Bull Eng Geol Environ (2014) 73:1273–1292
DOI 10.1007/s10064-014-0584-x

ORIGINAL PAPER

Influence of petrographic characteristics on physico-mechanical properties of ultrabasic rocks from central Greece

K. Diamantis · E. Gartzos · G. Migiros

Received: 1 December 2012 / Accepted: 18 February 2014 / Published online: 8 March 2014

Abstract Ultrabasic rocks show a variety of engineering properties that may affect quarrying operations, tunnelling, mining, slope stability and the use of rock as a construction material. The physico-mechanical properties are influenced by the mineralogical and textural characteristics as well as the weathering of the rock. For this reason, the relationships between petrographic and physico-mechanical properties of fresh (peridotites) and serpentinized (serpentinites) ultrabasic rocks from central Greece, were investigated using correlation analysis. Thin sections, from the 47 samples, were prepared and examined under the polarizing microscope with the aim of describing the main mineralogical composition, the grain size, the serpentinization percentage and the structure of the rocks. The mineralogical and textural characteristics of some of them were also studied by X-ray diffraction analyses and the scanning electron microscope. The 47 samples were tested to determine dry and saturated unit weight, effective porosity, uniaxial compressive strength and static modulus of elasticity. The relationships between these properties and the petrographic characteristics are described by simple regression analyses. The research demonstrates that the physico-mechanical characteristics are strongly influenced by the petrographic characteristics except for mineral grain size. Negative linear correlations exist between serpentinization percentage and dry unit weight, while the effective porosity has a strong positive relationship with degree of serpentinization. Positive relationships are also obtained between the mechanical properties and dry unit weight and micropetrographic index I_{ps}, while the increase of effective porosity causes a decrease in the index I_{ps} (logarithmically in peridotites, and exponentially in serpentinites). The mechanical properties are exponentially related (negatively) to the serpentinization percentage in serpentinites and logarithmically (negatively) in peridotites. The serpentine plays a very important role in strength and elasticity modulus reduction, while the primary minerals have a smaller effect on the mechanical properties.

K. Diamantis (✉) · E. Gartzos · G. Migiros
Laboratory of Mineralogy-Geology, Division of Geological Science and Atmospheric Environment, Department of Sciences, Agricultural University of Athens, 75 Iera odos Street, 11855 Athens, Greece
e-mail: kostasdiam@aua.gr

Keywords Ultrabasic rocks · Quantitative petrography · Physico-mechanical properties · Correlations

Introduction

The physico-mechanical properties of rocks are the most important parameters in any geotechnical application and in the classification of rocks for engineering purposes. They are mainly influenced by the mineral composition, texture (size, shape and arrangement of mineral grains, nature of grain to grain contacts and degree of grain interlocking), degree of alteration, weathering and deformation of the source rock (Hartley 1974; Irfan and Dearman 1978; Shakoor and Bonelli 1991; Grönholm 1994; Haney and Shakoor 1994; Tugrul and Zarif 1999; Akesson et al. 2001; Lundqvist and Göran 2001; Miskovsky et al. 2004; Zorlu et al. 2004; Al-Oraimi et al. 2006; Pomonis et al. 2007; Tamrakar et al. 2007; Rigopoulos et al. 2010).

Owing to the fact that ophiolitic complexes have become important earth crust components in some areas like south-eastern Europe, they are used extensively as engineering materials and many works are constructed on/in them. Ophiolitic suite rocks represent remnants of the

Earth's oceanic crust and upper mantle and are fundamentally characterized by underlying ultrabasic rocks, which are covered by basic, hypabyssal and extrusive rocks. This succession is idealized and in most cases some members may be absent.

This research concentrates on ultrabasic rocks. They include a wide range of rock types (harzburgites, lherzolites, plagioclastic peridotites, dunites, etc.) which, due to ocean-floor metamorphism (serpentinization), lead to a modification of their petrographic characteristics (serpentinized varieties of them). Variations in mineralogical and textural characteristics as well as the serpentinization affect their physico-mechanical properties, which vary from excellent to fair, becoming poor to very poor when extensive alteration and/or intense deformation is present (Christensen 1966, 2004; Ramana et al. 1986; Escartin et al. 2001; Marinos et al. 2006; Diamantis 2010; Ozsoy et al. 2010).

The aim of this study is to quantify the relationships of the dry and saturated unit weight (γ_d, γ_s), effective porosity (n_e), uniaxial compressive strength (UCS) and static tangent modulus (E_{st}) with the petrographic characteristics (serpentinization percentage, mineral composition, grain size and the micro-petrographic index I_{ps}: ratio between primary and secondary minerals) of 33 serpentinite and 14 peridotite samples, taken from central Greece. Physico-mechanical tests were performed according to ISRM and ASTM specifications and petrographic characteristics were described from one polished thin section per sample using a polarizing microscope. Point counting was carried out to quantify the mineralogical data. Furthermore, X-ray diffractions (XRDs) were used to estimate the mineral composition, while textural characteristics were studied using scanning electron microscope (SEM).

Geological setting-tectonics

The study area is situated in central Greece and specifically in the Kallidromo and Othrys Mountains, consisting mainly of Alpine formations (Mountrakis et al. 1983; Katsikatsos et al. 1986). From bottom to top, the following formations can be distinguished (Marinos 1974; Ferriere 1982; Migiros 1990):

(a) A carbonate sequence of Triassic-Jurassic age which constitutes the basement of the area;
(b) A tectonic nappe, mainly ophiolitic (Katsikatsos et al. 1986), and
(c) An unconformable sequence of Cretaceous limestones, which passes upward to flysch.

The ophiolitic formations have thrusted over the Triassic-Jurassic carbonate sequence and belong to the Subpelagonian geotectonic unit consisting of volcano-sedimentary formations, basaltic lavas, basic rocks and ultrabasic masses. The present research focusses only on the ultrabasic rocks. They are comprised of harzburgites, lherzolites, plagioclastic peridotites and dunites which vary in their degrees of serpentinization.

According to Migiros (1990), the tectonic analysis of the geological formations exhibits the following prominent tectonic features in the ultrabasic rock masses:

(a) Schistosity: NW–SE direction and NE dip less than 30°.
(b) Low thrusts: E–W direction and N dip between 30° and 45°.
(c) Thrusts: NW–SE direction and NE dip between 45° and 60°.
(d) Faults: E–W, NW–SE, NE–SW directions and dips more than 60°.

Petrographic properties of ultrabasic rocks

The mineralogical and textural characteristics of the samples were studied, as described above, by optical microscopy, XRD and SEM analyses. Point counting under a polarizing microscope was used to determine grain size, grain shape and the modal composition. Approximately 300 equally distributed points were counted in each polished thin section. The mineralogical analysis results, the structure and the name of each rock type are given in Table 1.

Peridotites

The peridotites investigated are unserpentinized or slightly serpentinized (serpentinization <30 % by volume) ultrabasic rock types. They are mainly medium-grained homogeneous isotropic rocks and, in general, present a granular or porphyritic structure (Fig. 1a) and compact texture without preferred mineral orientation. In some samples, the structure is characterisized as porphyroclastic because both the crystals of olivine and orthopyroxene are broken in many pieces (Fig. 1b). Olivine, which is the main constituent of these rocks, ranges between 50 and 85 % (by volume). The orthopyroxene (mainly enstatite, Fig. 1a, b, d) varies from 4 % to 24 %, while opaque minerals (mainly chromite) are present in small amounts (1–3 %, by volume, Fig. 1b, c). The mentioned above minerals are characterized as primary (parent) minerals (Table 1). They are influenced by the serpentinization (low-temperature, metamorphic process) and transformed into secondary minerals. The secondary mineral constituents (Table 1)

Table 1 Mineralogical composition and structures of the ultrabasic rocks investigated (Diamantis 2010)

Sample no.	Name	Structure	Primary minerals					Secondary minerals				Degree of serpentinization β (%)
			Ol (%)	Opx (%)	Cpx (%)	Pl (%)	Sp (%)	Serp (%)	Chl (%)	Tc (%)	Act (%)	
KP05	LERZOLITH	PORPHYRITIC	50	11	12	–	1	22	2	1	1	26
KP09	LERZOLITH	PORPHYRITIC	72	11	4	–	2	9	1	–	1	11
OP02	HARTZBOURGITE	GRANULAR	67	4	–	–	2	21	5	–	1	27
OP04	HARTZBOURGITE	GRANULAR	70	9	–	–	–	16	3	2	–	21
OP06	HARTZBOURGITE	GRANULAR	71	14	–	–	–	12	2	1	–	15
OP07	HARTZBOURGITE	PORPHYRITIC	66	21	–	–	2	10	1	–	–	11
OP08	HARTZBOURGITE	PORPHYRITIC	60	14	–	–	–	22	2	1	1	26
OP09	DUNITE	GRANULAR	85	10	–	–	1	2	2	–	–	4
OP11	DUNITE	GRANULAR	79	12	–	–	–	8	1	–	–	9
OP12	PLAGIOCLASTIC LERZOLITH	PORPHYRITIC	55	24	5	2	3	10	1	–	–	11
OP15	LERZOLITH	PORPHYRITIC	74	19	3	–	–	3	1	–	–	4
OP17	HARTZBOURGITE	PORPHYRITIC	68	19	–	–	2	7	2	1	1	11
OP20	HARTZBOURGITE	PORPHYRITIC	73	15	–	–	–	8	1	2	1	12
OP24	HARTZBOURGITE	GRANULAR	75	21	–	–	1	3	–	–	–	3
KS01	SERPENTINITE	MESH	2	6	1	–	1	84	2	2	2	90
KS03	SERPENTINITE	MESH	4	8	2	–	1	76	3	5	1	85
KS05	SERPENTINITE	MESH	1	–	–	–	2	82	6	6	3	97
KS06	SERPENTINITE	MESH	4	7	1	–	2	74	6	3	3	86
KS08	SERPENTINITE	MESH	9	9	5	–	1	63	4	5	4	76
KS09	SERPENTINITE	MESH	6	–	–	–	2	83	4	3	2	92
KS10	SERPENTINITE	MESH	10	6	3	–	1	71	2	7	–	80
KS11	SERPENTINITE	MESH	10	7	11	–	2	62	7	1	–	70
KS12	SERPENTINITE	MESH	9	12	2	–	2	68	4	3	–	75
KS13	SERPENTINITE	MESH	17	12	–	–	–	68	2	1	–	71
KS16	SERPENTINITE	MESH	13	7	3	–	–	67	5	3	2	77
OS01	SERPENTINITE	MESH	5	10	–	–	1	76	2	5	1	84
OS02	SERPENTINITE	MESH	5	3	–	–	–	84	5	2	1	92
OS03	SERPENTINITE	MESH	9	5	–	–	1	77	4	4	–	85
OS05	SERPENTINITE	MESH	12	6	1	–	1	72	6	1	1	80
OS06	SERPENTINITE	MESH	11	7	1	–	4	66	4	5	2	77
OS08	SERPENTINITE	MESH	8	6	–	–	–	76	6	3	1	86
OS09	SERPENTINITE	MESH	7	6	–	–	–	79	7	1	–	87
OS11	SERPENTINITE	MESH	14	8	–	–	2	63	8	3	2	76
OS17	SERPENTINITE	MESH	8	5	–	–	–	79	5	2	1	87
OS21	SERPENTINITE	MESH	17	11	–	–	3	62	5	2	–	69
OS22	SERPENTINITE	MESH	5	8	–	–	1	78	6	2	–	86
OS23	SERPENTINITE	MESH	11	7	5	–	2	67	6	1	1	75
OS25	SERPENTINITE	MESH	8	11	7	–	1	66	4	2	1	73
OS28	SERPENTINITE	MESH	13	8	1	–	1	66	4	5	2	77
OS29	SERPENTINITE	MESH	12	9	–	–	–	72	6	1	–	79
OS30	SERPENTINITE	MESH	6	9	–	–	2	79	2	1	1	83
OS34	SERPENTINITE	MESH	13	8	–	–	1	68	5	4	1	78
OS36	SERPENTINITE	MESH	14	11	–	–	1	69	4	1	–	74
OS37	SERPENTINITE	MESH	9	10	2	–	1	72	4	2	–	78
OS38	SERPENTINITE	MESH	14	6	–	–	2	72	5	1	–	78
OS40	SERPENTINITE	MESH	4	9	–	–	–	75	8	4	–	87
OS42	SERPENTINITE	MESH	14	10	1	–	1	64	6	3	1	74

KP Peridotite of Kallidromo, *OP* Peridotite of Othrys, *KS* Serpentinite of Kallidromo, *OS* Srpentinite of Othrys, *Ol* Olivine, *Opx* Orthopyroxene, *Cpx* Clinopyroxene, *Pl* Plagioclase, *Sp* Spinel, *Serp* Serpentine, *Chl* Chlorite, *Tc* Talc, *Act* Actinolite

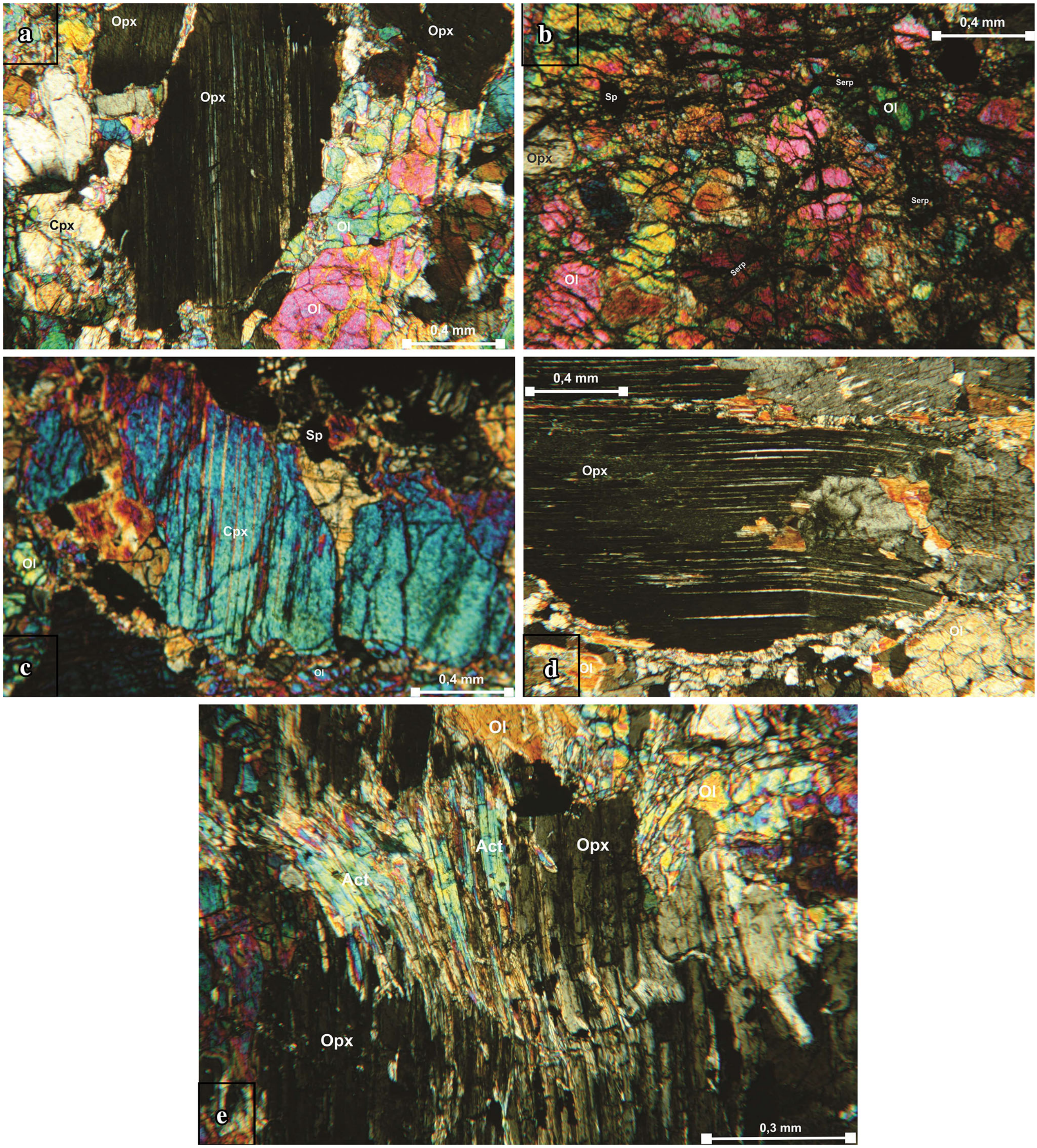

Fig. 1 **a–d** Peridotite with allotriomorphic olivines (Ol), phenocrysts of orhopyroxenes and clinopyroxenes (Opx, Cpx), opaque minerals (mainly chromite, Sp) and serpentines (Serp) in the fractures (corss Nicols). **e** orthopyroxene crystals are secondarily replaced by actinolite (Act)

are serpentine (2–22 % by volume), chlorite, talc and actinolite comprising up to 5 %. Using the classification system of Streckeisen (1976), these peridotites are classified as unserpentinized or slightly serpentinized harzburgites. In some samples, except for the above minerals, clinopyroxene phenocrysts (3–12 %) are present, while in sample OP12 collected from Othrys, subhedral to euhedral plagioclases (up to 2 %, by volume) are also found. According to the Streckeisen classification system (1976), these peridotites are characterized as lherzolite and plagioclastic lherzolite, respectively. Finally, when the percentage of olivine is

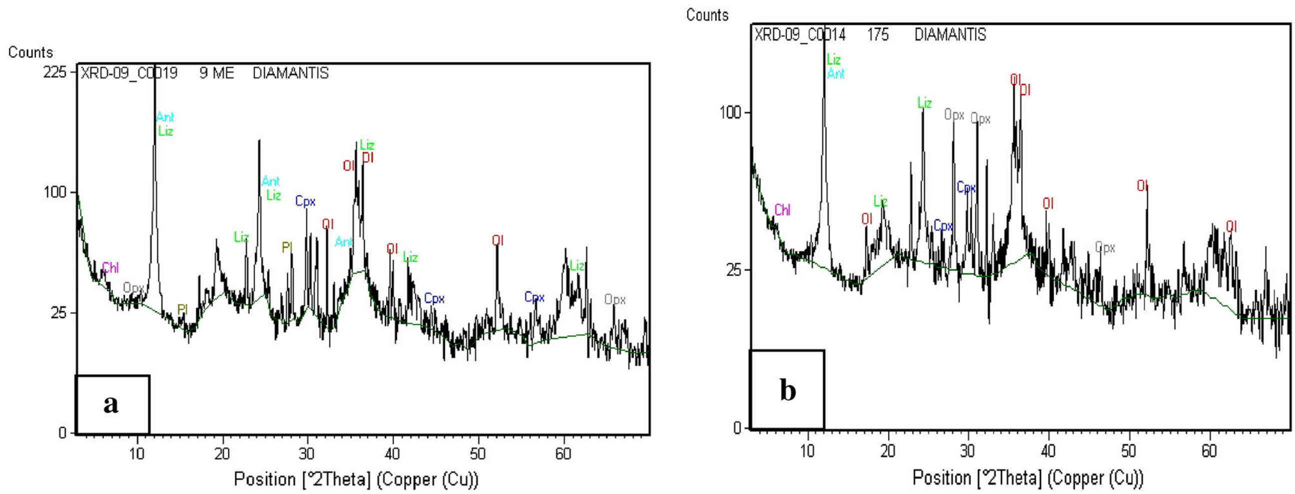

Fig. 2 **a**, **b** X-ray graphs show that serpentines, detected, are lizardite (Liz) and antigorite (Ant) and there are chlorite (Chl) and plagioclase (Pl)

higher than 90 %, then the rocks are classified as dunites (Table 1).

The olivine grains are mainly allotriomorphic (Fig. 1a–d), while sometimes they appear as neoblasts. Their size ranges from 0.3 to 0.8 mm, and they show intense microcracking and undulose extinction. The orthopyroxenes appear as porphyroclasts with the form of hypidiomorphic to allotriomorphic prisms and their mean size is 1.7 mm (varies from 0.6 to 2.8 mm, Fig. 1a, b, d). Most of them show exsolution lamellea of clinopyroxene (Fig. 1a, d). Plastic deformation is manifested by the undulose extinction and the deformation of the exsolution lamellea (Fig. 1d). Clinopyroxene porphyroclasts appear as hypidiomorphic prisms and their size is between 0.4 and 1.8 mm (Fig. 1a, c). The plagioclases (An-rich) appear as very small (<0.2 mm) allotriomorphic crystals between the grains of olivine, pyroxene and opaque minerals.

The olivine, as mentioned, is the first mineral that undergoes serpentinization. This alteration is mainly initiated along cracks in the olivine, but, as the process continues, the remaining olivine decreases. Serpentinization moves inwards to the centers of the grains often leaving concentric rings of serpentine around the grains which may represent pauses in the process. The orthopyroxenes then get serpentinized, while the clinopyroxenes are preserved in significant amounts, as they are less influenced by the serpentinization. The serpentinization of orthopyroxenes mainly occurs along the cracks and cleavage and progressively moves inwards. Thus, in a crystal which is not completely altered, the fresh orthopyroxene is in the centre. The alteration products, called bastites, often show zoning in thin sections with the central parts of the pseudomorph being in extinction at a different position to the edges. Some orthopyroxene and clinopyroxene crystals are secondarily replaced by talc, chlorite, and actinolite (uralitization, Fig. 1e).

The study of representative samples using X-ray Diffraction (XRD) shows that the serpentines are lizardite and antigorite (Fig. 2a, b) and that in most of the samples lizardite prevails. The X-ray analyses also show that in some samples basic plagioclases occur (Fig. 2a).

Serpentinites

As far as the serpentinites are concerned, they constitute the majority of the ultrabasic rocks and occur in both western Othry and in Kallidromo. They are mainly composed of secondary minerals (69–97 %, by volume), while the presence of the primary (parent) minerals is limited to <30 %. Serpentine is the dominant (secondary) mineral phase (62–84 %, Table 1, Diamantis 2010) and is usually found in the form of antigorite or lizardite (leaf form, *SEM*-Fig. 3a), while fibrous structures like chrysotile are absent. Other ocean-floor metamorphic products are chlorite, actinolite, and talc (Fig. 3b). The serpentinites are mainly fine-grained (they form fine-grained matrix grains), dark green coloured, isotropic, homogeneous rocks and show mesh structures (Fig. 3c, d), while in some cases, an interpenetrating structure is observed without any preferred orientation of serpentine minerals (Fig. 3a, e, SEM). The hour-glass shape is scarce, and where they do appear, they are not well developed. The polygonal-shaped cells are mainly generated by serpentinized olivine grains, so in some samples in the center of the cell, a residual olivine crystal is observed (Fig. 3c–e). The involvement of the residual mineral phases in the paragenesis is important for the determination of the protoliths of serpentinites. The length of serpentines is <0.3 mm, while their thicknss and width are <0.015 and <0.05 mm, respectively.

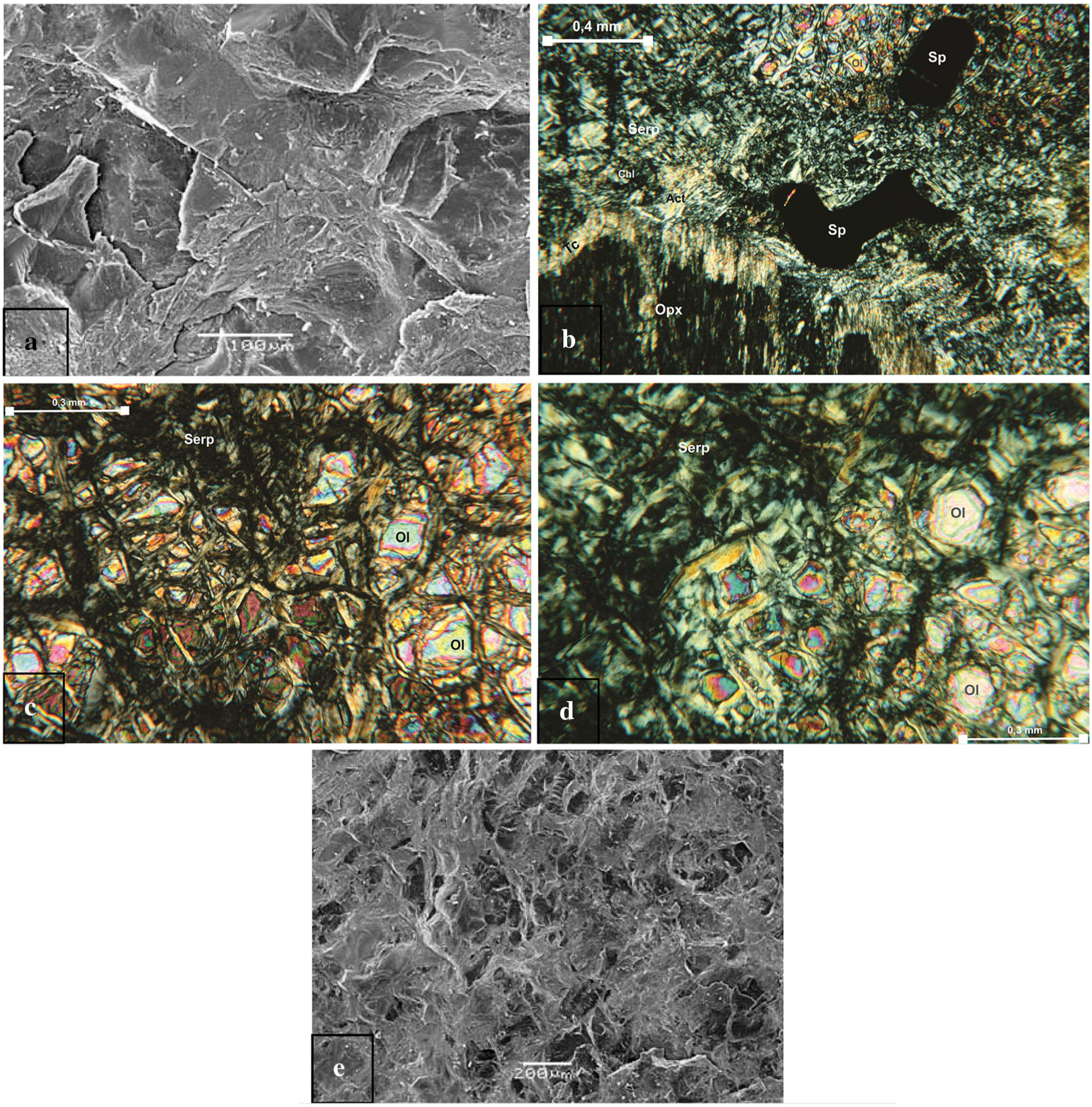

Fig. 3 **a** Leaf form of serpentine (SEM), **b** participation of chlorite, actinolite, and talc in serpentinites, **c**–**e** mesh structure (residual olivine crystals)

The values of serpentinization percentage are given in Table 1.

Physical and mechanical properties of ultrabasic rocks

Physical properties

A variety of laboratory tests was used to obtain physical indices expressing the characteristics of ultrabasic samples. The rock blocks were cored to give cylindrical test specimens and the dry (γ_d) and saturated unit weight (γ_s), as well as the effective porosity (n_e) were determined using the following functions (ISRM 2007):

$$\gamma_{\mathrm{d}} = \frac{W_d}{V_t}\frac{M_s * g}{(M_{\mathrm{sat}} - M_{\mathrm{sub}})/\rho_{\mathrm{w}}}\mathrm{kN/m^3}, \quad (1)$$

$$\gamma_{\mathrm{sat}} = \frac{W_{\mathrm{sat}}}{V_t}\frac{M_{\mathrm{sat}} * g}{(M_{\mathrm{sat}} - M_{\mathrm{sub}})/\rho_{\mathrm{w}}}\mathrm{kN/m^3}, \quad (2)$$

Table 2 Dry, saturated unit weight and effective porosity values using saturation and buoyancy techniques

Sample no.	Dry unit weight, γ_d (kN/m^3)	Saturated unit weight, γ_s (kN/m^3)	Effective Porosity, n_e (%)
KP05	30.86	30.88	0.26
KP09	32.21	32.22	0.13
OP02	30.99	31.01	0.23
OP04	31.28	31.30	0.20
OP06	31.91	31.93	0.17
OP07	32.13	32.15	0.14
OP08	30.95	30.97	0.24
OP09	32.82	32.83	0.08
OP11	32.43	32.44	0.14
OP12	32.41	32.43	0.14
OP15	33.07	33.07	0.07
OP17	32.45	32.46	0.10
OP20	32.17	32.19	0.18
OP24	33.27	33.28	0.08
KS01	25.70	25.83	1.34
KS03	25.52	25.75	2.35
KS05	24.53	25.00	4.74
KS06	25.63	25.85	2.23
KS08	26.20	26.27	0.64
KS09	25.49	25.71	2.25
KS10	26.12	26.19	0.75
KS11	26.79	26.83	0.39
KS12	26.00	26.04	0.44
KS13	26.48	26.52	0.43
KS16	25.86	25.91	0.56
OS01	25.73	25.79	0.59
OS02	24.95	25.30	3.59
OS03	25.44	25.63	1.92
OS05	25.87	25.99	1.25
OS06	26.57	26.65	0.81
OS08	25.08	25.31	2.36
OS09	25.37	25.59	2.29
OS11	26.49	26.55	0.56
OS17	25.18	25.42	2.45
OS21	26.72	26.76	0.40
OS22	25.17	25.45	2.86
OS23	26.33	26.36	0.39
OS25	26.60	26.65	0.51
OS28	26.42	26.46	0.44
OS29	25.84	25.90	0.67
OS30	25.61	25.77	1.60
OS34	25.93	26.05	1.26
OS36	26.35	26.40	0.53
OS37	26.00	26.04	0.47
OS38	25.98	26.04	0.59
OS40	25.04	25.38	3.43
OS42	26.25	26.30	0.52

$$n_e = \frac{V_v}{V_t} \frac{(M_{sat} - M_s)/\rho_w}{(\mathrm{M}_{sat} - M_{sub})/\rho_w} \%, \quad (3)$$

where, W_d, is the dry weight of the specimen (kN/m^3), W_{sat}, is the saturated weight of the specimen (kN/m^3), V_t, is the total volume of the specimen (m^3), V_v, is the volume of the voids (m^3), M_s, is the dry mass of the specimen (gr), M_{sat}, is the saturated mass of the specimen (dry on the surface, gr), M_{sub}, is the submerged mass of the specimen (gr), g is the gravitational acceleration (m/s^2), ρ_w, is the density of water (gr/cm^3).

At least three tests were carried out on each sample for each property and the average values were then obtained (Table 2). As shown, the total volume was obtained from saturation and buoyancy techniques and not from the measurements of their dimensions.

The dry and saturated unit weight (γ_d, γ_s) range from 24.53 to 26.79 and from 25.00 to 26.83, respectively, in serpentinites, while in the peridotites γ_d and γ_s vary between 30.86 and 33.27 and between 30.88 and 33.28, respectively (Tables 2, 3). In general, it is commonly known that unit weight is related to the mineralogical and textural characteristics of the rocks. Serpentinites are mainly composed of minerals (secondary) that have smaller specific gravities than those of peridotites, and, thus, serpentinites show lower values of unit weight than peridotites. The effective porosity varies from 0.39 % to 4.74 % in serpentinites and between 0.07 % and 0.26 % in peridotites. Porosity is an important factor in rock strength, since a small change in pore volume can have an appreciable effect on the mechanical properties. The ranges, the mean values and the standard deviations of the mentioned above properties for serpentinites and peridotites are given in Table 3. The big differences in unit weight and porosity values between serpentinites and peridotites are due to their different degress of serpentinization .

Mechanical properties

The mechanical properties of the ultrabasic rocks were determined by a variety of laboratory tests. The uniaxial compressive strength (UCS) of the ultrabasic rocks was determined using a uniaxial compression testing machine in accordance with ASTM (1986), while the static tangent modulus (E_{st}) was determined using stain gauges. Samples cored for these properties had length/diameter ratios of 2–2.5 (ASTM 2001). Test results obtained for this range do not suffer from sample size effects (Hoek and Brown 1980; Hawkins 1998). The cylindrical rock specimens' diameters ranged between 53 and 55 mm. The specimens were inspected macroscopically and only the isotropic, homogeneous, unweathered (or slightly weathered) ultrabasic rocks free of visible joints were considered. The UCS was

Table 3 Statistical analysis of physical properties and serpentinization percentage

	Range	Maximum value	Minimum value	Mean value	Standard Deviation
Peridotites					
Dry unit weight, γ_d (kN/m^3)	2.41	33.27	30.86	32.07	0.78
Saturated unit weight, γ_s (kN/m^3)	2.39	33.28	30.88	32.08	0.78
Effective porosity, n_e (%)	0.19	0.26	0.07	0.15	0.06
Degree of serpentinization, β (%)	24	27	3	14	8
Serpentinites					
Dry unit weight, γ_d (kN/m^3)	2.26	26.79	24.53	25.86	0.57
Saturated unit weight, γ_s (kN/m^3)	1.84	26.83	25.00	25.99	0.47
Effective porosity, n_e (%)	4.35	4.74	0.39	1.38	1.14
Degree of serpentinization, β (%)	28	97	69	81	7

measured by axial loading of specimens, while the static tangent modulus was derived from the slope of the stress–strain curves. Fractures created by the tests did not follow internal discontinuities and were always fresh. The mechanical tests were carried out in dry conditions for a better correlation of the results.

The UCS values vary from 19.21 to 125.73 MPa in serpentinites and from 79.31 to 241.56 MPa in peridotites (Tables 4, 5, Diamantis et al. 2009; Diamantis 2010) exhibiting a large variation. In general, peridotites are stronger than serpentinites (Table 4). This big difference may be attributed to the different degrees of serpentinization and/or to the internal fractures/cracks, macroscopically undetected and/or petrographic variety and/or the structural complexity of ultrabasic rocks. Peridotites present greater variations (standard deviation, Table 5) than serpentinites because according to Escartin et al. (2001) and Shimada et al. (1983) small amounts (>9 %) of lizardite and chrysotile reduce the strength of the unaltered peridotite by more than a factor of two. Thus, the strength of these peridotites is similar to that of pure oceanic serpentinites. The strength of peridotite, which contains <9 % of a serpentine phase, is intermediate between that of pure serpentinite and unaltered peridotite. In accordance with ISRM (1981), the majority of peridotites are characterized as rocks with very high strength, while the majority of serpentinites range in strength between 50 and 100 MPa (rocks with high strength). The mean value for peridotites is 138.94 MPa, while for serpentinites the mean is 64.06 MPa. The mean value for both of them is 86.37 MPa. Similar values were given by several authors: Rao and Ramana (1974) found that for highly serpentinized peridotites and under a confining pressure of 75 MPa, the UCS values vary between 70.5 and 156.2 MPa. According to Koumantakis (1982), for slightly, moderately and highly serpentinised peridotites, the mean value of UCS was 95.44 MPa.

The E_{st} varies from 5.2 to 27.8GPa in serpentinites and between 29.1 and 69.3 GPa in peridotites (Tables 4, 5). The modulus ratio (MR) was calculated as the ratio of tangent modulus to uniaxial compressive strength and ranges between 180 and 413 in serpentinites and from 264 to 403 in peridotites. Deere and Miller (1966) classificated rocks into three categories: (a) High Ratio, (b) Medium Ratio and (c) Low Ratio. The values of MR for the rocks studied are illustrated in Fig. 4 using the diagram of Deere and Miller (1966).

From Fig. 4 it is obvious that the peridotites all plot in the Medium Ratio Zone (*M*), while serpentinites mainly plot in the lower portion of the Medium Ratio Zone (*M*) with a few results in the Low Ratio Zone (*L*). The results are reasonable because, according to Deere and Miller (1966), igneous rocks plot in the Medium Ratio Zone. The values, which plot in the Low Ration Zone, indicate that these serpentinite samples may not be homogeneous and isotropic.

Correlations of petrographic characteristics with physical and mechanical properties

Simple regression analyses with confidence limits of 95 % were applied to check whether petrographic variables could significantly explain the physical and mechanical properties. Selected petrographic, physical and mechanical properties were plotted against each other in order to predict one parameter from another. The equations of the best fit curves (e.g., linear, logarithmic, exponential, power) and the coefficients of determination (R^2) were calculated by the "least squares" method.

In order to determine the influence of the petrographical characteristics on the engineering properties, correlations were attempted between the serpentinization (β), the percentages of minerals, their grain size, the micro-petrographic index (I_{ps}) and the physico-mechanical properties.

Some researchers (Christensen 1966, 2004; Escartin et al. 2001; Diamantis 2010, Rigopoulos et al. 2010) have studied the relationships between the degree of

Table 4 Uniaxial compressive strength, static tangent modulus and modulus ratio values

Sample no.	Uniaxial compressive strength, UCS (MPa)	Static tangent modulus, E_{st} (GPa)	Modulus ratio (MR)
KP05	84.98	31.3	368
KP09	107.75	34.7	322
OP02	135.61	41.0	302
OP04	122.85	35.6	290
OP06	136.34	36.0	264
OP07	172.35	60.1	349
OP08	79.31	29.6	373
OP09	188.82	63.1	334
OP11	148.89	43.9	295
OP12	105.43	42.5	403
OP15	205.39	66.3	323
OP17	123.58	32.6	264
OP20	92.35	29.1	315
OP24	241.56	69.3	287
KS01	28.94	7.5	260
KS03	31.25	8.0	255
KS05	19.21	7.9	413
KS06	41.72	12.0	287
KS08	76.73	17.4	227
KS09	23.07	5.2	227
KS10	79.83	17.6	221
KS11	112.91	20.4	181
KS12	79.77	19.0	238
KS13	96.40	22.8	236
KS16	76.17	16.9	222
OS01	77.74	14.0	181
OS02	32.12	9.6	299
OS03	45.59	8.7	191
OS05	51.98	9.6	184
OS06	58.90	13.8	234
OS08	37.63	8.1	216
OS09	47.80	10.7	224
OS11	75.48	16.8	222
OS17	43.80	8.8	202
OS21	125.73	27.8	221
OS22	44.31	8.0	180
OS23	79.96	14.9	186
OS25	78.61	16.9	215
OS28	82.96	17.1	206
OS29	69.85	18.3	261
OS30	52.14	11.2	215
OS34	72.49	14.7	203
OS36	90.28	22.1	245
OS37	79.48	15.0	189
OS38	70.41	17.2	244
OS40	25.14	6.4	255
OS42	105.68	26.1	247

serpentinization and physical characteristics and have concluded that these properties are closely related. Unit weight decreases with increasing serpentinization, while effective porosity decreases with the reduced low-temperature metamorphic process.

In this paper, an attempt to correlate degree of serpentinization with physical characteristics is presented in Fig. 5. The dry unit weight decreases linearly as the serpentinization increases, while the increase of secondary minerals increases the effective porosity (exponentially in serpentinites, linearly in peridotites). The empirical equations and the determination coefficients (R-square) are given in the same figures. Both of these functions give strong correlations.

The uniaxial compressive strength (UCS) and the static tangent modulus (E_{st}) are two of the most fundamental engineering parameters, but they require a large number of high quality core samples and use of expensive laboratory equipment. Thus, indirect, simpler, faster and more economical tests are usually used to estimate UCS and E_{st}. For this reason, in this study, empirical equations have been investigated to correlate the uniaxial compressive strength and the static tangent modulus with petrographic parameters. The relationship between the percentage of secondary minerals (serpentinization) and the uniaxial compressive strength is given in Fig. 6a, b. As can be seen in this figure, the secondary minerals play a very important role in strength reduction. The regression line representing the best fit between UCS and β is logarithmic for peridotites ($R^2 = 0.69$) and exponential ($R^2 = 0.87$) for serpentinites. The estimated UCS using the β values can be expressed by the empirical equations:

$$\mathrm{UCS} = -56.06\mathrm{Ln}(\beta) + 273.93 \quad \text{for peridotites,} \tag{4}$$

$$\mathrm{UCS} = 10989\exp^{-0.065\beta} \quad \text{for serpentinites.} \tag{5}$$

Serpentinites present higher determination coefficients than peridotites because as above-mentioned, small amounts (>9 %) of serpentine reduce the strength of the unaltered peridotite by more than a factor of two. So the strength values of these peridotites are much lower than those of unaltered peridotites.

Similar correlations have been obtained by Rao and Ramana (1974), Koumantakis (1982), Escartin et al. (2001) and Diamantis et al. (2009) studied the mentioned above parameters.

The plots of the E_{st} values as a function of serpentinization percentage values are also shown in Fig. 6c, d. The logarithmic trend seems to fit better ($R^2 = 0.68$) the β with the E_{st} in peridotites, while the same relationship is better described by the exponential equation in serpentinites

Table 5 Statistical analysis of mechanical properties

	Range	Maximum value	Minimum value	Mean value	Standard deviation
Peridotites					
Uniaxial Compressive Strength, UCS (MPa)	162.25	241.56	79.31	138.94	47.96
Static tangent modulus, E_{st} (GPa)	40.2	69.3	29.1	43.9	14.5
Modulus ratio (MR)	139	403	264	321	41
Serpentinites					
Uniaxial compressive strength, UCS (MPa)	106.53	125.73	19.21	64.06	27.06
Static tangent modulus, E_{st} (GPa)	22.6	27.8	5.2	14.3	5.8
Modulus ratio (MR)	233	413	180	230	44

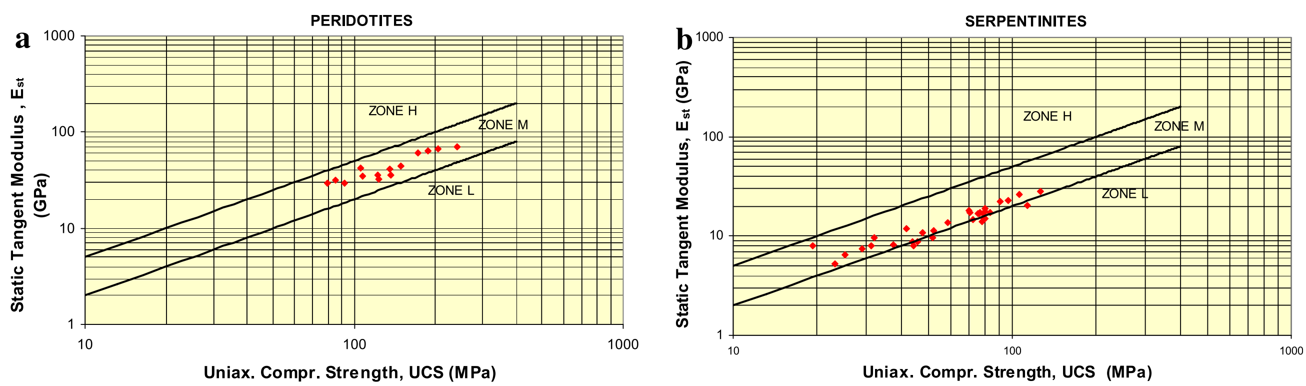

Fig. 4 **a**, **b** The results of this study plotted on the Deere and Miller diagram for peridotites and serpentinites, respectively

($R^2 = 0.78$). The determined correlations are described by the functions:

$$E_{st} = -16.71\text{Ln}(\beta) + 84.18 \quad \text{for peridotites,} \tag{6}$$

$$E_{st} = 1060\exp^{-0.0544\beta} \quad \text{for serpentinites.} \tag{7}$$

The correlations of the physico-mechanical parameters with (a) mineral percentage and (b) grain size were also determined. The relation between the percentage of the main minerals (serpentine, olivine, ortho and clinopyroxene, etc.) and the physico-mechanical properties is illustrated in Fig. 7. As is commonly known, dry unit weight is negatively affected (Fig. 7a, b) by an increase in serpentine (decrease of primary minerals), while a decrease in serpentine, evidently decreases the effective porosity (Fig. 7c, d). Moreover, in the majority of samples, serpentine has a very important role in strength and elasticity modulus reduction, while the primary minerals have a smaller effect on the mechanical properties (Fig. 7e–h). Serpentine is softer and results in lower strength and elasticity modulus values than the primary minerals.

The graphs of the test result values between the serpentine percentage and the physico-mechanical properties are illustrated in Fig. 8. The serpentine percentage and the γ_d are better related by a positive linear function (Fig. 8a, $R^2 = 0.96$) in peridotites and by a logarithmic equation in serpentinites (Fig. 8b, $R^2 = 0.74$). The functions of the two regression lines are:

$$\gamma_d = -0.11\text{Serp} + 33.28 \quad \text{for peridotites,} \tag{8}$$

$$\gamma_d = -5.30\text{Ln}(\text{Serp}) + 48.49 \quad \text{for serpentinites.} \tag{9}$$

The regression lines representing the best fit between serpentine percentage and effective porosity are linear in peridotites and exponential in serpentinites (Fig. 8c, d). The estimated n_e using the serpentine percentage can be expressed by the empirical equations:

$$n_e = 0.009\text{Serp} + 0.059\ \left(R^2 = 0.93\right) \quad \text{for peridotites,} \tag{10}$$

$$n_e = 0.001\exp^{0.0965\text{Serp}}\left(R^2 = 0.66\right) \quad \text{for serpentinites.} \tag{11}$$

From Fig. 8c, d and the above functions, it is obvious that the n_e is less influenced by the serpentine percentage in serpentinites than in peridotites.

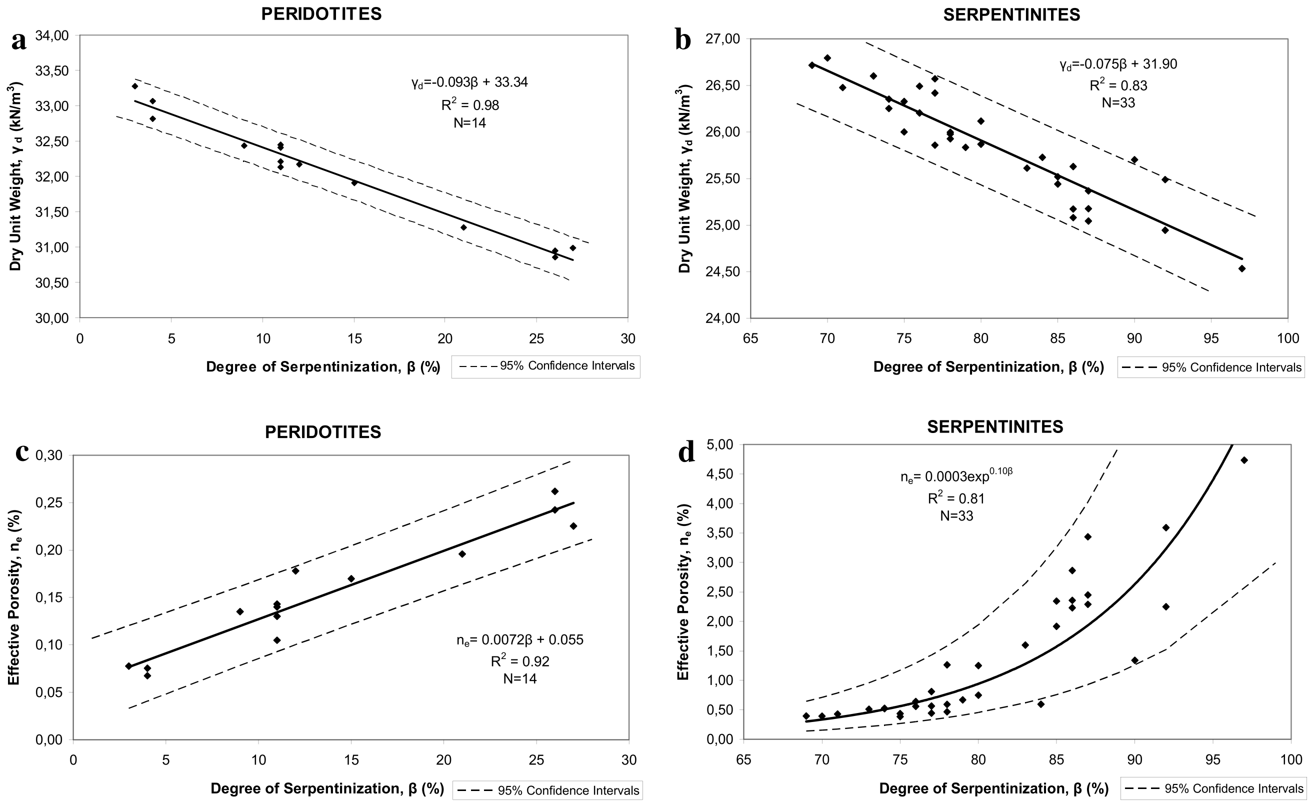

Fig. 5 Variation of serpentinization degree versus physical properties

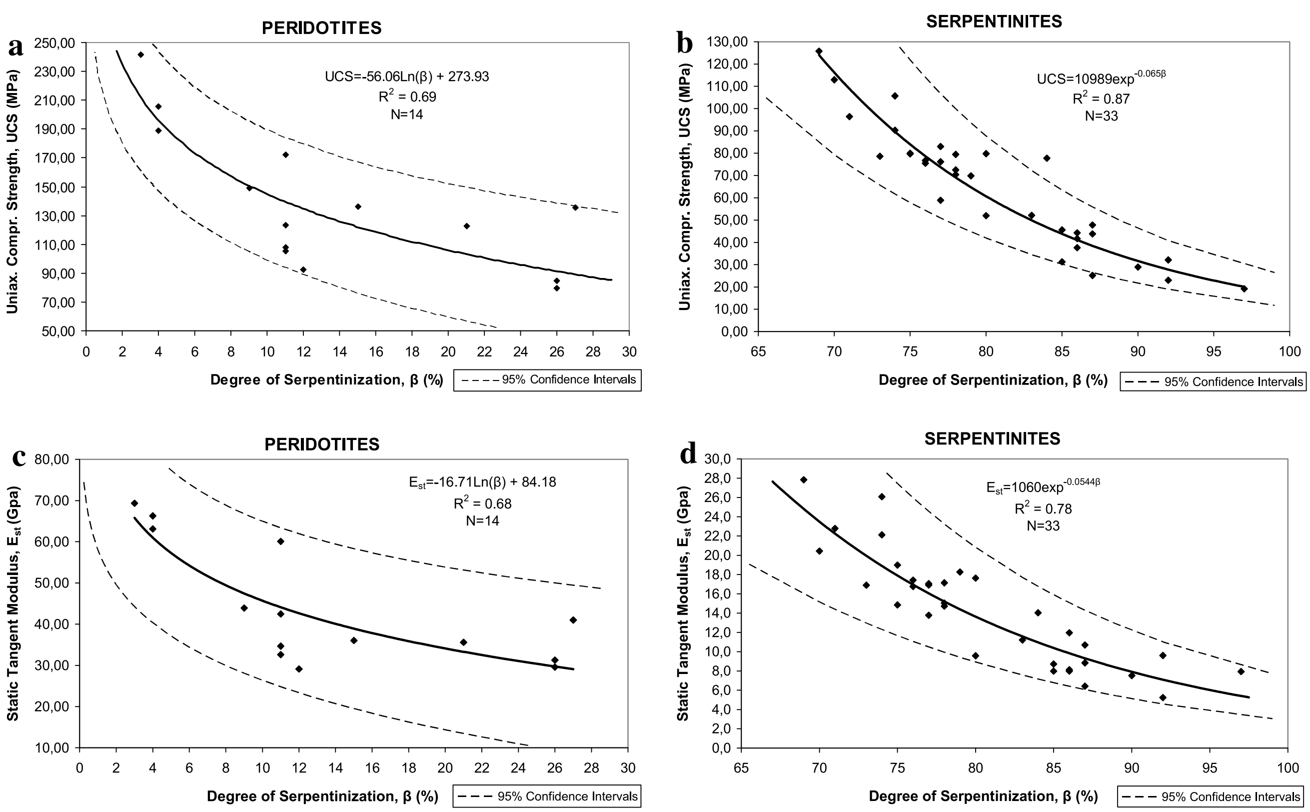

Fig. 6 Correlation between serpentinization and mechanical properties

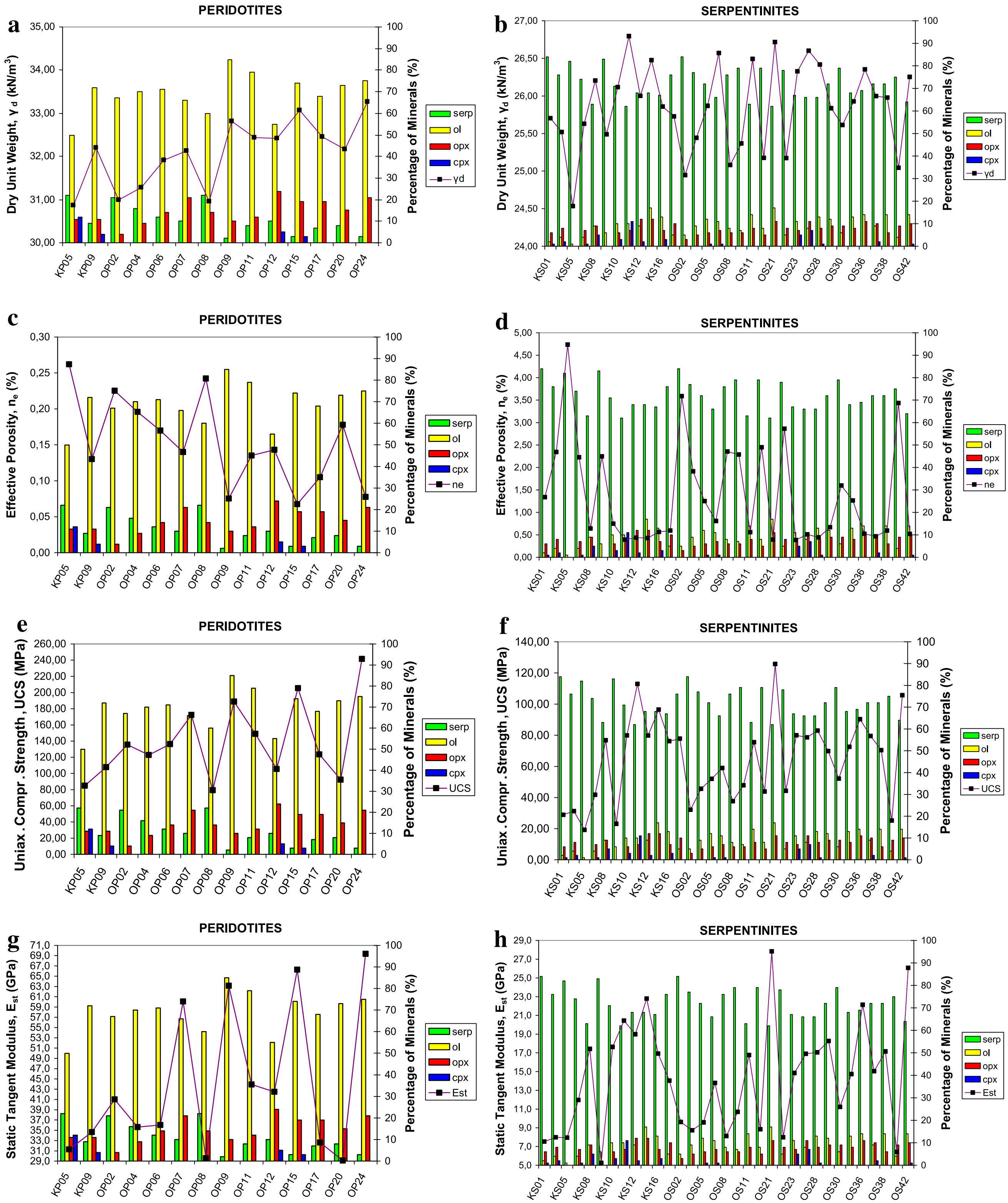

Fig. 7 *Bar chart* showing the relationship between the percentage of minerals and the physicomechanical characteristics

Strong positive correlations of quartz content with (a) compressive strength and (b) dry unit weight have been obtained by Gunsallus and Kulhawy (1984), Tugrul and Zarif (1999), while some authors (Pomonis et al. 2007; Zorlu et al. 2004; Tamrakar et al. 2007) have suggested an inverse relationship between quartz content and effective porosity.

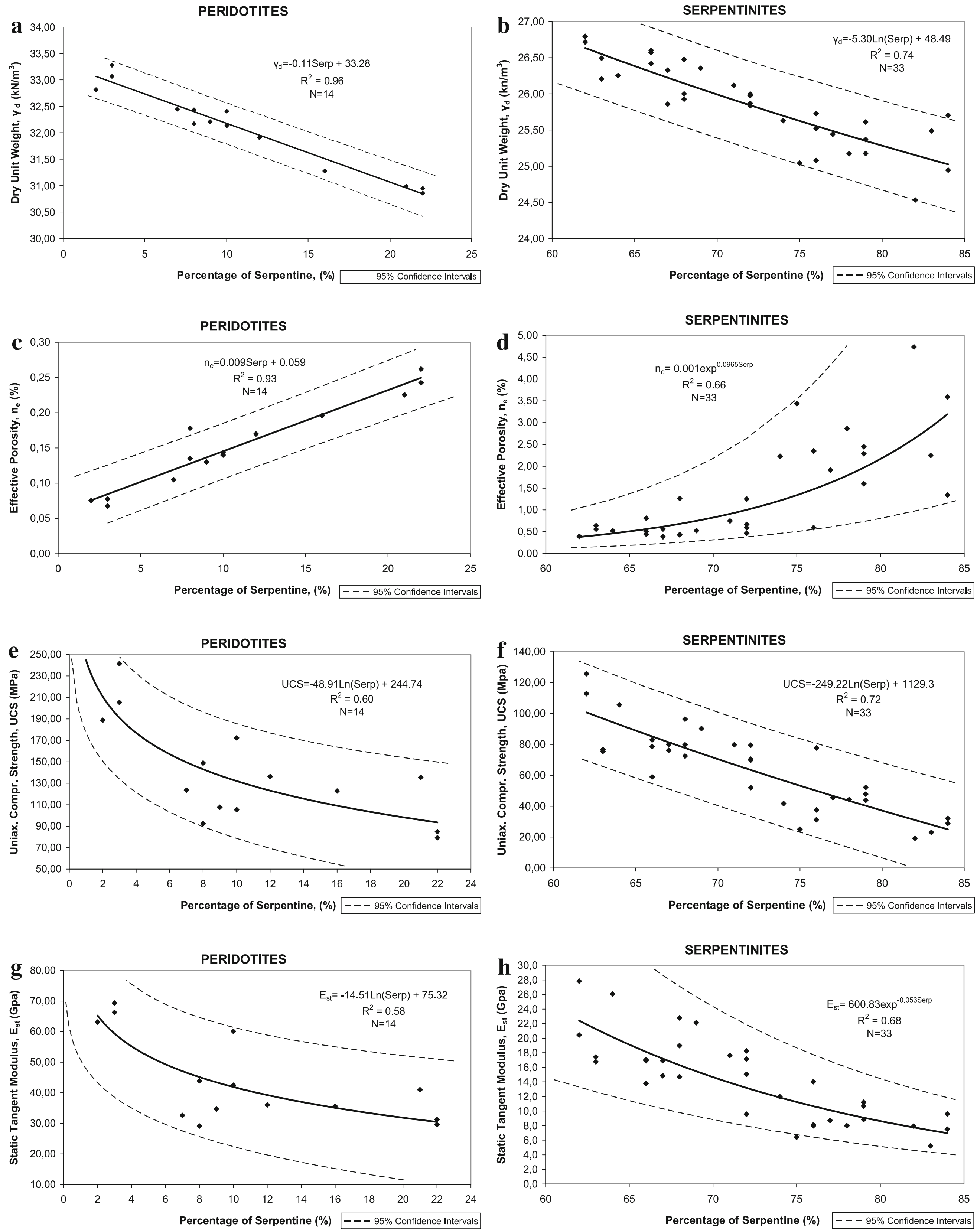

Fig. 8 Relationship of serpentine percentage with physicomechanical properties

Table 6 Regression equations and determination coefficients (R^2)

Parameters to be related	Rocks	Regression Equations	RR^2
Uniax. compr. strength and serpentine percentage	Peridotites	UCS = −48.91Ln(Serp) + 244.74	0.60
	Serpentinites	UCS = −249.22Ln(Serp) + 1,129.3	0.72
Static tangent modulus and serpentine percentage	Peridotites	E_{st} = − 14.51Ln(Serp) + 75.32	0.58
	Serpentinites	$E_{st} = 600.83\exp^{-0.053\mathrm{Serp}}$	0.68

The UCS and E_{st} decrease logarithmically with the increase of serpentine percentage in peridotites (Fig. 8e, g) while in serpentinites the relationships of serpentine percentage with UCS and E_{st} are logarithmic (Fig. 8f) and exponential, respectively (Fig. 8h). The determination coefficients are not very high (Table 6) indicating that the serpentine percentage does not influence the mechanical properties as significantly as the other above-mentioned petrographic characteristics.

Several investigators have studied the effect of grain size on the mechanical properties of rock. In general, the strength and elasticity modulus of rocks are greater for fine-grained than coarse-grained rocks (Brace 1961). Onodera and Asoka Kumara (1980) and Tugrul and Zarif (1999) reported that the strength decreased significantly as the grain size increased in igneous rocks. They determined a linear relationship between the grain size and strength, that is, as the grain size of the granite decreased, the strength increased.

In this study, an attempt has been made to correlate the maximum grain size (Table 7) with UCS and E_{st}. As shown in Figs. 9, 10, there is a very poor relationship between strength and the static tangent modulus with mineral size (except clinopyroxene) in peridotites, while in serpentinites, there is no correlation between these characteristics. This means that in ultrabasic rocks, the mechanical properties are much more affected by the other petrographic parameters than the mineral size and the low-temperature metamorphic process plays the greatest role. Only the correlations of clinopyroxene size with the UCS and E_{st} (in peridotites) presents high determination coefficients ($R^2 = 0.77$ and $R^2 = 0.88$, respectively). That may be due to clinopyroxenes that are less influenced by the serpentinization than the other primary minerals. The logarithmic trends describe better the correlation between the above-mentioned parameters and the functions of the two regression lines are:

$$\mathrm{UCS} = -73.98\mathrm{Ln}(\mathrm{Cpx}) + 114.98 \quad \text{for peridotites,} \tag{12}$$

$$E_{st} = -23.03\mathrm{Ln}(\mathrm{Cpx}) + 40.28 \quad \text{for peridotites.} \tag{13}$$

We cannot be absolutely based on the above-mentioned equations because we have only four points. Additional data may result in similar trends as other minerals.

Onodera and Asoka Kumara (1980) and Tugrul and Zarif (1999), as mentioned above, suggested strong inverse equations between grain size and strength because they examined granite samples, which as is commonly known, do not undergo the phenomenon of serpentinization.

Particular emphasis was also given to the degree of dependence between the micropetrographic index I_{ps} (ratio between primary and secondary minerals) and the physical and mechanical parameters of the studied samples. The I_{ps} forms good to strong correlations with almost all the engineering parameters ($R^2 = 0.74$–0.94). As can be seen in Fig. 11a, b, significant negative correlations (logarithmic in peridotites and exponential in serpentinites) exist between the micropetrographic index and effective porosity, indicating that with increase of the I_{ps}, the voids decrease according to the following equations:

$$n_e = -0.073\mathrm{Ln}(\mathrm{I_{ps}}) + 0.30 \quad \text{for peridotites,} \tag{14}$$

$$n_e = 5.37\exp^{-6.73\,\mathrm{I_{ps}}} \quad \text{for sepentinites.} \tag{15}$$

As it is illustrated in Fig. 11c, d, the dry unit weight presents visible correlations with the micropetrographic index. The γ_d increases logarithmically with the increase of I_{ps} in peridotites, while the same relationship in serpentinites is better described by a linear equation. The logarithmic function presents a higher determination coefficient ($R^2 = 0.94$) than the linear trend ($R^2 = 0.84$). Moreover, the plots of the mechanical properties as a function of the micropetrographic index are shown in Fig. 11e–h. The estimated empirical equations indicate linear correlations among these variables except for the relation between E_{st} and I_{ps} in serpentinites which is obviously expressed by an exponential function. The empirical equations and the determination coefficients (R^2) of the mentioned above relations are given in Table 8. Rigopoulos et al. (2010) suggested strong inverse equations between I_{ps} and UCS.

As shown in Fig. 11, the relationship between the physical characteristics and the micropetrographic index presents better correlation in peridotites than in serpentinites, while the mechanical properties with the I_{ps} are better correlated in serpentinites than in peridotites. That happens because as mentioned above, small amounts (>9 %) of serpentine reduce the strength and elasticity modulus of the unaltered peridotite by more than a factor of two. So the strength and static tangent modulus values in peridotites are much lower than those of unaltered peridotites.

Table 7 Grain size of minerals

Sample no.	Primary minerals					Secondary minerals			
	Ol (mm)	Opx (mm)	Cpx (mm)	Pl (mm)	Sp (mm)	Serp (mm)	Chl (mm)	Tc (mm)	Act (mm)
KP05	0.1–0.4	0.9–1.5	1.2–1.8	–	0.2–0.3	<0.15	0.1–0.3	<0.1	<0.1
KP09	0.02–0.3	1.1–2.8	0.6–1.1	–	0.1–0.2	<0.2	<0.2	–	<0.1
OP02	0.1–0.5	0.6–0.8	–	–	0.1–0.4	0.05–0.3	<0.2	–	<0.2
OP04	0.1–0.6	0.5–0.9	–	–	–	0.05–0.3	<0.2	<0.2	–
OP06	0.05–0.6	0.4–0.9	–	–	–	<0.2	<0.1	<0.1	–
OP07	0.1–0.7	0.5–1.0	–	–	0.2–0.3	<0.2	<0.1	–	–
OP08	0.1–0.5	0.8–1.6	–	–	–	<0.3	<0.2	<0.1	<0.1
OP09	0.1–0.3	0.3–0.7	–	–	0.2–0.5	<0.1	<0.3	–	–
OP11	0.02–0.7	0.3–0.7	–	–	–	<0.2	<0.3	–	–
OP12	0.1–0.4	0.4–0.6	0.4–0.7	0.2	0.3–0.4	<0.2	<0.2	–	–
OP15	0.02–0.6	0.8–1.5	0.3–0.4	–	–	<0.3	<0.2	–	–
OP17	0.03–0.7	1.4–1.9	–	–	0.2–0.4	<0.2	<0.2	<0.1	<0.2
OP20	0.02–0.8	1.5–2.1	–	–	–	<0.3	<0.2	<0.1	<0.1
OP24	0.03–0.4	0.3–0.6	–	–	0.2–0.5	<0.1	<0.1	–	–
KS01	<0.2	0.9–1.6	0.4–0.6		0.2–0.3	<0.15	0.05–0.3	<0.2	<0.1
KS03	<0.2	1.3–2.7	0.6–0.8		0.3–0.4	<0.2	0.1–0.9	<0.2	<0.1
KS05	<0.1	–	–		0.2–0.3	<0.15	<0.2	<0.1	<0.2
KS06	<0.1	0.7–1.3	0.4–0.6		0.3–0.4	<0.2	<0.1	<0.2	<0.1
KS08	<0.1	0.8–1.1	0.4–0.7		<0.2	<0.15	0.05–0.3	<0.1	0.06–0.3
KS09	<0.1	–	–		0.1–0.3	<0.2	0.03–0.3	0.05–0.3	<0.2
KS10	<0.1	0.7–1.6	0.5–0.8		0.1–0.3	<0.2	<0.2	<0.2	–
KS11	<0.1	0.3–0.7	0.5–0.6		0.1–0.3	<0.1	<0.1	<0.1	–
KS12	<0.2	0.5–0.8	1.1–1.5		0.1–0.3	<0.1	<0.2	<0.1	–
KS13	<0.2	1.4–2.2	–		–	<0.2	<0.1	<0.1	–
KS16	<0.2	0.8–1.3	0.9–1.1		–	<0.2	<0.15	<0.1	<0.2
OS01	<0.1	1.4–1.7	–		0.4–0.6	<0.1	0.05–0.4	<0.1	<0.2
OS02	<0.1	0.9–1.2	–		–	<0.1	<0.2	<0.1	<0.2
OS03	0.02–0.3	1.0–1.5	–		0.2–0.4	<0.15	0.04–0.3	<0.2	–
OS05	0.05–0.3	1.3–1.8	0.6–0.9		0.2–0.6	0.05–0.3	<0.2	<0.2	0.03–0.3
OS06	0.03–0.3	0.6–0.9	0.8–1.0		0.1–0.3	0.05–0.3	0.06–0.4	<0.2	<0.1
OS08	0.02–0.4	1.4–2.0	–		–	0.03–0.3	0.08–0.5	<0.1	<0.2
OS09	0.01–0.3	1.1–1.6	–		–	<0.2	<0.2	<0.1	–
OS11	<0.2	0.8–1.3	–		0.1–0.4	<0.2	0.05–0.3	<0.1	<0.1
OS17	0.05–0.4	0.7–0.9			–	0.04–0.3	<0.1	<0.1	<0.1
OS21	<0.2	1.6–1.9	–		0.2–0.5	<0.2	0.05–0.4	<0.1	–
OS22	0.05–0.3	1.2–1.6	–		0.1–0.4	<0.15	0.06–0.3	<0.1	–
OS23	<0.2	1.1–1.4	0.7–1.0		0.2–0.4	<0.2	<0.2	<0.1	<0.2
OS25	0.02–0.3	0.6–0.8	1.2–1.5		0.4–0.6	<0.2	<0.2	<0.1	<0.2
OS28	<0.2	1.1–1.3	0.5–0.7		0.2–0.4	<0.2	0.05–0.3	<0.1	<0.1
OS29	<0.2	1.4–1.6	–		–	0.05–0.3	0.06–0.3	<0.1	–
OS30	<0.2	1.3–1.7	–		0.1–0.4	<0.1	0.05–0.3	<0.1	0.03–0.3
OS34	<0.2	1.2–1.4	–		0.2–0.5	<0.2	0.05–0.3	<0.2	<0.1
OS36	<0.1	1.0–1.2	–		0.1–0.4	<0.2	0.05–0.4	<0.2	–
OS37	<0.1	0.8–1.1	1.0–1.2		0.3–0.4	<0.2	<0.2	<0.2	–
OS38	<0.2	0.6–0.9	–		0.2–0.5	<0.15	<0.2	<0.1	–
OS40	0.04–0.6	1.0–1.2	–		–	0.04–0.3	0.06–0.3	<0.1	–
OS42	0.03–0.4	1.4–2.5	0.4–0.7		0.1–0.4	<0.15	<0.2	<0.1	<0.2

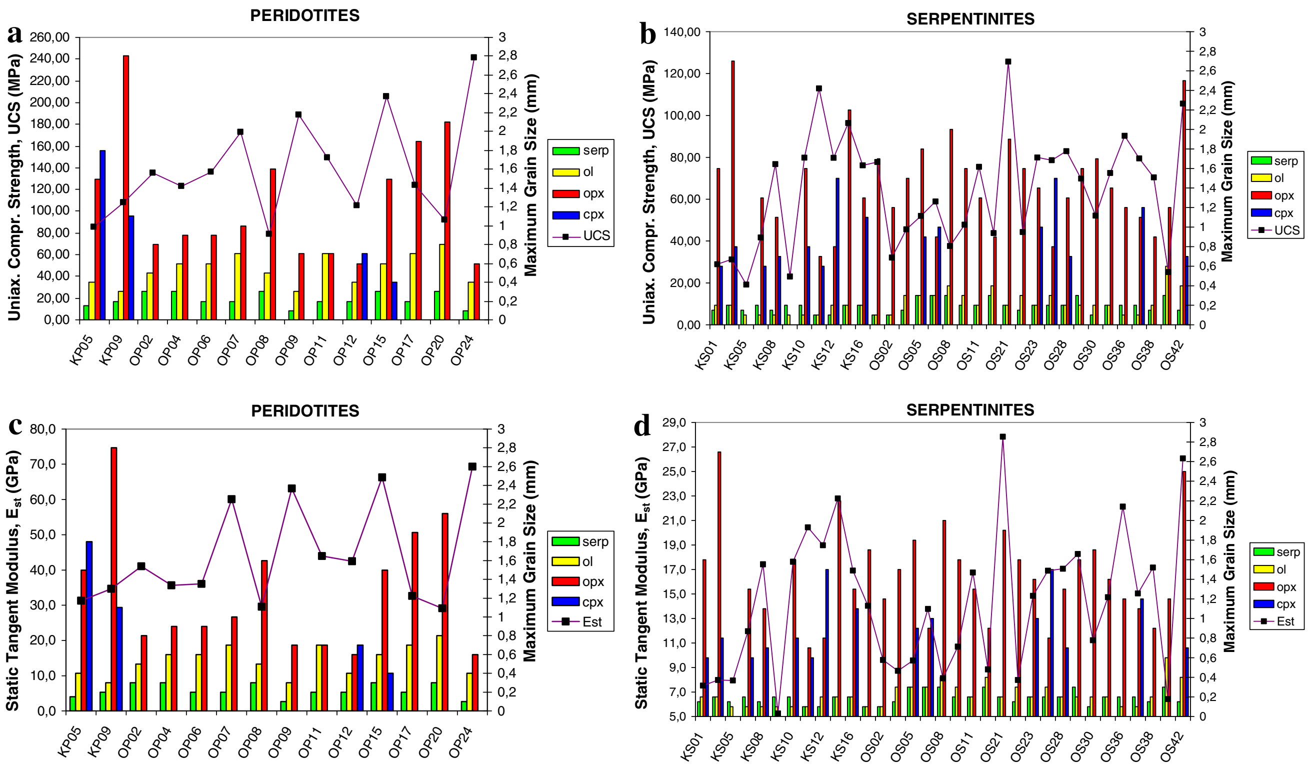

Fig. 9 *Bar chart* showing the relationship between the minerals maximum size and the mechanical properties

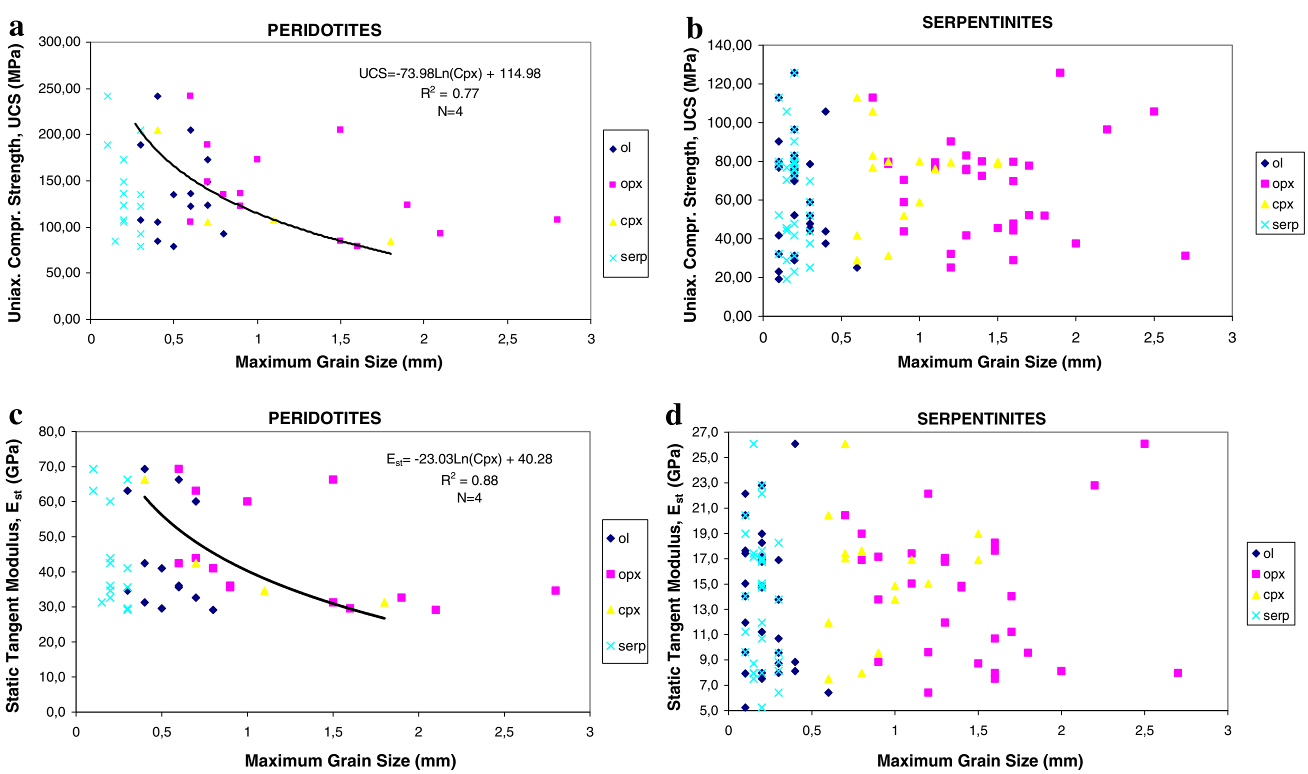

Fig. 10 Correlation between the minerals maximum size and the mechanical characteristics

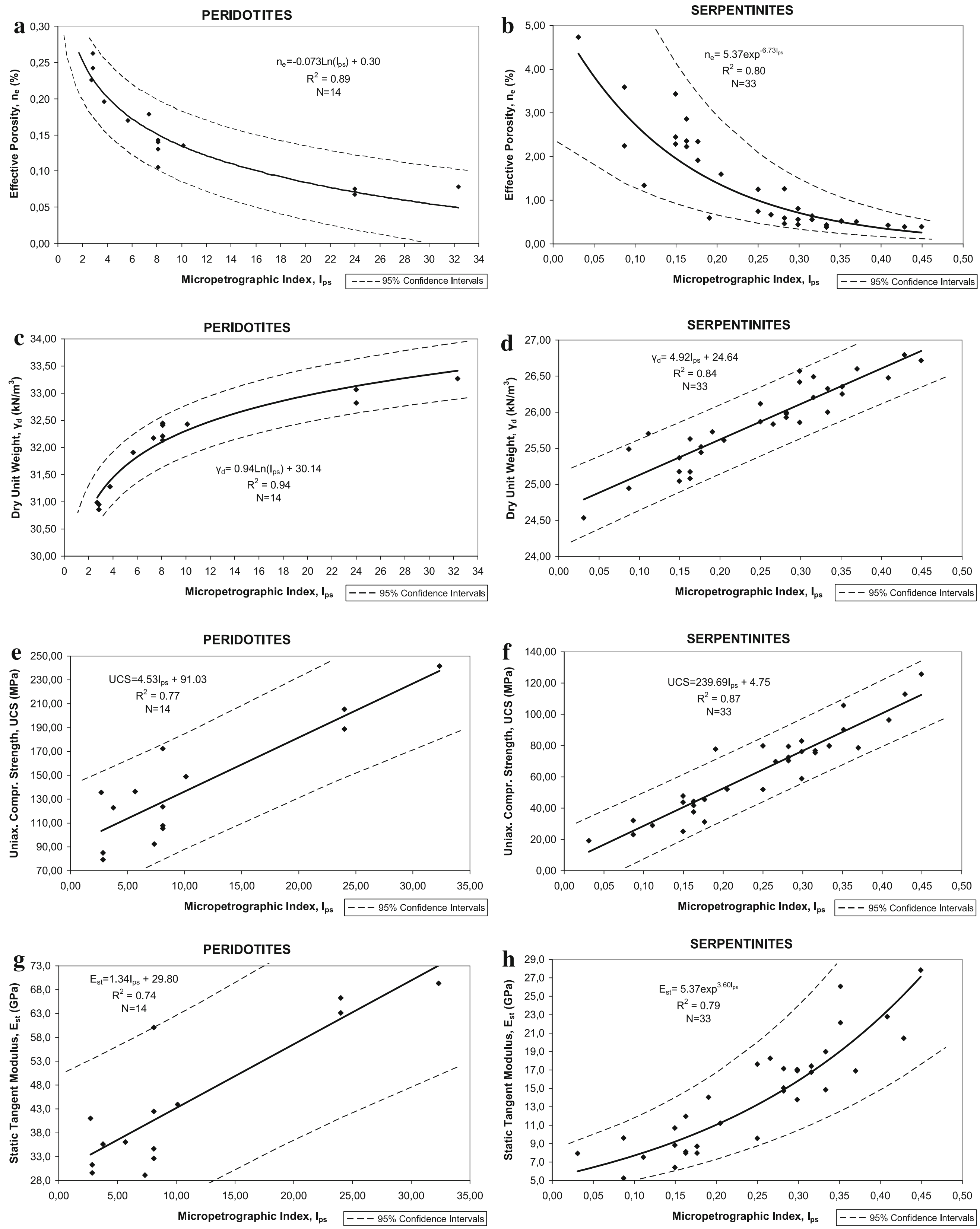

Fig. 11 Variation between micropetrographic index and physicomechanical properties for the studied rocks

Table 8 Regression equations and determination coefficients (R^2)

Parameters to be related	Rocks	Regression equations	RR^2
Effective porosity and micropetrographic index (I_{ps})	Peridotites	$n_e = -0.073\text{Ln}(I_{ps}) + 0.30$	0.89
	Serpentinites	$n_e = 5.37\exp^{-6.73 I_{ps}}$	0.80
Dry unit weight and micropetrographic index (I_{ps})	Peridotites	$\gamma_d = 0.94\text{Ln}(I_{ps}) + 30.14$	0.94
	Serpentinites	$\gamma_d = 4.92 I_{ps} + 24.64$	0.84
Uniax. compr. strength and micropetrographic index (I_{ps})	Peridotites	$\text{UCS} = 4.53 I_{ps} + 91.03$	0.77
	Serpentinites	$\text{UCS} = 239.69 I_{ps} + 4.75$	0.87
Static tangent modulus and micropetrographic index (I_{ps})	Peridotites	$E_{st} = 1.34 I_{ps} + 29.80$	0.74
	Serpentinites	$E_{st} = 5.37\exp^{3.60 I_{ps}}$	0.79

Conclusions

During the last decades, a number of researchers have attempted to ascertain the influence of petrographic characteristics on the physico-mechanical properties of various rock types; however, only a few have been devoted to the ultrabasic rocks. These rocks have become important earth crust components in some areas like south-eastern Europe, especially in the countries of the former Yugoslavia, and Albania, Greece, and Turkey. Furthermore, estimation of the rock physico-mechanical properties is considered to be the most important component in any engineering geology project. In spite of their easy and simple determination, they require a large number of well prepared (regularly shaped) rock specimens. But ultrabasic rocks (especially serpentinites) are usually not suitable for preparing specimens. The immediate determination of physico-mechanical characteristics is usually difficult for these rocks. For this reason, this study mainly attempts to develop empirical equations between petrographic characteristics and physico-mechanical properties.

Thus, in this paper, ultrabasic rock samples taken from central Greece (western part of Othrys mountain and the Kallidromo mountain), were tested in the laboratory and the physico-mechanical properties were predicted from the petrographic characteristics by simple regression analysis.

The effect of alteration on the physico-mechanical properties of ultrabasic rocks can be characterized quantitatively by the serpentinization percentage (β). Strong inverse linear relationships exist between the β and the dry unit weight (γ_d) for both peridotites ($R^2 = 0.98$) and serpentinites ($R^2 = 0.83$), while the increase of secondary minerals (serpentinization percentage) increases the effective porosity (n_e) exponentially in serpentinites ($R^2 = 0.81$) and linearly in peridotites ($R^2 = 0.92$).

Serpentinization generally results in mechanically weaker rocks. The uniaxial compressive strength (UCS) values extend from 19.21 to 125.73 MPa in serpentinites and from 79.31 to 241.56 MPa in peridotites, while the static tangent modulus (E_{st}) varies from 5.2 to 27.8 GPa and between 29.1 and 69.3 GPa, respectively. The variation of the mechanical properties is related to the degree of preservation of the primary subophitic texture and the development of soft minerals during alteration. The relatively high strength of the fresh peridotites is a result of the low proportions of soft minerals, along with the preservation of primary textures. In accordance with ISRM (1981), the majority of studied peridotites are characterized as rocks with very high strength, while the majority of serpentinites range between 50 and 100 MPa (rocks with high strength). As far as the modulus ratio values are concerned, the peridotites plot in the Medium Ratio Zone (M) in the Deere and Miller (1966) diagram. On the other hand, serpentinites mainly plot in the lower portion of the Medium Ratio Zone (*M*) with a few results in the Low Ratio Zone (*L*). This difference indicates that some serpentinite samples may not be homogeneous and isotropic. It may also be attributed to the internal fractures/cracks that are macroscopically undetected.

Both the UCS and E_{st} exhibit negative relationships with the degree of serpentinization. The best fit equations are logarithmic for peridotites and exponential for serpentinites.

The correlations of the physico-mechanical parameters with mineral percentage are also determined. Significant linear relationships exist between the serpentine percentage and the physical properties (γ_d, n_e) in peridotites, while the increase of serpentine exponentially increases ($R^2 = 0.66$) the effective porosity and decreases linearly ($R^2 = 0.74$) the dry unit weight in serpentinites. The UCS and E_{st} are negatively correlated with the percentage of serpentine. The best fit equations are logarithmic in peridotites and logarithmic and exponential, respectively, in serpentinites. The determination coefficients are not very high indicating that the serpentine percentage has a smaller influence on the mechanical properties than the other petrographic characteristics.

Contrary to several investigations suggestions (Brace 1961; Onodera and Asoka Kumara 1980; Tugrul and Zarif 1999), that the strength decreases significantly as the grain size increases in rocks, a very poor relationship between UCS and E_{st} with size of the minerals (except clinopyroxene) was found in this research. This due to that, in the mentioned above researches, the examined rocks have not undergone the phenomenon of serpentinization, contrary to this study in which serpentinization plays an important role. The relations of clinopyroxene size with UCS and E_{st} are expressed by logarithmic equations. They present high determination coefficients ($R^2 = 0.77$ and $R^2 = 0.88$, respectively) because clinopyroxenes are much less influenced by the serpentinization than the other primary minerals.

Finally, significant positive correlations (logarithmic in peridotites, $R^2 = 0.94$ and linear in serpentinites, $R^2 = 0.84$) exist between the micropetrographic index and dry unit weight, indicating that with increasing I_{ps}, the density also increases. The relationship between n_e and I_{ps} is better described by a logarithmic relationship ($R^2 = 0.89$) in peridotites and an exponential relationship ($R^2 = 0.80$) in serpentinites. Moreover, the mechanical characteristics and I_{ps} correlated well by linear functions apart from the relation between E_{st} and I_{ps} in serpentinites, which is obviously expressed by an exponential function.

In summary, the correlation between petrographic and mechanical properties present a higher determination coefficient in serpentinites than in peridotites, because small amounts (>9 %) of serpentine reduce the strength of the unaltered peridotite by more than a factor of two. So the strength values in peridotites are much lower than those of unaltered peridotites.

The relationships between the petrographic parameters and the engineering properties show that they can be used for an assessment of the physico-mechanical characteristics of ultrabasic rocks. However, it is commonly known that the prediction equations derived by different researches are dependent on rock types, quality and test conditions. Further research is necessary in order to investigate if ultrabasic rocks taken from different locations will present different physico-mechanical values than those which are determinate in this study.

Acknowledgments This study was funded by the State Scholarship Foundation of Greece (I.K.Y) to the first author (K. D). The authors would also like to express their thanks to the Public Works Central Laboratory of Greece (KEDE) and to Ass. Professor Anastasios Tsagalidis for his help in petrography.

References

Akesson U, Lindqvist JE, Göransson M, Stigh J (2001) Relationship between texture and mechanical properties of granites, central Sweden, by use of image—analysing techniques. Bull Eng Geol Environ 60:277–284

Al-Oraimi SK, Taha R, Hassan HF (2006) The effect of the mineralogy of coarse aggregate on the mechanical properties of high-strength concrete. Constr Build Mater 20:499–503

ASTM (1986) Standard test method of unconfined compressive strength of intact rock core specimens. Annual Book of Standards, 4.08. American Society for Testing and Materials, Philadelphia, D2938

ASTM (2001) Standard practices for preparing Rock core specimens and determining dimensional and shape tolerances. American Society for Testing and Materials, D4543

Brace WF (1961) Dependence of fracture strength of rocks on grain size. In: Proceedings of 4th symposium. Rock Mech., Univ. Park, Penn., PA, pp 99–103

Christensen NI (1966) Shear-wave vetocities in metamorphic rocks at pressures to 10 kbar. J Geophys Res 71:3549–3556

Christensen NI (2004) Serpentinites, peridotites and seismology. Int Geol Rev 46(2004):795–816

Deere DU, Miller RP (1966) Engineering classification and index properties for intact rock. US Air Force Systems Command, Air Force Weapons Lab., Kirtland Air Force Base, New Mexicom, Technical Report, AFWL-TR, pp 65–116

Diamantis K (2010) Engineering geological properties of the ultrabasic rocks in Othrys and Kallidromo mountains (central Greece). Phd Thesis, Athens, p 386

Diamantis K, Gartzos E, Migiros G (2009) Study on uniaxial compressive strength, point load strength index, dynamic and physical properties of serpentinites from Central Greece: test results and empirical relations. Eng Geol 108:199–207

Escartin J, Hirth G, Evans B (2001) Strength of slightly serpentinized peridotites: implications for the tectonics of oceanic lithosphere. Geol Soc Am 29(11):1023–1026

Ferriere J (1982) Paleogeographies et Tectoniques Superposees dans les Hellenides Internes au Niveau de l' Othrys et de Pelion (Grece). Univ. des Sciences et Techniques de Lille

Grönholm S (1994) Influence of mineral composition and microstructures on the mechanical properties of host rocks of the Kemi (Elijärvi) Chromite Deposit: Finland, Report of Investigation N126. Geological Survey of Finland, Finland

Gunsallus KL, Kulhawy FH (1984) A comparative evaluation of rock strength measures. Int J Rock Mech Min Sci Geomech Abstr 21:233–248

Haney MG, Shakoor A (1994) The relationship between tensile and compressive strengths for selected sandstones as influenced by index properties and petrographic characteristics. In: Proceedings of 7th international IAEG Cong., Lisbon, Portugal, vol IV, pp 3013–3021

Hartley A (1974) A review of the geological factors influencing the mechanical properties of road surface aggregates. Q J Eng Geol 7:69–100

Hawkins AB (1998) Aspects of rock strength. Bull Eng Geol Environ 57:17–30

Hoek E, Brown ET (1980) Underground excavations in rock. Inst. Min. 537 Metall, London

Irfan TY, Dearman WR (1978) The engineering petrography of a weathered granite in Cornwall, England. Q J Eng Geol 11:233–244

ISRM (1981) Rock characterization testing and monitoring. In: Brown ET (eds) ISRM suggested methods, Pergamon Press, Oxford, p 211

ISRM (2007) In: Ulusay R, Hudson JA (eds) The complete ISRM suggested methods for rock characterization, testing and monitoring: 1974–2006. Suggested methods prepared by the commission on testing methods, International Society for Rock Mechanics, compilation arranged by the ISRM Turkish National Group Ankara, Turkey, 2007, p 628

Katsikatsos G, Migiros G, Triantaphyllis M, Mettos A (1986) Geological structure of internal Hellenides (E. Thessaly-SW Macedonia. Euboea-Attica-Northern Cyclades islands and Lesvos). I.G.M.E.. Geol. and Geoph. Res. Special Issue 191–212

Koumantakis J (1982) Comportement des peridotites et serpentinites de la Grece en travaux public. Leur propretes physiques et mechaniques. Bul IAEG 25:53–60

Lundqvist S, Göran M (2001) Evaluation and interpretation of microscopic parameters versus mechanical properties of precambrian rocks from the Stockholm region, Sweden. In: Proceedings of 8th Euroseminar on microscopy applied to building materials, 4–7 Sept, Athens

Marinos G (1974) Geology of Orthrys and issues on its ophiolites. Ann Geol d Pays Jieneiiiciue. s_t26, University of Athens, pp 118–148

Marinos P, Hoek E, Marinos V (2006) Variability of the engineering properties of rock masses quantified by the geological strength index: the case of ophiolites with special emphasis on tunnelling. Bull Eng Geol Environ 65:129–142

Migiros G (1990) The lithostratigraphic-tectonic structure of Othris (Central Greece). Bull Geol Soc Greece XXVI:107–120

Miskovsky K, Taborda Duarte M, Kou SQ, Lindqvist PA (2004) Influence of the mineralogical composition and textural properties on the quality of coarse aggregates. J Mater Eng Perform 13(2):144–150

Mountrakis D, Sapountzis E, Kilias A, Eleftheriadis G, Christofides G (1983) Paleogeographic conditions in the western Pelagonian margin in Greece during the initial rifting of the continental area. Can J Ear Sci 20:1673–1681

Onodera TF, Asoka Kumara HM (1980) Relation between texture and mechanical properties of crystalline rocks. Bull Int Assoc Eng Geol 20:173–177

Ozsoy EA, Yilmaz G, Arman H (2010) Physical, mechanical and mineralogical properties of ophiolitic rocks at the Yakakayi dam site, Eskisehir, Turkey. Sci Res Essays 5(17):2579–2587

Pomonis P, Rigopoulos I, Tsikouras B, Hatzipanagiotou K (2007) Relationships between petrographic and physico-mechanical properties of basic igneous rocks from the Pindos ophiolitic complex, NW Greece. Bull Geol Soc Greece XXXX(2):947–958

Ramana YV, Gogte BS, Sarma KVLNS (1986) Physical properties of Indus ophiolites from Kashmir Himalaya. Phys Earth Planet Int 43:104–122

Rao MVMS, Ramana YV (1974) Dilatant behaviour of ultramafic rocks during fracture. Int J Rock Mech Min Sci Geomech Abstr 11: 193–203. Pergamon Press 1974. Printed in Great Britain

Rigopoulos I, Tsikouras B, Pomonis P, Hatzipanagiotou K (2010) The influence of alteration on the engineering properties of dolerites: the examples from the Pindos and Vourinos ophiolites (northern Greece). Int J Rock Mech Min Sci 47:69–80

Shakoor A, Bonelli RE (1991) Relationship between petrographic characteristics, engineering index properties and mechanical properties of selected sandstones. Bull Int Assoc Eng Geol XXVIII(1):55–71

Shimada M, Cho A, Yukutake H (1983) Fracture strength of dry silicate rocks at high confining pressures and activity of acoustic emission. Tectonophysics 96:159–172

Streckeisen AL (1976) Classification of the common igneous rocks by means of their chemical composition: a provisional attempt. Neues Jahrbuch for Mineralogie, Monatshefte H. 1:1–15

Tamrakar NK, Yokota S, Shrestha SD (2007) Relationships among mechanical, physical and petrographic properties of Siwalik sandstones, Central Nepal Sub-Himalayas. Eng Geol 90:105–123

Tuğrul A, Zarif IH (1999) Correlation of mineralogical and textural characteristics with engineering properties of selected granitic rocks from Turkey. Eng Geol 51:303–317

Zorlu K, Ulusay R, Ocakoglu F, Gokceoglu C, Sonmez H (2004) Predicting intact rock properties of selected sandstones using petrographic thin-section data. Int J Rock Mech Min Sci 41(1):93–98