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Estimation of tensile strength of ultramafic rocks using indirect approaches

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Abstract. Because the estimation of the tensile strength is very important in any geotechnical project, many attempts have been made to determine. But the immediate determination of the tensile strength is usually difficult owing to well-shaped specimens, time-consuming, expensive and sometimes unreliable. In this study, engineering properties of several ultramafic rock samples were measured to assess the correlations between the Brazilian Tensile Strength (BTS) and degree of serpentinization, physical, dynamic and mechanical characteristics. For this purpose, a comprehensive laboratory testing program was conducted after collecting thirty-two peridotite and fifty-one serpentinite rock samples, taken from central Greece, in accordance with ASTM and ISRM standards. In addition, a representative number of them were subjected to petrographic studies and the obtained results were statistically described and analysed. Simple and multiple regression analyses were used to investigate the relationships between the Brazilian Tensile Strength and the other measured properties. Thus, empirical equations were developed and they showed that all of the properties are well correlated with Brazilian Tensile Strength. The curves with the 45° line (y = x) were extracted for evaluating the validity degree of concluded empirical equations which approved approximately close relationships between Brazilian Tensile Strength and the measured properties.

Keywords: ultramafic rocks; rock mechanics; correlation; Brazilian tensile strength; serpentinization percentage; engineering properties

1. Introduction

The tensile strength of rocks is a key design parameter for determining the mechanical properties of rockmasses and their load bearing capacity in most of the geotechnical projects such as underground openings, slope stability and dam foundations (Wang *et al.* 2004, Shin *et al.* 2005, Okubo and Qingxin 2006). Because rocks are much weaker in tension than in compression, tensile strength plays an important, often the most important, role in geotechnical engineering applications. The direct determination of tensile strength becomes with the collection and the test of the specimens (Brazilian test) in the laboratory. It is standardized by ASTM (2001a) and ISRM (2007). Though, this test looks like relatively simple, the procedure can be difficult, because it requires a large number of well-prepared rock samples and this test method is time consuming. Thus, reliable, quick, simple and economical ways are necessary to estimate tensile strength of rocks. For this reason, some researchers developed different predictive models –indirect approach (empirical correlations and statistical methods) for determining tensile strength of rocks, considering simple parameters such as physical, dynamic, mechanical properties and petrographic characteristics (Bell 1978, Fahy and Guccione 1979, Young *et al.* 1985, Shakoor and Bonelli 1991, Chen and Hsu 2001, Singh *et al.* 2001, Gokceoglu and Zorlu 2004, Palchik and Hatzor 2004, Kilic and Teymen 2008, Vasconcelos *et al.* 2008, Heidari *et al.* 2011, Khanlari *et al.* 2014, Kurtulus *et al.* 2015, Fereidooni 2016, Fereidooni and Khajevand 2018, Khajevand and Fereidooni 2018). Regression analyses were used in the literature to accomplish these models. The tests for determining of the physical, dynamic parameters and Schmidt Hammer values are easy to apply and also are non-destructive. Although, the point load test is destructive, it is the most commonly used for field specimens' strength calculation, because it does not require regular-shaped specimens. All of them are quick to carry out, cheap and can be employed both on site and in the laboratory.

Though, the relationships between the Brazilian Tensile Strength (*BTS*) and physical, dynamic and mechanical properties have been studied by some researchers, no one has been concentrated on ultramafic rocks. But, because of the last years they have been used extensively as aggregates and many works have been constructed on/ in them, the tensile strength determination of them is very important and useful.

The main aim of this study is to develop reliable empirical equations for the quick estimation of the Brazilian Tensile Strength (*BTS*) through effective porosity (n_e), dry unit weight (γ_d), wave velocities (V_p, V_s), point load index (I_{s50}), Schmidt rebound hardness (*Srh*) and degree of serpentinization (β). For this reason thirty-two peridotites and fifty-one serpentinites block samples were taken from the central parts of Greece and the above-mentioned physical, dynamic, mechanical and petrographic characteristics were determined (Diamantis 2010). Regression analyses (simple and multiple) were applied to

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

Sample No.	Rock Type	Primary Minerals						Secondary Minerals			
		β (%)	Ol (%)	Opx (%)	Cpx (%)	Pl (%)	Sp (%)	Serp (%)	Chl (%)	Tc (%)	Act (%)
S1	SERPENTINITE	90	2	6	1	-	1	84	2	2	2
S3	SERPENTINITE	85	4	8	2	-	1	76	3	5	1
S5	SERPENTINITE	97	1	-	-	-	2	82	6	6	3
S6	SERPENTINITE	86	4	7	1	-	2	74	6	3	3
S8	SERPENTINITE	76	9	9	5	-	1	63	4	5	4
S9	SERPENTINITE	92	6	-	-	-	2	83	4	3	2
S10	SERPENTINITE	80	10	6	3	-	1	71	2	7	-
S11	SERPENTINITE	70	10	7	11	-	2	62	7	1	-
S12	SERPENTINITE	75	9	12	2	-	2	68	4	3	-
S13	SERPENTINITE	71	17	12	-	-	-	68	2	1	-
S15	SERPENTINITE	77	13	7	3	-	-	67	5	3	2
S16	SERPENTINITE	85	9	5	-	-	1	77	4	4	-
S18	SERPENTINITE	80	12	6	1	-	1	72	6	1	1
S19	SERPENTINITE	92	5	3	-	-	-	84	5	2	1
S20	SERPENTINITE	86	8	6	-	-	-	76	6	3	1
S21	SERPENTINITE	87	7	6	-	-	-	79	7	1	-
S23	SERPENTINITE	76	14	8	-	-	2	63	8	3	2
S28	SERPENTINITE	87	8	5	-	-	-	79	5	2	1
S29	SERPENTINITE	84	5	10	-	-	1	76	2	5	1
S31	SERPENTINITE	69	17	11	-	-	3	62	5	2	-
S32	SERPENTINITE	86	5	8	-	-	1	78	6	2	-
S33	SERPENTINITE	75	11	7	5	-	2	67	6	1	1
S35	SERPENTINITE	73	8	11	7	-	1	66	4	2	1
S38	SERPENTINITE	77	13	8	1	-	1	66	4	5	2
S39	SERPENTINITE	79	12	9	-	-	-	72	6	1	-
S40	SERPENTINITE	83	6	9	-	-	2	79	2	1	1
S44	SERPENTINITE	78	13	8	-	-	1	68	5	4	1
S45	SERPENTINITE	74	14	11	-	-	1	69	4	1	-
S46	SERPENTINITE	78	9	10	2	-	1	72	4	2	-
S47	SERPENTINITE	78	14	6	-	-	2	72	5	1	-
S49	SERPENTINITE	87	4	9	-	-	-	75	8	4	-
S51	SERPENTINITE	74	14	10	1	-	1	64	6	3	1
P5	HARTZBOURGITE	11	66	21	-	-	2	10	1	-	-
P8	LERZOLITH	11	72	11	4	-	2	9	1	-	1
P10	HARTZBOURGITE	27	67	4	-	-	2	21	5	-	1
P12	HARTZBOURGITE	21	70	9	-	-	-	16	3	2	-
P14	HARTZBOURGITE	15	71	14	-	-	-	12	2	1	-
P15	HARTZBOURGITE	26	60	14	-	-	-	22	2	1	1
P16	DUNITE	4	85	10	-	-	1	2	2	-	-
P18	DUNITE	9	79	12	-	-	-	8	1	-	-
P19	PLAGIOCLASTIC LERZOLITH	11	55	24	5	2	3	10	1	-	-
P21	LERZOLITH	4	74	19	3	-	-	3	1	-	-
P23	HARTZBOURGITE	11	68	19	-	-	2	7	2	1	1

Table 1 Continued

Sample No.	Rock Type	Primary Minerals						Secondary Minerals			
		β (%)	Ol (%)	Opx (%)	Cpx (%)	Pl (%)	Sp (%)	Serp (%)	Chl (%)	Tc (%)	Act (%)
P26	HARTZBOURGITE	12	73	15	-	-	-	8	1	2	1
P30	HARTZBOURGITE	3	75	21	-	-	1	3	-	-	-
P32	LERZOLITH	26	50	11	12	-	1	22	2	1	1

P: Peridotite, S: Serpentinite, β: Degree of serpentinization, Ol: Olivine, Opx: Orthopyroxene, Cpx: Clinopyroxene, Pl: Plagioclase, Sp: Spinel, Serp: Serpentine, Chl: Chlorite, Tc: Talc, Act: Actinolite

define the relations among the tensile strength and the other properties. The determination coefficients (R^2) and the equations of the fitted lines were calculated by the "least squares" method and the validity of them was investigated.

2. Materials and experimental procedures

During the extensive field study, eighty-three block samples were collected from different locations of central Greece (from the surface). Laboratory core drill and saw machines were used to prepare several cylindrical specimens (3 to 7 per sample) and the edges of these specimens were cut parallel and smooth in accordance with ASTM (2001b) and ISRM (2007) guidelines. After a macroscopical inspection, three hundred and ninety-one isotropic, homogeneous, unweathered (or slightly weathered) and free of visible joints, cracks, fissures and other discontinuities ultramafic specimens (147 peridotites and 244 serpentinites) were considered. Then, a representative number of specimens were subjected to petrographic studies with the aim of determining the mineralogical constitution, the texture and the serpentinization percentage (β) of ultramafic rocks. Moreover, effective porosity (n_e), dry unit weight (γ_d), wave velocities (V_p, V_s), point load index (I_{s50}), Schmidt rebound hardness (*Shr*) and Brazilian Tensile Strength (*BTS*) tests are conducted on dry conditions for a better relation of the results. Fractures created by the tests, did not follow internal discontinuities and were always fresh. All of them were carried out at the Department of Natural Resources Management and Agricultural Engineering, Laboratory of Minerology and Geology, Agricultural University of Athens. The results obtained from the laboratory tests were presented and statistically analysed.

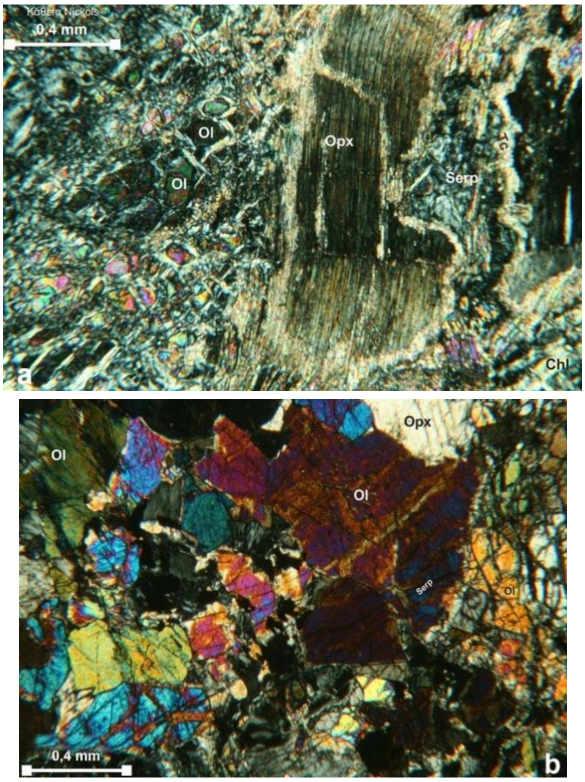

Fig. 1 (a) Serpentinite with mesh structure and remaining olivine crystals (cross Nicols) and (b) Peridotite with allotriomorphic olivines (Ol), phenocrysts of orhopyroxenes (Opx), and serpentines (Serp) in the fractures (cross Nicols)

2.1 Petrography of the rocks

Different rocks may be composed of hard or weak minerals which the engineering behavior of rocks is closely related to them (Fereidooni 2018). The tested rock samples are ultramafic rocks, which are members of the ophiolitic tectonic suite (remnant of the Earth's oceanic crust and upper mantle, Katsikatsos *et al.* 1986, Migiros *et al.* 2000). The ultramafic rocks include particular rock types (peridotites) with large variability (harzburgites, lherzolites, plagioclastic peridotites, dunites, etc) and structural complexity (serpentinized varieties of them) owing to tectonic deformation and serpentinization (Foucault and Rault 1995, Diamantis 2010). Due to the serpentinization, which is a low-temperature, metamorphic process, peridotites are hydrated and transformed into serpentinites, which represent partially to completely serpentinized (serpentinization >70% by volume) ultramafic rocks and which present lower physical, dynamic and mechanical values than the parent rocks (Christensen 1966, 2004, Escartin *et al.* 2001, Diamantis 2010, Ozsoy *et al.* 2010).

A representative number of forty-six thin sections were prepared and examined under an optical microscope to study the mineralogical and textural characteristics as well as the serpentinization percentage of the peridotite and serpentinite rocks (Table 1).

The serpentinites are mainly coarse-grained, dark green coloured, isotropic, homogeneous rocks and the degree of serpentinization, range between 70 and 97%. The major mineral constituent is serpentine (62-84% by volume, Table

Table 2 Statistical analysis of serpentinization percentage, physical and dynamic properties

	Range	Maximum value	Minimum value	Mean value	Standard Deviation
SERPENTINITES					
Degree of serpentinization, β (%)	32	97	69	81	7
Effective porosity, n_e (%)	4.35	4.74	0.39	1.26	0.94
Dry unit weight, γ_d (kN/m^3)	2.26	26.79	24.53	25.91	0.48
Primary wave velocity, V_p (m/s)	887	5730	4843	5357	193
Secondary wave velocity, V_s (m/s)	653	3078	2425	2802	150
PERIDOTITES					
Degree of serpentinization, β (%)	24	27	3	14	8
Effective porosity, n_e (%)	0.20	0.06	0.26	0.16	0.07
Dry unit weight, γ_d (kN/m^3)	2.69	33.33	30.64	32.10	0.87
Primary wave velocity, V_p (m/s)	933	7981	7048	7548	296
Secondary wave velocity, V_s (m/s)	744	4560	3816	4210	226

1, Diamantis 2010), while other ocean-floor metamorphic products are chlorite, talc and actinolite. The residual minerals of the parent rocks are mainly Olivine. Serpentinites structure is mainly hourglass mesh (Fig. 1(a)).

On the other hand, peridotites are mainly medium-grained homogeneous isotropic rocks and the serpentinization degree varies between 3% and 27%. The primary (parent) minerals are Olivine (50 to 85%, by volume), orthopyroxene (4 to 24%), clinopyroxene (3 to 12%), while opaque minerals (mainly spinel) are present in small amounts (1-3%, by volume, Table 1, Diamantis 2010). The secondary mineral constituents (Table 1) are serpentine (2-22% by volume), chlorite, talc and actinolite (comprising up to 5%, Table 1). Also, they present a porphyritic or granular structure and compact texture without preferred mineral orientation (Fig. 1(b)). The serpentinization percentage values are analytically listed in Table 1, while the range, the mean value and the standard deviation are shown in Table 2.

2.2 Physical properties

Physical properties including effective porosity (n_e) and dry unit weight (γ_d) were determined for the peridotites and serpentinites using the saturation and buoyancy methods in accordance with ISRM (2007). The results were calculated using the following equations

$$n_e = \frac{V_v}{V_t}\ \frac{(M_{sat} - M_s)/\rho_w}{(M_{sat} - M_{sub})/\rho_w}\ \% \tag{1}$$

$$\gamma_d = \frac{W_d}{V_t}\ \frac{M_s * g}{(M_{sat} - M_{sub})/\rho_w}\ \text{kN/m}^3 \tag{2}$$

where, V_v, is the volume of the voids (m^3), V_t, is the total volume of the specimen (m^3), M_{sat}, is the saturated mass of the specimen (dry on the surface, gr), M_s, is the dry mass of the specimen (gr), M_{sub}, is the submerged mass of the specimen (gr), W_d, is the dry weight of the specimen (kN/m^3), g, is the gravitational acceleration (9.807 m/sec^2), and ρ_w, is the density of water (1 gr/cm^3).

At least three specimens from each sample (from 32 peridotites and 51 serpentinites) were used and then the mean values were obtained. The n_e fluctuates between 0.39 and 4.74% in serpentinites and from 0.06 to 0.26% in peridotites, while the γ_d varies from 24.53 to 26.79 and between 30.64 and 33.33 kN/m^3 respectively. It is widely known that porosity decreases as unit weight (density) increases. In Table 2, the maximum, the minimum, the average values and the standard deviations are given.

2.3 Wave velocities (V_p, V_s)

The P- and S-wave velocities (V_p, Vs) were determined in accordance with ASTM test designations (1983). This technique is often used to determine and characterize the dynamic properties of rocks (Li and Tao 2015). Since this method is non-destructive and relatively easy to apply, it is being increasingly used in geological and geotechnical engineering.

Pulse is generated by a source-transducer which is transmitted through the sample and is registered by a receiver transducer. After the complete of the measurements, the wave velocities are calculated from the measured travel time and the distance between the transmitter and receiver. In this study, these tests were performed on 64 peridotites and 102 serpentinites (two specimens of each sample) and the average values were used. The Primary wave velocity (V_p) and Secondary wave velocity (V_s) for peridotites extend between 7048 and 7981 m/s and from 3816 to 4560 m/s respectively, the mean values are 7548 and 4210 and the standard deviation is 296 and 226 respectively (Table 2).

2.4 Point load strength index (I_{s50})

The point load test is an attractive, alternative, indirect and the most commonly used way to determine the uniaxial compressive strength (σ_{ci}) owing to the ease of testing, simplicity of specimen preparation, the low cost and feasibility of field application. The point load test allows the determination of the uncorrected point load index (I_s). It must be corrected to the standard equivalent diameter (D_e) of 50 mm. The point load test was determined according to ASTM (2005) requirements and the point load strength index values (I_{s50}) were calculated by the following functions

$$I_s = \frac{P}{D^2_e} \tag{3}$$

$$F = \left(\frac{D_e}{50}\right)^{0.45} \tag{4}$$

$$I_{s50} = F * I_s \quad (5)$$

where, P, is the failure load in N, D_e, is the equivalent core diameter in mm, and F, is a factor for the correction of equivalent diameter in 50 mm.

In this study, diametrical point load tests were carried out on 80 specimens (from 32 peridotites and 48 serpentinites). The point load strength index values range from 1.04 to 4.93MPa in serpentinites and between 5.84 and 12.82MPa in peridotites. The mean values are 3.25MPa and 8.72MPa, while the standard deviation values are 0.91MPa and 1.89MPa respectively (Table 3).

2.5 Schmidt rebound hardness (Srh)

The Schmidt hammer tests are conducted on specimens following ISRM (2007). In the context of rock mechanics, *Srh* is perhaps the most frequently used index for the estimation of strength. This test is quick, inexpensive as well as mainly non-destructive and it gives an indication of the strength of the material being tested. The Schmidt hammer is a light hand-held device which consists of a spring-loaded mass inside a piston that is released when the hammer is pressed orthogonally onto a surface. Ten impacts are carried out at each specimen and the mean value is calculated. In this research, a L-Type Schmidt hammer was applied. The Schmidt hammer tests were performed on 64 peridotites and 102 serpentinites (two specimens of each sample) and the average values were used. The *Shr* values vary between 59.16 and 65.17 in peridotites and from 48.45 to 55.05 in serpentinites, presenting mean values 62.59 and 51.89 respectively. Their standard deviation values are 1.85 and 1.62 respectively (Table 3).

2.6 Brazilian tensile strength (BTS)

Tensile strength values were indirectly determined by Brazilian method (splitting tensile test) using the procedure given in ISRM (2007). The principle of this test is to apply a line load diametrically across the specimen and thereby obtain a tensile stress perpendicular to the line of loading. Specimens used for Brazilian tensile strength are NX size drill core samples in 1:2 height/diameter ratios. Owing to its convenience, the method has been adopted in many projects. The Brazilian Tensile Strength (*BTS*) of the rock is calculated by the following function

$$BTS = \frac{0.636 * P}{D * t} \quad (6)$$

where, P, is the failure load, D, and t are the diameter and thickness of the rock specimen, respectively.

In this research, the Brazilian tests were carried out on 83 specimens (from 32 peridotites and 51 serpentinites) and the statistical results are shown in Table 3. The tensile strength values are evaluated with an average value of 5.98 MPa in serpentinites and 18.59 MPa in peridotites and fluctuate from 2.58 MPa to 10.69 MPa and from 11.76 MPa to 24.93MPa respectively. The standard deviation is of 1.78MPa in serpentinites and 3.75MPa in peridotites (Table 3).

Table 3 Statistical analysis of point load strength index, Schmidt rebound hardness and Brazilian Tensile Strength

		Point Load Strength Index, (I_{S50})	Schmidt rebound hardness, Srh	Brazilian Tensile Strength, BTS
Peridotites	Maximum value	12.82	65.17	24.93
	Minimum value	5.84	59.16	11.76
	Mean value	8.72	62.59	18.59
	Standard deviation	1.89	1.85	3.75
Serpentinites	Maximum value	4.93	55.05	10.69
	Minimum value	1.04	48.45	2.58
	Mean value	3.25	51.89	5.98
	Standard deviation	0.91	1.62	1.78

3. Regression analysis

The most widely applied technique in the literature for prediction purposes is the classical regression analysis. In this study, it was applied in order to express the relationships among the above-mentioned properties of ultramafic rocks and mainly to derive reliable, empirical approaches for the determination of tensile strength. So, the best fitting curve of those correlations was found. The determination coefficient (R-square value, R^2) values were utilized as the basis of comparing the developed models in regard to the goodness of fit of the model (Solanki *et al.* 2008, 2009). The equations of the best fit curves (e.g., linear, logarithmic, exponential, power) and R^2 were calculated by the "least squares" method. Moreover, multiple regression analyses were carried out to correlate the measured tensile strength to three of the rock properties namely, effective porosity, dry unit weight, wave velocities, Schmidt rebound hardness and point load index. Multivariate regression is one of the most commonly accepted methods of data analysis that may be appropriate whenever a quantitative variable (dependent variable) is to be examined in relationship to any other parameters (independent variables).

3.1 Relationship between degree of serpentinization and tensile strength

As it is commonly known, strength decreases with serpentinization increase. Thus, generally, peridotites present higher strength values than serpentinites. In this paper, an attempt to correlate degree of serpentinization with Brazilian Tensile Strength is presented in Figs. 2-3. A logarithmic correlation between BTS and β was considered as the best fit in peridotites (Fig. 2), while in serpentinites an exponential function describes better than the others the relation between the above-mentioned properties (Fig. 3). The estimated BTS using the β values can be expressed by the following empirical equations

$$BTS = -4.91Ln(\beta) + 30.37 \text{ for peridotites} \quad (7)$$

$$BTS = 189.32exp^{-0.044\beta} \text{ for serpentinites} \quad (8)$$

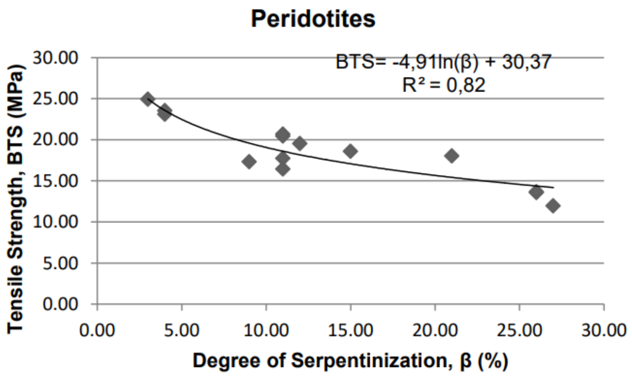

Fig. 2 Correlation between degree of serpentinization and Brazilian Tensile Strength for peridotites

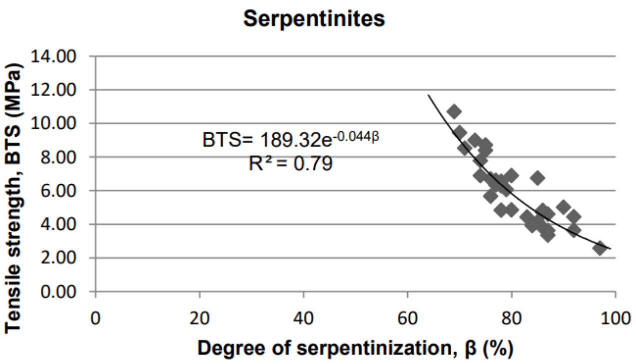

Fig. 3 Variation of serpentinization degree versus Brazilian Tensile Strength for serpentinites

3.2 Correlation between physical properties and tensile strength

As is commonly known, *BTS* increases with dry unit weight increase, while it reduces with porosity increase. According to Bell (1978) there is a highly significant tendency for *BTS* to increase with increasing γ_d, while there is inverse relationship between *BTS* and n_e for sandstones. Both Shakoor and Bonelli (1991) for sandstones and Palchick and Hatzor (2004) for porous chalks suggested that the *BTS* is closely related (r>0.7) to γ_d and n_e.

As it can be seen in Figs. 4-7, in this study, there is a good correlation between the measured Brazilian Tensile Strength and physical properties (effective porosity and dry unit weight) for the samples tested. *BTS* is negatively affected (logarithmically) by the increase of n_e both in serpentinites and peridotites. Also, it increases exponentially with the increase of γ_d in serpentinites, while the same relationship in peridotites is better described by a linear equation. In other words, this research resulted into similar correlations with the literature. The extracted experimental equations and the determination coefficients (R-square) of the above-mentioned relations are given in Table 4.

3.3 Relationship between wave velocities and tensile strength

As wave velocities are concerned, strength increases with the increase of these parameters. The plots of the *BTS*

Table 4 Regression equations and determination coefficients (R^2)

Parameters to be related	Rocks	Regression Equations	RR^2
Brazilian Tensile Strength and dry unit weight	Peridotites	$BTS=3.83\gamma_d-104.24$	0.79
		$BTS=122.57\ln(\gamma_d)-406.53$	0.78
		$BTS=0.021\exp^{0.21\gamma}{}_d$	0.77
	Serpentinites	$BTS=4*10\text{-}06*\exp 0.55\gamma_d$	0.76
		$BTS=6*10^{-20}*\gamma_d{}^{14.14}$	0.75
		$BTS=3.13\gamma_d-75.00$	0.71
Brazilian Tensile Strength and effective porosity	Peridotites	$BTS=-7.10\ln(n_e)+4.76$	0.78
		$BTS=-50.02n_e+26.45$	0.77
		$BTS=28.02\exp^{-2.74n}{}_e$	0.76
	Serpentinites	$BTS=-2.23\ln(n_e)+5.94$	0.76
		$BTS=8.09\exp^{-0.28n}{}_e$	0.74
		$BTS=-1.49n_e+7.85$	0.62

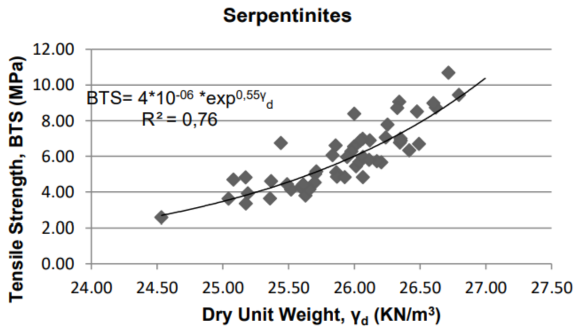

Fig. 4 Relationship of dry unit weight with Brazilian Tensile Strength for serpentinites

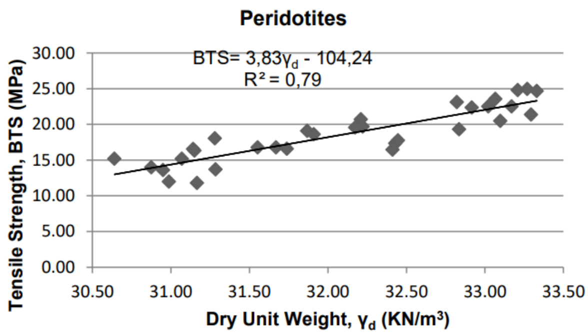

Fig. 5 Variation between dry unit weight and Brazilian Tensile Strength for peridotites

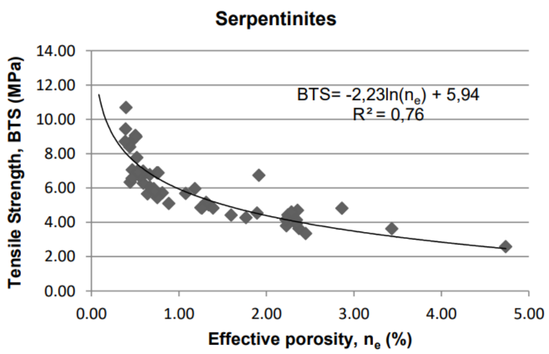

Fig. 6 Correlation of effective porosity versus Brazilian Tensile Strength for serpentinites

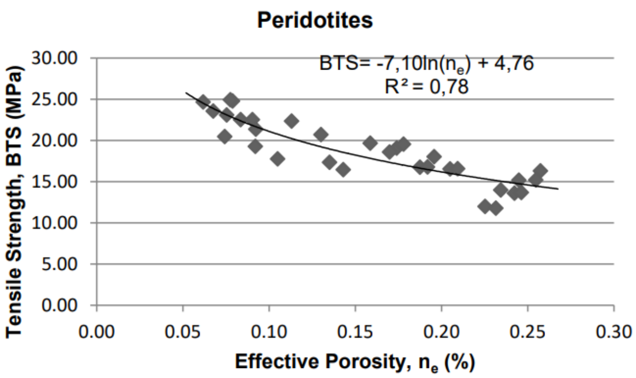

Fig. 7 Relation between effective porosity and Brazilian Tensile Strength for peridotites

values as a function of wave velocities (V_p, V_s) are shown in Figs. 8 and 9. The best fit relationships are found to be linear for peridotites and exponential for serpentinites. The determined correlations can be described by the following functions

$$BTS = 0.011V_p - 63.67 \quad \text{for peridotites } (R^2{=}0.74) \quad (9)$$

$$BTS = 0.014V_s - 40.01 \quad \text{for peridotites } (R^2{=}0.70) \quad (10)$$

$$BTS = 0.0064exp^{0.0013V_p} \quad \text{for serpentinites } (R^2{=}0.66) \quad (11)$$

$$BTS = 0.054exp^{0.0017V_s} \quad \text{for serpentinites } (R^2{=}0.68) \quad (12)$$

Kurtulus *et al*. (2015) for limestones and sandstones and Khajevand and Fereidooni (2018) for sedimentary rocks suggested linear functions, while Vasconcelos *et al.* (2008) for granites proposed exponential trend. Moreover, Kilic and Teymen (2008) studied the relationship between *BTS* and wave velocities and suggested power function for several rocks.

3.4 Correlation of point load index and Schmidt rebound hardness with tensile strength

Particular emphasis was also given to the degree of dependence between the Schmidt rebound hardness and Brazilian Tensile Strength of the samples studied because as afore-mentioned the Schmidt hammer test is a non-destructive, simple, quick and low cost procedure. According to Fereidooni and Khajevand (2018) for sedimentary rocks, *BTS* increases linearly with the *Srh* increase.

Kilic and Teymen (2008) using test results of different rock types and Fereidooni (2016) for hornfelsic rocks observed a power relationship between these two properties.

As it is illustrated in Figs. 10-11, in this study, *Srh* forms good to strong positive correlations with the *BTS* both in serpentinites (exponential relation, R^2=0.64) and peridotites (linear relation, R^2=0.81), validiting that with the increase of *Srh*, the *BTS* increases.

As far as point load index is concerned, four functions can mainly describe the relationship between *BTS* and I_{s50}. The equations of these curves-lines and the determination coefficients are listed in Table 5.

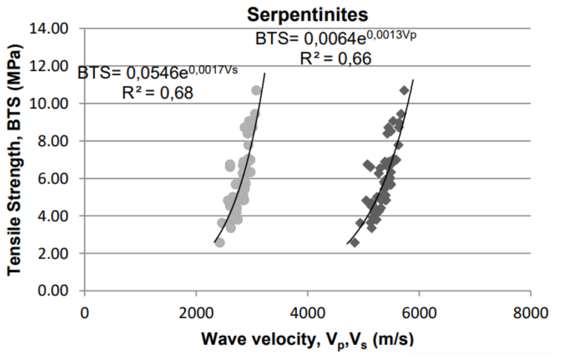

Fig. 8 Correlation of wave velocities with Brazilian Tensile Strength for serpentinites

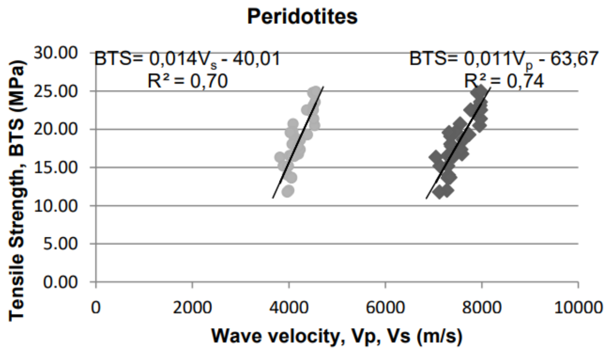

Fig. 9 Wave velocities versus Brazilian Tensile Strength for peridotites

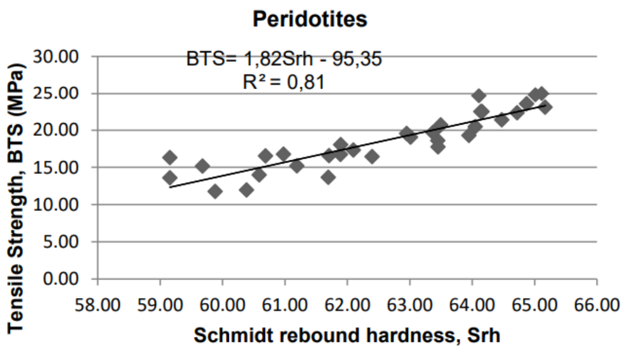

Fig. 10 Variation between Schmidt rebound hardness and Brazilian Tensile Strength for peridotites

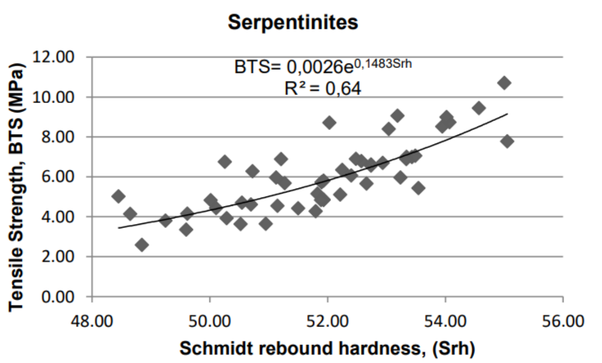

Fig. 11 Correlation of Schmidt rebound hardness against Brazilian Tensile Strength for serpentinites

The linear function in peridotites and the exponential equation in serpentinites describe better than the other

Table 5 Regression equations and determination coefficients (R^2)

Parameters to be related	Rocks	Regression Equations	RR^2
Brazilian Tensile Strength and point load strength index	Peridotites	$BTS=1.84I_{s50}+2.53$	0.86
		$BTS=15.92\ln(I_{s50})-15.53$	0.85
		$BTS=2.12I_{s50}$	0.84
		$BTS=2.80I_{s50}^{0.87}$	0.83
	Serpentinites	$BTS=2.17\exp^{0.29I}{}_{s50}$	0.78
		$BTS=2.37I_{s50}^{0.77}$	0.73
		$BTS=1.66I_{s50}+0.52$	0.72
		$BTS=1.80I_{s50}$	0.71

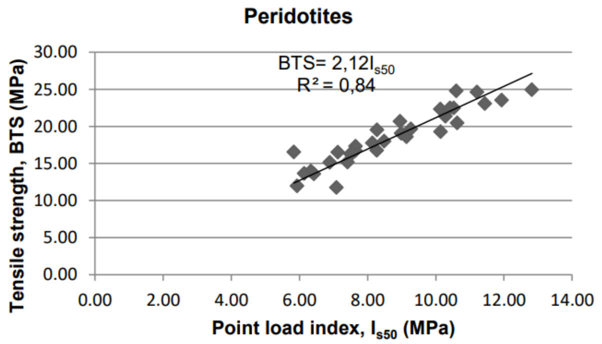

Fig. 12 Linear zero-intercept function between tensile strength and point load strength index for peridotites

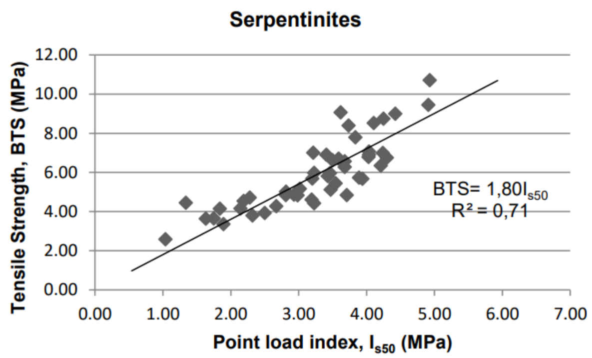

Fig. 13 Linear zero-intercept function between tensile strength and point load strength index for serpentinites

Table 6 Model equations derived from multiple regression analysis for determination of BTS

Peridotites		Serpentinites	
Equations	R^2	Equations	R^2
$BTS=0.0034V_p-0.31\beta-2.79$	0.93	$BTS=1.45\gamma d-0.15\beta-19.70$	0.79
$BTS=0.15\gamma_d-0.39\beta+19.11$	0.90	$BTS=1.64\gamma_d+0.94I_{s50}-39.52$	0.78
$BTS=1.44\gamma_d+1{,}27I_{s50}-38.52$	0.89	$BTS=0.002V_p-0.20\beta+10.63$	0.77
BTS=-15,93ne+1,35IS50+9,33	0.88	$BTS=2.15\gamma_d+0.36Srh-68.11$	0.74

trends, the relations between *BTS* and Is_{50}, exhibiting an R-square values equal to 0.86 and 0.78 respectively, but the author of this paper believes that a linear zero-intercept function (Figs. 12 and 13), describes in a more realistic

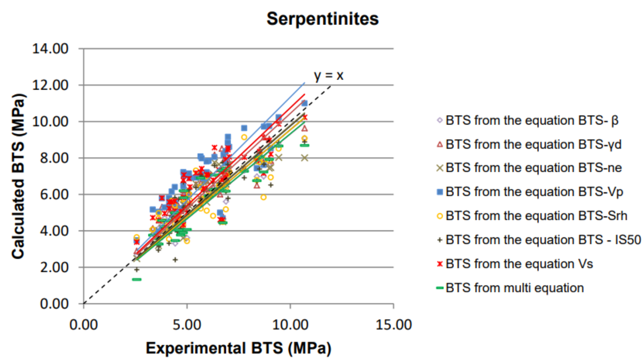

Fig. 14 Correlation between experimental and calculated values of the Brazilian Tensile Strength for serpentinites

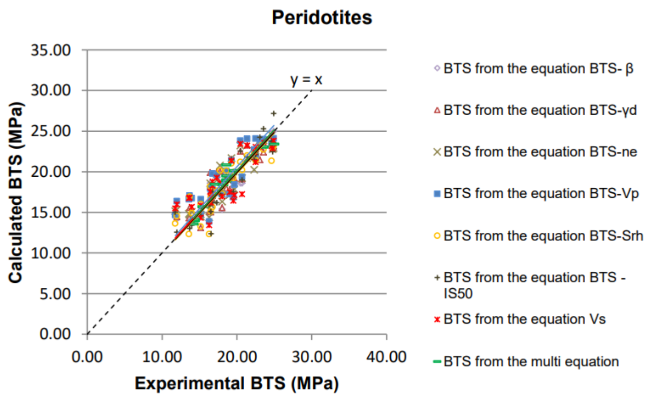

Fig. 15 Correlation between experimental and calculated values of the Brazilian Tensile Strength for peridotites

manner the physical meaning of the prediction models (when Is_{50} is zero, then *BTS* will be zero. It is reasonable) between these two mechanical properties and suggest its use.

$$BTS = 2.12I_{s50} \text{ for peridotites} \tag{13}$$

$$BTS = 1.80I_{s50} \text{ for serpentinites} \tag{14}$$

Several studies, for all rock types, have shown similar relationships. Specifically, Heidari *et al.* (2011) for gypsum rocks, Fereidooni (2016) for hornfelsic rocks as well as Fereidooni and Khajevand (2018) for sedimentary rocks presented linear relationships between these two mechanical properties. On the other hand, Kilic and Teymen (2008) for several rocks suggested logarithmic correlations and Khanlari *et al.* (2014) for metamorphic rocks proposed power relationships. All of them agree that the *BTS* increases with the point load strength index increase.

Furthermore, a multiple regression analysis was used to investigate the correlation between the Brazilian Tensile Strength and physical, dynamic and mechanical properties and the degree of serpentinization both for peridotites and serpentinites. As it can be seen in the Table 6, the best fit multiple models for the determination of *BTS,* are the following

$$BTS=0.0034V_p-0.31\beta-2.79 \text{ for peridotites} \tag{15}$$

$$BTS=1.45\gamma_d-0.15\beta-19.70 \text{ for serpentinites} \tag{16}$$

These functions demonstrate that there was strong correlation among *BTS, V_p* and β for peridotites and significant relationship among *BTS,* γ_d and β for serpentinites.

Correlations between experimental and calculated values of Brazilian Tensile strength are shown in Figs. 14-15 for serpentinites and peridotites respectively. For assessing validity degree of the results, a 45° line (y=x) has been plotted in this figure. It is clear that the lines are closely fitted the 45° line, which confirms the validity of the equations. The lines conducted by peridotites are better fitted with the y=x line than that resulted from serpentinites. The results of peridotites present higher validity than that of serpentinites.

4. Conclusions

This research mainly attempts to estimate the tensile strength of ultramafic rocks (peridotites and serpentinites) through physical, dynamic, Schmidt hammer and point load tests, which are simple, quick to carry out, inexpensive and can be employed both on site and in the laboratory. For this reason, 32 peridotite and 51 serpentinite samples, taken from central Greece, were tested in the laboratory and the Brazilian tensile strength was predicted through the above-mentioned properties by simple and multiple regression analyses.

The study demonstrates that the Brazilian Tensile Strength (*BTS*) exhibits strong correlations with the degree of serpentinization (β). For peridotites the best fit equation between *BTS* and β is logarithmic (R^2=0.82), while in serpentinites an exponential function describes better than the others the relation between the above-mentioned properties (R^2=0.79).

High relationships exist between the *BTS* and the physical properties. The *BTS* is positively correlated with dry unit weight (γ_d) for both peridotites (linear equation, R^2=0.79) and serpentinites (exponential trend, R^2=0.76), while inverse logarithmic equation is found between *BTS* and the effective porosity (n_e) for both of them. Moreover, the *BTS* and the wave velocities (V_p, Vs) are correlated well by linear functions in peridotites and exponential in serpentinites.

In addition, the correlations of the *BTS* with Schmidt rebound hardness (*Srh*) are also determined. Exponential function (R^2=0.64) exists between the *Srh* and *BTS* in serpentinites, while the linear equation seems to fit better these two characteristics in peridotites (R^2=0.81).

As far as point load strength index (I_{s50}) is concerned, it can be related to *BTS* values by four different models. The linear zero function in peridotites and the exponential equation in serpentinites describe better than the other trends, the relations between *BTS* and Is_{50}.

Furthermore, multiple regression analysis was used to give linear prediction models for *BTS* determination for both peridotites and serpentinites. The most reliable linear prediction equations are $BTS=0.0034V_p-0.31\beta-2.79$ for peridotites (R^2=0.93) and $BTS=1.45\gamma_d-0.15\beta-19.70$ for serpentinites (R^2=0.79). As a result, these determination coefficients revealed that estimation performances of the multivariate regression equations are higher than those of simple regression equations. The validity of the above-mentioned were checked by plotting in the same figure the correlations between experimental and predicted *BTS* and a 45° line (y=x). It is clear that the lines are closely fitted the 45° line, which confirms the validity of the equations. The lines conducted by peridotites are better fitted with the y=x line than that resulted from serpentinites. Thus, the results of peridotites present higher validity than that of serpentinites.

Finally, it is obvious that the determination of *BTS* value in an easy, indirect and economical way can provide an important help to geotechnical engineers at the preliminary stage of designing a geotechnical project in ultramafic rocks. However, it is commonly known that the prediction equations derived by different researches are dependent on rock types, quality and test conditions and different tectonic settings.

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