Δελτίο της Ελληνικής Γεωλογικής Εταιρίας, τόμος L, σελ. 1989-1998
Πρακτικά 14ου Διεθνούς Συνεδρίου, Θεσσαλονίκη, Μάιος 2016

Bulletin of the Geological Society of Greece, vol. L, p. 1989-1998
Proceedings of the 14th International Congress, Thessaloniki, May 2016

COMPARATIVE STUDY OF PHYSICOMECHANICAL PROPERTIES OF ULTRABASIC ROCKS AND ANDESITES FROM CENTRAL MACEDONIA (GREECE)

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Abstract

Petrographic, geochemical and physicomechanical features were determined and inter-correlated in two representative ultrabasic samples from the Veria-Naousa ophiolite and two Pliocenic andesite samples, occurring at the east of the above complex. Results show that mineralogical and textural features are major factors affecting the physicomechanical properties in both lithotypes. The ultrabasic rocks display higher resistance to attrition and abrasion and lower water absorption values relative to the intermediate volcanic rocks, hence the first are predicted to show better in-service engineering performance. However, the degree of serpentinisation is detrimental, as a highly serpentinised ultrabasic sample yielded poor results, analogous to the andesites, in certain laboratory tests. Ophiolite complexes in Greece are abundant and they are distributed along several mainland areas. Hence setting evaluation criteria for their quality is important as they can potentially replace limestones, which are less resistant and durable, in several environmental and industrial applications.

Keywords: *aggregates, physicomechanical properties, andesites, serpentinite, harzburgite, ophiolite.*

Περίληψη

Προσδιορίστηκαν πετρογραφικά, γεωχημικά και φυσικομηχανικά χαρακτηριστικά σε δυο αντιπροσωπευτικά δείγματα υπερβασικών πετρωμάτων από το οφιολιθικό σύμπλεγμα Βέροιας-Νάουσας και δυο δείγματα Πλειοκαινικών *ανδεσιτών οι οποίοι απαντούν στα ανατολικά του παραπάνω συμπλέγματος. Τα αποτελέσματα υποδεικνύουν ότι τα ορυκτολογικά και ιστολογικά χαρακτηριστικά και των δυο λιθοτύπων είναι σημαντικοί παράγοντες που επηρεάζουν τις φυσικομηχανικές τους ιδιότητες. Οι υπερβασικοί λιθότυποι παρουσιάζουν υψηλότερη αντοχή σε φθορά από τριβή και κρούση με την μηχανή* Los Angeles *και μικρότερες τιμές υδαταπορροφητικότητας σε σχέση με τα ενδιάμεσα ηφαιστειακά πετρώματα. Όμως, ο βαθμός σερπεντινίωσης παίζει αρνητικό ρόλο καθώς παρατηρήθηκε ότι ένα έντονα σερπεντινιωμένο δείγμα έδωσε πτωχές τιμές, ανάλογες με αυτές των ανδεσιτών, σε συγκεκριμένες εργαστηριακές δοκιμές. Οφιολιθικά πετρώματα αφθονούν στον Ελληνικό χώρο καταλαμβάνοντας μεγάλες εκτάσεις σε περιοχές της ηπειρωτικής χώρας. Για το λόγο αυτό θεωρούμε σημαντικό να καθοριστούν κριτήρια εκτίμησης της καταλληλότητάς*

τους, καθόσον δυνητικά μπορούν να αντικαταστήσουν τα ασβεστολιθικά πετρώματα, τα οποία γενικά παρουσιάζουν χαμηλότερη αντοχή και ανθεκτικότητα, σε διάφορες περιβαλλοντικές και βιομηχανικές εφαρμογές.
Λέξεις κλειδιά: *αδρανή υλικά, φυσικομηχανικές ιδιότητες, ανδεσίτες, σερπεντινίτες, χαρτσβουργίτες, οφιολιθικό σύμπλεγμα.*

1. Introduction

Research of the engineering properties of ophiolitic and acidic to intermediate volcanic rocks, for industrial purposes, shows an increasing interest. Basic and ultrabasic rocks find a wide variety of uses as aggregates for antiskid road surfacing, concrete, railway ballast, etc. (French and Gammond, 1989; Tsikouras *et al.*, 2005; Pomonis *et al.*, 2007; Rigopoulos *et al.*, 2010), whereas those of acidic-intermediate composition comprise very good mortar aggregates for various uses (Miskovsky *et al.*, 2004; Zorlu *et al.*, 2004). Use of petrography as a tool in the assessment of aggregates quality dates back to the early part of the 20th century (Knight and Knight, 1935; Griffiths, 1989; Rhoades and Mielenz, 1946). The influence of alteration on strength and durability properties of rocks has been discussed by many researchers in recent years and various micropetrographic and weathering indices have been proposed (Harben and Bates, 1990; Irfan *et al.*, 1978; Mendes *et al.*, 1966).

The present paper aims at the comparison of the physicomechanical properties and engineering performances of ultrabasic rocks (from the Veria-Naousa ophiolitic complex) and andesites (from a Pliocene intrusive series at the east of the complex). Moreover, we intend to investigate the influence of their petrographic characteristics to their mechanical behaviour and to assess their quality.

2. Geological setting

The Veria-Naousa ophiolite represents a dismembered ophiolite unit, which is superimposed on a basement consisting of rocks belonging to the Pelagonian and Axios (Almopias subzone) isopic zones in northern Greece (Fig. 1).

The ophiolite is obducted onto Cretaceous platform carbonates and a flysch succession of the Pelagonian Zone during Upper Jurassic to Lower Cretaceous time (Mercier *et al.*, 1975; Economou, 1983; Michailidis, 1990; Economou-Eliopoulos, 2003; Tsoupas and Economou-Eliopoulos, 2008). The ophiolite suite includes, from bottom to top, serpentinised lherzolite and harzburgite, intruded by a sparse network of pyroxenitic dykes, gabbro, diabase and pillow basalts. Field work revealed that it is an incomplete and dismembered suite, due to intensive tectonism. The serpentinised peridotites are intensely tectonised, showing a dense network of joints. Rare rodingite dykes occur in the serpentinised ultramafic rocks. The ophiolite is unconformably overlain by sediments (conglomeratic limenstone, flysch).

Pliocenic volcanic rocks of the Almopias subzone ranging in composition fromtrachyte to trachyandesite occur to the east of the ophiolitic complex. Nd/Sr isotopic data indicate that these rocks are associated with melting of the mantle wedge in supra-subduction zone regime (Eleftheriadis *et al.*, 2003).

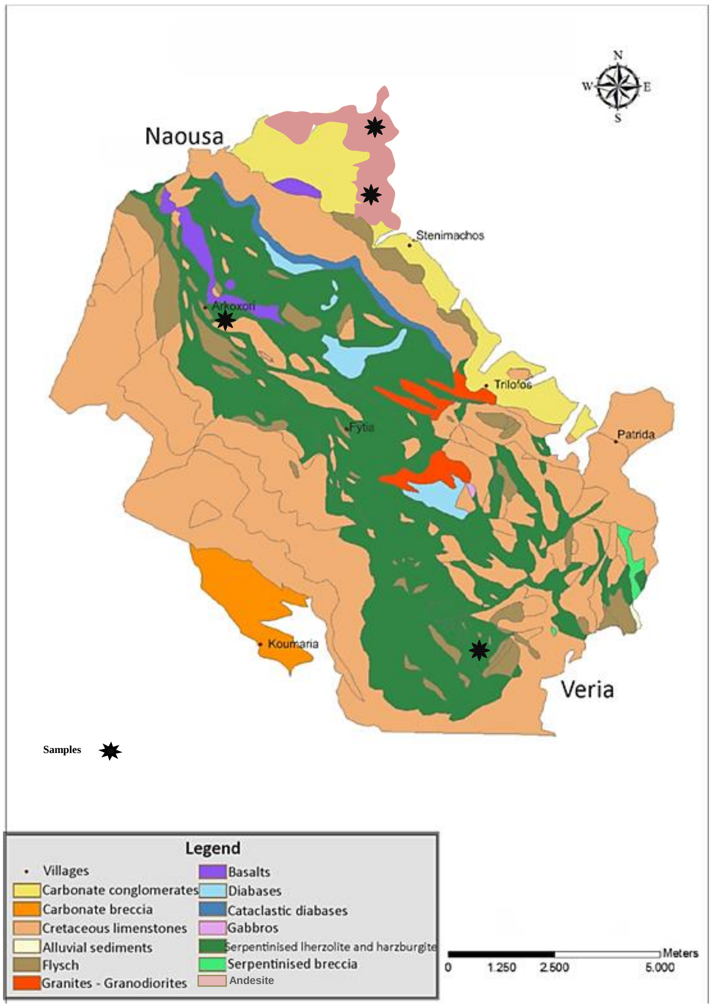

Figure 1 - Geological map of Veria-Naousa region.

3. Analytic methods

The mineralogical and textural characteristics of the samples were studied in polished-thin sections using polarising and scanning electron microscopes (SEM). SEM operating conditions were accelerating voltage 15 kV and beam current 3.3 nA, with 4 μm beam diameter. Whole-rock chemical analyses for major and trace elements were performed at ACME Analytical Laboratories LTD in Canada. Whole-rock major element analyses were carried out using an XRF spectrometer and a sequential spectrometer (ICP-OES). Trace elements were determined on totally digested samples by inductively coupled plasma-mass spectrometry (ICP-MS). Detection limits for major elements is 0.01 wt. %. The analytical precision calculated from replicate analyses is better than 3% for most major elements and better than 5% for trace elements. Laboratory tests for the determination of physicomechanical properties were conducted according to international standards and included: flakiness index (I_F; B5 812:105:01), moisture content (w; AASHTO T255), water absorption (w_a; EΛOT EN 1097-06), Los Angeles (LA; ASTM C 131), uniaxial compressive strength (USC; ASTM D 2938), Schmidt Hammer Value (SHV; ISRM 1985) and soundness (S; EΛOT EN 1367-2).

4. Results

4.1. Petrographic Features

4.1.1. Serpentinised Harzburgite

The serpentinised harzburgite shows mainly cataclastic texture, due to intense brittle deformation and a variety secondary textural features. Its primary modal mineralogical composition includes relics of orthopyroxene, Cr-spinel, as well as rare olivine, and scarce clinopyroxene. Orthopyroxene appears as subhedral porphyroclasts and most of them show exsolution lamellae of clinopyroxene, typical feature of Upper Mantle peridotites. Serpentine is the major secondary phase showing typical mesh (Fig.2a, b), local bastite after orthopyroxene (Fig. 2c) and ribbon (Fig. 2d) textures. Chlorite and magnetite are also products of hydrothermal alteration of the harzburgite. Magnetite commonly fills microcracks of or rims Cr-spinel crystals. Brittle deformation is expressed mainly by intense of fragmentation of spinel as well as by intergranular microcracks.

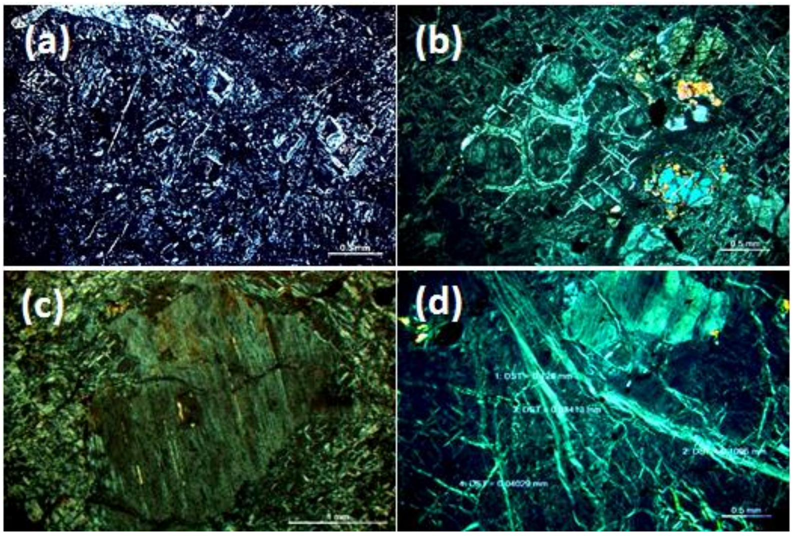

Figure 2 - Photomicrographs (XPL) of textural characteristics of the serpentinised harzburgite from the Veria-Naousa ophiolite: a and b. serpentine mess texture (samples BE.12 and BE.01, respectively), c. orthopyroxene porphyroclast with exsolution lamellae of clinopyroxene (sample BE.12), d. ribbon texture in serpentinised mass (sample BE.01).

4.1.2. Andesite

The collected andesite samples are vesicular and have porhyritic texture with phenocrysts of plagioclase, up to 1 cm, biotite (rarely phlogopite) and lesser clinopyroxene surrounded by a microcrystalline and amorphous groundmass in places with flow structure (Fig. 3). Locally, plagioclase phenocrysts are surrounded by sanidine. Plagioclase phenocrysts are optically zoned showing both normal and oscillatory reverse zoning (Fig. 3c, d). Accessory minerals commonly include apatite, titanite, zircon and magnetite. Alteration products in the andesites include clay minerals, albite, chlorite, Fe-oxides and calcite. Numerous intergranular cracks are present as a result of brittle deformation.

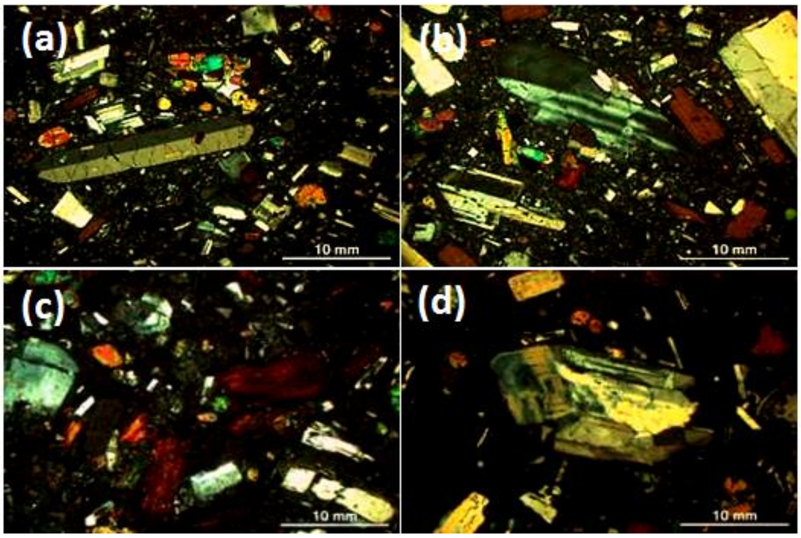

Figure 3 - Photomicrographs (XPL) of the characteristic of the Pliocene andesites from Edessa: a and b. porhyritic texture with plagioclase and clinopyroxene phenocrysts; biotite is present in b, too (sample BE.81), c. phenocrysts of oxidised biotite and zoned plagioclase in a microcrystalline to glassy groundmass (sample BE.82), d. phenocryst of a zoned and altered to albite plagioclase surrounded by glassy groundmass (sample BE.82).

4.2. Geochemical features

Whole-rock composition of representative andesites and ultrabasic rocks from the Veria-Naousa ophiolitic complex are listed in Table 1. SiO_2 in the serpentinised harzburgites typically ranges from 39.82% to 40.95% and Fe_2O_3 from 8.06% to 8.86%. The high degree of serpentinisation is reflected by high loss-on-ignition (LOI) values (13.50%-14.60%).

Table 1 - Whole-rock geochemical analyses of representative serpentinised harzburgites from the Veria –Naousa ophiolite and Edessa andesites.

	Serpentinised Harzburgite		Andesite			Serpentinised Harzburgite		Andesite	
	BE.01	BE.12	BE.81	BE.82		BE.01	BE.12	BE.81	BE.82
Major elements (wt. %)					Trace elements (ppm)				
SiO_2	39.82	40.95	60.91	56.39	Zn	8.00	26.00	43.00	26.00
TiO_2	*	*	0.52	0.63	Rb	0.40	0.40	220.60	203.50
Al_2O_3	1.01	1.11	17.32	17.;84	Sr	2.00	0.70	1101.40	1896.20
$Fe_2O_3^t$	8.86	8.06	3.94	5.91	Y	0.90	33.00	20.10	27.00
MnO	0.11	0.13	0.10	0.09	Zr	0.10	0.10	305.60	290.50
MgO	34.17	34.81	1.50	2.25	Nb	0.30	*	21.60	20.60
CaO	0.10	0.21	3.93	5.28	Pb	21.70	4.60	20.60	50.00
Na_2O	*	*	4.12	3.78	Ba	1.00	3.00	1591.00	2020.00
K_2O	*	*	5.24	4.80	V	60.00	33.00	86.00	115.00
P_2O_5	*	*	0.35	0.39	Sc	11.00	11.00	8.00	12.00
LOI	14.60	13.50	1.6	2.0	Ga	3.10	3.30	20.40	20.00
Total	98.67	98.77	99.53	99.36	Hf	*	*	7.70	7.40
Trace elements (ppm)					Ta	*	*	1.20	1.20
Cr	2963.00	2792.00	*	*	Th	*	*	61.70	62.70
Co	91.10	102.80	9.50	17.30	U	0.20	*	16.60	17.80
Ni	2655.80	2481.30	9.20	11.60	MgO/FeO^t	4.29	4.80	0.42	0.42
Cu	12.90	7.50	19.70	29.50					

* Below detection limit

The andesites show expectedly higher SiO2 contents (56.39%-60.91%). High Na2O, CaO and Al2O3 percentages in them reflect the participation of plagioclase in these rocks. They show low loss-on-ignition (LOI) values (1.60%-2.00%) due to the restricted participation of hydrous minerals.

4.3. Physicomechanical properties

The results of the determined geometrical, physical, mechanical and physicomechanical properties from the serpentinised harzburgites and andesites are listed in Table 2. The tested peridotites are mechanically stronger than the andesites, showing higher uniaxial compressive strength (UCS), Schmidt hammer value (SHV) and lower Los Angeles (LA) values (Table 1). Soundness test (S) and water absorption (w_a) values are largely different in the two ultrabasic rocks, as sample BE.01 appear much less durable and more absorbent than BE.12 (Table 2). The lower UCS and S and the higher LA values of sample BE.12 reflect its higher degree of serpentinisation relative to sample BE.01. Moisture contents (2.94%-3.35%) and water absorption (5.54%-5.9%) values are slightly higher whereas flakiness index is much lower (15.42%-16.91%) in the andesites than the serpentinised harzburgites (Table 2). The two andesite samples show rather consistent S values of 67.4% and 77.5%, analogous to the relatively fresher peridotite sample.

Table 2 - Results of physicomechanical tests in the Veria-Naousa ultrabasic rocks and Edessa andesites.

Sample No		*Uniaxial compression strength*	*Los Angeles*	*Schmidt hammer value*	*Moisture contect*	*Water absorption*	*Soundness test*	*Flakiness index*
		UCS (Mpa)	*LA (%)*	*SHV*	*W (%)*	*W_a (%)*	*S (%)*	*I_F (%)*
Serpendinised harzburgite	**BE.01**	75.62	19.20	60.90	2.58	4.40	75.34	42.10
	BE.12	56.40	25.16	60.00	2.18	1.68	18.05	37.20
Andesite	**BE.81**	34.52	37.93	49.00	2.94	5.90	77.50	15.42
	BE.82	35.62	39.41	50.30	3.35	5.54	67.40	16.91

4.4. Correlations of physicomechanical properties

Regression and factor analyses were applied to test the acquired results and to detect the interrelationships between their geometrical, physical and mechanical properties (Fig.4). Evidently, the two different rock-types cluster at different areas on the correlation diagrams, apparently due to their considerably dissimilar values in certain tests. Decoupling of the ultrabasic samples in some diagrams results from their different strength and durability, owed to the different degree of serpentinisation. However, all samples form cohesive trends that can be described by statistical equations and important correlations can be obtained.

Linear regression was used based on the linearity assumption and the determination coefficients R^2 and equations of the fitted lines were calculated by the "least squares" method. Other types of relationships were also tested (e.g. logarithmic, power, etc.) but it is always observed that the linear model fits best, giving the highest R^2 values. Uniaxial compression strength and Schmidt hammer value show excellent negative linear correlations with Los Angeles coefficient (Fig. 4a, b), which can be described by the equations:

$$UCS = -1.9488\times LA+109.83,\ R^2 = 0.9665$$

$$SHV = -0.6184\times LA+73.864,\ R^2 = 0.9432$$

Los Angeles shows excellent negative and good positive linear correlations with Flakiness index and moisture content, respectively (Fig. 4c, d) and these relationships can be modelled with the following equations:

$$LA = -0.7097\times I_F+50.232,\ R^2 = 0.9782$$

$$LA = 15.65\times w-12.808,\ R^2 = 0.6311$$

Soundness test demonstrate an excellent positive linear relationship with water absorption (Fig. 4e), which can be described by the equation:

$$S = 13.589\times w_a+0.0506,\ R^2 = 0.8582$$

Flakiness index shows an excellent positive linear relationship with uniaxial compressive strength (Fig. 4f) and the relationship is given by the equation:

$$I_F = 0.6779\times UCS-6.3523,\ R^2 = 0.9298$$

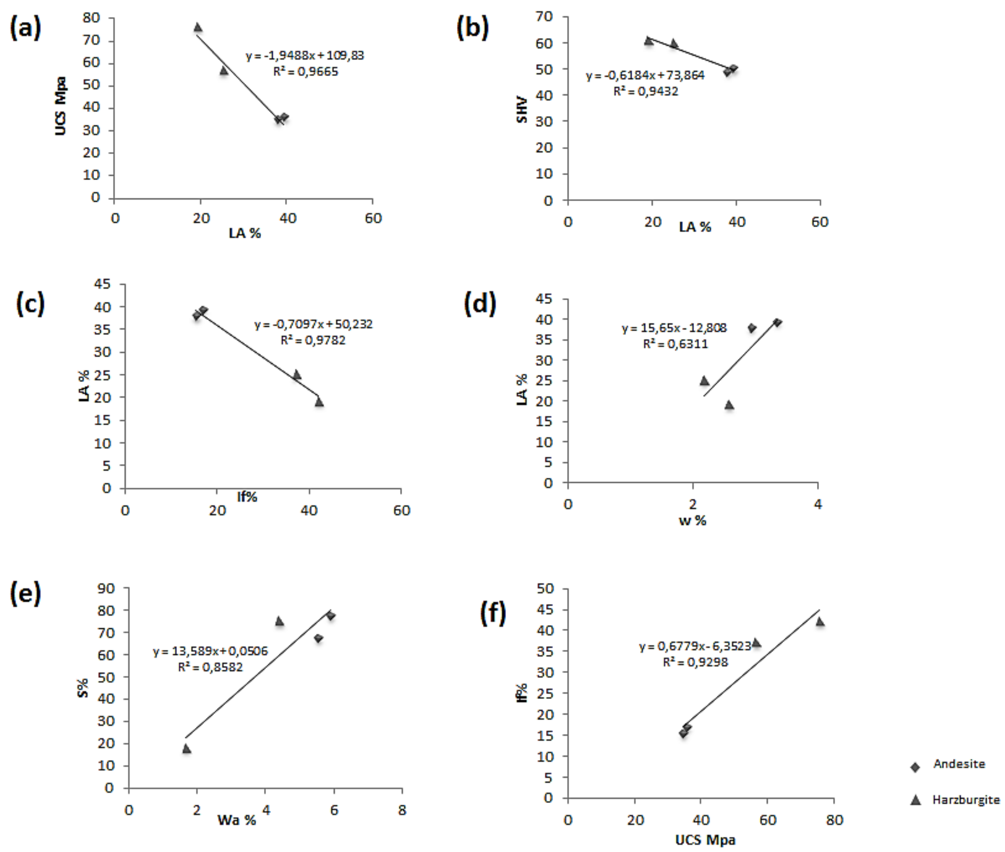

Figure 4 - Correlations of physicomechanical properties of the ultrabasic rocks from the Veria-Naousa ophiolite and the Edessa andesites.

5. Discussion

5.1. The Influence of Alteration on the Engineering Properties of the Rocks

Mineralogical composition, textural features, degree of alteration/deformation and weathering are the main factors which affect the physicomechanical properties and consequently the suitability of aggregates in industrial applications (Hartley, 1974; Brattli, 1992). Primary assemblages of ultramafic rocks are often converted to secondary mineral phases as a result of ocean-floor metamorphic process. Ocean-floor metamorphism has variably affected the collected ultrabasic samples and despite the fact that we present a limited number of samples, it is evident that serpentinisation has a negative influence on the engineering behaviour of these rocks, as sample BE.12 is clearly weaker and less durable relative to the less serpentinised sample BE.01; similar results have been previously proposed by other authors, too (Rigopoulos *et al.,* 2010; Smith and Collins, 2001). The much lower hardness of the secondary minerals (serpentine polymorphs and chlorite) relative to the primary relics (olive and pyroxenes) results in differential mechanical behaviours, thus contributing to the weakness and easier deterioration of the rocks under stress and subsequently during their in-service. This is assigned to the fact that the secondary minerals have substantially different mechanical behaviour compared with the primary ones, leading to a modification of rock strength (Rigopoulos *et al.,* 2010).

The andesites include secondary clay minerals as a result of plagioclase alteration. These clay minerals have the ability to absorb water within their structure, therefore, even present in low amounts, they contribute to the disintegration and low coherence of the rocks. The andesites have been greatly affected by brittle deformation, as it is deduced by a dense network of cracks and joints in their mass. This feature along with their vesicular structure are considered as the main factors for their reduced strength and durability relative to the significantly altered serpentinised harzburgites.

5.2. Interdependence of Physicomechanical Properties

Regression analysis indicate significant interrelationships between the physicomechanical properties in both the ultrabasic and andesitic rocks. Inverse correlation of LA with UCS and SHV, suggest that the resistance of these rocks in attrition and grinding is a linear function of their strength. Similar correlations have been previously reported for mafic and ultramafic rocks, too (Rigopoulos *et al.,* 2006; Rigopoulos *et al.,* 2009; Davis, 2002; Räisänen, 2004) but from this research it is concluded that such a relationship can be extended to other rock types like intermediate volcanic rocks.

The flakiness index is a critical factor for the quality of aggregates as flaky particles may have adverse effects in several applications and impair the durability of constructions. The significantly higher I_F of the serpentinised samples can be explained by the large amount of secondary serpentine and chlorite (both of the phyllosilicate subclass) thus affecting their intrinsic mechanical properties. The andesites, which contain mostly prismatic and squat crystals as well as glass and lack abundant phyllosilicate minerals exhibit better I_F values. However, this coefficient shows a negative correlation with LA and a positive one with UCS suggesting that the adverse influence of the flaky shape of the aggregates is surpassed by other factors and most likely the mineralogical composition and texture as well as the brittle deformation of the rocks; the last appears to have a stronger influence on the quality of the aggregates.

Water absorption and moisture content are two parameters that are commonly considered to relate with open pores and the presence of minerals that have the capability to sequester water (like serpentine, chlorite and clay minerals). The positive correlations of S and LA with w_a and w, respectively, can be interpreted that open spaces (voids and/or joints) are detrimental to the mechanical strength and durability of both the ultrabasic and andesitic rocks. The later contain much lesser amounts of clay minerals than the amount of serpentine (and chlorite) in the ultrabasic lithologies, therefore it is plausible to assume that porosity and fracturing is a more important factor than the presence of water adsorbing minerals. These open spaces accommodate water and can host the crystallisation of salts, which are well-known disadvantageous factors for the engineering performance of rocks.

6. Conclusions

Ultrabasic and andesitic lithologies were studied and significant relationships are found between them. The ultrabasic rocks are variably serpentinised, a feature that influences negatively their performance. The sheet-like and soft character of the secondary minerals, as well as the coexistence of harder primary minerals contribute to the disintegration of the altered peridotites. Although the andesites show smaller degree of alteration, their tectonic disturbance and high porosity are extremely a negative factors for their in-service performance, contributed by the minor occurrence of secondary clay minerals, too. These factors cause a dramatic deterioration of their strength and durability as aggregates, hence the andesites show eventually worse engineering properties than the serpentinised peridotites. These low quality andesites are considered unsuitable for most industrial and construction applications, however they may be suitable for the production of mortars where high w and w_a values are favoured. The significant correlations observed between several physicomechanical parameters suggest the strong interdependence of these properties in a broad range of lithologies, like peridotites and andesites. Certain coefficients can be predicted from others and their determination coupled with petrographic information can assist to the explanation of the engineering behaviour of the rocks.

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