Evaluating the Triaxial Characteristics of Ultamafic Rocks from Central Greece Using the Physical, Dynamic and Mechanical Properties

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Abstract

Due to the fact that the estimation of the triaxial parameters is very important in any geotechnical project, many attempts have become with the aim of their determination. In spite of its relative simplicity, triaxial tests are time consuming, expensive, and require a large number of well prepared (regularly shaped) rock specimens and suitable testing procedures. For this reason, they cannot be easily determined in rocks which are thinly bedded, highly fractured, weak, and so indirect, fast, practical, easy and economical ways should be used such as the correlation of them with some other characteristics which are calculated easily. The aim of this study is to apply correlation analysis to investigate the relationships between physical, dynamic and mechanical characteristics and triaxial parameters for ultramafic rocks. Thus, sixteen samples, taken from the western part of Othrysmt (ten samples) and the Kallidromomt (six samples, central Greece), were tested and the relations among the properties were described by simple regression analyses. The study reveals strong negative, logarithmic correlations between the effective porosity and triaxial parameters (c, φ). Positive, linear relationships are also indicated between wave velocities, apparent cohesion and friction angle, while the increase of serpentinization percentage causes decrease of the c, φ. Both dry unit weight and Schmidt Hammer Values are logarithmically affected with c, φ. The point load strength index and apparent cohesion and friction angle are strongly correlated by both logarithmic and linear functions, but logarithmic trends present higher determination coefficients.

Subject Areas

Civil Engineering

1. Introduction

The construction of geotechnical engineering projects like foundations, rock slopes and underground structures is based on the estimation of the rock mass properties. The determination of the triaxial parameters is very important because the rock-mass properties are estimated through them. Despite of its relative simplicity, triaxial tests are time consuming, expensive, and require a large number of well prepared (regularly shaped) rock specimens and suitabletesting procedures. Some rocks are thinly bedded, highly fractured, weak, present alterations such as ultramafic rocks with the result they are usually not suitable for preparing specimens and the determination of triaxial parameters is very difficult. On the other hand the fact that ultramafic rocks are met in many areas all over the world and especially south-eastern Europe has as a result many engineering geology projects to be constructed on/in them [1]. For the above-mentioned reasons, indirect, reliable, quick, sample and economical ways are necessary to estimate the triaxial parameters for the ultramafic rocks.

Ultramafic rocks are members of ophiolitic suite rocks which represent remnants of the Earth's oceanic crust and upper mantle. Basic, hypabyssal and extrusive rocks cover ultramafic rocks. This succession is idealized and in most cases some members may be absent. This research focuses on ultramafic rocks. They include particular types of geological formation with both petrographic variety (harzburgites, lherzolites, plagioclastic peridotites, dunites, etc.) and structural complexity due to tectonic deformation and alteration. This ocean-floor metamorphism (serpentinization) lead to a modification of their petrographic characteristics (serpentinized varieties of them). Thus, they are from massive strong to weak rocks (peridotites and serpentinites, [1]-[8]).

Within the framework of the present study, sixteen ultramafic rocks (six peridotites and ten serpentinites) were taken from the Kallidromomt and the western part of Othrysmt (Central Greece), the dry unit weight (γ_d), the effective porosity (n_e), the compressional wave velocity (V_p), the shear wave velocity (V_s), the Schmidt Hammer Values (SHV), the point load strength index (I_{s50}) were determined and presented. The Uniaxial Compressive Strength (σ_{ci}) and the material constant (m_i) were estimated by the Hoek and Brown failure criterion and the triaxial characteristics (apparent cohesion, c and friction angle φ) were presented.

The main objective of this research is was to determine the predictability of apparent cohesion (c) and friction angle (φ) of ultramafic rocks (serpentinites and peridotites) with a simple, fast, practical and economical way through the physical, dynamic and mechanical properties at the preliminary site investigation stage. The results were statistically analyzed using the method of least-squares regression. The relationships among these parameters were described by the best fit equations and the highest correlation

coefficient, in each relationship, was also determined. The same samples were subjected to petrographic studies with the aim of describing the main mineralogical composition and the serpentinization percentage of ultramafic rocks.

2. Location and Geology of the Study Area

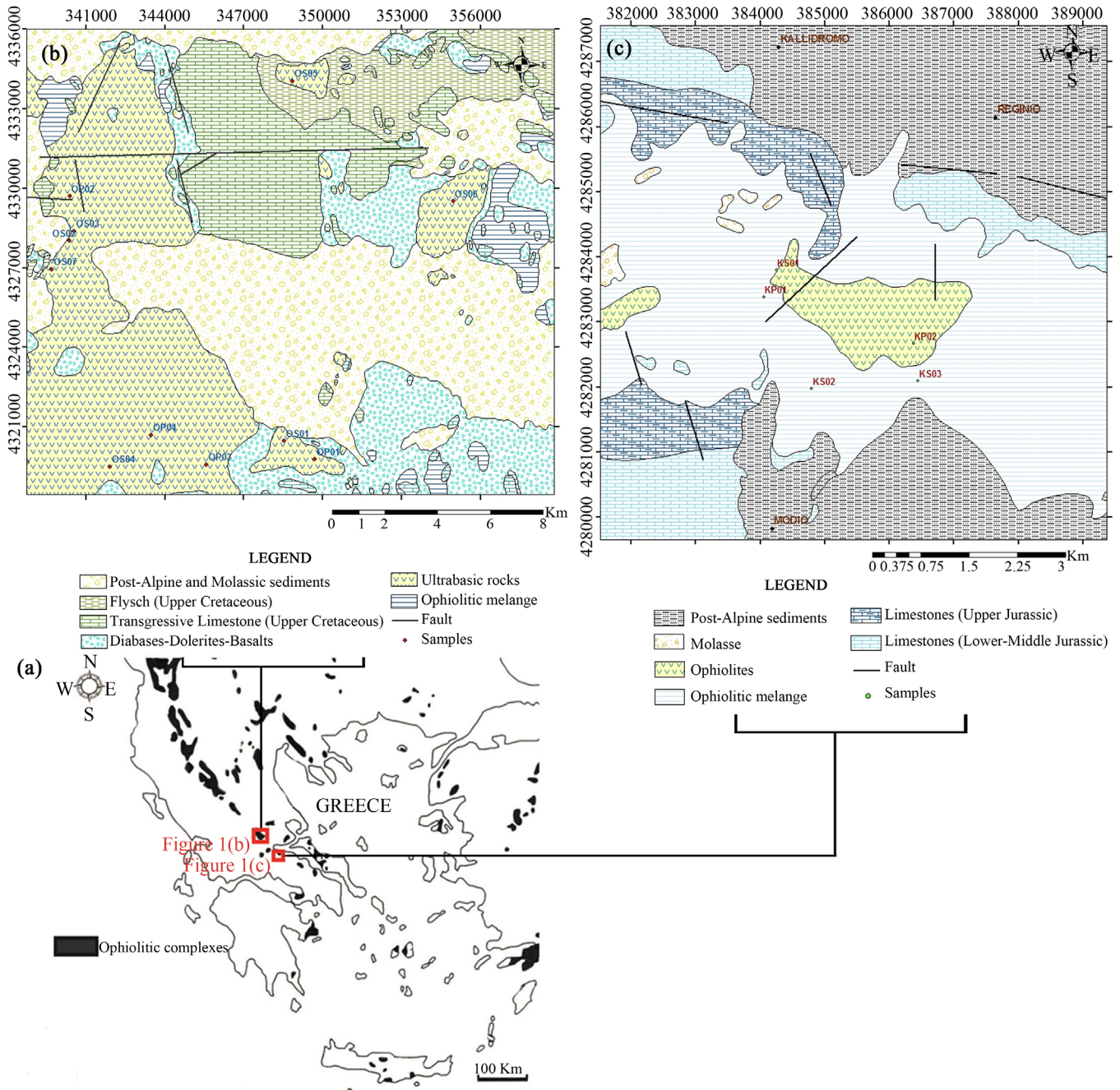The study area is to be found in the central part of Greece (Figure 1(a)) and specifically

Figure 1. (a) Study areas and ophiolitic complexes in Greece; (b) Geoligigal map and sampling points of the study area at Othrys Mt; (c) Geoligigal map and sampling points of the study area at Kallidromo Mt.

at western part of Othrys Mt. (near the villages of Moschokarya, Mega Isoma, Loutra-Kaitsas and Domokos, **Figure 1(b)**) and at the eastern-southeastern side of Kallidromo Mt (between the villages of Kallidromo, Reginio and Modio, **Figure 1(c)**). It belongs to the Sub-Pelagonian geotectonical unit, which is part of the Internal Hellenides and is mainly comprised of Alpine formations ([9] [10] [11] [12]). They can be distinguished into:

1) A carbonate sequence of Triassic-Jurassic age which constitutes the basement of the area.

2) A tectonic nappe, mainly ophiolitic (volcano-sedimentary formations, basaltic lavas, basic rocks and ultramafic masses, [11]).

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

The present study research focuses on ophiolitic sequence and mainly on ultramafic masses. They are mainly represented by the peridotites whose degree of serpentinization varies.

3. Methods and Results

3.1. Sample Preparation and Test Procedures

The data pertains to ultramafic rocks sampled from sixteen sites in the study areas (eleven from Othrys and six from Kallidromo, **Figure 1**). The samples were taken from the surface and cylindrical rock specimens for laboratory testing were prepared according [13] requirements. To reduce the uncertainty regarding the influence of the sample size on the measured properties and especially on strength [14] [15], their diameters range between 53 and 55 mm, the length to diameter ratio was between 2.0 and 2.5 and the edges of the specimens were cut parallel and smooth [13]. After a macroscopical inspection, seventy-four isotropic, homogeneous, unweathered (or slightly weathered) and free of visible joints ultramafic specimens were considered. The dry unit weight and the effective porosity were determined in accordance with [16]. The sound velocities (V_p, V_s) were calculated from the travel time with the application of ultrasonic compression wave pulses to the samples in accordance with test designations [17]. Moreover, point load strength index values were determined according to [18] requirements (in sixteen specimens, ten serpentinites and six peridotites) and a Type L Schmidt Hammer was used for the determination of Schmidt Hammer Values. Ten points on each specimen were taken and the mean values were calculated. The Schmidt hammer tests were carried out according to [16]. In addition, the triaxial tests were determined using a Hoek cell according to [19]. Three or four different confining pressures (σ_3) applied during the triaxial tests (fifty-eight specimens). Range of confining pressures of $0 < \sigma_3 < 0.5\sigma_{ci}$, proposed by [14], was used. The specimens were first subjected to the required confining pressure and then the axial load was applied until the specimen failed.

Thin sections, from samples of the sixteen areas, were prepared and examined under the polarizing microscope, at the Mineralogy-Geology Laboratory of the Agricultural

University of Athens, with the aim of describing the main mineralogical composition and the serpentinization percentage of ultramafic rocks. Fractures created by the tests, did not follow internal discontinuities and were always fresh. The tests were carried out in dry conditions for a better relation of the results.

3.2. Petrographic Properties of Ultramafic Rocks

The ultramafic rocks include rock types (peridotites) with large variability (harzburgites, lherzolites, plagioclasticperidotites, dunites, etc.), which due to their tectonic deformation and a low grade metamorphism (serpentinization, [20]) lead to a modification of their petrographic characteristics (serpentinites). Serpentinisation is the transformation of ferromagnesian minerals, olivine in particular, to serpentine, which is a lattice mineral of either fibrous or laminar form. This alteration allows the understanding of the dramatic changes in the behavior of ultramafic rocks, reduces their strength and generally the physical, dynamic and mechanical characteristics [1]-[8].

In this paper, sixteen thin sections were prepared and examined under a polarizing microscope. The studied rock samples are unaltered or slightly serpentinized (serpentinization < 30% by volume) ultramafic rock types, characterized as peridotites and partially to completely serpentinizedperidotites (serpentinization > 70% by volume) called as serpentinites. The investigated peridotites mainly comprised of olivines, ortho and clino pyroxenes which are characterised as parent-primary minerals (P_m > 74% by volume, Table 1).

When the peridotites are influenced by the serpentinization, they transformed into Serpentinites. Serpentinites are mainly composed of secondary minerals (70% - 92%, by volume, Table 1). Serpentine is the major mineral phase (62% - 84% by volume, Table1, [1]). Also, some other secondary minerals are chlorite, talc and actinolite comprising up to 13%. Thus, the percentage of the remaining parent rock minerals (olivine, pyroxene), is less than 30%. The mean values of serpentinization for peridotites and serpentinites are 9.17% and 79.90% respectively, while the standard deviations are 8.75 and 7.02 respectively (Table 2).

3.3. Physical, Dynamic and Mechanical Properties

The dry unit weight (γ_d) and effective porosity (n_e) were determinedfor 6 peridotites and 10 serpentinites samples and their values are listed in Table 3. The γ_d and n_e for peridotites range from 31.67 to 33.17 KN/m^3 and from 0.07 to 0.19 respectively. On the other hand, the values of γ_d and n_e for serpentinites fluctuate between 24.95 and 26.79 KN/m^3 and from 0.39 to 3.59 respectively. The serpentinites present lower dry unit weight values and higher effective porosity than peridotites because they are mainly composed of secondary minerals (as it is afore-mentioned) which have lower specific gravity and more voids.

The compressional wave velocity (V_P) and shear wave velocity (V_s), which were determined as above-mentioned in chapter 3.1, are given in Table 3 as well. The values of V_P for peridotites and serpentinites fluctuate between 7412 and 7991 m/sec and from 4955 to 5645 m/sec respectively, while the mean values are 7781 m/sec (S.D. 211) and 5361

Table 1. Primary minerals, secondary minerals and serpentinization percentage for ultramafic rocks.

Sample No	Primary Minerals					Secondary Minerals				Degree of Serpentinization b (%)
	Ol (%)	Opx (%)	Cpx (%)	Pl (%)	Sp (%)	Serp (%)	Chl (%)	Tc (%)	Act (%)	
KP01	71	22				6	1			7
KP02	75	21	-	-	1	3	-	-	-	3
OP01	50	11	12	-	1	22	2	1	1	26
0P02	66	21	-	-	2	10	1	-	-	11
OP03	74	19	3	-	-	3	1	-	-	4
OP04	85	10	-	-	1	2	2	-	-	4
KS01	9	9	5	-	1	63	4	5	4	76
KS02	10	6	3	-	1	71	2	7	-	80
KS03	10	7	11	-	2	62	7	1	-	70
OS01	5	3	-	-	-	84	5	2	1	92
OS02	8	6	-	-	-	76	6	3	1	86
OS03	7	6	-	-	-	79	7	1	-	87
OS04	8	11	7	-	1	66	4	2	1	73
OS05	6	9	-	-	2	79	2	1	1	83
OS06	13	8	-	-	1	68	5	4	1	78
OS07	14	11	-	-	1	69	4	1	-	74

KP: Peridotite of Kallidromo, OP: Peridotite of Othrys, KS: Serpentinite of Kallidromo, OS: Serpentinite of Othrys.

Table 2. Statistical analysis of the serpentinization percentage for ultramafic rocks.

	Peridotites	Serpentinites
	Serpentinization percentage, β (%)	Serpentinization percentage, β (%)
Maximum value	26	92
Minimum value	3	70
Mean value	9.17	79.90
Standard Deviation	8.75	7.02

m/sec (S.D. 225) respectively. As far as V_s values are concerned, they vary between 4171 and 4539 m/sec for peridotites and from 2464 to 3044 m/sec for serpentinites. The mean values for serpentinites and peridotites are 2795 and 4392 m/sec respectively. According to [2] [3] and [5], both unit weight and velocities decrease with increasing of serpentinization.

Moreover, the Schmidt Hammer Values (SHV) range between 61.25 and 64.69 for peridotites (Table 3), present mean value 63.75 and their standard deviation is 1.24. On

Table 3. Physical, dynamic and mechanical property values for ultramafic rocks.

Samples No	Effective Porosity, n_e	Dry Unit Weight, γ_d (KN/m³)	Comp. Wave Velocity, V_P (m/sec)	Shear Wave Velocity, V_s (m/sec)	Schmidt Hammer Values, SHV	The point load strength index, I_{s50} (MPa)
KP01	0.07	33.1	7959	4539	64.08	10.63
KP02	0.11	32.92	7850	4458	64.69	10.14
OP01	0.19	31.67	7412	4171	61.25	8.27
0P02	0.14	32.13	7704	4290	64.13	7.27
OP03	0.09	33.02	7769	4372	64.17	10.53
OP04	0.08	33.17	7991	4524	64.15	10.42
KS01	0.64	26.2	5442	2850	52.97	3.94
KS02	0.75	26.12	5473	2888	52.73	3.41
KS03	0.39	26.79	5646	3044	54.49	4.91
OS01	3.59	24.95	4955	2464	49.52	2.01
OS02	2.36	25.08	5152	2666	50.55	2.28
OS03	2.29	25.37	5154	2640	50.7	3.19
OS04	0.51	26.6	5637	3000	54.02	4.42
OS05	1.6	25.61	5313	2727	51.5	3.23
OS06	1.26	25.93	5320	2748	51.89	2.81
OS07	0.53	26.35	5520	2928	53.34	3.85

the other hand, in serpentinites the SHV vary from 49.52 to 54.49, the mean value is 52.17 and their standard deviation is 1.61 (Table 4).

In this research, only diametrical point load tests were carried out on the samples. The point load strength index (I_{s50}) (referred to a standard size 50 mm) values are listed in Table 3. The point load strength index values range from 2.01 to 4.91 MPa in serpentinites and between 7.27 and 10.63 MPa in peridotites. The mean values are 3.41 (S.D. 0.91) and 9.54 MPa (S.D. 1.42) respectively (Table 4).

In this research, the triaxial tests were carried out in fifty-eight specimens (three confining pressures at least in each sample ranging from 3 to 18 MPa, Table 5) and the material constant (m_i) and the σ_{ci} were estimated by the Hoek and Brown failure criterion (Table 5). For this criterion [14] [21] [22] [23] [24], the maximum and minimum total stresses at failure (σ_1 and σ_3) for intact rock are correlated by the following equation:

$$\sigma_1 = \sigma_3 + \sigma_{ci}\left[m_i\frac{\sigma_3}{\sigma_{ci}}+1\right]^{1/2} \qquad (1)$$

where,

σ_1, σ_3, the maximum and minimum (confining) total stresses at failure for intact rock,

Table 4. Statistical analysis of the physical, dynamic and mechanical properties for ultramafic rocks.

		Maximum value	Minimum value	Mean value	Standard Deviation
Peridotites	Effective Porosity, n_e	0.19	0.07	0.12	0.04
	Dry Unit Weight, γ_d (KN/m³)	33.17	31.67	32.67	0.62
	Comp. Wave Velocity, V_P (m/sec)	7991	7412	7781	211
	Shear Wave Velocity, V_s (m/sec)	4539	4171	4392	143
	Schmidt Hammer Values, SHV	64.69	61.25	63.75	1.24
	The point load strength index, I_{s50} (MPa)	10.63	7.27	9.54	1.42
Serpentinites	Effective Porosity, n_e	3.59	0.39	1.39	1.06
	Dry Unit Weight, γ_d (KN/m³)	26.79	24.95	25.90	0.63
	Comp. Wave Velocity, V_P (m/sec)	5645	4955	5361	225
	Shear Wave Velocity, V_s (m/sec)	3044	2464	2795	180
	Schmidt Hammer Values, SHV	54.49	49.52	52.17	1.61
	The point load strength index, I_{s50} (MPa)	4.91	2.01	3.41	0.91

σ_{ci}, the uniaxial compressive strength of intact rock,

m_i, the material constant which depends on the properties of intact rock.

Finally the apparent cohesion (*c*) and the friction angle (*φ*) for intact rock were calculated using triaxial compressive strength test data (Table 5). The confining pressures were plotted against axial stresses with the σ_3 as abscissa and the σ_1 as ordinates (Figure 2 and Figure 3). The best linear lines passing through the points are fitted using the least squares technique. The regression functions of this line for peridotites and serpentinites are respectively:

$$\sigma_1 = 9.16\sigma_3 + 188.72 \tag{2}$$

and

$$\sigma_1 = 5.85\sigma_3 + 73.07 \tag{3}$$

Furthermore, *c* and *φ* were calculated using the following equations:

Table 5. The maximum and minimum (confining) total stresses, the material constant, the friction angle, the apparent cohesion and the estimated uniaxial compressive Strength values for ultramafic rocks.

Sample No	Axial Load, P (kN)	Axial Stress, $\sigma_1 = P/A$ (MPa)	Confining Pressure, σ_3 (MPa)	Material constant, m_i	Friction Angle, φ (°)	Apparent Cohesion, c (MPa)	Estimated Uniax. Compressive Strength, σ_{ciestm} (Mpa)
KP01A	520	224.66	3				
KP01B	605	261.39	6	26.58	54.13	32.18	184.43
KP01C	857	370.26	18				
KP01D	651	281.26	9				
KP02A	573	247.56	3				
KP02B	609	263.12	6	28.16	54.78	35.54	206.44
KP02C	906	391.43	18				
KP02D	809	349.53	9				
KS01A	220	95.05	3				
KS01B	269	116.22	6	14.27	44.10	16.98	73.97
KS01C	338	146.03	12				
KS02A	232	102.11	3				
KS02B	276	121.47	6	14.39	44.64	17.94	79.95
KS02C	350	154.04	12				
KS03A	337	148.87	3				
KS03B	344	151.96	6	16.04	46.58	24.48	115.37
KS03C	539	238.11	18				
KS03D	406	179.35	9				
OP01A	284	122.70	3				
OP01B	369	159.43	6	21.09	48.17	20.96	95.89
OP01C	534	230.71	18				
OP01D	398	171.95	9				
OP02A	486	214.69	3				
OP02B	531	233.70	6	25.20	53.37	30.33	170.27
OP02C	789	348.54	18				
OP02D	596	263.29	9				
OP03A	582	250.53	3				
OP03B	609	262.15	6	27.76	55.01	33.85	200.41
OP03C	918	395.16	18				
OP03D	726	312.51	9				
OP04A	520	229.71	3	26.69	54.09	32.84	187.52

Continued

OP04B	567	250.48	6				
OP04C	837	369.75	18				
OP04D	685	302.60	9				
OS01A	116	50.12	3				
OS01B	163	70.42	6	12.76	38.05	9.88	33.55
OS01C	208	89.54	12				
OS02A	133	57.25	3				
OS02B	168	72.32	6	13.10	39.59	10.44	37.96
OS02C	228	98.14	12				
OS03A	161	69.30	3				
OS03B	174	74.90	6	13.52	39.44	12.54	45.00
OS03C	311	133.87	18				
OS03D	222	95.56	9				
OS04A	238	102.45	3				
OS04B	291	125.73	6	14.82	44.92	18.15	81.01
OS04C	362	155.83	12				
OS05A	174	74.90	3				
OS05B	222	95.56	6	13.67	42.00	13.81	55.47
OS05C	282	121.39	12				
OS06A	221	97.27	3				
OS06B	246	108.27	6	13.86	42.17	18.24	73.9
OS06C	391	172.08	18				
OS06D	305	134.23	9				
OS07A	268	117.95	3				
OS07B	297	131.20	6	15.52	44.64	21.21	92.32
OS07C	460	202.45	18				
OS07D	365	160.05	9				
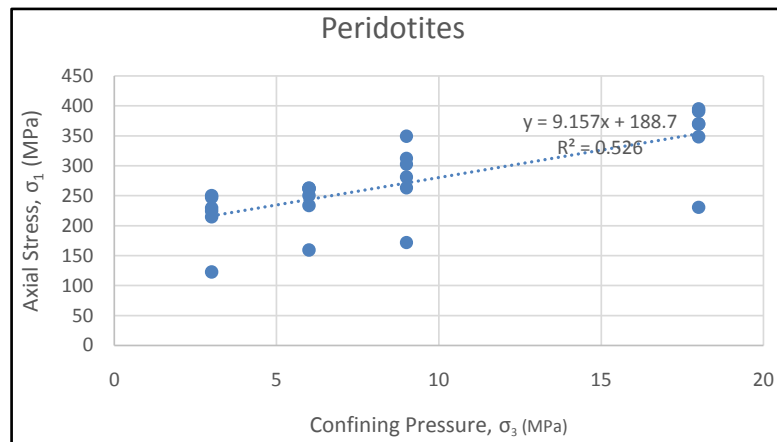
Figure 2. The confining pressures (σ_3) against axial stresses (σ_1) for Peridotites.
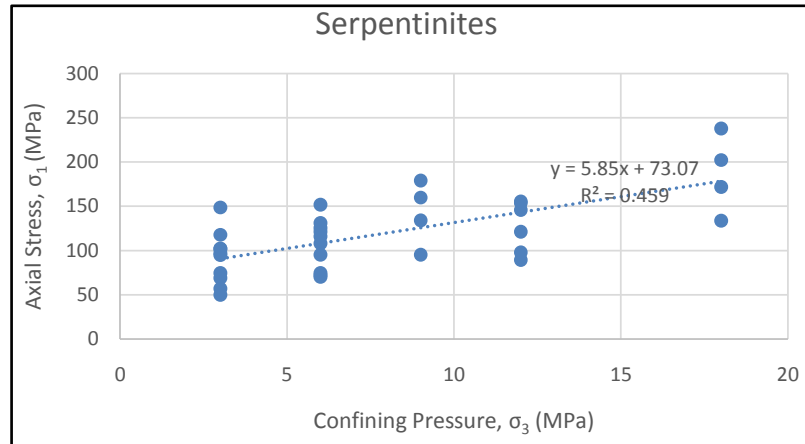
Figure 3. The confining pressures (σ_3) against axial stresses (σ_1) for Serpentinites.

$$\varphi = \arcsin\left((\alpha-1)/(\alpha+1)\right) \tag{4}$$

$$c = \sigma_{ci}\left(1-\sin\varphi\right)2\cos\varphi \tag{5}$$

where

a, the gradient of the Equations (2) and (3).

4. Correlation Analysis

Least squares regression analysis was applied in order to describe the relationships among triaxial characteristics (*c*, *φ*), physical, dynamic, mechanical properties and the petrographic data of the ultramafic rocks. The equation of the best-fit line and the determination coefficient (R^2) were determined for each regression. Techniques from Excel 2003 software (Analysis ToolPak program) was used to process the data.

Correlation between Triaxial Parameters and Physical, Dynamic and Mechanical Properties

In this study, an attempt to correlate *c* and *φ* with dry unit weight is respectively presented in **Figure 4** and **Figure 5**. The logarithmic equation seems to fit better ($R^2 = 0.84$) the dry unit weight with the apparent cohesion while the relationship between *φ* and γ_d is better described by the linear equation ($R^2 = 0.92$). The regression lines representing the best fit between effective porosity and *c*, *φ* are logarithmic (**Figure 6** and **Figure 7**). The apparent cohesion and the friction angle using the effective porosity values can be expressed by the empirical equations:

$$c = -6.34\ln\left(n_e\right)+16.83 \ \left(R^2 = 0.91\right) \tag{6}$$

$$\varphi = -4.46\ln\left(n_e\right)+43.08 \ \left(R^2 = 0.96\right) \tag{7}$$

Moreover, the plots of the apparent cohesion values as a function of sound velocities (V_p, V_s) values are shown in **Figure 8**. The best fit relationships are found to be linear and the determination coefficients are 0.83 and 0.84 respectively. The correlations between the friction angle and the wave velocities were also determined. A positive
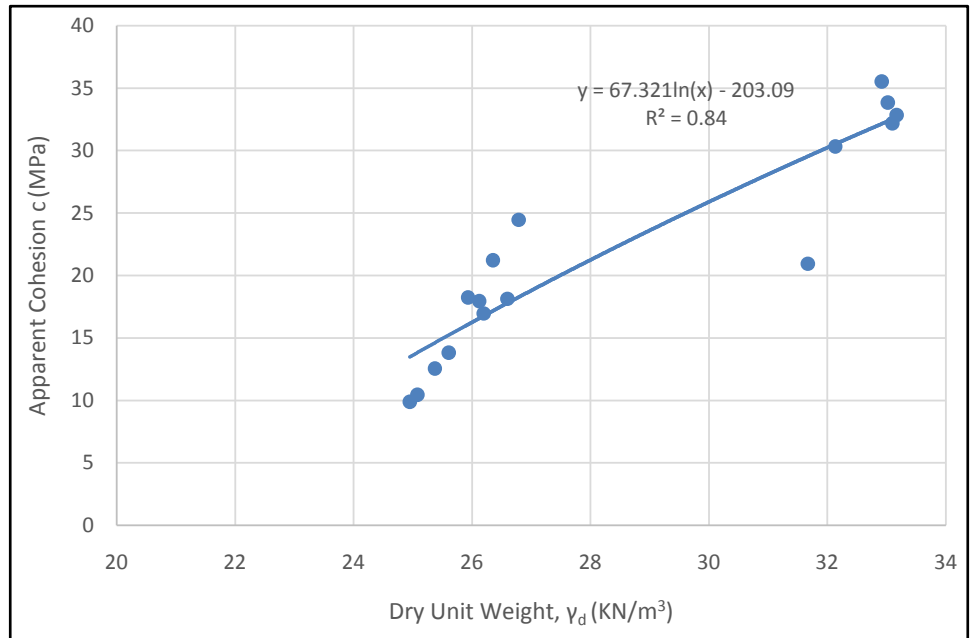
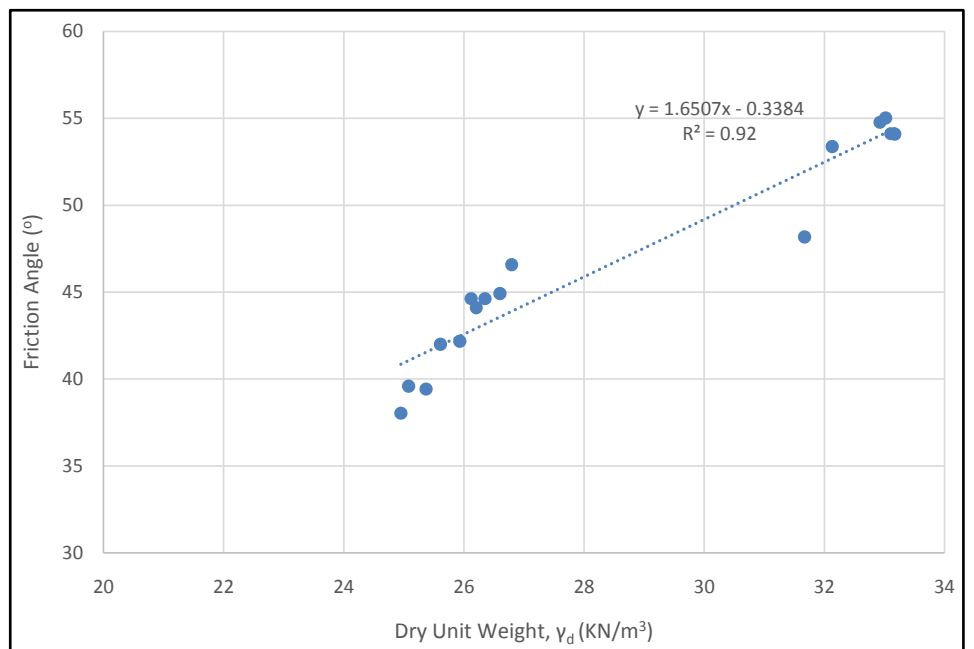**Figure 4.** Relationship between apparent cohesion and dry unit weight for ultramafic rocks.

Figure 5. Correlation between friction angle and dry unit weight for ultramafic rocks.

relationship was found between the φ and the V_P, V_s (**Figure 9**) indicating that the friction angle increase with increasing wave velocities. The logarithmic model gives high R^2 values, but better correlation is described by the linear trends (**Figure 9**).

As it is illustrated in **Figure 10**, **Figure 11** the friction angle and apparent cohesion present visible correlations with the degree of serpentinization (β). The c, φ decrease linearly with the increase of β. The relationship between φ and β presents higher
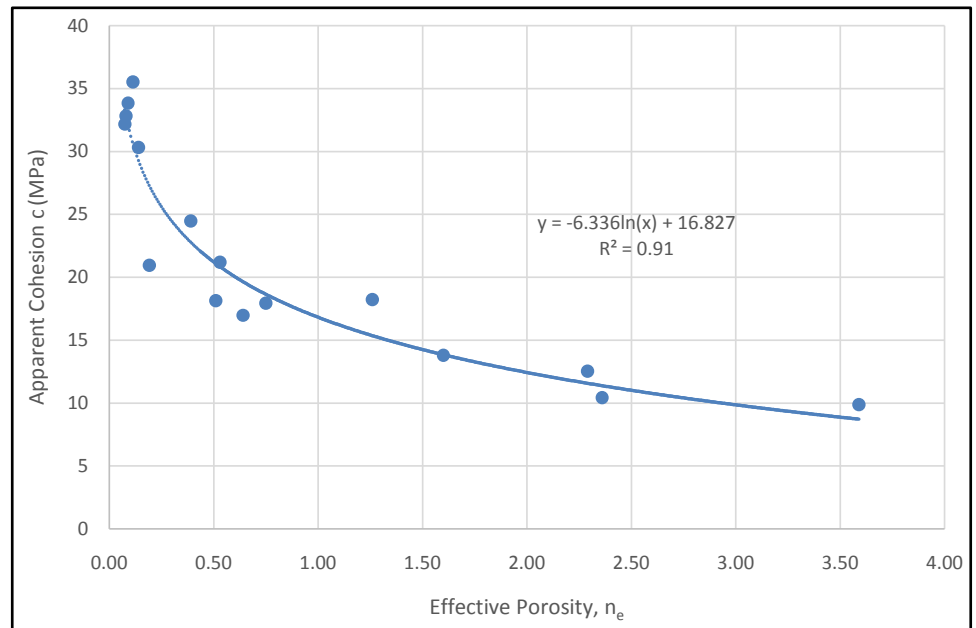
Figure 6. Relation between apparent cohesion and effective porosity for ultramafic rocks.
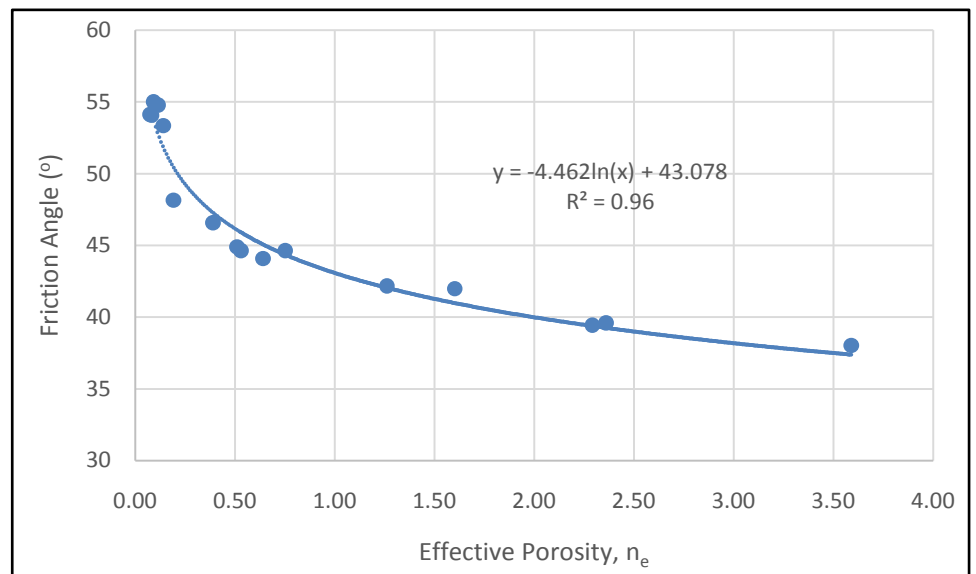

Figure 7. Logarithmic function between friction angle and effective porosity for ultramafic rocks.

determination coefficient ($R^2 = 0.93$) than that between c and β ($R^2 = 0.86$).

In addition, **Figure 12** presents the plot of the apparent cohesion against Schmidt Hammer Values (*SHV*). The best fit equation is logarithmic and the relation between them presents high determination coefficient ($R^2 = 0.88$). The plots of the friction angle as a function of the SHV are shown in **Figure 13**. The best fit equation is logarithmic with high determination coefficient ($R^2 = 0.95$).

As shown in **Table 6**, linear and logarithmic functions can describe the relationships between c and I_{s50} and between φ and I_{s50}. The logarithmic equations seem to fit better
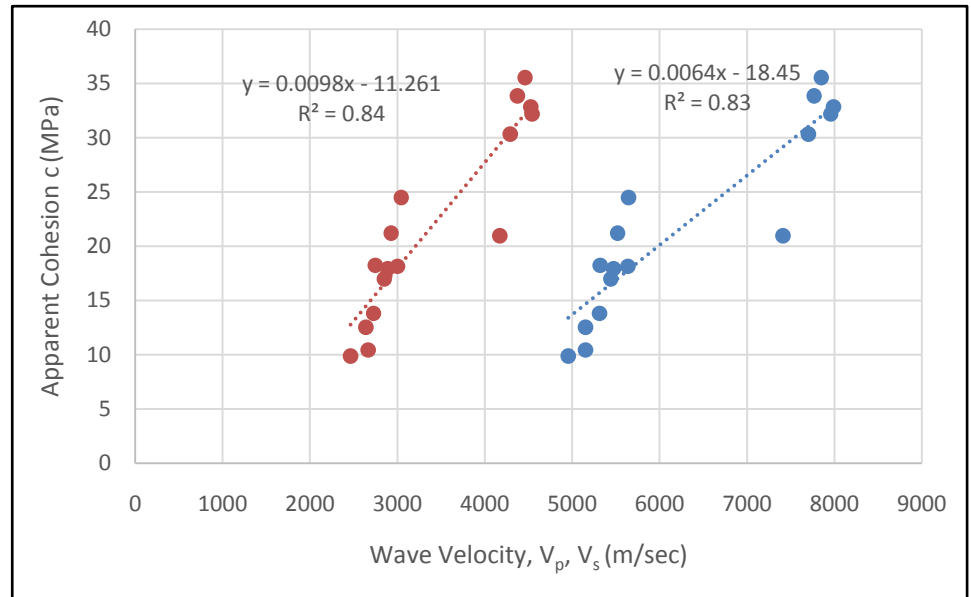
Figure 8. Relationship of wave velocities with apparent cohesion for ultramafic rocks.
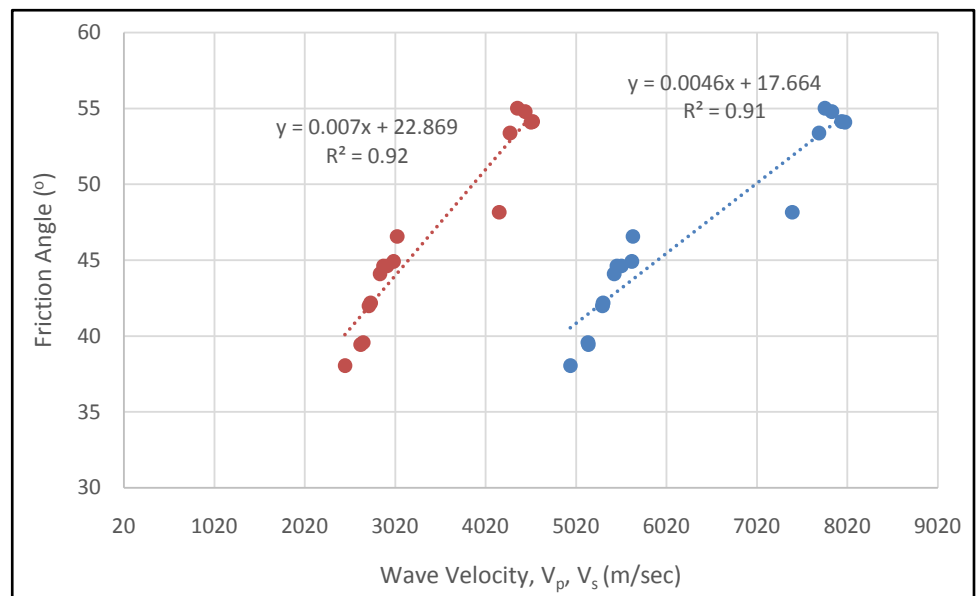

Figure 9. Correlation between wave velocities and friction angle for ultramafic rocks.

the above-mentioned properties than the linear equations, exhibiting *R*-square values 0.87 and 0.93 respectively. The logarithmic functions are illustrated in **Figure 14** and **Figure 15**.

5. Conclusions

The estimation of the triaxial parameters is considered to be the most important component in any engineering geology project because the rock-mass properties are calculated through them. Despite of their simple, fast and easy determination, they require a
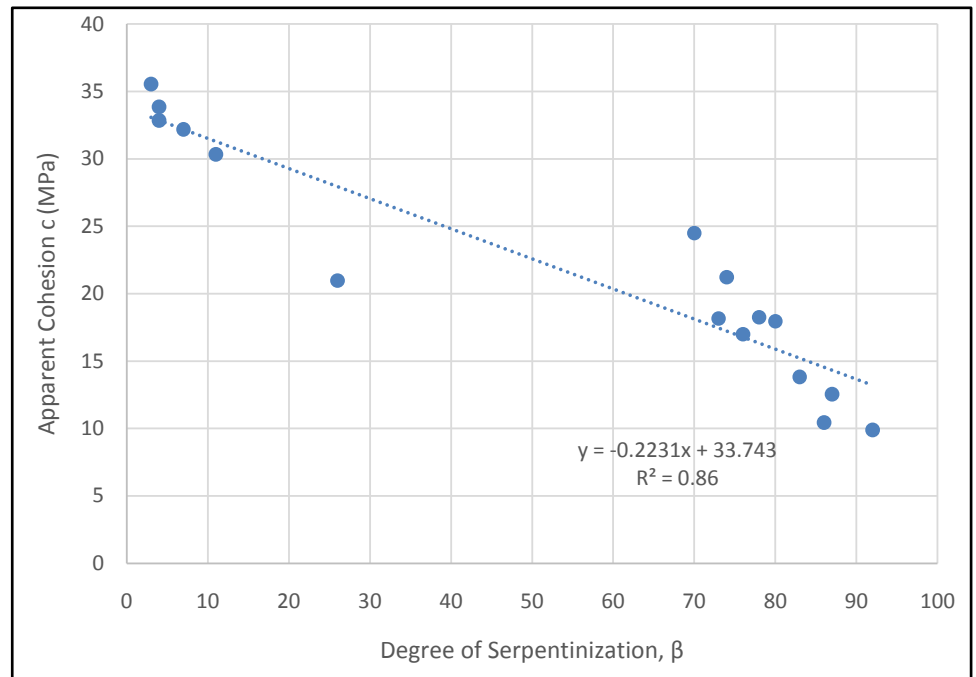
Figure 10. Relationship between degree of serpentinization and apparent cohesion for ultramafic rocks.
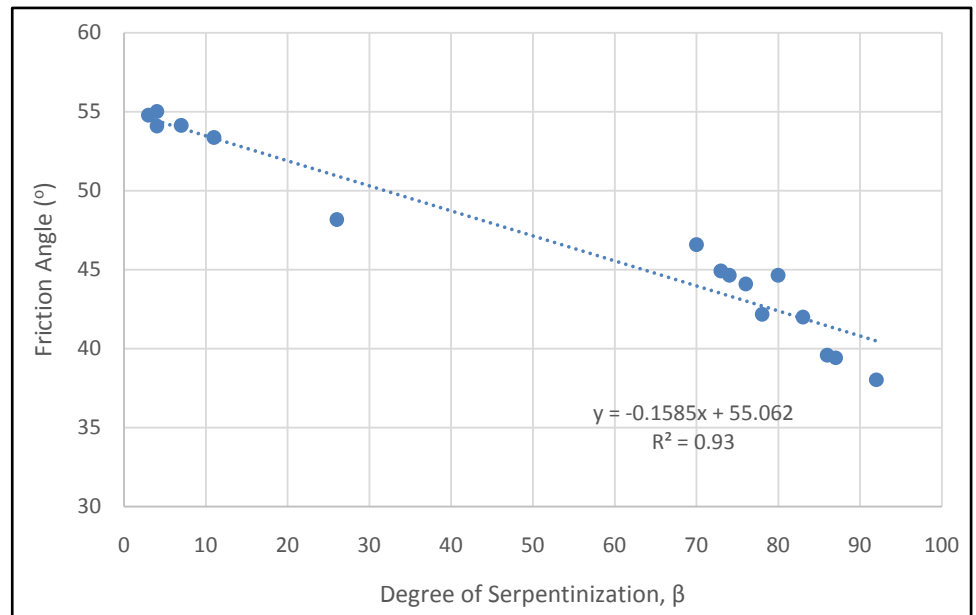

Figure 11. Correlation between degree of serpentinization and friction angle for ultramafic rocks.

large number of well prepared (regularly shaped) rock specimens. But ultramafic rocks (especially serpentinites) are usually not suitable for preparing specimens. Thus, the immediate determination of the triaxial characteristics is usually difficult for these rocks. For this reason, this study mainly attempts to develop empirical equations between triaxial parameters and physico-mechanical properties.
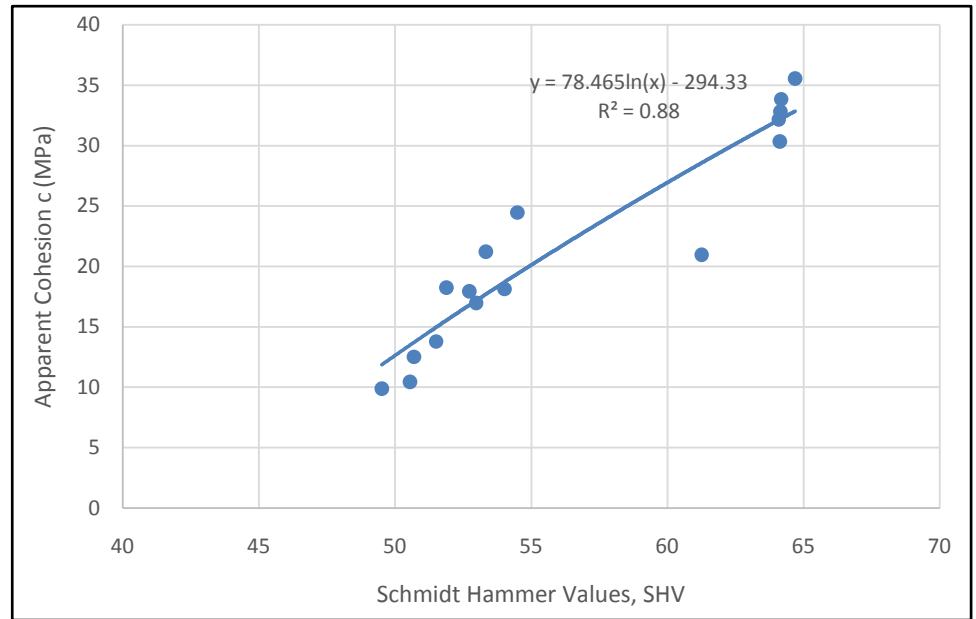
Figure 12. Relationship of Schmidt hammer values with apparent cohesion for ultramafic rocks.
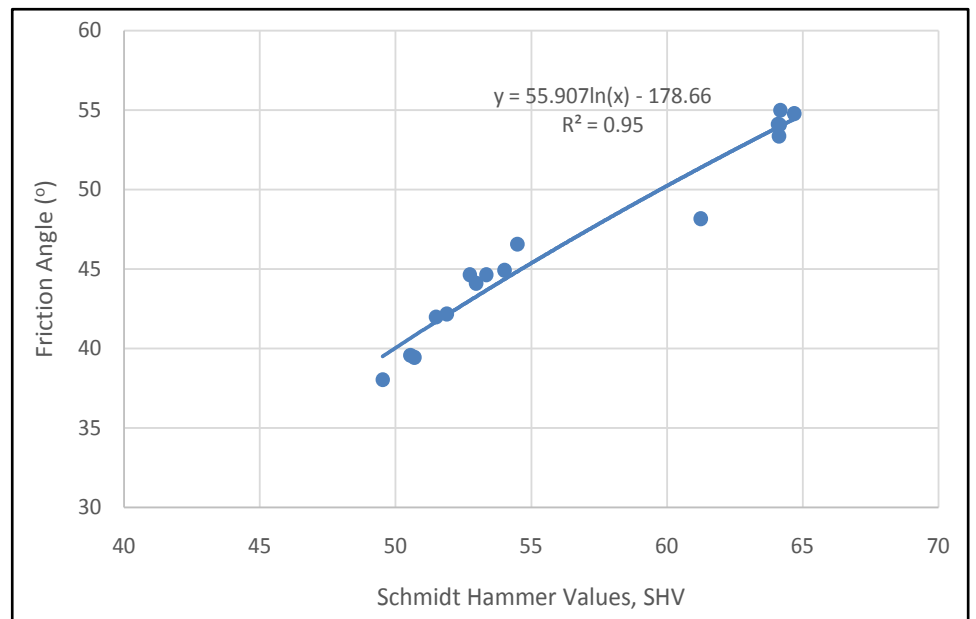

Figure 13. Variation of Schmidt hammer values against friction angle for ultramafic rocks.

In this paper ultramafic samples, taken from sixteen sites of central Greece (western part of Othrysmt and the Kallidromomt), were tested in laboratory and the triaxial properties were predicted through the wave velocities by simple regression analysis.

The research demonstrates that the friction angle (φ) exhibits strong linear correlation with the dry unit weight (γ_d) ($R^2 = 0.92$) while the logarithmic equation seems to correlate better ($R^2 = 0.84$) the dry unit weight with the apparent cohesion (c).

Significant negative logarithmic relationships exist between the triaxial parameters
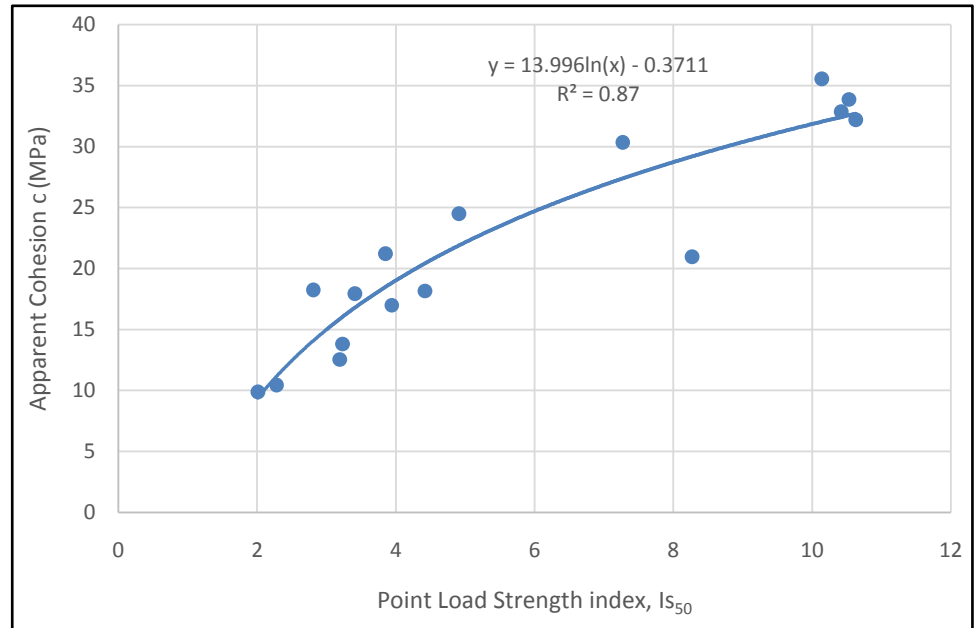
Figure 14. Correlation between point load strength index and friction angle for ultramafic rocks.
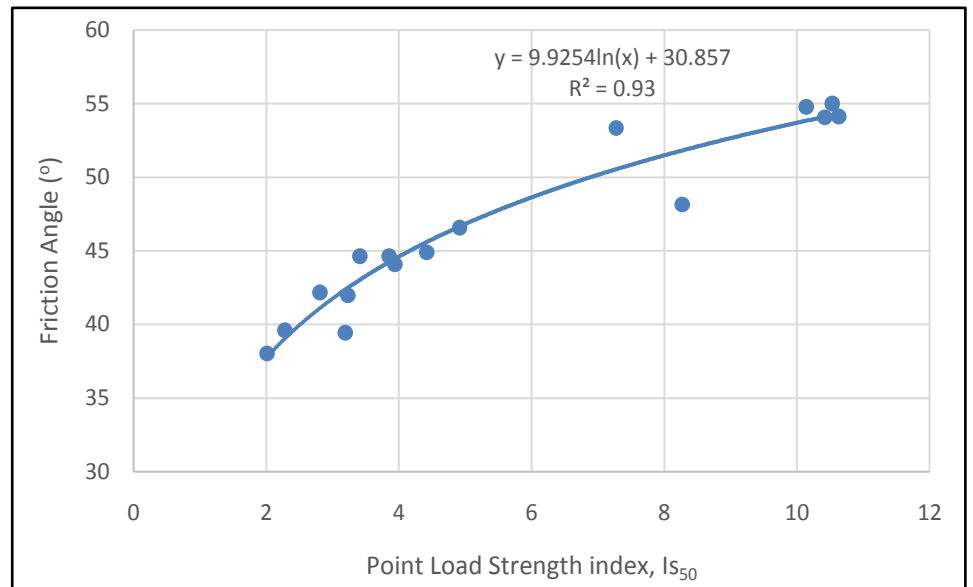

Figure 15. Relationship between point load strength index and apparent cohesion for ultramafic rocks.

and the effective porosity (n_e). The relation between φ and n_e presents higher determination coefficient ($R^2 = 0.96$) than that between c and n_e ($R^2 = 0.91$).

The wave velocities are positively correlated with c and φ and provide high determination coefficient. In particular, φ presents higher correlation with V_p, V_s ($R^2 = 0.91$, $R^2 = 0.92$ respectively) than c ($R^2 = 0.83$, $R^2 = 0.84$ respectively).

The effect of alteration on the physico-mechanical properties of ultramafic rocks can be characterized quantitatively by the serpentinization percentage (β). Strong inverse linear

Table 6. Regression equations and determination coefficients (R^2) for ultramafic rocks.

Parameters to be related	Regression Equations	R^2
Apparent cohesion and point load strength index	$c = 13.996\ln\left(I_{s50}\right) - 0.3711$	0.87
Apparent cohesion and point load strength index	$c = 2.4611 I_{s50} + 7.7905$	0.85
Friction angle and point load strength index	$\varphi = 9.9254\ln\left(I_{s50}\right) + 30.857$	0.93
Friction angle and point load strength index	$\varphi = 1.7408 I_{s50} + 36.67$	0.91

relationships exist between the β and c, φ. The relationship between φ and β presents higher determination coefficient ($R^2 = 0.93$) than that between c and β ($R^2 = 0.86$).

The relations between c, φ and Schmidt hammer values (*SHV*) are also expressed by logarithmic functions. The SHV shows higher correlation ($R^2 = 0.95$) with the friction angle than that with apparent cohesion ($R^2 = 0.88$).

Both the c and φ exhibit negative relationships with the point load strength index (I_{s50}). The best fit trends are logarithmic and φ presents higher correlation with I_{s50} ($R^2 = 0.93$) than that c with I_{s50} ($R^2 = 0.87$).

Some observed deviations may be due to the petrographic variety, the different serpentinization degree, the structural complexity and the internally imprinted tectonic deformation of studied rocks.

All empirical methods evaluated in this study can be used for an assessment of the triaxial characteristics of ultramafic rocks, especially for serpentinites whose preparation in standard size cores, is quite difficult. However, it is commonly known that the prediction equations derived by different researches are dependent on rock types, quality, test conditions and different tectonic settings.

Acknowledgements

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