Engineering Geological Properties of the Volcanic Rocks and Soils of the Canary Islands

Luis I. González de Vallejo, Teresa Hijazo, Mercedes Ferrer

Abstract. This paper analyses the engineering geological properties of the rocks and soils of the Canary Islands based on data from field studies, laboratory tests and extensive databases for volcanic materials. Geological properties and processes most relevant to geo-engineering are described. Geomechanical characterization of rock masses and soil deposits including rock mass classification, index and strength properties are presented. Some of the most relevant results show materials of low to very low density and low to very low values of strength and expansiveness. These materials, with an exceptional high anisotropy and irregular spatial distribution, are intensely affected by jointing of thermal origin and large discontinuities due to dykes; cavities and tubes can be also present. Landsliding and slope instability, collapse phenomena and other processes causing geotechnical problems are described. Discussion on the geomechanical properties and conditions that may help to identify and differentiate the geotechnical behaviour of the volcanic materials is included.

Key words: volcanic rocks, volcanic soils, Canary Islands, Tenerife, geomechanical properties.

1. Introduction

Geological materials in islands of volcanic origin show geomechanical properties and geotechnical behaviour completely different of materials with non-volcanic origin. This paper is focused on the geomechanical characterization of the volcanic rock masses and soil deposits of the Canary Islands and on the main geotechnical problems associated with these materials. Active geological processes such as landslides, collapse phenomena and expansiveness are also described. This study is based on field geomechanical surveys, laboratory tests and geotechnical data obtained from different sources including Regional Governmental agencies (Rodríguez-Losada *et al.*, 2007a) and geotechnical companies. From this information more than 400 data have been compiled (González de Vallejo *et al.*, 2006) which have been used for the purpose of this study. Geological and geotechnical maps (http://mapa.grafcan.com/Mapa) have been also used as basic information for field studies.

2. Geological Formations

The Canary Islands is a volcanic archipelago composed of seven islands (Fig. 1). Their volcanic activity, which spans from over 20 M.a. ago to the present, and their active geological processes, such as their great paleolandslides, have attracted the attention of scientists worldwide. The geology of Canary Islands has been extensively studied since the XIX Century. An update and comprehensive geological description can be found in Ancochea *et al.* (2004) and Carracedo *et al.* (2002).

The main geological formations of the Canaries relevant to engineering geology can be grouped in the following units: Basaltic, trachybasaltic and phonolitic lava flows; pyroclastic rocks, pyroclastic deposits and soil deposits of volcanic origin. A detailed geological and petrological description of these units is given by Rodríguez-Losada (2004).

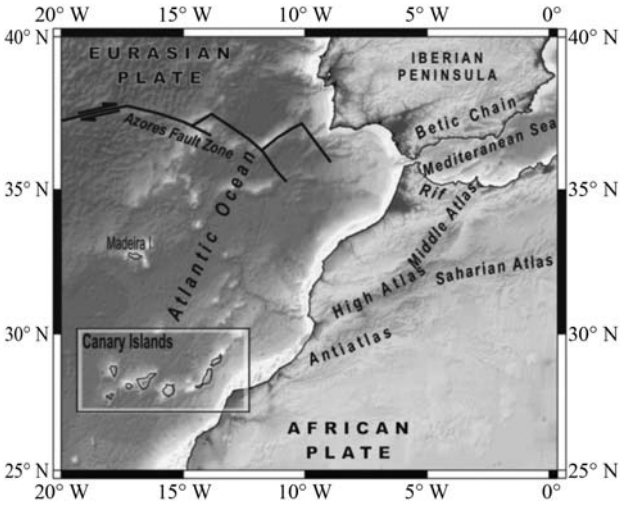

Figure 1 - Location of the Canary Islands (Spain).

The **basaltic, trachybasaltic and phonolitic lava flows** and also **dykes,** form the most abundant rock group in the Canary Islands. The typical structure of these rocks is a succession of basalt and scoria layers, with rough surfaces composed of broken lava blocks known as clinker. Among the basaltic materials, several types of basalts according to their texture, crystallinity and grain size, are distinguished. Basalts can also be characterized in terms of their vesicles, and are referred to as vesicular basalts when there is a high

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proportion of vesicles and as amygdaloidal basalts if the vesicles are infilled with minerals. Secondary clay minerals can occur as replacement of olivine, pyroxenes and interstitial glass materials in altered basalts forming smectites, chlorites, corrensites, etc. which can jeopardize the rock quality and its geomechanical behaviour.

Scoriaceous materials appear at the flow top or bottom, being often the result of lava flows of the "aa" type. Their thickness is variable, usually tens of centimetres, although it can exceed 1m. The appearance of the scoria is very irregular, being highly porous with many voids and cavities. Figure 2 shows a succession of basalt and scoria layers with a seam of red ochre paleosoil.

Discontinuities are the most outstanding features of the lava flows. Basalt layers are affected by vertical columnar joints, which are generally fairly open. Horizontal or spherical discontinuities may also appear. Apart from discontinuities, it can be found cavities, mostly no larger than half a meter in diameter. Occasional caves may appear, and less commonly lava tubes.

The **pyroclastic rocks** are divided in **tuffs, ignimbrites**, **agglomerates and agglomerate breccias** according to the compaction, welding, grain size and morphology of the rock fragments.

The **tuffs** generally appear in a massive state, with scarce discontinuities, appearing as a very homogenous deposit. Most tuff deposits are deposit of pyroclastic flow and pumiceous nature, with light-coloured or yellowish pumice clasts, although they may also be of basaltic composition. Their thickness varies from over one meter to dozens of meters depending on the zone. The size of grains or particles normally are between 2 and 64 mm, corresponding to lapilli.

The **ignimbrites** are comprised of welded pyroclastic deposits whose fragments are flattened and stretched to form so-called *fiammes*. These are generally hard, massive rocks although flow structures may also be observed, showing foliation, and cooling discontinuities.

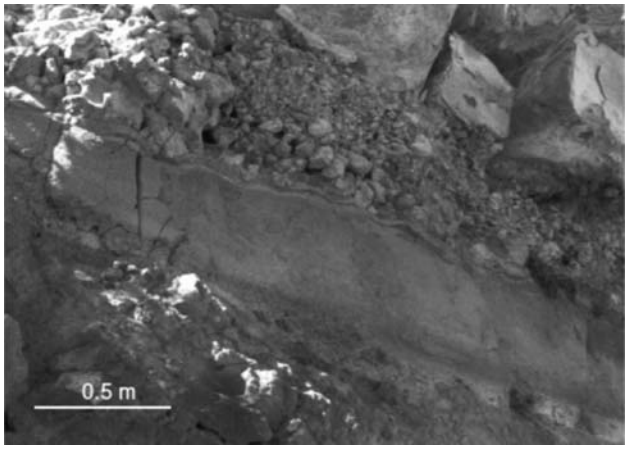

Figure 2 - Scoriaceous layer at the base of a lava flow on a well-developed reddish soil, northern Tenerife.

The **agglomerates** are compact rocks, which may display a high degree of consolidation, comprised of large uneven-sized heterogeneous clastic materials, often pyroclastic, within a finer matrix.

The **agglomerates breccias** are discerned owing to their angular fragments, being generally large with a matrix that can be sandy or clayey. These may form as the result of pyroclastic falls or may have an epiclastic mechanical-type origin related to landslides, avalanches and mudflows (debris avalanches, lahars, etc.). When their origin is epiclastic, the matrix is sandy or clayey since it is generated by the grinding of dragged materials. In this case, the fragments or clasts are generally angular and large and this agglomerate material is designated volcanic breccia (Fig. 3).

The **pyroclastic deposits** are comprised of fragments of glassy rock, generally loose or weakly compacted. They can be grouped as pyroclastic falls, with clean surfaces with no adhered particles, well-preserved crystal edges, with fragments without fractures and highly vesiculated glass with vesicles varying in shape (Fig. 4); pyroclastic surges,

Figure 3 - Volcanic breccia composed of large fragments embedded in a fine-grained matrix.

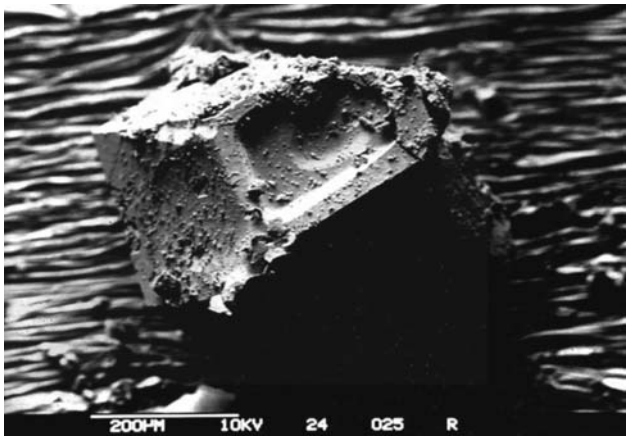

Figure 4 - Electron microscope image of pyroclastic fall from southern Tenerife showing a crystal with non-fractured edges. Approximate particle size 0.4 mm (Alonso, 1989).

with poorly vesiculated glass, highly modified by pyroclast abrasion (glass and crystals), equal-sized fragments with smooth concave-convex fracture surfaces and surfaces with cooling fissures; and pyroclastic flows with highly modified crystal edges, abundance of adhered ash, especially infilling vesicles and highly vesicular glass with a tendency towards elongated vesicles.

The **soil deposits** of the Canary Islands are mainly of coluvial origin, present in many areas particularly along the northern slopes of the western islands. Alluvial deposits are founded in gorges. River-lacustrine soils are also present in some valleys such as La Laguna Valley. Residual soils are the product of *in situ* weathering of pyroclastic materials, predominating silts and clays.

3. Geomechanical Properties of Volcanic Rocks

Basalt, trachybasalt and phonolite lava flows generally show high strength values, corresponding to geotechnical characteristics of hard or very hard rocks. Dykes with this composition can be also included in this geotechnical unit. The lithological heterogeneity determined by the alternating layers of basalts and scorias, the presence of discontinuities and cavities, the highly variable thicknesses of the lava layers and their irregular persistence are characteristical features of these materials that give rise to highly anisotropic and heterogeneous rock masses (Fig. 5).

The following types of rocks comprised of basalt lava flows have been distinguished (Table 1):

- Basalts with columnar jointing
- Basalts with spherical jointing
- Scoriaceous layers intercalated among the basalts
- Dykes

Rock masses formed by successions of basaltic lavas and associated scorias were classified according to their geomechanical indices RMR and Q. Table 1 shows the mean RMR and Q values obtained by analysing outcrops of fresh rocks or very scarcely weathered rocks with an extent of fracturing representative of the most common situations, excluding outcrops with extensive fractures or altered rocks.

From laboratory tests, the basalt lava flows show the following properties: dry densities range from 15 and 31 kN/m^3, being the most common values 23 to 28 kN/m^3; vesicular basalts can have densities of 15 to 23 kN/m^3, while massive basalts usually exceed 28 kN/m^3 (Fig. 6); uniaxial compressive strength values depends on mineral composition and volatile elements, giving rise to a wide range of strength values between 25 and 160 MPa, although the most common range is 40 to 80 Mpa; vesicular basalts can have strength under 40 MPa, while massive basalts may exceed 80 MPa (Fig. 7).

The main geotechnical problems related with the basaltic lava flow are as follows:

- Great spatial heterogeneity both in thickness and lateral and frontal extension.

Figure 5 - Cliffs showing basaltic lava flows successions and pyroclastic layers, dyke intrusions and different types of discontinuities, Anaga, Tenerife. Photograph window approximately 150 m wide.

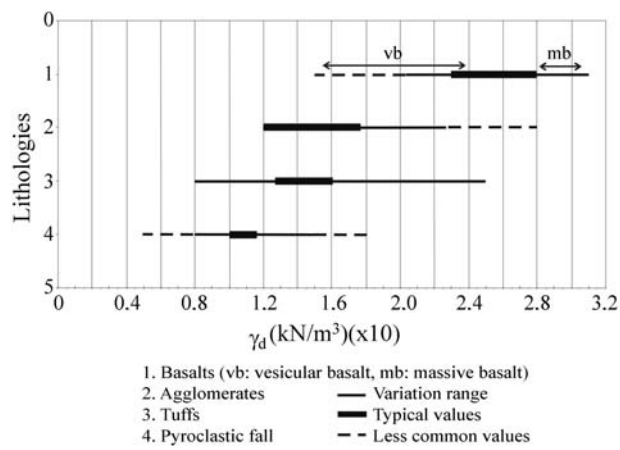

Figure 6 - Dry density values of the volcanic materials from the Canary Islands.

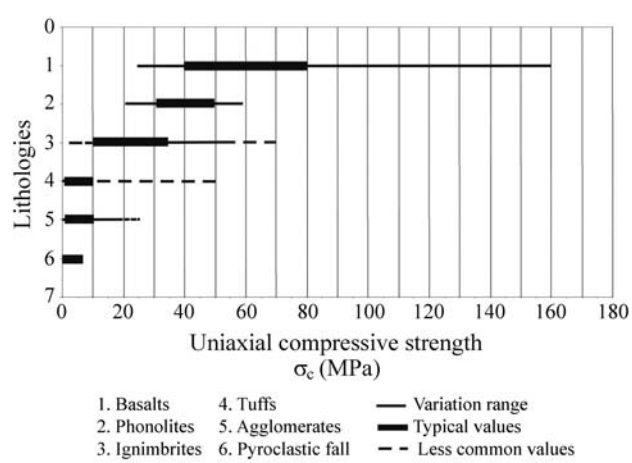

Figure 7 - Uniaxial compressive strength values according to the lithologies of the volcanic materials of the Canary Islands.

- Alternating layers of very hard material (basalts) with very porous and discontinuous levels (scorias).
- Soft materials underlying lava flows: lapillis, ashes and paleosoils.
- Vertical, open joints which can induce stability and water filtration problems, especially in tunnels and slopes.
- Cavities and volcanic tubes can lead to the collapse of basaltic scoriaceous cover lava materials.
- Overhangs may occur due to differential scoriaceous-basaltic layer erosion.
- Low strength surfaces between lava flows and pyroclastic layers favoring instabilities.
- Mechanical planes of discontinuities between dykes and wallrock that involve potential instability surfaces of great continuity.
- Slope instability mainly in cliff zones.
- Differential settlements in foundations when overlying different lithological formations.
- Alkaline reactions in concrete due to the glassy composition of volcanic materials with the possible formation of fissures and structural damage.
- Very hard and abrasive materials for excavations purposes.

Tuffs show the following representative properties: dry densities display a large range of values from below

Table 1 - Geomechanical characterization of basaltic and scoriaceous rock masses obtained from field surveys.

Characteristics		Columnar basalts		Spherical basalts	Scoriaceous layers
Lithology		Basalts, trachybasalts		Basalt	Basaltic with glassy texture
Thickness (m)		2-5		5-10	Several cm to 2 m
Structure		Vertical jointing		Spherical jointing	Non structured, abundant voids and welded
Intact rock	Texture	Aphanitic		Aphanitic	-
	Colour	Black, dark grey		Dark grey	-
	Weathering (ISRM, 1981)	Fresh- decoloured		Decoloured	-
	Strength (σ_c) (MPa) (Manual Test Hammer)	150-180 (Fig. 5 does not show these values)		Intermediate: 38	-
Discontinuities	Orientation	Vertical	Horizontal	Subvertical	-
	Dip	85º-90º	0º-5º (can reach 30º)	85º	-
	Spacing (mm)	200-600 (60-200)	200-600	60-200 to 200-600	-
	Continuity (m)	1-3	1	3-10	-
	Opening (mm)	0.25-2.5	0.2-0.5 to 0.5-2.5	-	-
	Roughness	Smooth, undulated	Rough	Smooth	-
	Infill	Uncommon but sandy if present	-	-	-
	Observations	-	Associated with massive basalts in thick layers	-	-
Rock mass	N. of sets of discontinuities	2 and 3		1	-
	Joints/m^3 (Jv)	4-8		< 1 (4-5)	-
	Block size (m^3)	< 0.5		Decimetric	Centimetric
	Block shape	Columnar, cubic & irregular		Irregular	Irregular fragments
	Weathering degree	II		III	II-VI
	Water	In general, there is no water		In general, there is no water	-
	Observations	-		-	Blocks welded but with granular appearance. Large cavities may form
Geomechanical classifications	RMR	70-75 Class II		60-65 Class II	Basalts and scorias 60-80 Class II
	Q	15 - 22 Good		30 - 180 Good to extremely good	Basalts and scorias 10-40 Intermediate to good

10 kN/m^3 to more than 25 kN/m^3, the range 8 to 18 kN/m^3 being typical for poorly-compacted tuffs and higher than 20 kN/m^3 for well-compacted tuffs; tuff composition affects their density, with higher densities shown by the basaltic tuffs and lower ones by acidic tuffs. The strength of the tuffs varies with the degree of compaction, grain size and composition, among other factors; uniaxial compressive strength ranged from 1 to 50 MPa for intact rock (Fig. 7); for saturated tuffs typical values are under 10 MPa. Angles of internal friction range from 30° to 50° for unweathered tuffs, although for a high degree of weathering these angles can be 12° to 30° (Fig. 8).

The use of geomechanical classifications based on discontinuity parameters that mainly affect the RMR and Q values is not recommended for massive tuffs due to their continuous and homogenous nature. Independently of this opinion, the results obtained were: RMR index ranged from 80-90, Class I; Q index ranged over 250 up until a value of 1000, classifying this rock as good to exceptionally good.

Ignimbrites have a uniaxial compressive strength ranging from 2 to 5 MPa for weathered ignimbrites and from 15 to 70 MPa for fresh ignimbrites (Fig. 7). Friction angles vary from 27° to 38°. RMR ratings assign these rocks to Class II, indicating good rock quality. Geotechnical properties of welded ignimbrites have been also described by Rodríguez-Losada *et al.* (2007b).

Volcanic agglomerates form a quite heterogeneous group. Dry densities depend on the nature of their clast components and the degree of compaction and porosity of the deposit. Agglomerates with a predominance of pumice clasts show low densities, even lower than 10 kN/m^3. In contrast, if the clasts are basaltic, densities are similar to those of basalt lavas. The most frequent dry density range for agglomerates is 12 to 18 kN/m^3, although there is a great scatter of values up to 28 kN/m^3 (Fig. 6). Uniaxial compressive strength is directly related to density and, therefore, to composition. Highest strength values were observed for agglomerates containing clasts of basic composition, and lowest values corresponded to those of felsic, or acidic, composition. The characteristic range is 0.5 to 25 MPa. Strength above 15 MPa were recorded for basaltic agglomerates; sometimes these were as high as 70 MPa (Fig. 7).

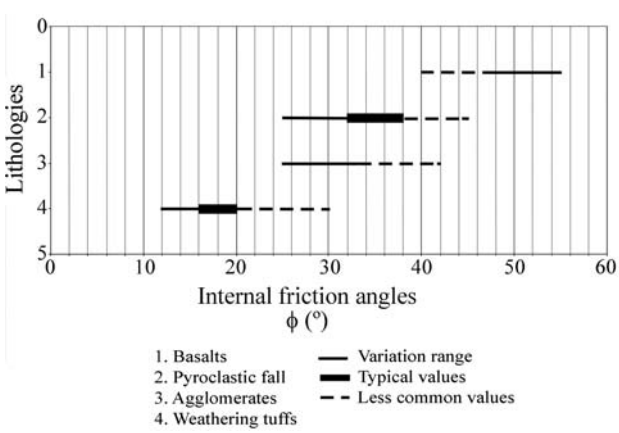

Figure 8 - Internal friction angles for different volcanic materials of the Canary Islands.

Tuffs, agglomerates, ignimbrites and pyroclastic flows can show the following geotechnical problems:

- Collapse of low-density tuffs or agglomerates.
- Weathering and devitrification processes producing expansive smectitic minerals (montmorillonites and nontronites).
- Open vertical fractures in ignimbrites may cause instability and water infiltration problems.
- Abrasive actions on machinery of the fine materials in these formations.
- Long-term plastic deformation.

The geomechanical properties of **pyroclastic deposits** depend on grain size, shape, porosity and petrologic composition, as well as the degree of packing between particles, the compaction state of the deposit and the strength of the particles. Dry densities of pyroclast falls range from 5 and 18 kN/m^3 (Fig.6). Density depends on the nature of the clasts and the extent of vesiculation, with basic pyroclasts being denser than felsic ones. The angle of internal friction ranges from 25° to 45° (Fig. 8). Uniaxial compressive strength varies from very low to 5 MPa (Fig. 7). Strength and deformability of low density pyroclasts has been described by Serrano *et al.* (2007a) and properties of lapilli for raw material uses has been also described by Lomoschitz *et al.* (2003).

The main geotechnical related problems of pyroclastics deposits are as follows:

- Very low density materials
- High deformation of lapilli and ashes in response to static or dynamic loads due to particle compaction and fracturing
- Collapsible ashes
- Low durability

4. Engineering Geological Properties of Soil Deposits

The properties of soils of volcanic origin in the Canary Islands are very dependent on the depositional environment and particle sizes. In coluvial materials the large grain sizes are predominant. Large boulders are very frequent in the alluvial deposits of the numerous gorges present in the islands. Alluvial and coluvial are very heterogeneous deposits with a wide range of particle sizes, but most of them are coarse materials. Fine soils are predominant in river-lacustrine deposits filling valleys or topographic depressions, with a range of granulometry from clays to sandy sizes.

Residual soils are the product of *in situ* weathering of pyroclastics materials with abundant silts to sandy soils and less frequently silty clays.

The lacustrine clays of La Laguna (Tenerife) have been studied by González de Vallejo *et al.* (1981). In some zones these clays have shown some degree of expansivity due to their montmorillonitic composition. However, their expansiveness is moderate due to the open structure of their microfabric, especially if this fabric is aggregated, which prevents volume changes. The swelling index for clay soils is 0.02 to 0.2 MPa, classifying these soils as non critical to critical. Clay soils of lacustrine origin show activity corresponding to inactive or normal clays. Atterberg limits range from 25% to 115% for the liquid limit and 15% to 95% for the plastic limit (Fig. 9). Specific weight of particles range from 22 to 30 kN/m^3 and dry density from 11 and 14 kN/m^3, although densities below 10 kN/m^3 may be found in other volcanic regions of the world.

The angle of friction varied from 23° to 40°, with the lower values corresponding to non-drained soils in non-consolidated conditions, whose pore pressure is very high. Friction angles above 35º were obtained for soils with a large proportion of sand-sized fractions and/or the presence of cementing agents. In clayey soils, residual friction angles were under 25°. In silty soils consolidated but not drained, the internal friction angle was generally low, less than 20°. Cohesion ranged from 0-0.2 MPa, the most common interval being 0-0.1 MPa. High cohesion values can be attributed to cementation processes between particles.

The compaction conditions of volcanic clayey soils improve when particles are more orientated such that the soil acquires an anisotropic structure. It has been demonstrated that compaction by kneading (Harvard miniature compaction test) is more efficient than by impact (standard Proctor test), (Lenz, 2004). The maximum density obtained here were between 12 and 15 kN/m^3 and optimum moisture values spanned a wide range, from 18 to 43%.

The properties of soils of volcanic origin and non-volcanic soils show a series of significant differences. Some of these differences determine that the usual correlations between properties and geotechnical behaviour used for non-volcanic soils are not directly applicable to volcanic soils (González de Vallejo, 1981). Among these differences next should be mentioned:

- In general, volcanic soils present high liquid limits and a much lower plasticity index than that of a non-volcanic clay-soil of similar liquid limit. The results of plasticity tests depend on the treatment applied to the sample; thus, usually the liquid limit increases with water content, dispersion and mixing time, while it decreases with drying.
- Granulometric fractions of less than two microns show large variation, from under 10% to over 80%, according to the treatment to which the sample was subjected before testing, and the way in which the granulometric analysis is conducted. Thus, the fraction under two microns increases depending on the energy of the dispersion agent used.
- Irreversible changes occur in properties as the moisture conditions are modified, particularly during the process of drying. This is among the most sensitive factors and the one that mostly affects the properties.
- Expansiveness is high to moderate for clays of montmorillonitic composition and high for halloysitic and allophanic clays, with abnormally low expansiveness observed in some montmorillonitic clays due to the effects of the microfabric.
- Shear strength is high despite the elevated liquid limits and very fine particle sizes. Similarly, unusual high internal friction angles are observed in relation to the index properties of the soils. The presence of cementing agents confers much higher shear strength than that expected for their composition.
- Compressibility index is lower than that corresponding to the soils' plasticity and granulometric properties.

The above mentioned differences between properties can be observed not only in the Canary Islands but in other volcanic regions, where it can be find slopes that are much steeper than would be expected according to the composition and granulometry of the soils. In addition, volcanic soils are highly sensitive to moisture conditions, which markedly affect their strength properties. Under intense rainfall, there is a rapid increase in pore pressures and a marked drop in strength, which may gives rise to slope instability problems. The presence of highly absorbent minerals and an open microfabric with weak particle junctions determines a highly unstable behaviour both in static and dynamic conditions (Konagai *et al.*, 2004).

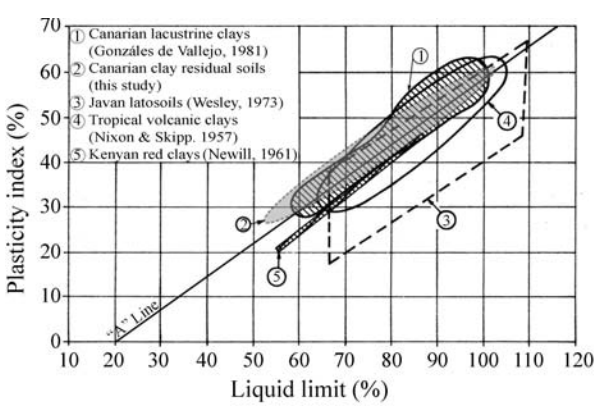

Figure 9 - Representation of volcanic soils on Casagrande's plasticity chart (modified from Gonzalez de Vallejo, 1981).

5. Discontinuities, Cavities and Tubes

Volcanic materials show an extensive sort of features comprising **joints, cavities and tubes**. Joins of thermal origin (cooling and retraction/contraction joints, with vertical, columnar, polygonal, radial, subhorizontal and spherical

jointing), of tectonic origin (faults, fractures and joints), discontinuities generated by intrusive structures (dykes, sills, plugs, etc.), discontinuities of gravitational origin (tension cracks, collapse fractures, slip surfaces, etc.), and discontinuities corresponding to contact surfaces between lava formations of depositional or erosive origin. The most common discontinuities found in the study areas are those of thermal origin, although all the discontinuities mentioned above may also be observed. Columnar joints are characteristic of basalt flows and often appear in massive lava materials, being generally polygonal or spherical in shape (Figs. 10 and 11). Spherical joints are the outcome of water infiltration towards inner zones of the flows. If the flow is very thick, retraction may also occur in horizontal planes creating bands that usually form at a distance of a third from the base (Fig. 12).

Discontinuities of tectonic origin are rarely observed in outcrops yet they can be easily recognized in caves and tunnels. Discontinuities produced by intrusion mechanisms (dykes) can be important for slope instability processes. In some cases, they constitute potential shear surfaces and hydrological barriers. Zones of mechanical contact between the wallrock rock and dyke exhibit series of open fractures parallel to the dyke; in some cases, relative displacements may be observed, behaving as normal faults.

Lava tubes and caves are the result of lava flow processes. When flows are very fluid, lavas continue to circulate beneath the already cooled outside crust to form so-called lava tubes. Since basalt rocks are very poor heat conductors, the surface of the flow solidifies and the molten lava continues flowing in its interior. This process ends with the material cooling down and subsequent formation of retraction fractures, which sometimes leads to the collapse of the tube roofs (Figs. 13 and 14).

6. Instability Processes

6.1. Collapse phenomena due to cavities

Collapse phenomena can occur as a consequence of the loss of strength of the materials that form the roof of lava tubes or cavities. These collapsing processes depend on the thickness of the lavas overlying the cavity and on their mechanical properties, as well as the size and depth of the cavities, although these are generally superficial. Figures 13 and 14 depict an example of collapsing lava tube roofs on the island of Lanzarote. Sometimes, these struc-

Figure 10 - Columnar jointing, Los Organos, La Gomera.

Figure 11 - Basaltic lava showing radial jointing, northern Tenerife. Photo window approxmate 4 x 3 m.

Figure 12 - Retraction band at a distance of a third from the base of the lava flow, northern Tenerife.

Figure 13 - Collapsed lava tube, Lanzarote.

Figure 14 - Cracking and collapsing of the roof of a lava tube, Lanzarote.

Figure 15 - Landslide on the cliffs of Famara, Lanzarote. Cliff height is 300 m.

tures appear as kilometres of sinuous troughs following the path of the flow that formed them.

The presence of cavities in lava-type volcanic materials is relatively frequent in the Canary Islands. Their origin could be the result of lava flows adapting to topographic irregularities, to spaces left by the fluids inside flows, to gasses associated with the flow or to differential cooling processes. The sizes of these cavities range from a few dm^3 to several m^3, forming caves. Their presence can give rise to geotechnical instability problems related to loads on foundations (Serrano *et al.*, 2007b).

6.2. Landslides and rockfalls

Instabilities associated with gravitational processes are relatively common in the Canary Islands and are usually induced by intense rainfall or linked to volcanic activity or even human actions. Some outstanding examples due to their magnitude and volume are found on the island of Gran Canaria, in the Tenteniguada basin (Quintana and Lomoschitz, 2001) and in the Tirajana depression (Lomoschitz, 1995). The latter are slow translational movements activated on repeated occasions, probably during rainy periods. In Lanzarote, ancient instabilities may be observed on the coastal cliffs of Famara, in the north of the island (Fig. 15). Of all the instability processes of the Canaries, the most common are those of rockfalls. Rockfall is provoked by intense rainfall and storms in coastal zones, and associated to high slopes in zones with escarpments and cliffs. Rockfall is particularly intense in high slope areas where lava and pyroclast layers alternate and in coluvial masses of low strength containing rocky blocks.

6.3. Paleolandslides

Massive large landslides have had a great influence on the evolution of volcanic islands and especially the Canary Islands. Thus, numerous large landslides have been described, mainly in the archipelago's western islands. Their impact in terms of risk is undeniable, although being linked to complex geological factors of extremely long return periods, their hazards are extremely low. The discovery and interpretation of the deposits of these gigantic landslides on marine bottoms has confirmed previous controversial hypotheses based on morphological features (Krastel *et al.*, 2001; Masson *et al.*, 2002; Acosta *et al.*, 2005). Deposits of the generally designated *debris avalanches* can cover areas of 200 to 2600 km^2 of the sea bottom, with calculated volumes between 25 and 650 km^3 and more than a hundred kilometers spanned from the island flank. On the Canaries, over 20 large landslides of this type have been described, 15 of which affected the western islands (Ferrer *et al.*, 2007).

7. Discussion and Conclusions

The main types of rock masses relevant to engineering geology in the Canary Islands are comprised of volcanic materials formed by basaltic, phonolitic and trachytic lava flows, along with materials of pyroclastic origin. The weatherings of pyroclastics products have developed surface formations of residual and transported soils. A summary of the properties of intact rocks, rock masses and soils are shown in Tables 2 and 3.

The effusive origin of these materials, their basic mineralogical composition, and the specific conditions of temperature, pressure, gasses, along with the environment and depositional setting, are the main geological influencing factors on geotechnical properties. The vitreous composition of pyroclastic products and their rapid decompression and cooling on expulsion causes rapid weathering, sometimes accompanied by hydrothermal alterations, with decisive effects on the geotechnical properties. The low density of many pyroclastic deposits, shape and size of their particles, degree of compaction and junctions between particles, can give rise to collapse phenomena.

The weathering of the rock minerals can generate soil deposits, which can sometimes show an expansive behaviour. Hygroscopic, mineralogic and microfabric properties, as well as moisture changes in volcanic soils, render differ-

Table 2 - Summary of geotechnical properties of the volcanic materials of Canary Islands.

Geotechnical properties / Material		G (kN/m^3)	γ_d (kN/m^3)	σ_c (MPa)	C (MPa)	ϕ (º)	E (GPa)	LL (%)	PL (%)	EI (MPa)	Other
Basalts		-	15-31 (23-28)	25-160 (40-80)	-	40-55	15-30	-	-	-	-
Tuffs		-	8-18 (poorly compacted) 18-25 (compacted)	1-50 < 10 (saturated)	0-1.45	12-30 (weathered tuffs)	0.1-22	-	-	-	-
Ignimbrites		13 to > 20	13 - > 20	2-5 (weak) 15-70 (hard)	0.1-2	27-38	30-50 (welded)	-	-	-	-
Agglomerates		-	12-28	0.5-25	≤ 0.4	25-42	0.1-3	-	-	-	-
Pyroclastic fall deposits		22-25	5-18	0-5	≤ 0.1	25-45 (32-38)	0.01-0.1	-	-	-	n(%): 45-65
Volcanic soils	Residual soils	22-30	12-13	-	≤ 0.1	23-40	0.510^{-3}-1110^{-3}	52-102	15-95	0.02-0.2	e: 1.6-2.88 W(%): 12-180 τ_u: 56-130 kPa $\gamma_{máx}$: 5-17.3 kN/m^3 Cc: 0.13-0.24
	Transported soils	27-29	11-14	-	-	-	-	35-90	25-45	0.02-0.15	

Indicated are maximum and minimum values. Most common values appear in brackets.
G: specific weight, γ_d: dry density, σ_c: uniaxial compressive strength, C: cohesion, ϕ: internal friction angle, E: elasticity modulus, LL: liquid limit, PL: plastic limit, EI: expansive index, n: porosity, e: pore index, W: moisture content, τ_u: shear strength, $\gamma_{máx}$: maximum Proctor density, C_c: compressibility coefficient.

Table 3 - Summary of engineering geological characteristics of pyroclastic materials.

Material	Composition	Granulometry-morphology	Structure	Origin	State*					Other geological features
					1	2	3	4	5	
Pyroclastic deposits	Acid (pumice) or basic	Ash < 2 mm Lapilli 2-64 mm Blocks, bombs & scorias > 64 mm	Bedded layers. Cinder cones	Pyroclastic fall	XXX	O or XX	O	O	X	Heterogeneous, discontinuous deposits
Tuffs	Pyroclastic generally of a pumitic nature	Lapilli & ash	Homogenous & continuous	Pyroclastic fall	O	XXX	XX	X	O	Massive, continuous deposits
				Pyroclastic flow	O	X	XXX	XX	O	
Ignimbrites	Pyroclastic major component: pumice	Lapilli & ash	Arranged as flow layers. Eutaxitic texture	Pyroclastic flow	O	O	XXX	XXX	O	Joints and fractures may develop as in flows
Agglomerates & agglomeratic breccias	Pyroclastic or polygenic. Large angular fragments in breccias	Unclassified thick, angular, heterometric fragments in fine matrix	Massive and lacking structure	Airfall	XX	XXX	XX	O	XX	Water transport
				Lahars	O	X	X	O	XX	
				Avalanches	O	X	X	O	XX	Gravitational sliding

(*)1: loose, 2: compact, 3: consolidated, 4: welded, 5: cemented ([1]), XXX: most common state, XX: Sometimes, X: scarcely, O: never, ([1]) Since cementation is a post-depositional process, its presence depends on the geochemical conditions of the environment.

ent geotechnical behaviour patterns to those expected for non-volcanic soils of similar granulometric characteristics. The low density of volcanic soils, their very open microstructure with weak junctions between particles and their mineralogic composition lead to unfavorable geotechnical behaviour patterns in terms of their strength, deformability, compactability and stability in response to static and dynamic loads.

Anisotropy and heterogeneity of the volcanic rock masses along with their irregular spatial organization determine abrupt changes in thickness and continuity. These circumstances markedly condition site investigations and consequently the geomechanical characterization of the rocks, which translates to further difficulties and uncertainties when trying to establish representative ground profiles. Dyke intrusion processes frequently observed on islands constitute very characteristic discontinuity structures that affect the strength of the rock masses and their hydrogeological conditions. Conditions of rapid cooling of lavas, flows and their build-up, render typologies of discontinuities specific to these materials as well as cavities and tubes.

Site investigation techniques in volcanic islands usually require larger number of boreholes and specific geophysical methods appropriated for volcanic materials. Some of the limitations on geophysical methods include the identification of low density materials, such as pyroclastics deposits underlying basaltic lava flows by using seismic refraction methods. The detection of cavities by geo-radar techniques is limited to 10 m depth; electric tomography is also limited to 50 m depth and gravimetric methods are not appropriate to identify small size cavities. Searching for cavities using geophysical methods should be complemented by rotary or percussion drilling and down-hole television cameras techniques. As a consequence of the particular geotechnical and geological characteristics of the volcanic materials a specific geotechnical group of materials should be established.

In spite of these unfavourable engineering geological conditions, most of the volcanic rocks show generally acceptable geomechanical behaviour for many conventional excavations and foundations, due to the high strength properties, roughness of their contact surfaces, irregular shape of their particles and excellent drainage conditions. Human actions such as deforestation, desertification, uncontrolled excavations, blocking the natural drainage network and inadequate site investigations, as well as environmental factors like intense rainfall or coastal erosion, can induce severe geotechnical problems, highlighting the importance of acquiring sound geomechanical knowledge and appropriated site investigation procedures.

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