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General characterization of the mechanical behaviour of different volcanic rocks with respect to alteration

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ABSTRACT

Physical–mechanical properties and the mechanical behaviour of volcanic rocks are extremely sensitive to their original structure and successive hydrothermal alteration. Various mechanical tests have been performed on different volcanic rocks to evaluate the relationships between chemical and mineralogical composition, microstructure and texture, and physical mechanical properties. A wide-ranging description of mechanical behaviour is obtained through a series of uniaxial, triaxial, isotropic and oedometric tests, and of pre- and post-failure non-destructive analyses. X-ray tomographies show deformation and compaction within the samples and the influence of porosity distribution. Results are interpreted in the key of degree of alteration (lava and tuff series) and of texture differences (pyroclastic and ignimbrite series); empirical relationships between strength and physical properties are presented and discussed, together with trends in change of an E_{t50} vs UCS ratio. The influence of facies and water saturation on strength and behaviour of ignimbrite rocks is discussed. A 45 to 85% loss both in strength and ultrasonic waves velocity is found for altered lava and pyroclastic rocks. Weak highly porous ignimbrite shows a 50% strength loss under water saturated conditions and the complete collapse of porous structure.

1. Introduction

Rocks in volcanic environments can undergo a broad range of mechanical behaviours because of the exceptional physical and chemical changes occurring during weathering and hydrothermal alteration (Ceryan et al., 2008). It is known that in weathering Earth's atmosphere, biota and waters interact with the rock system; while in hydrothermal alteration, groundwater interacts with intrusive bodies generating hot and often acidic fluids (Frank, 1995; Finizola et al., 2002; Hurwitz et al., 2002; Aizawa et al., 2005; Hase et al., 2005), favouring rock dissolution, mineral deposition and clay mineral formation (López and Williams, 1993; Watters et al., 2000). The effect of weathering and hydrothermal alteration is difficult to quantify and not always related to a reduction in the mechanical characteristics of the materials (Watters et al., 2000). Many contributions relative to chemical changes and mineral alteration processes have been published (Irfan, 1999; Duzgoren-Aydin et al., 2002; Zimbelman et al, 2004), but little effort has been spent on the effects in terms of strength reduction of altered materials (Watters and Delahaut, 1995; Zimbelman et al., 2003), and obtained results are far from being definitive. Material property degradation has been proposed as an important factor in inducing volcanic flanks collapse (Reid et al., 2001; Finn et al., 2007), but their definition, together with hazard and instability mechanisms remains a difficult task (Finn et al., 2007; del Potro and Hürlimann, 2009). Moreover, a lack of knowledge exists with regard to the physical–chemical processes that could generate instability by a progressive alteration of the materials. In fact, limit equilibrium (Voight and Elsworth, 1997; Donnadieu et al., 2001; Okubo, 2004) and numerical slope stability studies (Hürlimann, 1999; Zimbelman et al., 2004; Tommasi et al., 2007) sometimes indicate stable conditions, also in saturated conditions, due also to the fact that they are based on properties, constitutive laws and failure criteria, neglecting the changes in physical and mechanical properties induced by the progressive alteration processes as well as thermo-chemo-mechanical conditions.

It is known that the behaviour of rocks is a result of the long- and short-term influences of chemical and mineralogical heterogeneities. Recently, these heterogeneities have been evaluated by several chemical weathering indices (e.g. Duzgoren-Aydin et al., 2002), but limitations at identifying the degree of alteration in a rock system still exist, mainly because the distribution of chemical elements is determined by local conditions.

Other researchers studied geotechnical parameters of rocks and tried to find correlations with the degree of weathering (e.g. Lump, 1983; Kate, 1993; Gupta and Rao, 2000; Avar and Hudyma, 2007; Marques et al., 2010). It is now well established that uniaxial compressive strength (UCS) of rock decreases with an increase in porosity. Correlations with rock density (ρ), modulus of elasticity (E_{t50}), ultrasonic waves velocities (Vp and Vs), and volumetric water content (θ) have been proposed. UCS and Vp and Vs are considered the most appropriate quantitative indexes for establishing the influence of alteration on the strength and deformability.

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Physical, petrographical, and mineralogical tests were performed to understand the nature of the relationship between rock strength and deformation (Kate, 1993; Gupta and Rao, 2000, for crystalline rocks). Even though data is scattered and exhibits large variations, elastic modulus and strength show a significant reduction with increasing porosity. Avar and Hudyma (2007) analysed the variations in E_{t50} and strength with respect to porosity of tuffs and suggest that strength vs E_{t50} plots well describe the heterogeneous nature of tuff. Marques et al. (2010) show that basic physical (e.g. porosity, water content and P–S wave velocities) and mechanical characterization could be used to establish the state of alteration of metamorphic rocks and their degree of anisotropy. Moon (1993) discusses the great influence of groundmass fabric (texture, fabric of the crystals, clasts and pores shape) on mechanical behaviour of ignimbrite. Binal (2009) determined physical–mechanical properties of moderately welded and unwelded ignimbrite (e.g. apparent porosity, ultrasonic velocities, point load index, compressive strength and modulus of elasticity) and analysed the results by multiple regression analysis. Vp, Vs and geomechanical properties of different tuffs were investigated by Vinciguerra et al. (2009) and the authors concluded that those properties could be significantly affected by the presence of clasts.

Rodríguez-Losada et al. (2009) performed the most conspicuous testing campaign (uniaxial, triaxial and Brazilian tests, ultrasonic velocities) on volcanic rocks (mainly basalts and ignimbrites) from the Canarian Archipelago, determining the range of values for various properties and suggesting a possible relationship between strength and alteration. del Potro and Hürlimann (2008, 2009) discuss the effect of argillitic hydrothermal alteration on phonolithic lavas, for rock mass characterization and volcanic soils, but detailed data are missing for a more complete assessment. Unfortunately, other contributions in the literature do not take into account alteration in rock description, or do not present a complete geomechanical characterization both for fresh and altered volcanic rocks.

This paper starts from the observation that a qualitative relationship was recognized between alteration and physical mechanical properties, but that a quantitative description and analysis is missing. The aims of this paper are, namely: the characterization of different volcanic rocks from a physical mechanical point of view; the analysis of the relationships among physical mechanical properties and lithology, degree of alteration (for lava and pyroclastic rocks), and changes in pore structure and texture. These relationships are examined with the purpose of defining quantitatively the loss or gain in strength and the influence on the observed failure modes. Such knowledge of the rock behaviour is fundamental for a correct use of engineering geological and geomechanical classifications in volcanic rocks, and for the parametrization of materials in modelling processes occurring in volcanic deposits and edifices.

2. Sampling sites

Three different lithologies have been sampled at different Italian sites:

1) Lava and pyroclastic samples from the Solfatara (Pozzuoli), a hydrothermally altered tuff cone (Civetta et al., 1997; Di Vito et al., 1999) (Fig. 1).
2) Tuff samples, from the island of Ischia, belonging to the Green Tuff, a welded pyroclastic flow deposit (Gillot et al., 1982; Orsi et al., 1991; Civetta et al., 1997) (Fig. 1).
3) An unwelded ignimbrite from the last two eruptive phases of the Vulsini volcanic zone, characterized by lava flows, scoria cones, trachytic Plinian pumice falls and ignimbrites (Beccaluva et al., 1991; Nappi et al., 1998) (Fig. 1).

2.1. Petrographical, chemical and physical properties

A detailed description of sampled lithologies (e.g. total and effective porosity, pore network evolution, texture, structure, degree of alteration) is given by Pola et al. (2012) and here only the most important characters are presented.

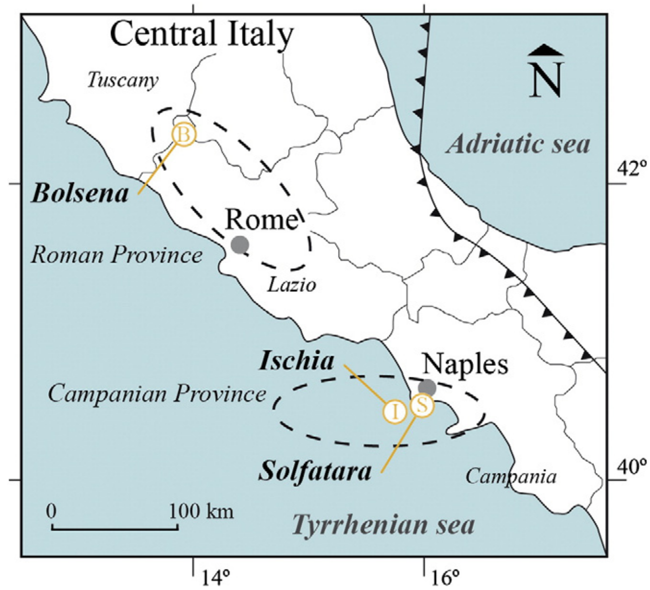

Fig. 1. Localization map of field study area of Solfatara (S), Ischia (I) and Bolsena (B). Dark lines represent the limit of the Italian regions. Dash lines represent the volcanic provinces. Dark line with small triangles represents the limit of the Apennine front. Grey circles represent the localization of the mean cities. See Pola et al. (2012) for a detailed description and localization of the outcrops.

The chemical index of alteration (CIA) is used to identify the chemical changes between samples and its increase can be associated with the alteration of the crystal structure. According to the CIA index, and physical and mechanical properties, four different lithotypes (lava, pyroclastic, tuff and unwelded ignimbrite) and five main degrees of alteration (fresh, slightly altered, moderately altered, highly altered, and completely altered) were recognized (Table 1).

2.1.1. Lava sequence (SLA)

This sequence is composed of five sets of samples with five different degrees of alteration. The major constituents of fresh sample (SLA1) are

Table 1
Summary of some physical properties determined for the studied volcanic rock sequences. All values are given as an average. CIA = degree of alteration (chemical index of alteration); F = fresh; SA = slightly altered; MA = moderately altered; HA = highly altered; CA = completely altered; ρ = density; η_T = total porosity; η_e = effective porosity; XRT = X-ray tomography images; Hg = mercury porosimetry; Vp = compressional wave velocity; Vs = shear wave velocity; αs = spatial attenuation.

Sample	Degree	CIA	ρ	ηT (%)	ηe (%)	Waves (km/s)		αs
			(kg/m3)	XRT	Hg	Vp	Vs	(dB/cm)
Lava								
SLA1	F	42.73	2375	6	11	4.39	2.13	1.98
SLA2	SA	45.98	2500	6.4	15	4.14	2.91	4.06
SLA3	MA	46.33	1938	25.6	18.6	3.16	2	2.76
SLA4	HA	70.93	1650	30.7	32	3.11	1	4.66
SLA5	CA	58.8	1500	31.5	26.8	2.79	1.48	2.53
Pyroclastic								
SPRA1	HA	70.41	1483	20.3	41.5	2.18	1.02	2.54
SPRA2	HA	67.04	1540	34.9	44.8	2.06	0.79	2.91
SPRA3	HA	–	1425	42.9	–	1.65	0.51	3.23
Tuff								
IGTF	SA	47.09	1540	25	25.5	1.14	0.42	4.42
IGTA	HA	55.13	1810	24	29.7	2.25	0.81	3.39
Ignimbrite								
BoPRA-C	HA	–	955	42.3	55.7	1.15	0.92	
BoPRA-F	HA	69.24	933	49.8	65	1.12	0.88	2.9