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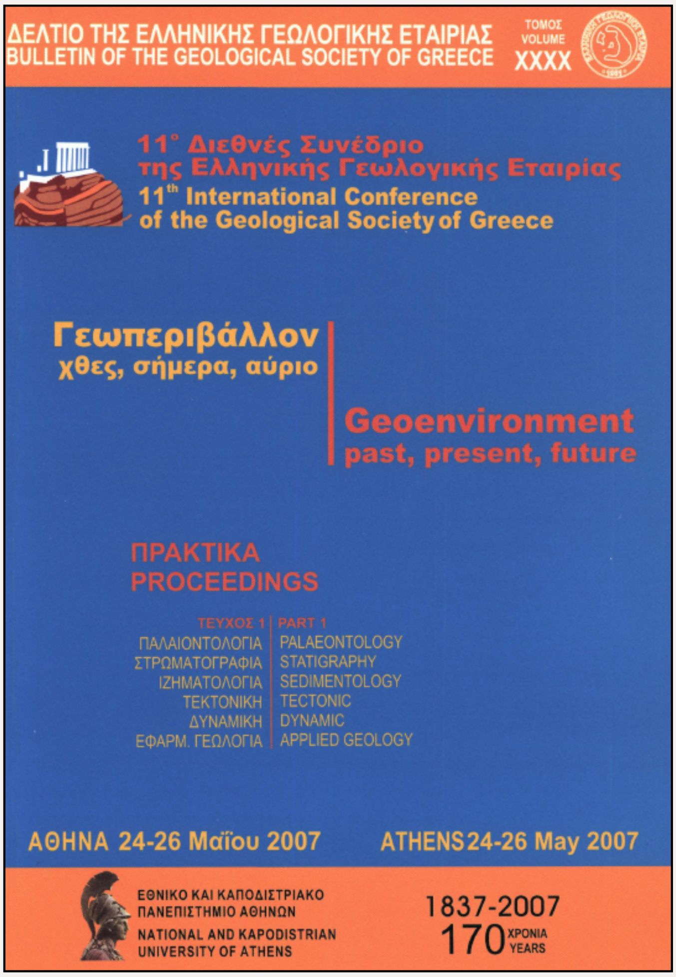

UNIAXIAL COMPRESSIVE STRENGTH, DRY UNIT WEIGHT AND FRACTURE PATTERNS OF ULTRABASIC ROCKS IN OTHRYS MOUNTAIN (CENTRAL GREECE): CORRELATIONS AND EVALUATION

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UNIAXIAL COMPRESSIVE STRENGTH, DRY UNIT WEIGHT AND FRACTURE PATTERNS OF ULTRABASIC ROCKS IN OTHRYS MOUNTAIN (CENTRAL GREECE): CORRELATIONS AND EVALUATION.

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Abstract

Ultrabasic rocks, taken from the Othrys mt. (Central Greece), are studied in this paper. The structural geology and tectonics of the study area are described. Uniaxial Compressive Strength (UCS) and dry unit weight (γ) values are calculated and fracture angles are measured. The results are statistically assessed and empirical relationships (exponential equations) between UCS and γ are presented for the ultrabasic rocks, divided in Peridotites, Serpentinised Peridotites and Serpentinites. Due to the low correlation coefficient of the Serpentinised Peridotites, it was decided that the Serpentinised Peridotites and Serpentinites should be examined together. The correlation coefficient of the combined category is much better than the separate ones.

Furthermore, this paper demonstrates that the majority of the ultrabasic rocks tested were breaking at one angle (φ°), which mainly fluctuated between 75° and 90°. The fracture angles correlate with previously recognised geological (mainly tectonic) structures.

The observed deviations are due to petrographic variety, structural complexity, preferred orientation of olivine and orthopyroxene and internal imprinted tectonic deformation.

Key words: *Rock mechanics, ophiolites, laboratory tests.*

Περίληψη

Στη παρούσα δημοσίευση μελετούνται τα υπερβασικά πετρώματα από την περιοχή της Όθρυος (Στερεά Ελλάδα). Η γεωλογική δομή και η τεκτονική της εξεταζόμενης περιοχής περιγράφοντα συνοπτικά. Οι αντοχές σε ανεμπόδιστη μονοαξονική θλίψη και τα φαινόμενα βάρη υπολογίζονται και οι γωνίες θραύσης μετρούνται. Τα αποτελέσματα αξιολογούνται στατιστικά και παρουσιάζονται εμπειρικές σχέσεις μεταξύ της αντοχής σε μονοαξονική θλίψη και του φαινόμενου βάρους. Εξαιτίας του χαμηλού συντελεστή συσχέτισης στους Σερπεντινιωμένους Περιδοτίτες, αποφασίσαμε οι Σερπεντινιωμένοι Περιδοτίτες και οι Σερπεντινίτες να εξεταστούν μαζί. Ο νέος συντελεστής συσχέτισης είναι πολύ μεγαλύτερος από τον προηγούμενο.

Επιπλέον, στην παρούσα δημοσίευση φαίνεται πως η πλειοψηφία των υπερβασικών πετρωμάτων θραύεται σε μια μόνο γωνία (φ°), η οποία κυμαίνεται κυρίως μεταξύ 75° και 90°, ενώ γίνεται και συσχετισμός των γωνιών θραύσης με την τεκτονική.
Οι όποιες αποκλίσεις παρατηρήθηκαν αποδίδονται στην πετρογραφική ποικιλία, στη δομική πολυπλοκότητα, στον προτιμητέο προσανατολισμό του ολιβίνη και του ορθο-πυρόξενου και στην εσωτερικά αποτυπωμένη τεκτονική παραμόρφωση.
Λέξεις κλειδιά: *Βραχομηχανική, οφιόλιθοι, εργαστηριακές δοκιμές.*

1. Introduction

Many attempts have been to correlate the Uniaxial Compressive Strength (UCS), which is undoubtedly the geotechnical property of rocks which is most often quoted, with certain mechanical and physical characteristics. Nevertheless, only few studies have been concentrated on ultrabasic rocks (Koumantakis 1982, Paventi *et al.* 1996, Marinos *et al.* 2006). An opportunity to conduct such investigation came up when the Laboratory of Mineralogy-Geology of the Agricultural University of Athens undertook the geomechanical tests from ERGOSE S.A. for the construction of railway tunnels in Othrys mt.

The study area is located in Othrys (Central Greece) and specifically between the villages of Lianokladi and Domokos (Fig. 1). It belongs to the Sub-Pelagonian geotectonical unit and it is mainly comprised of ultrabasic rock masses (Marinos 1974, Migiros 1990).

A number of boreholes were drilled along a narrow N-S zone, from which 138 representative samples were chosen to be examined.

Uniaxial Compressive Strength and dry unit weight (γ) values were calculated following the international standards. Photographs were taken before and after each test, fracture patterns were drawn, the angles were measured and statistically classified.

Within the framework of the present study, the fluctuations of UCS and γ values and the statistical analysis of the fracture angles are presented. This paper attempts to derive reliable empirical equations between UCS and γ, to correlate them with both fracture angles and depth and to outline the influence of the geological structure.

2. Materials and methods

Drill core samples from the Othrys mt. were investigated for geotechnical purposes (construction of railway tunnels by ERGOSE S.A.) in the Laboratory of Mineralogy-Geology of the Agricultural University of Athens. The boreholes were carried out in a 25 km long N-S direction, from Lianokladi to Domokos villages, perpendicular to the geological and tectonic structures of the area and they were drilled at depths up to 300 m from the surface. The wide range of sample depth along with the quite large numbers of samples, render our results representative for the Othrys ultrabasic rock masses.

The initial choice of the samples and the sequence of tests were decided by the supervising rock mechanics engineer and geologists. At our laboratory a second check was done by taking into account the isotropy and homogeneity of the samples and some were disqualified as inappropriate (about 33 %), mainly due to visible discontinuities, i.e. fractures, reducing the number of samples to 138.

Due to the variable grade of serpentinisation of the peridotite samples, many thin sections were cut and examined under a polarising microscope and some samples were further analysed by the XRD method. Three petrologic types of peridotites were distinguished based on their different physical and mechanical properties.

The Uniaxial Compressive Strength (UCS) tests were carried out in accordance with the ISRM (1981) standard. The core samples, whose diameters were 61, 71 and 83 mm, were carefully prepared keeping an L/D ratio between 2,5 and 3,0. The edges of the samples were cut parallel and smooth. The samples were then oven dried and before every test the samples were weighted with accuracy in order to calculate the dry unit weight. After each test, the pattern of the fractures was drawn and the angles of the fractures were measured.

The data was analysed with the Analysis Tool Pack of Microsoft Excel 2003 and the results were evaluated and then correlated with the geological structures of the area.

3. Geology

The area between the Lianokladi and Domokos villages (Othrys mt.) consists mainly of Alpine formations (Fig. 1) that belong to the Sub-Pelagonian geotectonic unit (Mountrakis *et al.* 1983, Katsikatsos *et al.* 1986). We can distinguish them, from bottom to top, in the following formations (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).

(c) An unconformable sequence of Cretaceous limestones which passes upward to flysch.

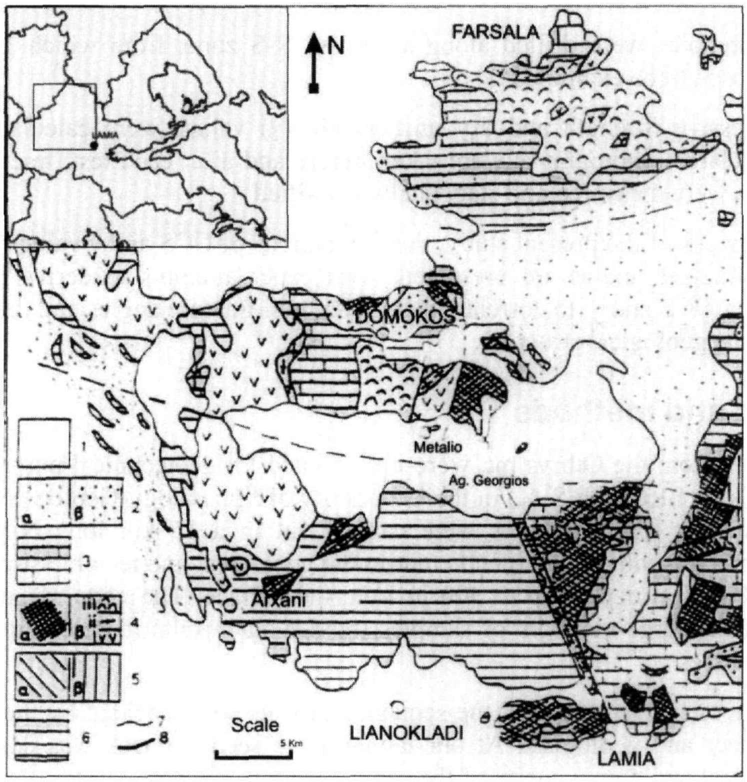

Figure 1 – Geological map of Othrys area (Migiros 1990): 1. Postalpine formations 2. Flysch (α) Paleocene – Eocene (β) Upper Cretaceous 3. Cretaceous formations of eastern and central Othrys 4. Pre-Upper Cretaceous tectonic nappe (α) Undivided (β) Ophiolitic formations (i) tectonites (ii) cumulates (iii) non-cumulites and volcanic sequence 5. Pre-Cretaceous formations (α) eastern (β) central Othrys 6. Western Othrys formations (undivided) 7. Geological boundary 8. Tectonic contact

The ophiolitic formations have thrusted the Triassic-Jurassic carbonate sequence and are consisted of volcano-sedimentary formations, basaltic lavas, basic rocks and ultrabasic masses. The ultrabasic rock masses are mainly represented by the peridotites whose grade of serpentinisation varies.

In our study we classified the peridotite samples into the following three rock groups taking into account petrological and mineralogical studies:

(a) Peridotites: We refer mainly to lerzoliths, hartzbourgites and plagioclastic peridotites with a grade of serpentinisation less than 30 %.

(b) Serpentised Peridotites: The same rock type but its grade of serpentinisation lies between 30 % and 70 %.

(c) Serpentinites: Ultrabasic rock types, mainly hartzbourgites, whose grade of serpentinisation is more than 70 %.

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°-45°.

(c) Thrusts: NW-SE direction and NE dip between 45°-60°.

(d) Faults: E-W, NW-SE, NE-SW directions and dips more than 60°.

4. Laboratory test results

4.1. Dry unit weight (γ)

The dry unit weight was calculated for the total number of 138 ultrabasic samples and their values are illustrated in Figure 2. As seen in Table 1 (statistical analysis), the dry unit weight fluctuates between 22.99 and 33.77 kN/m^3 and the average value is 27.64 kN/m^3.

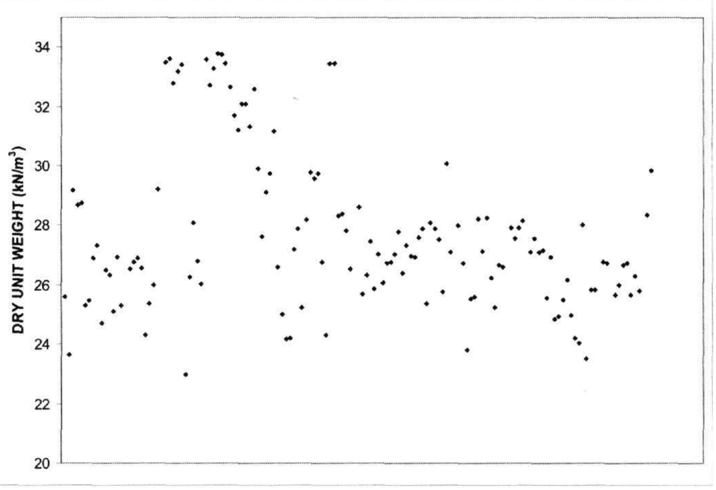

Figure 2 - Dry Unit weight values of the investigated ultrabasic samples

The ultrabasic rocks, based on their dry unit weight and taking into account their petrological studies are divided in Peridotites, Serpentinised Peridotites and Serpentinites.

The dry unit weights of Peridotites range from 29.56 kN/m^3 to 33.77 kN/m^3, those of Serpentinites from 22.99 kN/m^3 to 25.98 kN/m^3 and the values of Serpentinised Peridotites vary from 26.00 kN/m^3 to 29.19 kN/m^3 (Table 2).

From the above mentioned and taking into account the low standard deviations of the groups that were formed petrologically, we conclude that there is also a clear differentiation to the dry unit weight values, as it was expected, which is due to the grade of serpentisation.

Table 1 - Statistical analysis results of the investigated ultrabasic samples

ULTRABASIC ROCKS	
	DRY UNIT WEIGHT (KN/m^3)
MAX	33,77
MIN	22.99
MEAN	27.64
STDEV	2.62

Table 2 - Statistical analysis results of the investigated ultrabasic samples.

		DRY UNIT WEIGHT (KN/m^3)
PERIDOTITES	MAX	33.77
	MIN	29.56
	MEAN	32.04
	STDEV	1.52
SERPENTINISED PERIDOTITES	MAX	29.19
	MIN	26.00
	MEAN	27.29
	STDEV	0.81
SERPENTINITES	MAX	25.98
	MIN	22.99
	MEAN	25.02
	STDEV	0.77

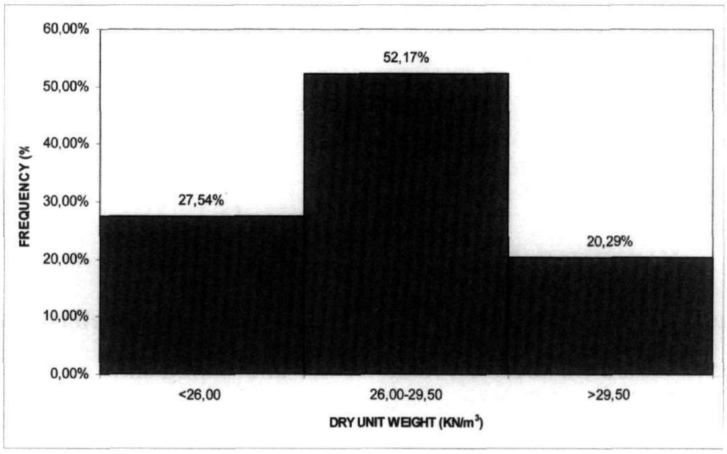

Figure 3 - Dry unit weight histogram

Finally based on the results of the dry unit weight statistical analysis for each petrological group and regarding 29.50 kN/m^3 as the minimum value for Peridotites and 26.00 kN/m^3 as the maximum value for Serpentinites, a histogram was created (Fig. 3). As can be seen the largest number of samples belong to Serpentinised Peridotites (52.17 %).

4.2. Uniaxial Compressive Strength (UCS)

A scatter diagram of all UCS values is illustrated in Figure 4. The UCS values range from 169.63 to 0.40 MPa exhibiting a great fluctuation. Some very uncommon low values of UCS are due to internal discontinuities, macroscopically undetected. The mean value is 53.62 MPa and the standard deviation is 35.34 MPa (Table 3). The high value of the standard deviation can be attributed to the fact that the majority of the samples belong to the Serpentinised Peridotites group (52.17 %), which exhibit great anisotropy.

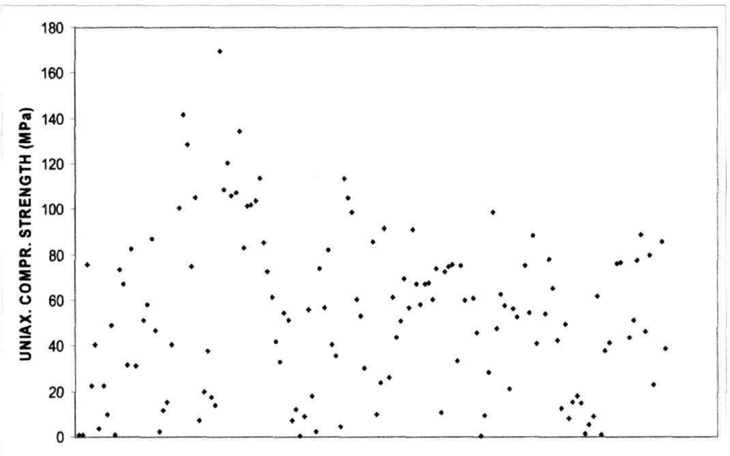

Figure 4 - Uniaxial Compressive Strength values of the investigated samples

Table 3 - Statistical analysis results of the investigated ultrabasic samples

ULTRABASIC ROCKS	
	UNIAXIAL COMPRESSIVE STRENGTH (MPa)
MAX	169.63
MIN	0.40
MEAN	53.62
STDEV	35.34

4.3. Fracture Angles (φ°)

Following the UCS tests, photographs of the samples were taken and fracture patterns were drawn. Of the 138 samples, 86.96% had single dipping fractures, while the 13.04 % was broken in two angles (Fig. 5). These two groups of samples were statistically analyzed separately. After distinguishing four bins (30°≤φ°<45°, 45°≤φ°<60°, 60°≤φ°<75°, 75°≤φ°≤90°), it is shown that both groups were mainly broken in angles between 75° and 90° (Figs 6, 7). In addition, no fracture angle values less than 30° were observed. Detailed statistical analysis is shown in Table 4.

Finally, for each sample the dominant angle was identified. A histogram of the prevalent fracture angles is shown in Figure 8. It is evident that the majority of the samples (60.14 %) had a prevalent fracture angle between 75° and 90°, while only the 2.17 % broke between 30° and 44°.

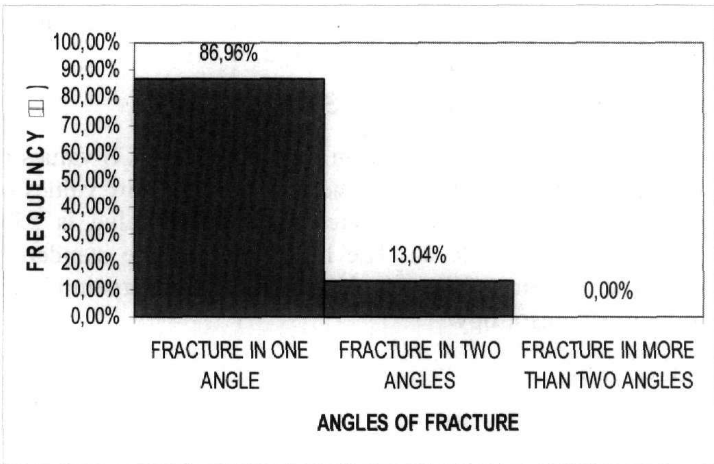

Figure 5 - Frequency of the fracture angles

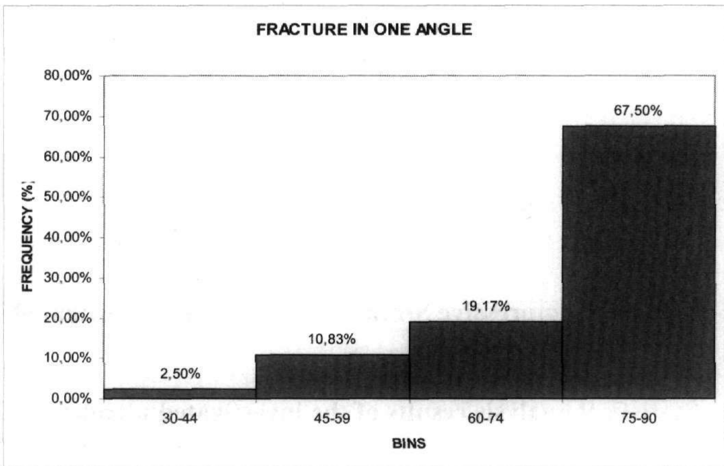

Figure 6 - Frequency of one fracture angle

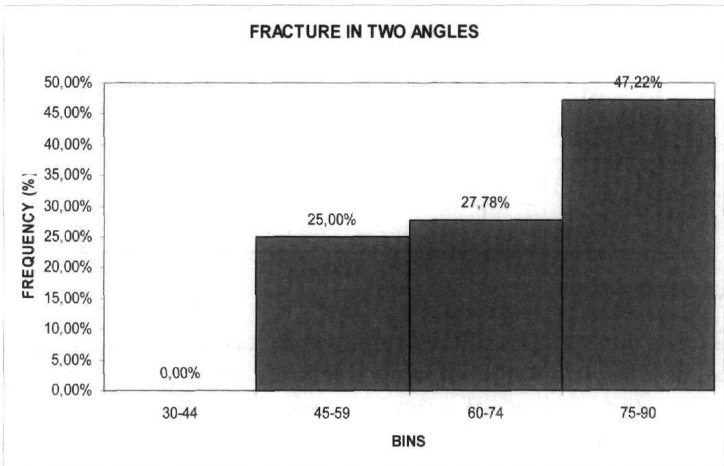

Figure 7 - Frequency of two fracture angles

Table 4 - Statistical analysis results of fracture angles

	FRACTURE IN ONE ANGLE				FRACTURE IN TWO ANGLES			
BINS	30-44	45-59	60-74	75-90	30-44	45-59	60-74	75-90
FREQUENCY	3	13	23	81	0	9	10	17
FREQUENCY (%)	2,50%	10,83%	19,17%	67,50%	0,00%	25,00%	27,78%	47,22%
MEAN	37,33	55,69	67,48	84,15	0	52,00	67,10	82,41
MODE	42	54	70	85	0	50	64	85

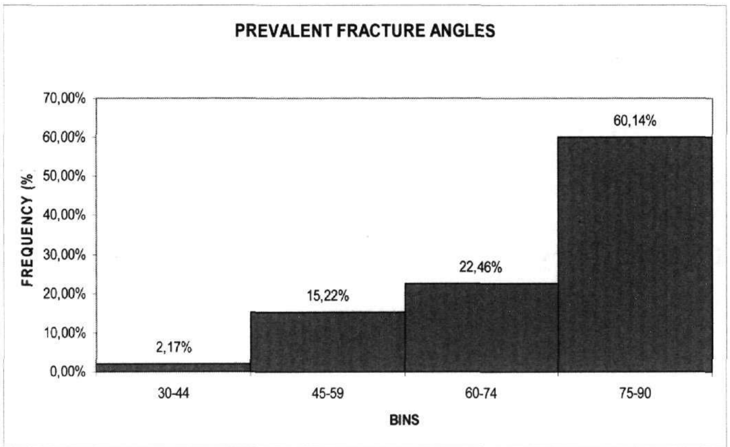

Figure 8 - Histogram of the prevalent fracture angles

5. Results & Discussion

The statistical analysis software used to correlate UCS and dry unit weight was the Analysis Tool Pack of the Microsoft Excel 2003. Figure 9 is a plot diagram of UCS against γ for the total number of the samples. The relationship gives a good correlation coefficient (R=0.66) and is defined by the equation $UCS=0.0063e^{0.3117\cdot\gamma}$. A closer examination of Figure 9 reveals a discrepancy of the normally exponential relationship between dry unit weight and UCS. This is attributed to the anisotropic single-crystal elastic properties and the lattice preferred orientation of olivine and orthopyroxene. Specifically for the Peridotites, the relationship between UCS and γ gives a high correlation coefficient (R=0.78) and is represented by $UCS=0.2067e^{0.1892\cdot\gamma}$ (Fig. 10). The same relationship gives a low correlation coefficient (R=0.26) for Serpentinised Peridotites (Fig. 11) and a good one (R=0.66) for Serpentinites (Fig. 12). Thus it is suggested that Serpentinised Peridotites and Serpentinites should be examined together. The new correlation coefficient is 0.74 and the equation is defined by the $UCS=3\cdot10^{-7}e^{0.6962\cdot\gamma}$ (Fig. 13). Moreover, the deviations are due to the varied grade of serpentinisation, the petrographic variety (hartzburgites, lerzolites, plagioclastic peridotites) and the internal structural complexity due to the tectonic deformation and alteration.

It can be seen from Figures 5-6, that the majority of the ultrabasic samples broke in one angle, which predominately fluctuated between 75° and 90°. When samples fractured in two angles, the percentage of the bins 45°-59° and 60°-74° increased while the percentage of the bin 75°-90° decreased (Fig. 7), which is quite reasonable.

From the aforementioned, it is obvious that the fracture angles of the samples deviate from the expected value of 45°. This is mainly attributed to the internal imprint of tectonic structures; specifically, angles lower than 45° are related to low thrusts, between 45° and 60° to the thrusts and those with angles greater than 60° are correlated to the faults and/or collapse effect.

Finally, there is no obvious relationship between the UCS and the fracture angle as in between the fracture angle and the depth from which the samples were taken. As it is aforementioned, this is attributed to the petrographic variety and/or to the preferred orientation and the internally imprinted tectonic structures.

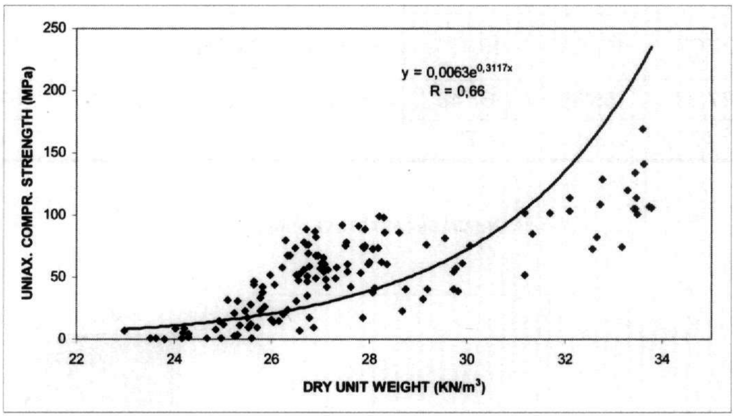

Figure 9 - UCS against Dry unit weight for the total number of ultrabasic samples

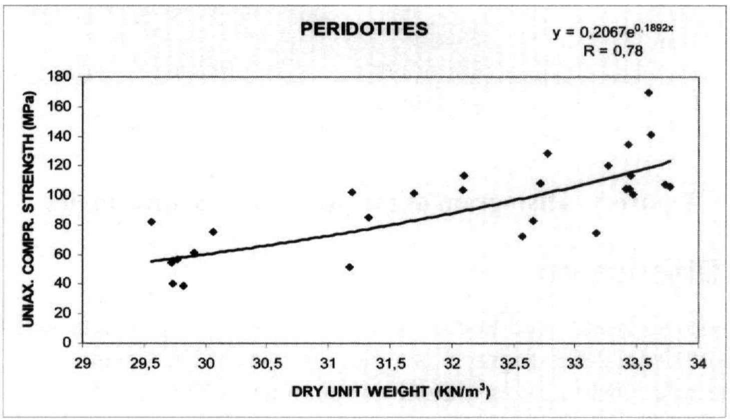

Figure 10 - UCS against Dry unit weight only for the Peridotites

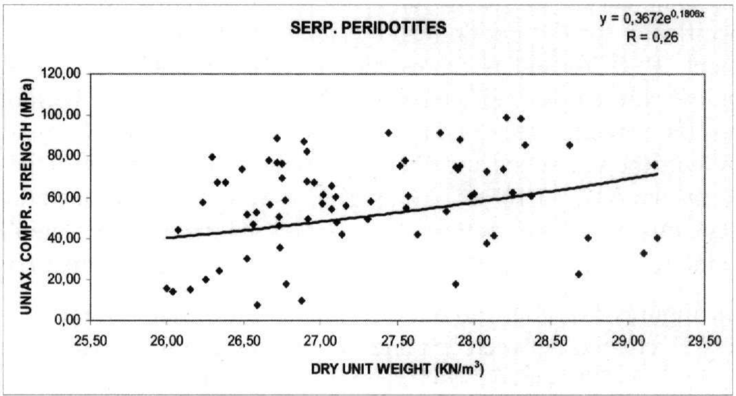

Figure 11 - UCS against Dry unit weight only for the Serpentinised Peridotites

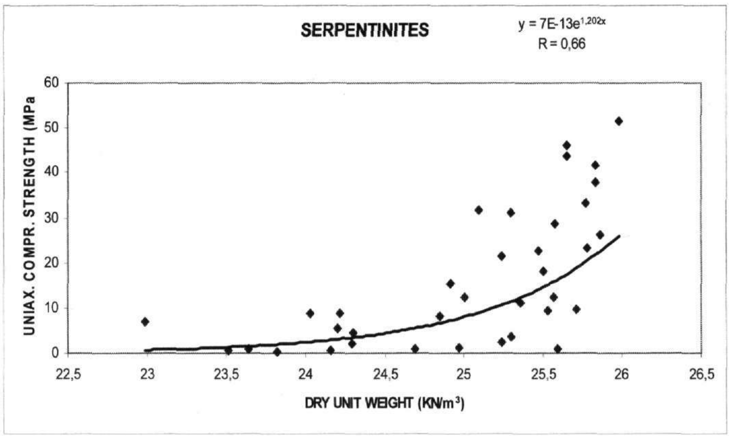

Figure 12 - UCS against Dry unit weight only for the Serpentinites

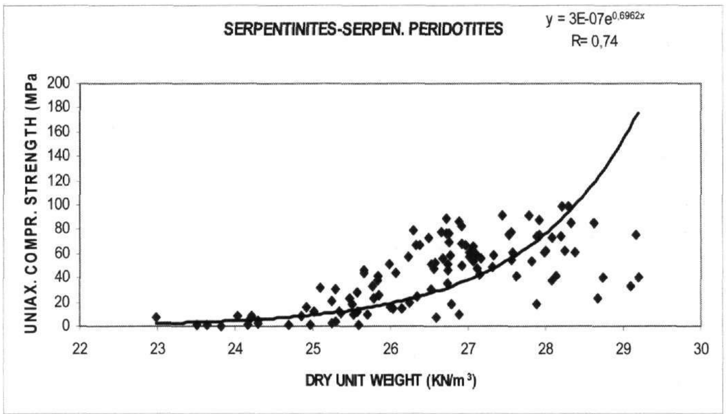

Figure 13 - UCS against Dry unit weight combining Serpentinised Peridotites and Serpentinites

6. Conclusions

Due to the petrographic variety, the grade of serpentinisation, preferred orientation of olivine and orthopyroxene, the structural complexity and the internally imprinted tectonic deformation, ultrabasic rocks were divided in three groups (Peridotites, Serpentinised Peridotites and Serpentinites). Each group presents a wide range of geomechanical and physical properties.

This paper demonstrates that for ultrabasic rocks, the relationship between UCS and γ gives a good correlation coefficient (R=0.66) and is defined by the equation $UCS=0.0063e^{0.3117\cdot\gamma}$. For the Peridotites only, the relationship between UCS and γ gives a high correlation coefficient (R=0.78) and is represented by $UCS=0.2067e^{0.1892\cdot\gamma}$. As far as Serpentinised Peridotites are concerned, the relationship between UCS and γ presents a low correlation coefficient (R=0.26) in contrast to Serpentinites (R=0.66). It was realized that the examination of Serpentinised Peridotites and Serpentinites together provides a good correlation coefficient (0.74) and the new equation is defined by the $UCS=3\cdot10^{-7}e^{0.6962\cdot\gamma}$. It is obvious that the determination of UCS value with an easy and economical way (estimation of γ) can provide an important help to the geotechnical engineers.

Furthermore, the majority of the ultrabasic samples were fractured in one angle, which mainly varied between 75° and 90°. The samples broken in two fractures, presented an increase of the percentage of the bins 45°-59° and 60°-74° while the percentage of the bin 75°-90° got decreased. Moreover, the fracture angles of 30°-44° were mainly correlated with low angle thrusts, the bin of 45°-59° corresponds to the thrusts and that of 60°-90° to the faults or collapse effects.

Finally, there is no apparent relationship between the fracture angle and the depth from which the sample was taken and between the UCS and the fracture angle.

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