar jointing.

### 2.3 *Pyroclastic deposits*

Pyroclasts are fragmental rocks ejected from volcanic vents during explosive eruptions. The deposition and accumulation of these solid fragments, as a consequence of the eruptive processes, forms volcanic cones and (layered) deposits, depending their extent and distribution on the density and size of the fragments, height of the eruptive column, wind regime and topographical conditions.

Pyroclastic materials can be described, attending to their genesis on: pyroclastic flow, pyroclastic surge, and pyroclastic fall.

Depending on the size of the fragments, pyroclasts are classified into: bombs or blocks (grain size $>64$ mm), *lapilli* (2–64 mm) and ash ($<2$ mm), being blocks more angular fragments than bombs.

Scoria, is a general term for a porous, dark and glassy pyroclast of basaltic composition, while pumice is a broad term for a light colour, highly vesicular, low-density pyroclast of acid composition.

### 2.4 *Tuffs*

This term is descriptive, and it is not related to the origin of the material. Tuff can be defined as a pyroclastic rock formed by lithification of *lapilli* and ash deposits. Depending on the composition of these *lapilli* and ash fragments, tuffs can be classified as basic or acid. When tuff is formed from pyroclastic fall deposits associated with hydrovolcanic eruptions, the fragments are compacted and consolidated in the post-sedimentary process.

### 2.5 *Ignimbrites*

Ignimbrites originate from pyroclastic flows, originally called *nuée ardente*. While some authors classify as ignimbrites any deposit from a pyroclastic flow, others consider them mainly as the rocks formed by flows of pumitic *lapilli* and ash fragments, with eutaxitic texture or *fiamme* structures. This criterion has been followed in this study, and ignimbrites were considered as welded pyroclastic flow deposits whose coarse fragments are flattened and stretched, as *fiamme*; Their high welding degree, one of the main characteristics of this type of material, is related to its deposition at temperatures higher than 400°–550°C, and the foliation and joints that they present are due to its cooling.

### 2.6 *Agglomerates*

Agglomerates are heterogeneous compacted rocks formed by large heterometric fragments, rounded in some cases, in a micro-agglomerate coarse-grain matrix. They can be formed from pyroclastic flows or they can have a mechanical epiclastic origin, related to debris avalanches, debris flows or mud flows. When from epiclastic origin, they present sandy or clay matrix, resulted from the crushing of the mobilized material. In this case fragments are mainly angular and large sized, and the agglomerate material is named as volcanic breccia.

## 3 DISCONTINUITIES

Volcanic materials are generally affected by joints and discontinuities. Depending on the origin, the more characteristics are:

- Thermal discontinuities due to cooling and retraction processes: vertical, columnar, polygonal, radial, sub-horizontal and spherical jointing.
- Tectonic discontinuities: faults, fractures and joints.
- Discontinuities formed by intrusive structures: dykes, sills, plugs, etc.
- Discontinuities formed by gravitational processes: tension cracks, collapse fractures, landslide planes, etc.
- Discontinuities corresponding to contact surfaces between lava formations, depositional or erosive.

In Tenerife Island, most of discontinuities have a thermal origin, although the other types can also be observed.

## 4 GEOMECHANICAL CHARACTERISTICS OF BASALTIC, PHONOLITIC AND TRACHYTIC LAVA FLOWS

Most lava flows present basaltic, trachybasaltic or phonolitic composition. The more usual structure of the rock masses consists on a succession of lava flow units and clinker. Different types of basalt can be differentiated depending on their texture, crystals content, morphology, etc.

Basaltic lava flows can be also characterized by the presence/type/amount of vesicles, being named as vesicular, if the rock presents a high percentage of vesicles, or amygdaloidal if the vesicles are filled with minerals.

Clinker appears on top and/or bottom of the lava flows, with irregular aspect, high porosity and many voids. Their thickness, generally several dm, can be more than 1 m.

One of the main characteristics of the lava flows is the presence of discontinuities. The basaltic flows are affected by vertical columnar joints, generally open, and sometimes by horizontal and spherical joints.

Apart from open discontinuities, there can be found cavities generally sized no more than 0.5 m diameter, and also sometimes caves and volcanic tubes are found.

The lithological heterogeneity due to the alternation of basalt and clinker layers, the presence of discontinuities and cavities, the highly variable thickness of the lava flows and their irregular persistence, are common characteristics of these materials, forming highly anisotropic and discontinuous rock masses.

The geotechnical properties of basalts, at intact rock scale, are listed below:

– The dry density varies between 15 and 31 kN/m$^3$, with more frequent values between 23 and 28 kN/m$^3$. Vesicular basalt can present values between 15 and 23 kN/m$^3$, while massive basalts usually present >28 kN/m$^3$.
– The influence of the mineral composition and vesicularity in the density also influence the uniaxial compressive strength, with values between 25 and 160 MPa, and more frequent values between 40 and 80 MPa. The vesicular basalts may reach less than 40 MPa, while the massive basalts present usually present >80 MPa.

Rock masses formed by basaltic lava flows have been differentiated mainly attending to the type of discontinuities. The description has been carried out in representative outcrops. The main types are:

– Basalts affected by columnar jointing
– Basalts affected by spherical jointing
– Clinker layers intercalated with basalts.

Their main geomechanical characteristics are included in Tables 1, 2 and 3.

Table 1. Geomechanical characteristics of basaltic lava flows affected by columnar jointing.

| | |
|---|---|
| Lithology: | basalt and trachybasalt |
| Thickness: | 2–5 m |
| Structure: | massive basalt with columnar jointing (vertical and sub-horizontal joints) |
| Intact rock | |
| Mineralogy: | generally afanitic texture |
| Colour: | black or dark grey |
| Weathering: | fresh to decoloured |
| Strength: | very hard according to field indexes; Schmidt strength: 150–180 MPa |
| Vertical joints | |
| Dip: | 85°–90° |
| Spacing: | 200–600 mm (moderately); closer in heavily jointed rock masses |
| Persistence: | depends on the thickness of the lava flow; mean values between 1 and 3 m |
| Aperture: | partially open to open joints |
| Roughness: | mainly undulated-smooth; if the lava flow is heavily jointed, steeped-rough |
| Filling: | when present, sandy fills less than 2 mm and usually highly weathered |
| Horizontal joints | |
| Horizontal joints are generally associated to massive basalt, no affecting to low thickness layers. | |
| Dip: | horizontal 0–5°; sometimes until 30°. |
| Spacing: | 200–600 mm |
| Persistence: | very low |
| Aperture: | generally partially open to open. |
| Roughness: | stepped-rough predominant. |
| Rock mass | |
| N° of sets of discontinuities: | 2 or 3 |
| Fracture degree: | medium size block; small to very small blocks if the rock mass is heavily jointed. Mean value Jv = 4–8. |
| Block size: | generally < 0.5 m$^3$, sometimes 0.5–1 m$^3$. |
| Block shape: | three types can be differentiated: columnar, cubic and irregular. |
| Weathering degree: | generally slightly weathered |
| Water: | no observed |

### 4.1 *Geomechanical classification of basaltic lava flows*

#### 4.1.1 *RMR classification*

Table 4 include the RMR values assigned to basaltic lava flows affected by columnar and spherical jointing and successions of lava flows and clinker. Values correspond to the more representative parameters for the studied rock masses.

#### 4.1.2 *Q classification*

Table 5 include the Q values assigned to basaltic lava flows affected by columnar and spherical jointing and successions of lava flows and clinker. Values correspond to the more representative parameters for the studied rock masses.

### 4.2 *Phonolitic lava flows*

In Tenerife, phonolitic lava flows can be differentiated depending on the fracture degree, as can be observed in *Montaña de Guaza* area (Grande et al., 2005). Heavily jointed rock masses present RMR = 20–40, corresponding to class IV; rock masses affected by columnar jointing present RMR = 60–80, class II. In both cases, uniaxial strength of intact rock varies between 100 and 150 MPa, and the dry density is 21–22 kN/m$^3$.

## 5 GEOMECHANICAL CHARACTERISTICS OF TUFFS

Tuffs generally present massive structure, with few discontinuities and low fracture degree, being their properties very similar to those of the intact rock,

Table 2. Geomechanical characteristics of basaltic lava flows affected by spherical jointing.

| | |
|---|---|
| Lithology: | basalt |
| Thickness: | several meters |
| Structure: | spherical jointing |
| Intact rock | |
| Mineralogy: | afanitic texture |
| Colour: | dark grey |
| Weathering degree: | decoloured |
| Strength: | extremely hard according to field indexes; Schmidt strength: 85 MPa |
| Subvertical discontinuities | |
| Dip: | 85° |
| Spacing: | generally 60–200 mm or 200–600 mm |
| Persistence: | moderate |
| Aperture: | <0.5 mm or 0.5–2.5 mm, partially open to open |
| Roughness: | undulated-smooth |
| Rock mass | |
| N° of sets of discontinuities: | 1 predominant, 2–3 |
| Jointing: | very large to medium blocks. Juntas/m$^3$ = <1 to 4–5, depending on the fracture degree |
| Block size: | decimetre |
| Block shape: | undefined |
| Weathering degree: | moderately weathered |
| Water: | no observed |

Table 3. Geomechanical characteristics of clinker.

| | |
|---|---|
| Lithology: | mainly basaltic with vitreous texture, as a consequence of the cooling process |
| Thickness: | several cm to 2 m |
| Structure: | no structure, no jointing, high porosity, fragments are welded. |
| Rock mass | |
| Welding degree: | most deposits present a high welding degree, but keeping a granular structure. Sometimes the lower part of the deposit looses its original granular texture due to the heat. |
| Fragment size: | generally centimetres; intensely jointed when affected by high weathering degree |
| Voids: | generally <0.5 m diameter, although the size depends on the size of the fragments |
| Weathering degree: | slightly weathered by oxidation. Sometimes clinker appears completely weathered or disintegrated, loosing the granular texture. Sometimes a calcareous level can be observed on the clinker layers |

Table 4. RMR geomechanical classification of basaltic lava flows.

| Parameters | Affected by columnar jointing | Affected by spherical jointing | Succession of lava flows and clinker |
|---|---|---|---|
| Intact rock strength | 7–12 | 7 | 7–12 |
| RQD | 17 | 20 | 6–13 |
| Spacing* | 10 | 8–10 | 15 |
| Persistence* | 4 | 2 | 6 |
| Aperture* | 1–3 | 1–3 | 3–0 |
| Roughness* | 1 | 1 | 5 |
| Filling* | 6 | 6 | 6 |
| Weathering* | 5 | 3 | 5 |
| Water | 15 | 15 | 15 |
| RMR | 66–73 | 63–67 | 65–80 |
| Class | II Good | II Good | II Good |
| Cohesion** (kg/cm$^2$) | 3–4 | 3–4 | 3–4 |
| Friction angle** (°) | 35–45 | 35–45 | 35–45 |

*Parameters of the discontinuities
**Strength estimated parameters from quality indexes

Table 5. Q geomechanical classification of basaltic lava flows.

| Q Parameters | Affected by columnar jointing | Affected by spherical jointing | Succession of lava flows and clinker |
|---|---|---|---|
| RQD | 75–90 | 75–90 | 25–50; 50–75 |
| Jn | 4 | 0.5–1 | 3 |
| Jr | 2 | 2 | 3 |
| Ja | 1–2 | 2 | 2 |
| Jw | 1 | 1 | 1 |
| SRF | 1–2.5 | 1–2.5 | 1–2.5 |
| Q value | 15–22.5 | 30–180 | 10–37.5 |
| Classification | Good | Good to extremely good | Medium to good |

depending on the existence of some discontinuity plane:

- Nature: most of the tuff deposits are composed by fine-grained debris with pumice fragments, although also lithics of basaltic rocks can be observed.
- Type of deposit: pyroclastic flows.
- Thickness: >1 m to several dozen m, depending on the site.
- Grain size: generally *lapilli* (2–64 mm)
- Dry density: less than 10 kN/m$^3$ to >25 kN/m$^3$, with characteristic values between 8 and 18 kN/m$^3$

for poorly compacted deposits and $>20\,kN/m^3$ for well-compacted deposits. The mineral composition influences the density, having higher values the basaltic tuffs and lower the acid tuffs.

- Intact rock strength: depends on the composition, compaction degree and grain size. 1 to 10 MPa have been measured for dry and saturated tuff, surpassing these values for basaltic composition and coarse grain size. From field indexes: hard to very hard strength; Schmidt hammer: 15 to 20 MPa (dry density $= 20\,kN/m^3$). For saturated rocks the uniaxial strength decreases 30%.
- Cohesion: $<1$ MPa
- Friction angle: 30°–50°; for highly weathered tuffs: 12°–30° (these values correspond to tuffs from El Salvador)
- Young's modulus: 0.1 to 22 GPa, for dry and saturated tuffs.
- Weathering degree: generally superficial weathering, dissolving and disintegrating the pumice fragments and creating voids.
- Hydrogeology: no water observed; impermeable materials.

### 5.1 *Geomechanical classification of tuffs*

Geomechanical classifications have not been applied to tuff rock masses because of their massive and continuous structure. In the absence of discontinuities, the strength and the properties of the rock mass can be assumed to be similar to those of the intact rock.

## 6 GEOMECHANICAL CHARACTERISTICS OF IGNIMBRITES

Dry density for these rocks varies between 13 and $20\,kN/m^3$, sometimes $>20\,kN/m^3$.

For the intact rock, uniaxial strength varies between 15 to 70 MPa, being $<5$ MPa for weathered rocks.

Few data have been collected for the cohesion values. Nevertheless cohesion is usually $<0.1$ MPa for weathered ignimbrites and 2 MPa for fresh rocks. Friction angle varies between 27° and 38°, for both, fresh and weathered samples.

RMR values indicate Class II, that is, good quality rock masses.

## 7 GEOMECHANICAL CHARACTERISTICS OF AGGLOMERATES

Dry density for these rocks depends on the composition of the blocks, the compaction degree and porosity of the deposits. When fragments of pumice are predominant, agglomerates have low-density values, even less than $10\,kN/m^3$, while for basaltic blocks values similar to that of a basaltic lava flow can be reached. General values can vary between 12 and $28\,kN/m^3$.

Uniaxial compressive strength is related to density and composition. Higher values correspond to basic composition agglomerates, and lower values to felsic or acid composition agglomerates. The usual interval is between 0.5 and 25 MPa, and values $>15$ MPa correspond to basaltic agglomerates, which may reach 70 MPa.

Cohesion and friction angle vary between 0.03 and 0.4 MPa, and 25° and 42° respectively. Cohesion depends mainly on the nature of the matriz, and friction depends on the grain's imbrications.

The Young's modulus values, as well as other strength parameters, have been obtained from the paper from Uriel and Serrano (1975), and vary between 0.1 and 3 GPa. Values $<1$ GPa correspond to laboratory tests, and values $>1$ GPa correspond to in situ tests.

Other properties for agglomerates given by "Dpto. de Obras Públicas, Vivienda y Agua del Gobierno de Canarias" are: dry density $= 17–19\,kN/m^3$, cohesion $= 0.03–0.05$ MPa, friction angle $= 35°$ and Young's modulus $= 0.15$ GPa.

## 8 GEOMECHANICAL CHARACTERISTICS OF PYROCLASTIC DEPOSITS

Geomechanical properties of pyroclastic deposits, that can not be considered as rock masses or soils, depends mainly on the grain size and shape, sorting, packing degree, porosity, mineralogical composition and strength, compaction degree of the deposit, etc.

In Tenerife Island, thick acid pyroclastic deposits appear to the southeast, on the so-called *Bandas del Sur*. In this area, pyroclastic flow, surge, and fall deposits can be observed, with different characteristics.

With respect to pyroclastic fall deposits the main geotechnical properties are: particle specific weight $= 22.5–25.0\,kN/m^3$, dry density $= 8–15\,kN/m^3$, cohesion $= 0–0.1$ MPa, friction angle $=$ 30°–45° and uniaxial compressive strength $<5$ MPa. It should also be mentioned that in El Salvador porosity values of 45–65% have been measured and that Lomoschitz et al. (2003) present values of 0.13–0.17 MPa for cohesion on pyroclastic fall deposits.

## 9 GEOTECHNICAL PROPERTIES OF VOLCANIC SOILS

In Tenerife there exist residual and transported volcanic soils, mainly in the north of the island and in La Laguna valley. The former, formed from the in situ alteration of pyroclastic materials, are mainly composed of silt and clay, while transported soils proceed from alluvial, colluvial or lacustrine environments.

Geotechnical properties are similar in both types of soils: in the residual soils, silt-sandy fraction is predominant, and in the transported soils silt-clayey fraction predominates. Granulometric analysis can be affected by particle aggregation, showing larger size fractions that those corresponding with the soil particle size distribution (González de Vallejo et al 1981).

Atterberg's limits show intervals between 25% and 115% (liquid limit) and 15% to 95% (plastic limit). The main characteristics, according to Casagrande chart, are:

– Most of the residual soils present high plasticity.
– Residual soils as a product of ash alteration present plasticity index $<35\%$.
– Residual soils as a product of tuff alteration present liquid limit $>85\%$.
– Soils with lacustrine origin present liquid limit $\approx 50\%$ and plasticity index between 12 and 25%.
– Alluvial soils are close to A line (Casagrande chart), with variable values for the liquid limit and the plasticity index.

Montmorillonitic soils present higher plasticity values than halloysitic soils, while illite, sanidine and mica soils present the lower values (González de Vallejo et al 1981).

Particle specific weigh vary between 22 and $30\,kN/m^3$ and dry density from 11 to $14\,kN/m^3$, although values $<10\,kN/m^3$ have been measured in other volcanic regions.

Lacustrine clays of La Laguna valley (north Tenerife) are moderately expansive, in spite of their montmorillonitic composition, due to the open structure and aggregate microfabric (González de Vallejo et al 1981). The swelling index of these clay soils is 0.2–$2\,kg/cm^2$, giving a classification non critical to critical; the activity corresponds to inactive to normal.

Compaction conditions of these clay soils improve when particles are oriented, having the soil an anisotropic structure. Maximum density values are between 12 and $15\,kN/m^3$, and optimum wet vary between 18 and 43%.

Cohesion is $<0.2$ MPa being the more usual values between 0 and 0.1 MPa, and more frequent values 0–0.03 MPa: higher cohesion can be due to cementation of the particles.

Friction angle vary from 23° to 40°, corresponding the lower values to non-consolidated and undrained soils with high pore pressure. Values $>35°$ correspond to soils with sandy fraction or cemented, while in clayey soils values are $<25°$, and $<20°$ in consolidated undrained silty soils.

Due to the significant differences between the properties of volcanic and non volcanic soils, some of the more usual relationships properties-geotechnical behaviour are not applicable:

– In general, volcanic soils present high liquid limit values, and much lower values for the plasticity index that those corresponding to non volcanic soils with the same liquid limits.
– Expansiveness (swelling) is high to moderate in montmorillonitic clays, and low in halloysitic and alofanic clays, with unusual lower values in some cases due to the characteristics of the microfabric.
– Shear strength is high in spite of the high values of liquid limits and the fine size of particles. Also the friction angles are unusually high considering the physical properties of the volcanic soils. The existence of cementation agents increases the strength.
– The compressibility is low if compared to the granulometric and plasticity properties.

The influence of these special properties can be observed in practice in the field in Tenerife Island and other volcanic regions where many natural and excavated slopes present more inclination than that corresponding to the lithological composition and granulometry of soils.

On the other hand, volcanic soils are very sensible to wet conditions, which notably affect to their strength properties. When heavily rain occurs there is a rapid increase of the pore pressure and decrease of shear strength, producing slope stability problems. The presence of water absorbent minerals and open microfabric, with weak inter-particle forces, determine a highly unstable behaviour in static and dynamic conditions (Konagai et al., 2004).

## 10 GEOTECHNICAL PROBLEMS ASSOCIATED TO VOLCANIC MATERIALS AND PROCESSES

Volcanic materials generally present favourable geotechnical behaviour for most of conventional constructions, foundations and excavations.

This favourable behaviour is according to the high strength properties and good quality of rock masses. However, the wide range of lithological variations, spatial heterogeneities, highly variable thickness and geometry of beds, etc, determine a low reliability degree when extrapolating properties and behaviour. Also the presence of discontinuities can substantially modify the behaviour of the rock masses. These aspects differentiate the volcanic materials, which must be studied and characterized with proper methodologies, for geotechnical recognition as well as for measuring and interpretation of their properties.

Thus, some of more significant properties of volcanic materials and formations in relation to geotechnical problems and volcanic processes are summarized below.

### 10.1 *Basaltic lava flows and clinker*

Structure and geometry:

- High spatial heterogeneity in thickness and lateral and frontal extent.
- Soft formations or layers can underlay the lava flows: *lapilli*, ash, paleo-soils, etc.
- Succession of very hard (basalts) and very porous and discontinuous levels (clinker).
- Dip controlled by the previous relief or morphology.
- Inverted relief can be formed when paleo-basins are filled.

Discontinuities:

- Vertical open joints.
- Frequent small hollows and cavities.
- Possible caves and volcanic tubes.

Lithology:

- Very hard and abrasive rocks.
- Geotechnical problems:
- Low reliability when extrapolating the results of site investigations, in the surface and in depth.
- Specific limitations for the use of geophysical methods.
- Vertical open joints may cause stability problems and seepage, especially in slopes and tunnels.
- The possibility of lava flows overlying soft levels can cause stability problems in natural and excavated slopes.
- The presence of cavities and tubes can cause collapses affecting the surface.
- Stability problems due to differentia erosion clinker-lava flow.

### 10.2 *Tuffs, agglomerates, ignimbrites and pyroclastic flows.*

The main geotechnical problems are related to:

- Collapsibility in low density tuffs and agglomerates.
- Alterability and devitrifying processes in ignimbrites and tuffs with esmectitic expansive minerals (montmorillonitic and nontronitic).
- Vertical and open discontinuities in ignimbrites, with stability and seepage problems.
- Abrasivity due to fine-grained materials.
- Long-term plastic deformation.

### 10.3 *Pyroclastic fall deposits*

The main geotechnical problems are related to:

- Very low density.

Table 6. Resume of geotechnical properties of volcanic materials*.

| Geotechnical properties (Intact rock/soils) | | G kN/m³ | $\gamma_d$ kN/m³ | $\sigma_c$ MPa | C MPa | $\phi$ ° | E GPa | L.L. % | L.P. % | I.H. kg/cm² | Other |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Basalts | | – (23–28) | 15–31 (40–80) | 25–160 | – | – | – | – | – | – | – |
| Tuffs | | – | 8 –a >25 | 1–10 | 0–1.45 (30–50) | 12–50 | 0.1–22 | – | – | – | – |
| Ignimbrites | | – | 13 a >20 | 2–70 | 0.1–2 | 27–38 | – | – | – | – | – |
| Agglomerates | | – | 12–28 | 0.5–25 | 0.03–0.4 | 25–42 | 0.1–3 | – | – | – | – |
| Pyroclastic fall deposits | | 22.5–25 | 8–15 | 0–5 | 0–0.1 | 30–45 | – | – | – | – | – |
| Volcanic soils | Residual soils from weathered pyroclasts | 22–30 | 12–13 | – | 0–0.1 | 23–40 | $0.5 \times 10^{-3}$ – $11 \times 10^{-3}$ | 25–115 | 15–95 | 0.2–2.0 | n (%): 45–65<br>e: 1.6–2.88<br>W (%): 12–180<br>$\tau_u$: 56–130 kPa |
| | Transported soils: alluvial, colluvial and lacustrine | 27.5–29 | 11–14 | – | 0–0.1 | 23–40 | $0.5 \times 10^{-3}$ – $11 \times 10^{-3}$ | 35–90 | 25–45 | 0.2–1.5 | $\gamma_{max}$: 5–17.3 kN/m³<br>Cc: 0.13–0.24 |

*Maximum to minimum values. In brackets: more frequent values. G: specifi weigh, $\gamma d$: dry density, $\sigma_c$: uniaxial compressive strength, C: cohesion, $\phi$: friction angle, E: Young's modulus, L.L: liquid limit, L.P: plastic limit, I.H.: swelling index, n: porosity, e: void ratio, W: water content, $\tau_u$: shear strength, $\gamma_{max}$: proctor density, Cc: compressibility coefficient.

- High deformations in *lapilli* and ash deposits when static or dynamic loads are applied, by compression and particle fracture.
- Collapsibility in ash deposits.
- High alterability and soil formation.

### 10.4 *Soils*

The main geotechnical problems are related to:

- Low strength in silty and silty-clayey soils.
- High expansiveness in smectitic clays, and moderate to low in halloysitic clays.
- No favourable conditions for compaction.

Other problems identified are:

- Low strength in contact planes between lava flows and pyroclastic levels, favouring landslide processes.
- Mechanical contacts between the dykes and the host rock, which can work as persistent weak planes.
- Slope instability, mainly in steep slopes.
- Possible differential settlements in foundations when lying on different formations.
- Alkaline reactions in concrete due to vitreous composition of volcanic materials, and possibility of cracking and damaging the structures.
- Instability problems due to differential erosion of lava flows and pyroclastic deposits.

The geomechanical properties of the different types of volcanic materials previously analysed are resumed in Table 6.

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