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ORIGINAL ARTICLE

Influences of petrographic and textural properties on the strength of very strong granitic rocks

Hakan Ersoy[1] · **Serhat Acar**[2]

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Abstract In this study, the petrographic characteristics affecting the strength of granitic rocks were investigated and a new mineralogical-based model was suggested for the prediction of uniaxial compressive strength (UCS) in line with the obtained data. Increase in quartz and alkali feldspar contents with decrease in plagioclase content partially increase the strength of granitic rocks. However, the results of modal analyses show that the rate of physically competent minerals do not directly affect strength of the granitic rock because the mineral size has a greater effect on strength than that of mineral type. The higher strength values were determined for the rocks containing monotype mineral in terms of size and quantity. In the scope of the study, significant relationships with a 0.89 correlation coefficient between UCS values and the Quality Index values (QI) were determined using mineral percentages, content and size. Because the modal analysis technique is a time-consuming process, ultrasonic velocity ratio (UVR) was defined in order to evaluate rock strength in the study and significant relationships were found with the correlation coefficient of 0.77 between UVR and QI. To estimate UCS using only ultrasonic wave velocity, it was determined whether there is a statistical relationship between UVR and UCS. The test result shows significant relation was found characterized with correlation coefficient of 0.84 value. UCS values obtained from the proposed equation and experimental studies were compared to test the suggested model; the results of the study showed that UCS values can be predicted without needing modal analysis with the new method proposed.

Keywords Granite · Petrographic · Texture · UCS · Ultrasonic velocity ratio

Introduction

Uniaxial compressive strength (UCS) of rock material is perhaps the main strength parameter used in almost all engineering projects related to rock environment (Cargill and Shakoor 1990; Ersoy and Kanık 2012). The strength of rock material is obtained generally from compressive strength tests, especially uniaxial applied stress, which is standardized by ASTM (1999) on cube samples and ISRM (2007) on core samples in the laboratory. However, high-quality and well-prepared core/cube samples with regular geometry are necessary, and gathering sufficient number of samples is the most important difficulties for this test. For this reason, the prediction models for estimating UCS from simple, non-destructive and easily applied laboratory tests have been suggested to overcome such difficulties (Kahraman 2001; Katz et al. 2000; Koncagul and Santi 1999; Wong et al. 1996). However, some researchers have found that sound velocity is closely related to rock properties (Gaviglio 1989; Chang et al. 2006; Yalçınalp et al. 2008; Babacan et al. 2009; Moradian and Behnia 2009; Karakul and Ulusay 2013) while others have correlated UCS with index properties such as porosity, density and also P-wave velocity (Ramana and Venkatanarayana 1973; Yasar and Erdogan 2004).

✉ Hakan Ersoy
blavetirraa@hotmail.com

Serhat Acar
serhat_acar@windowslive.com

[1] Department of Geological Engineering, Karadeniz Technical University, 61080 Trabzon, Turkey

[2] TTS International Engineering and Architecture Company, 34736 Kozyatağı, İstanbul, Turkey

New statistical techniques such as analytic hierarchy process, artificial neural networks and fuzzy inference systems have also been used to estimate strength parameters (Grima and Babuska 1999; Gokceoglu and Zorlu 2004; Karakuş and Tütmez 2006; Dehghan et al. 2010; Yagiz et al. 2011; Ersoy and Kanik 2012; Mishra and Basu 2013). The development of the estimation models on the uniaxial compressive strength using petrographical characteristic of rock sample has become an attractive investigation area in rock engineering projects during recent years. Therefore, many researchers have carried out some studies in determining the strength properties of rock material by using petrographic characteristics (Tuğrul and Zarif 1999; Ulusay et al. 1994; Gokceoglu and Zorlu 2004; Ceryan et al. 2008; Zorlu et al. 2008; Özçelik et al. 2012).

Although some specific empirical models have been suggested and these recent trends have become attractive for engineering geologists, a general and functional model for the prediction of the UCS of rock material using index and properties for different types of rocks has not been developed in the literature (Gokceoglu 2002; Coggan et al. 2013; Heidari et al. 2013; Öztürk and Nasuf 2013). Besides, very different UCS values were determined on the core and/or cube samples obtained from the same rock block by many researchers. Mineral composition and size, texture as well as porosity, the arrangement of voids (fabric) and weathering state are the most important reasons for this situation. For this aim, the granitic rocks which exposed over large areas in the eastern Black Sea Region (NE Turkey) were selected within the scope of the study (Fig. 1) and the effects of the mineralogical parameters on uniaxial compressive strength are discussed in this paper. By using ISRM (2007) methods suggested on 250 rock samples obtained from nine different granite masses in Giresun, Trabzon and Rize, the index and strength tests were conducted, petrographic analyses were carried out, and the statistical relations were analyzed between obtained data. Based on the results of the statistical analysis, some general prediction models and a new approach related to mineralogical and physic-mechanical properties were suggested for very strong granitic rocks.

Regional geology and sampling location

The eastern Pontides, as an example of paleo-island arc setting, are a major metallogenetic province in the eastern Black Sea coastal region and form a 500 km long and 100 km wide mountain chain along the Black Sea coast. The eastern Pontides were subdivided into northern, eastern and axis zones on the basis of structural and lithological differences (Özsayar et al. 1981; Bektaş et al. 1995; Okay and Sahinturk 1997). The northern zone is dominated by Late Cretaceous, Middle Eocene volcanic and volcaniclastic rocks, whereas pre-Late Cretaceous sedimentary rocks are widely exposed in the southern zone (Arslan et al. 1997, 2013; Eyuboglu et al. 2011).

In this region, there are five different lithostratigraphic units: Paleozoic Gümüşhane Granite and Pulur Metamorphites forming the basement, Early to Middle Jurassic rift-related sediments and volcanoclastics, Late Jurassic to mid-Cretaceous platform carbonates, Middle to Late Cretaceous rift-related sediments, Eocene-Neogene volcano-sedimentary rocks (Yılmaz and Kandemir 2006). Also, in this region, plutonic rocks have a range of ages and compositions and were probably emplaced into a variety of geodynamic environments between Jurassic and Paleocene time (Okay and Sahinturk 1997; Arslan and Aslan 2006).

Granitic intrusions in the northern zone extend NW–SE whereas those in the southern zone are nearly E–W oriented. The contacts of the intrusions with the volcanic rocks are sharp, epidotized and include volcanic xenoliths. The margins of the southern zone intrusions often contain abundant angular mafic microgranular enclaves of diorite to quartz diorite composition. Petrographically, intrusions show variations in both color and mineralogy with fine to medium granular, monzonitic, poikilitic, rapakivi, anti-rapakivi and graphic textures (Arslan and Aslan 2006). Based on modal mineralogy, the northern rocks are monzonite, quartz monzonite, monzodiorite and quartz monzodiorite whereas the southern samples are monzogranite and granodiorite.

Within the scope of the study, granitic rocks which widely outcropped and confront in the various engineering projects in the northern zone of the eastern Pontides (NE Turkey) were analyzed. For this aim, nine different granite masses in Giresun, Trabzon and Rize in the northern zone of the eastern Black Sea Region were selected to investigate (Fig. 1).

Petrographic observations

In the study, 165 thin sections in total from the studied granitic rocks were examined under an optical microscope (Nikon-LV 100 Pol) to determine the petrographic properties and weathering stages of each sample. The modal mineralogy of selected samples was determined by point counting with a Swift automatic counter fitted with a polarizing microscope. In each thin-section, a total of 200–250 points (0.4 mm between two points) were counted and normalized to 100%. Thus, the granitoid was classified according to the QAPF (quartz, alkali feldspar, plagioclase, feldspathoid) diagram for coarse-grained plutonic rocks and was named according to the percentage of quartz, alkali feldspar and plagioclase on the QAP half of the

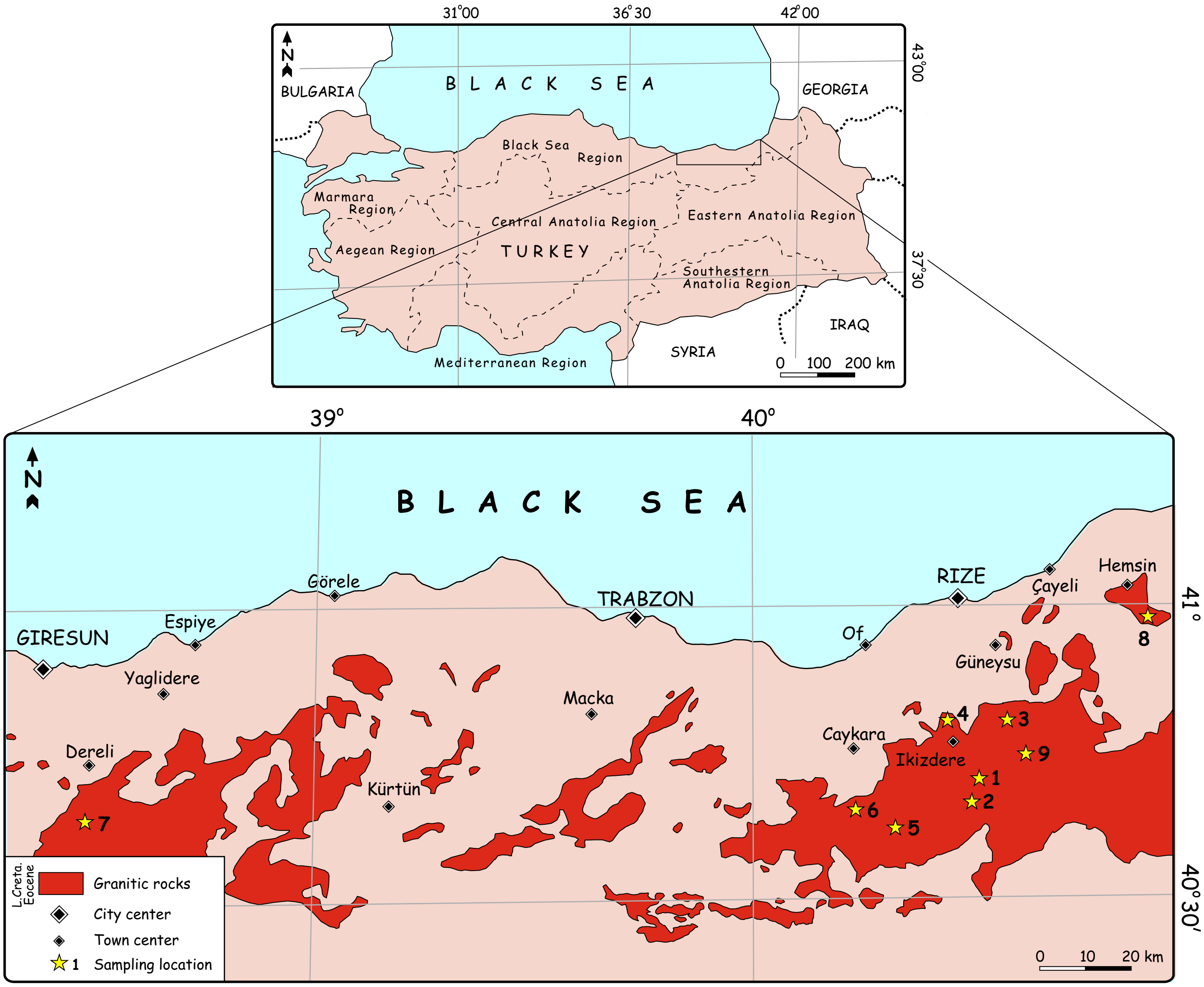

Fig. 1 Granitic rocks exposed in the eastern Black Sea Region (NE Turkey) and the sampling locations

diagram (Fig. 2). The main rock types, mineralogical compositions and textural features of the studied granitic rocks are summarized in Table 1.

The studied rocks include a wide variety of rock types such as syenogranite, monzogranite, granodiorite, tonalite, monzonite, quartz monzonite, quartz monzodiorite. Petrographically, granitic rocks show variations in terms of color, texture and mineralogy. The modal mineralogy is mainly 19–46% plagioclase, 6–40% orthoclase, 25–37% quartz, 4–18% mafic minerals such as hornblende, augite, biotite and 1% opaques. Chlorite, sericite, epidote and calcite are secondary. Generally, they have monzonitic, graphic and rarely myrmekitic textures and range from fine to medium-coarse-grained rocks (Fig. 3). The samples may contain abundant medium-fine grained plagioclase, biotite, hornblende and opaques. Plagioclase occurs as euhedral to subhedral crystals, and a myrmekitic texture is observed at the contact between orthoclase and plagioclase. Some large plagioclase crystals are alterated to sericite. Orthoclase mainly occurs as subhedral large crystals, and quartz is subhedral to anhedral with irregular internal cracks. Hornblende and biotite are the main mafic phase in the studied samples. The modal mineralogy and mineral size of selected samples from the granitic rocks are given in Table 2.

Granitic rocks with granular and phaneritic in texture are a common type of intrusive, felsic, igneous rocks. These rocks consisting of predominantly of alkali feldspar, plagioclase and quartz are a variety of coarse-grained plutonic rock. Alkali feldspar and quartz are physically competent minerals, but having the competent minerals does not mean that the rock is so hard. In accordance with the findings obtained from mineralogical-based analysis, it is not feasible to clearly speak of an effect of rock forming minerals on rock strength. However, it is likely to mention that the increase in the rate of alkali feldspar and the decrease in the

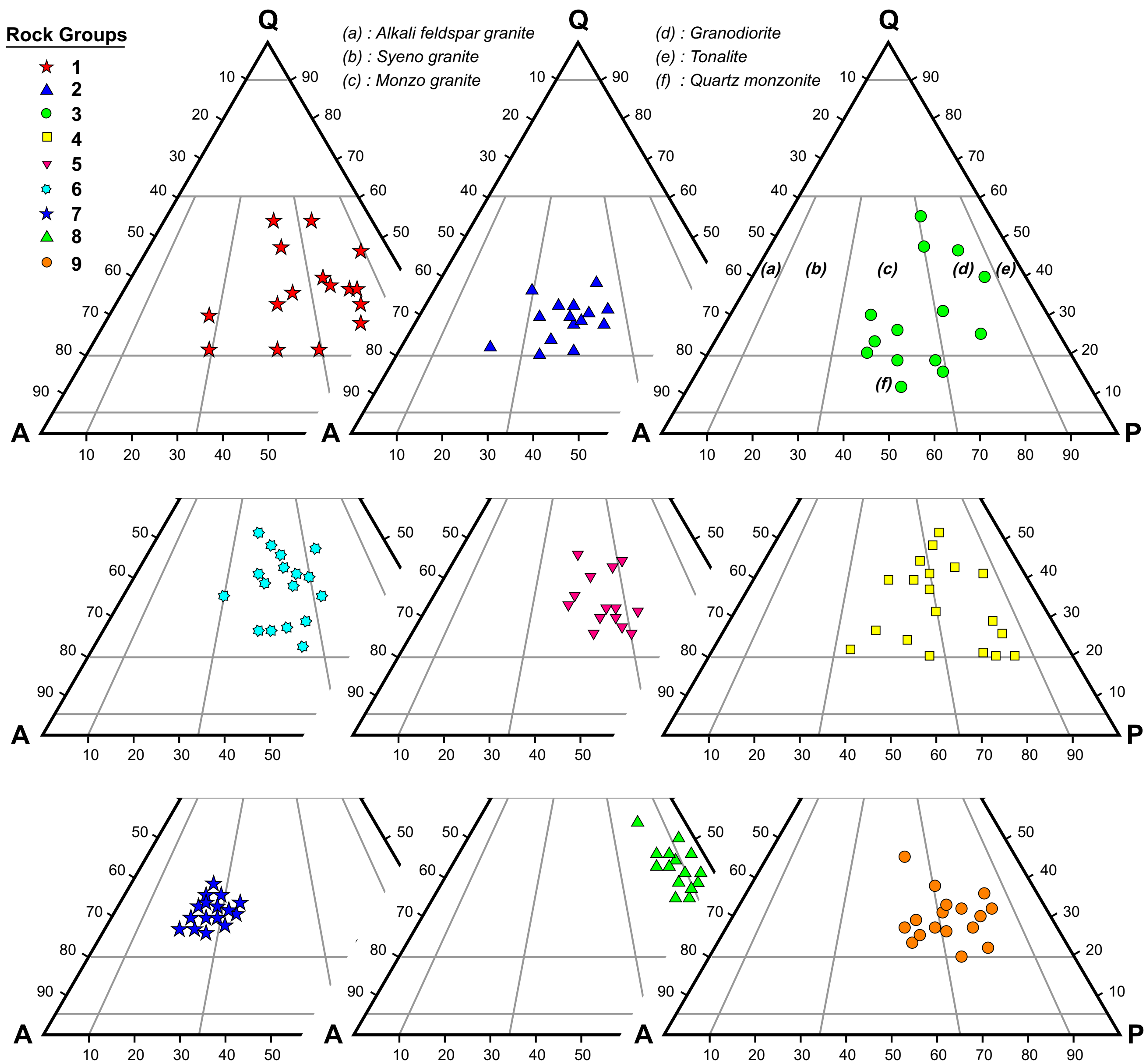

Fig. 2 Classification of the studied granitic rocks based on QAP modal mineralogy

rate of plagioclase may partially increase rock strength. Figure 4 shows the uniaxial compressive strength increase with the increase in quartz and alkali feldspar and decreasing plagioclase. Thus, there is a positive correlation between UCS and A/P. This gives an indication that the percentage of only quartz may not play an important role to determine the UCS of the studied granitic rocks.

Sample preparation and laboratory tests

An experimental program was conducted on rock cores for determination of both physical and strength properties of granitic rock materials. For that purpose, a total of twenty oriented block samples were collected from the nine different granitic bodies for laboratory testing and 250 NX-size core specimens having a 2.5:1 length to diameter ratio were prepared from the block samples. Rock samples were carefully inspected before testing, and the freshest and most representative samples from granitic rocks (163 samples) were selected to perform index and strength properties based on petrographical studies. Unit weight, water absorption by weight, apparent porosity and uniaxial compressive strength (UCS) were measured according to the ISRM (2007). A Pundit Plus ultra-sonic pulse instrument giving more precise rock sample measurements and two 54 kHz transducers having piezoelectric properties were used in this study to calculate ultrasonic longitudinal wave velocity.

Table 1 General mineralogical and petrographical characteristics of the studied granitic rock groups

Sample	Location	Texture	Mineralogy	Rock name
1	İkizdere (Rize)	Porphyric monzonitic	Plagioclase, quartz, orthoclase, hornblende and biotite	Monzogranite, granodiorite
2	İkizdere (Rize)	Microlitic Porphyric	Plagioclase, quartz, orthoclase, hornblende, chloride, sphene	Monzogranite, syenogranite
3	Ilıcaköy (Rize)	Porphyric	Plagioclase, quartz, orthoclase, hornblende, biotite chloride, sericite	Monzogranite, granodiorite, quartz monzonite
4	İkizdere (Rize)	Microlitic Porphyric	Plagioclase, quartz, orthoclase, Hornblende, biotite	Monzogranite, granodiorite
5	Çaykara (Trabzon)	Porphyric monzonitic	Plagioclase, quartz, orthoclase, hornblende, biotite, chloride	Monzogranite, granodiorite
6	Çaykara (Trabzon)	Porphyric	Plagioclase, quartz, orthoclase, hornblende, biotite, chloride, epidote	Monzogranite, granodiorite
7	Dereli (Giresun)	Microlitic, Porphyric	Plagioclase, quartz, orthoclase, hornblende, biotite, chloride,	Syenogranite, monzogranite
8	Hemşin (Rize)	Porphyric	Plagioclase, quartz, orthoclase, hornblende, biotite, chloride, epidote, sericite	Granodiorite, tonalite
9	Ilıcaköy (Rize)	Microlitic, Porphyric	Plagioclase, quartz, orthoclase, hornblende, biotite, chloride,	Granodiorite, monzogranite

Table 3 provides a summary of the physical properties of the granitic rock samples. The value of water absorption by weight varied from 0.14 to 0.56% and apparent porosity ranged between 0.38 and 1.47% for all samples. The unit weight of the granitic rocks fluctuated between 22.80 and 26.66 kN/m^3 for a dry condition, and these values ranged between 22.88 and 26.72 kN/m^3 for saturated condition. Depending more on the mineral shapes and occurrence of the microcracks and less on weathering features, the UCS values varied in a wide range as found in the study. While the minimum and maximum UCS values of the rock materials are 64 and 261 MPa, respectively, the average UCS values for all rock groups are between 134 and 211 MPa (Table 4).

In the study, the ultrasonic tests were also conducted for saturated and dry conditions. The minimum and maximum values of P-wave velocity for dry samples are 3163 and 5742 m/s; these values are 3759 and 5888 m/s for saturated condition, respectively, for all samples. The average value of P-wave velocity of the rock groups for dry condition ranged from 3888 and 4584, and 4407 and 5324 m/s for saturated condition (Table 4).

Rock materials are generally classified based on their strength values, especially from uniaxial compressive strength (Singh and Goel 2011). However, the mineralogical properties and also P-wave velocity can be often used for both predicting the rock material properties and evaluating of weathering degree (Bell 2007). Some definitions based upon the ultrasonic velocities and UCS of the rock material for the recognition of weathering grades for granitic rock were proposed (Iliev 1967; Brown 1981; Bieniawski 1974). Considering to these research, more than 90% of all rock samples are classified as fresh/slightly weathered and strong/very strong.

Statistical relations between UCS and index properties

The uniaxial compressive strength of rock materials greatly depends on their index properties such as porosity, water absorption and mineral composition. One of the most important measurements to assess the strength properties of the granitic rock is P-wave velocity (Sachpazis 1990; Tuğrul and Zarif 1999; Palchik 1999; Ceryan et al. 2008; Karakul and Ulusay 2013). Thus, there has been an upward trend on the prediction of UCS; therefore, many researchers have carried out studies in determining the strength characteristics of rock material more easily and in shorter time by simple index properties. Regression analysis is usually preferred for establishing the statistical relationships between these variables. Relationship intensity of between variables is defined by regression values and correlation coefficients. As regression analysis provides a means of summarizing the relationship between variables, simple regression analysis-based methodology was used to establish some numerical relationships among ultrasonic wave velocity, apparent porosity and UCS of

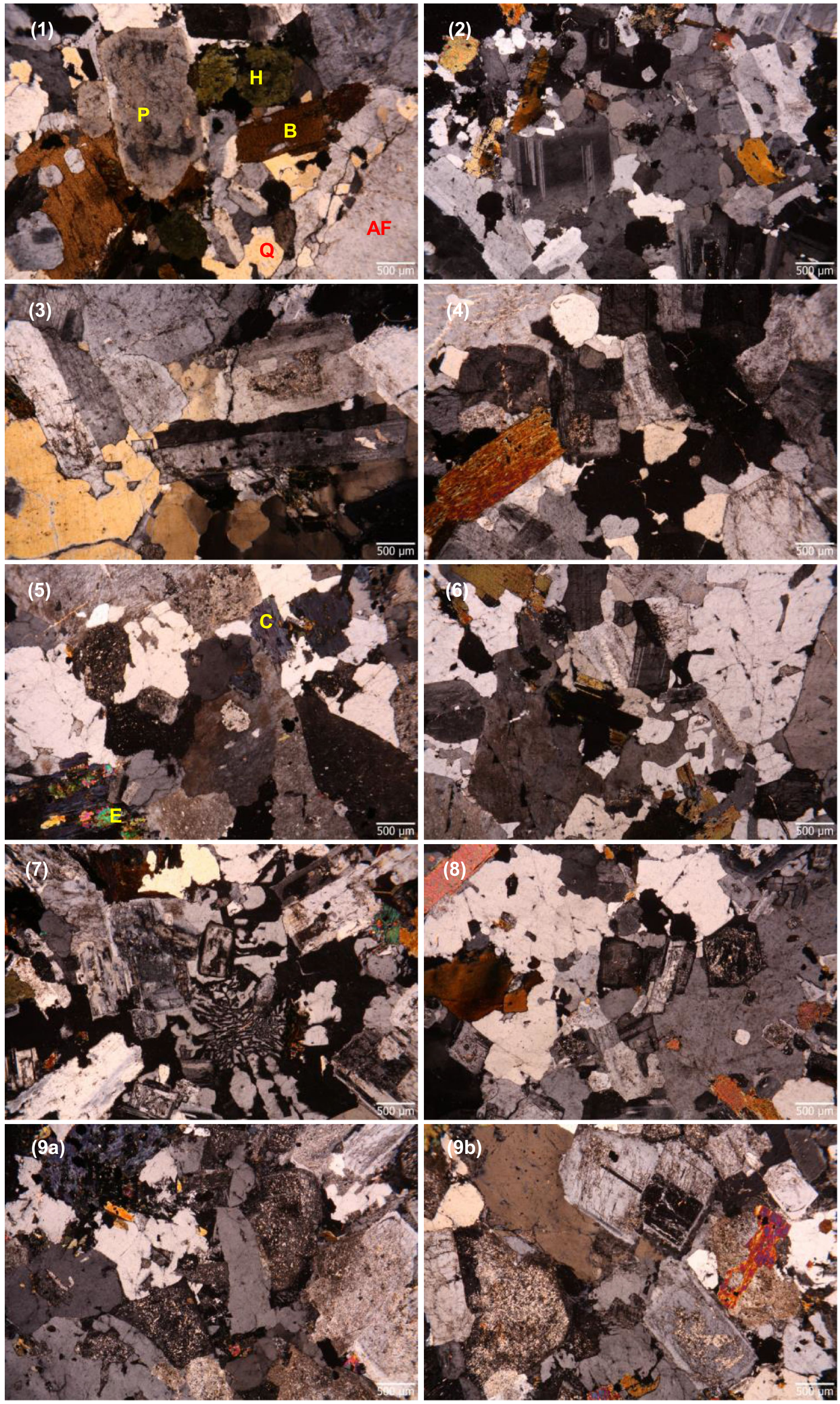

Fig. 3 Microphotographs of the studied granitic rocks (*P*: Plagioclase, *Q*: quartz, *AF*: orthoclase, *H*: hornblende, *B*: biotite, *E*: epidote)

rock materials. In the methodology, while the UCS and V_p are depending variable, index properties were considered to be explanatory variables. According to the regression analysis results, V_p and UCS decrease with increased apparent porosity and water absorption by weight. The relationships with some negative correlations were

Table 2 Modal mineralogy/mineral composition and mineral size of the studied granitic rock groups

Sample groups	Quartz (%)			Plagioclase (%)			Orthoclase (%)			Mafic (%)	Opaque (%)
	Max.	Min.	Ave.	Max.	Min.	Ave.	Max.	Min.	Ave.		
1 (*n*: 18)	55	21	34.38	55	20	37.59	52	5	19.60	8.68	0.49
2 (*n*: 19)	40	20	28.26	42	20	31.56	60	25	35.94	4.04	0.38
3 (*n*: 17)	56	10	24.79	55	25	37.22	45	10	31.70	5.93	0.73
4 (*n*: 20)	50	20	30.44	68	30	40.75	50	20	22.69	6.08	0.42
5 (*n*: 15)	46	24	29.64	48	25	36.62	45	20	24.77	9.85	0.00
6 (*n*: 17)	51	22	33.43	48	20	33.28	44	15	25.69	8.08	0.14
7 (*n*: 21)	40	25	26.02	30	15	19.02	60	42	39.86	17.57	0.12
8 (*n*: 18)	52	33	37.06	60	30	44.45	15	3	6.33	12.63	0.24
9 (*n*: 18)	48	28	33.55	65	35	45.54	35	11	19.65	5.65	0.18
Sample groups	Quartz (mm)			Plagioclase (mm)			Orthoclase (mm)			Mafic (mm)	Opaque (mm)
	Max.	Min.	Ave.	Max.	Min.	Ave.	Max.	Min.	Ave.		
1 (*n*: 18)	6.06	0.34	1.61	3.30	0.36	1.34	9.20	0.60	3.21	0.90	0.17
2 (*n*: 19)	4.00	0.20	0.96	3.40	0.36	1.08	13.00	0.40	1.74	0.70	0.40
3 (*n*: 17)	6.00	0.20	1.36	4.00	0.32	1.27	11.80	0.48	3.83	0.69	0.28
4 (*n*: 20)	3.90	0.30	1.29	5.50	0.56	1.58	18.20	0.52	2.52	0.99	0.30
5 (*n*: 15)	6.70	0.30	1.53	3.00	0.30	1.18	5.20	0.34	1.35	0.74	0.17
6 (*n*: 17)	7.40	0.60	2.00	3.00	0.40	1.31	6.40	0.50	1.59	0.85	0.19
7 (*n*: 21)	3.00	0.30	1.09	1.80	0.30	0.86	8.50	0.68	2.56	0.69	0.24
8 (*n*: 18)	5.26	0.40	1.46	2.90	0.40	1.37	1.40	0.30	0.82	0.74	0.26
9 (*n*: 18)	6.20	0.55	1.98	3.95	0.30	1.25	2.90	0.25	1.16	0.65	0.21

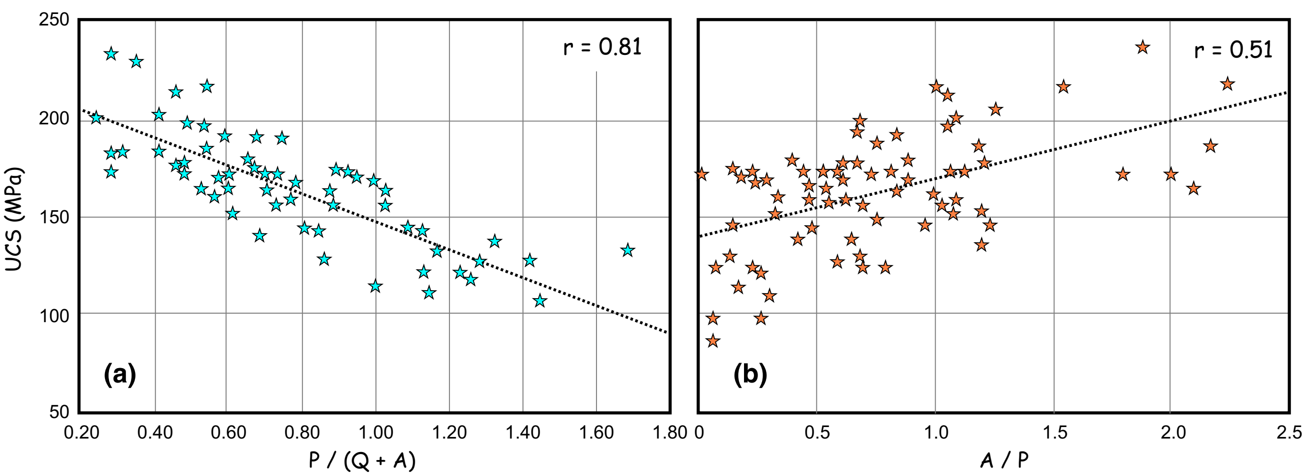

Fig. 4 Relationship between mineral content and UCS of the studied rocks

characterized by 0.85, 0.87 and 0.82 correlation coefficients (Fig. 5a–c). Thus, UCS and V_p were considered as a depending and explanatory variables, respectively, for the determination of the relationship between UCS and V_p. Figure 5d shows some positive correlations between UCS and V_p, and the relationships were characterized by 0.80 correlation coefficients.

Construction of the mineralogical-based methodology

The ultrasonic wave velocity of rock materials is directly affected by mineralogical properties and micro-fissure ratio. Thus, petrographical and longitudinal wave velocity based methodology was suggested by Fourmaintraux

Table 3 Some index properties of the studied granitic rocks

Sample groups	Water absorption by weight (%)				Apparent porosity (%)				Unit weight (dry, %)				Unit weight (saturated, %)			
	Max.	Min.	SD.	Ave.	Max.	Min.	SD.	Ave.	Max.	Min.	SD.	Ave.	Max.	Min.	SD.	Ave.
1 (*n*: 18)	0.32	0.26	0.03	0.28	0.82	0.66	0.08	0.73	26.36	24.66	0.8	25.5	26.43	24.73	0.9	25.5
2 (*n*: 19)	0.38	0.32	0.03	0.35	1.01	0.84	0.09	0.91	25.92	24.83	0.6	25.3	26.02	24.92	0.6	25.3
3 (*n*: 17)	0.42	0.27	0.08	0.32	1.11	0.72	0.20	0.84	26.03	24.48	0.8	25.6	26.12	24.56	0.8	25.6
4 (*n*: 20)	0.41	0.32	0.05	0.36	1.08	0.81	0.14	0.93	25.89	22.80	1.4	25.3	25.99	22.88	1.5	25.4
5 (*n*: 15)	0.56	0.42	0.07	0.45	1.47	1.11	0.19	1.18	25.90	25.09	0.4	25.7	26.05	25.20	0.3	25.8
6 (*n*: 17)	0.48	0.27	0.10	0.37	1.24	0.70	0.24	0.96	26.52	25.14	0.6	25.6	26.62	25.23	0.7	25.7
7 (*n*: 21)	0.34	0.21	0.07	0.26	0.88	0.54	0.16	0.68	26.35	25.33	0.5	25.8	26.43	25.39	0.4	25.9
8 (*n*: 18)	0.29	0.14	0.07	0.22	0.78	0.38	0.19	0.58	26.66	25.71	0.5	26.1	26.72	25.74	0.5	26.2
9 (*n*: 18)	0.55	0.35	0.10	0.49	1.47	0.91	0.23	1.30	26.46	25.35	0.6	25.9	26.59	25.48	0.6	26.0

Table 4 P-wave velocity (dry and saturated conditions) and UCS values of the granitic rocks

Sample groups	P-wave velocity (dry, m/s)				P-wave velocity (saturated, m/s)				Uniaxial compressive strength (dry, MPa)			
	Max.	Min.	SD.	Ave.	Max.	Min.	SD.	Ave.	Max.	Min.	SD.	Ave.
1 (*n*: 18)	4588	3773	248	4230	5464	4568	450	5108	189	121	32	157
2 (*n*: 19)	4319	3709	210	3978	5148	4547	386	4850	243	126	56	188
3 (*n*: 17)	4291	3163	234	3906	4891	3759	421	4407	184	100	40	150
4 (*n*: 20)	4272	3688	211	3888	5268	4548	432	4972	182	123	29	158
5 (*n*: 15)	4758	4345	201	4585	5510	4854	444	5324	243	124	55	182
6 (*n*: 17)	4820	3969	251	4374	5449	4778	398	5137	185	109	37	152
7 (*n*: 21)	4922	4070	246	4390	5634	4854	423	5192	203	64	71	134
8 (*n*: 18)	5743	4857	308	5535	5888	5402	249	5721	226	84	73	141
9 (*n*:s 18)	4764	3800	246	4206	5293	4479	391	4802	261	134	65	211

(1976) to determine the degree of the micro-fissure and the related "Quality Index (QI)" of rocks. QI is related to the ratio of the micro-fissure (directly weathering degree) especially for granitic rocks contrary to their mineral content. Using petrographic techniques, a weathering classification from fresh to residual soils was also established by Ceryan et al. (2008) based on the percentage of secondary minerals, microcracks and voids. Quality Index is the ratio of the measured longitudinal velocity of the samples to velocity calculated on a basis of the mineralogical composition and is calculated with the following equation.

$$\mathrm{QI}(\%) = \frac{V_l}{V_l^*} \times 100 \tag{1}$$

where QI: Quality Index, V_l: measured P-wave velocity of rock sample, V_l*: calculated P-wave velocity of fresh and unfissured rock. If the mineralogical content of the rock material is known, V_l* can be calculated with the following equation.

$$\frac{1}{V_l^*} = \sum_i \frac{C_i}{V_{l,i}} \tag{2}$$

where $V_{l,i}$: P-wave velocity of "mineral *i*" (Quartz = 6050 m/s, alkali feldispar = 5800 m/s; plagioclase = 6250, mafic minerals = 6500 according to Fourmaintraux 1976) and C_i: volumetric rate of "mineral *i*" in the rock (modal analysis).

In this study, QI values were calculated and fissuring degree of granitic rocks was determined for all samples using the results obtained (Fig. 6a). Thus, weathering classification of the rocks based on secondary mineral and percentage microcracks and voids was carried out (Fig. 6b). These analyses indicated that more than 95% of all samples of the rocks are fresh and more than 50% of the granitic rocks are unfissured and slightly fissured.

In this study, certain numerical relations between UCS and Quality Index values of the fresh granitic rocks were established to achieve more rapid and practical solutions for the prediction of UCS values. According to the regression analysis results, a positive linear relation was observed (Fig. 6c). The relationship is characterized by a correlation coefficient of 0.89 and is represented by the following formulas.

$$\mathrm{UCS} = 2.6\mathrm{QI} - 19 \tag{3}$$

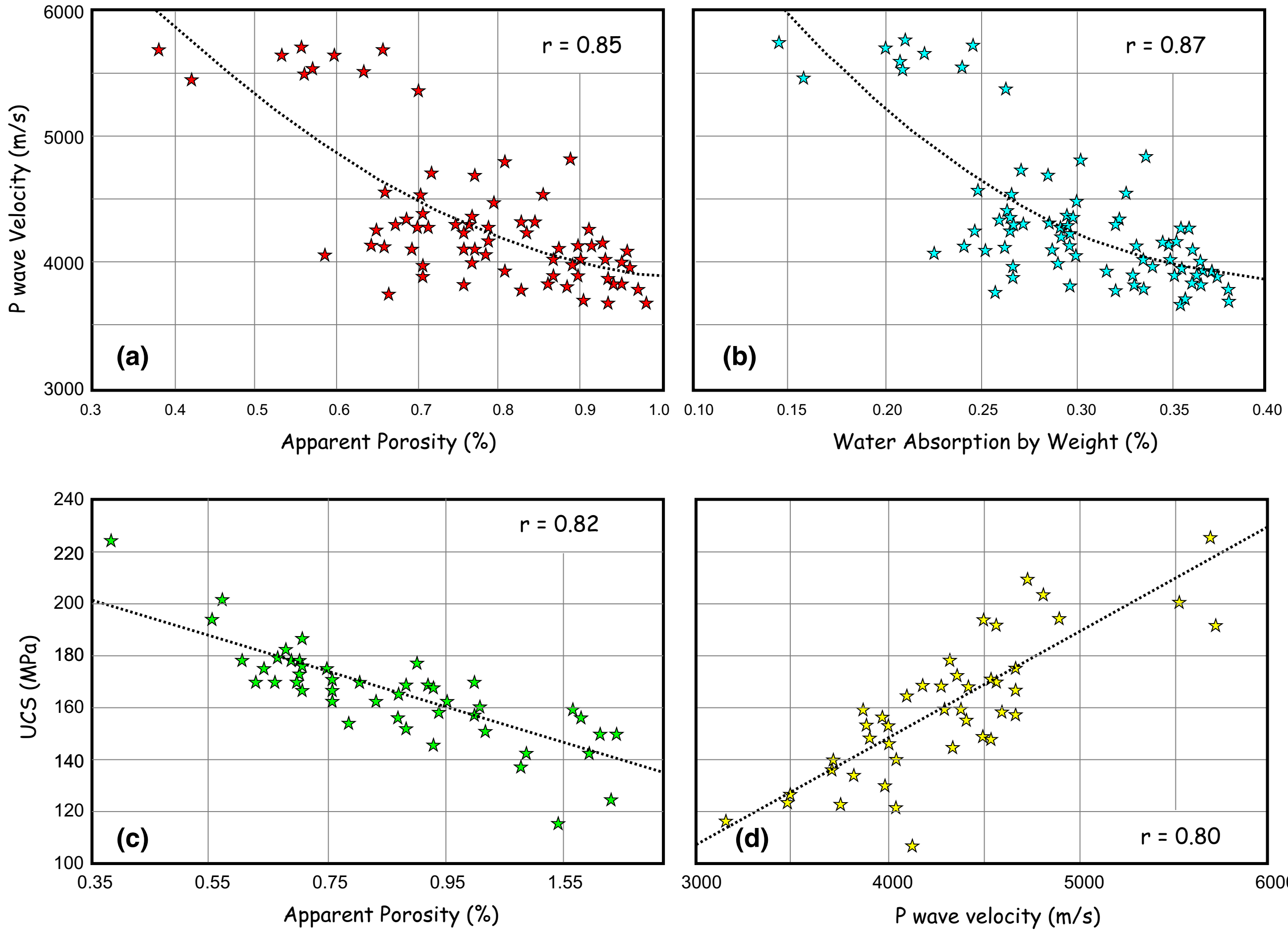

Fig. 5 Statistical relationships among some physico-mechanical properties of the studied granitic rocks

where UCS: uniaxial compressive strength (MPa) and QI: Quality Index (%).

A rock's strength can be dependent on many different factors such as micro-fissure ratio, the state of weathering, mineral composition, structure and texture. The previous studies on rock material indicate that the rocks containing large amounts of physically competent minerals are obviously strong (Tuğrul and Zarif 1999; Gokceoglu and Zorlu 2004; Özçelik et al. 2012; Gokceoglu 2002; Heidari et al. 2013; Öztürk and Nasuf 2013). The results of these said aforementioned studies show that weathering changes hard minerals into softer ones and loosens up the structure of a rock. Thus, the cohesive strength can be lost with the high micro-fissure ratio.

The statistical relationship among UCS, mineral content and average mineral size was investigated to determine the effect of mineral content and size on the uniaxial compressive strength of the studied granitic rocks (Fig. 7a, b). The modal mineralogy shows that the average quartz, plagioclase and orthoclase contents ranged between 25–34, 16–46 and 6–40%, respectively. The content of mafic minerals such as hornblende, augite, biotite is less than 15%. In taking note of the petrographic observations on 165 thin sections, it is realized that mafic minerals were subjected to chemical weathering (moderately) which was separate of the other minerals. The mineralogy-based analysis results on granitic rocks show that strength decreases with mafic mineral content and increases with the alkali feldspar ratio (except group 8). Grain size analysis result shows that the size of quartz and plagioclase ranged between 1 and 2 mm and the size of alkali feldspar is between 1 and 4 mm. Although increasing the quartz amount is considered to lead to a strength increase, contrary to this, the most important parameters effecting on UCS values are alkali feldspar amount and size for the granitic rocks that were studied.

Also, because the mineral composition and UCS do not directly show a significant statistical relation (Figs. 4b, 7a), multiple regression analysis could not be carried out between them. For this reason, for estimation of UCS values of granitic rocks, micro-fissure and weathering properties-based methodology was chosen for the study.

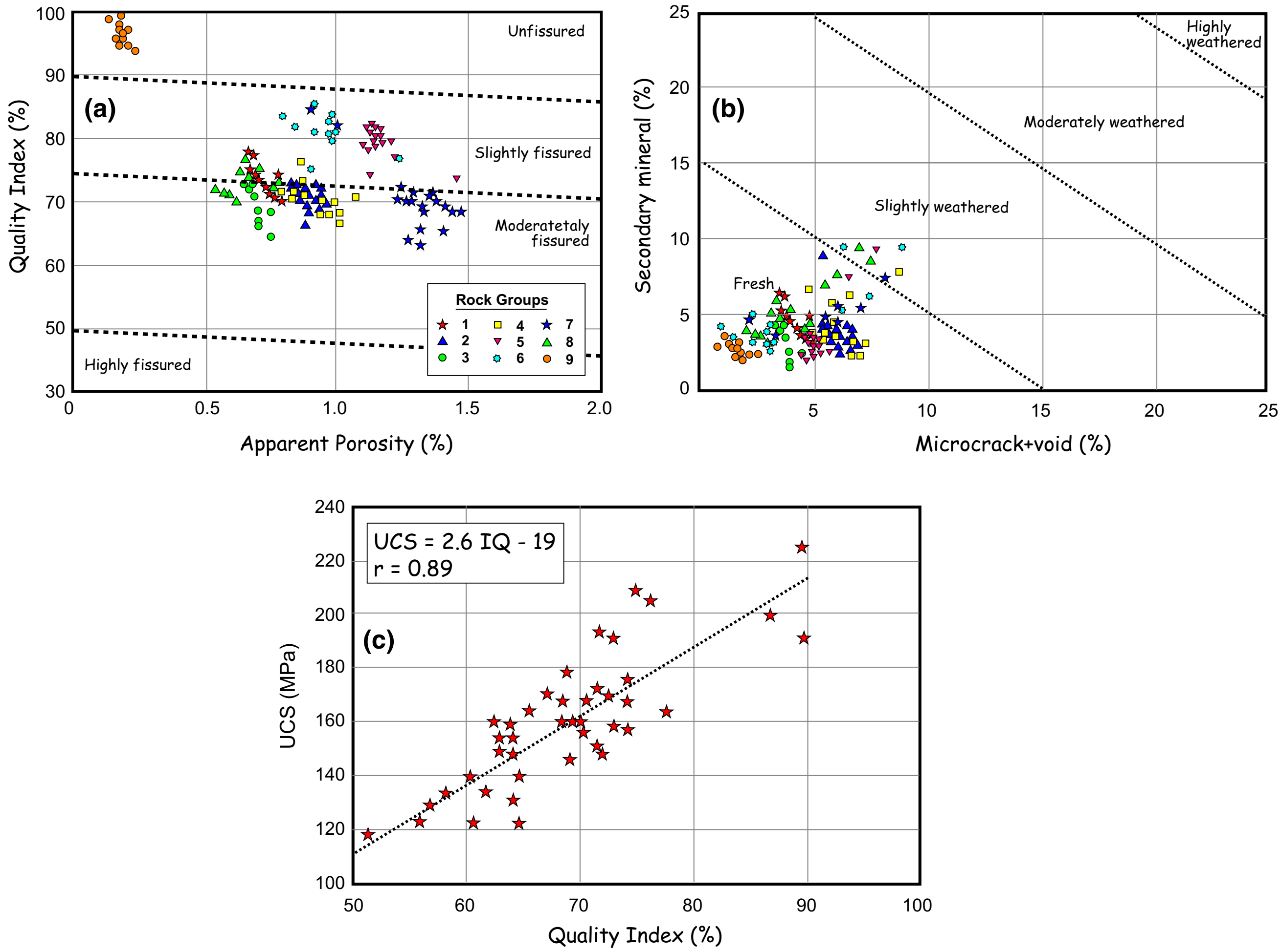

Fig. 6 Distribution of the rock types investigated on the classification scheme for fissuring developed by Fourmaintraux (1976) (**a**) and proposed by Ceryan et al. (2008) (**b**). Positive linear relation between UCS and QI (**c**)

The relationships between the UCS and V_p have been generally established only for dry condition, and the effect of saturation on test results was generally ignored (Kahraman 2001; Yasar and Erdogan 2004; Karakuş and Tütmez 2006; Çobanoglu and Celik 2008; Sarkar et al. 2012; Karakul and Ulusay 2013). Only in a few studies, two conditions (dry and saturated) were regarded and the results of the studies indicated that the effect of saturation of these properties is considerably different (Török and Vasarhelyi 2010). The differences are considered as a result of the mineralogical properties and the porosity of the rock materials. Thus, the study focuses on the correlation between UCS and V_p of various granitic rocks under saturated and dry condition because the experimental results indicated that strength properties of the rocks changed with different saturation conditions. A new model based on ultrasonic wave velocity that is related to the mineralogical properties of the granitic rock materials was proposed. For this purpose, the saturated and dry ultrasonic wave velocities were used in the determination of Quality Index of granitic rocks (Fig. 7c) and ultrasonic velocity ratio (UVR) was defined as below:

$$\mathrm{UVR} = \frac{[V_p(s) - V_p(d)]}{V_p(d)} \tag{4}$$

where UVR: ultrasonic velocity ratio, $V_p(s)$ and $V_p(d)$ are p-wave velocities for saturated and dry conditions.

According to the regression analysis results, a negative logarithmic relation was observed between UVR and QI. The relationship is characterized by a correlation coefficient of 0.77. In this case, if saturated and dry sonic velocity values of the rock are known, the Quality Index values of fresh granitic rocks can be defined with the equation below.

In addition to this, the determination of the mineral content of granitic rocks through modal analysis is time-consuming and also requires expertise. Therefore, in this study the graphic below was suggested for estimation of Quality Index values and thereby UCS values of rocks (Fig. 8). As it is seen in the graphic, if ultrasonic velocity

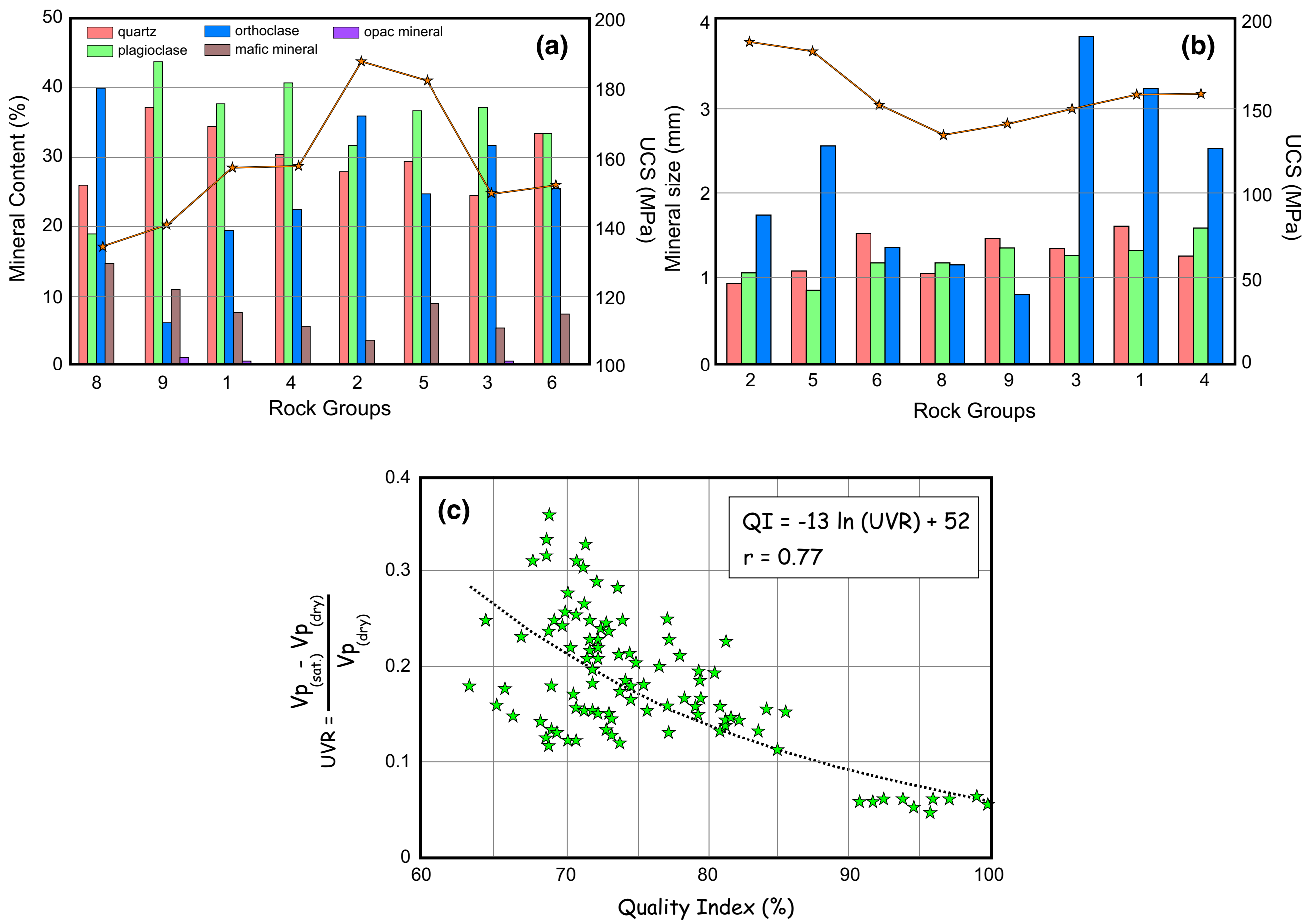

Fig. 7 Effect of the mineral content and size on UCS of the very strong granitic rocks (**a**, **b**) and relationship between Quality Index value and proposed ultrasonic velocity ratio of the studied rocks (**c**)

ratio of the very strong granitic rock is known, the uniaxial compression values can be calculated with the formula below:

$$UCS = 116 - 33.8UVR(r = 0.84) \quad (5)$$

where UCS (MPa), UVR: ultrasonic velocity ratio (Eq. 4).

It should be noted that this proposed formula can be used for only stronger to very stronger samples [$V_p(-s) > 4000$ m/sn and/or $V_p(d) > 5000$ m/sn] (Ersoy et al. 2014).

The significance of the r values was evaluated by the t test at a confidence level of 95%. As shown in Table 5, it is concluded that there is a significant relationship between UCS and UVR.

Model testing

There are statistically significant relationships with a correlation coefficient of 79% between the UCS and Quality Index of the fresh granitic rocks. However, there are the relationships with a correlation coefficient of 77% between Quality Index and ultrasonic velocity ratio. Nevertheless, there is a need for testing the usability of the strength parameters that have been determined statistically. A goodness of fit test establishes whether an observed frequency distribution differs from a theoretical distribution; however, a model's suitability is tested using the difference between observed and expected values. The normal distribution is a continuous probability distribution which is often used as a first approach for describing real-valued random variables tending to cluster around a single mean value. A normal distribution would thus be expected in the histograms showing the difference between observed and expected values.

For this purpose, the experimental program was conducted again on rock cores for determination of the meaningful relation between the UCS values obtained from compressive strength tests and the calculated UCS values using proposed graphs/equations. A total of thirteen oriented samples were collected from the three different granitic bodies for laboratory testing. Uniaxial compressive strength (UCS) and ultrasonic wave velocity for saturated

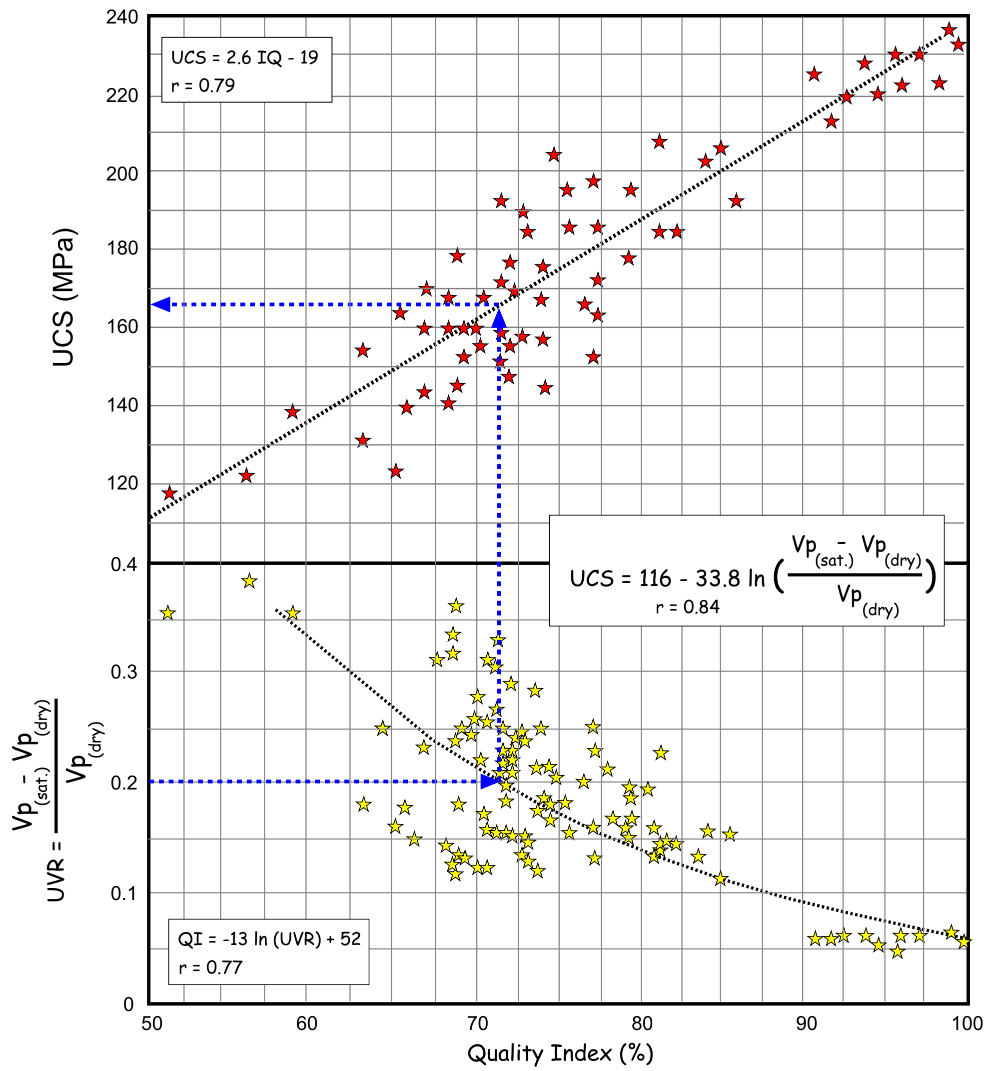

Fig. 8 Suggested graph to predict UCS values from the petrographic based methodology

Table 5 Significance of the *r* value

	UCS	UVR
UCS		
Pearson correlation	1	−0.835[a]
Sig. (2-tailed)		0.000
N	64	64
UVR		
Pearson correlation	−0.835[a]	1
Sig. (2-tailed)	0.000	
N	64	64

[a] Correlation is significant at the 0.01 level (2-tailed)

and dry conditions were measured according to the ISRM (2007). After the tests, the UCS values of same samples were calculated using the proposed graph. Table 6 provides a summary of the test results of the granitic rock samples. Line-scatter plot diagrams of the calculated with model and experimentally measured values were prepared. The UCS values calculated with the two different methods were compared, and it was observed that there was a statistically significant relation between the different methods. The correlation values were found to be 0.84 for these statistical relations (Fig. 9). The results showed that the proposed model was suitable for the fresh granitic rocks.

Conclusion and discussion

This study is related to discussion of the petrographic properties affecting on the strength of the very strong granitic rocks, determination of the statistical relations between the petrographical characteristics and UCS of these rocks, and a new approach on mineralogical/textural based predictive model for the indirect estimation of UCS for these rocks was proposed in the study.

The texture of granitic rocks is commonly granular and phaneritic, and main minerals of these rocks are alkali

Table 6 Summary of the test results for model testing

No	Location	V_p (m/s)		UVR	UCS (MPa)	
		Saturated	Dried		Calculated	Measured
1	Çaykara	4835	4173	0.16	178	170
2	Çaykara	4778	3969	0.20	170	145
3	Çaykara	4795	4104	0.17	176	162
4	Çaykara	5174	4311	0.20	170	169
5	Dereli	5203	4372	0.19	172	146
6	İkizdere	4891	4291	0.14	182	153
7	Çaykara	4878	4031	0.21	169	171
8	İkizdere	6015	5630	0.07	207	220
9	İkizdere	6028	5689	0.06	211	200
10	İkizdere	5875	5300	0.11	191	185
11	Dereli	4839	3987	0.21	168	137
12	Dereli	4909	4279	0.15	181	181
13	İkizdere	5201	4701	0.11	192	207

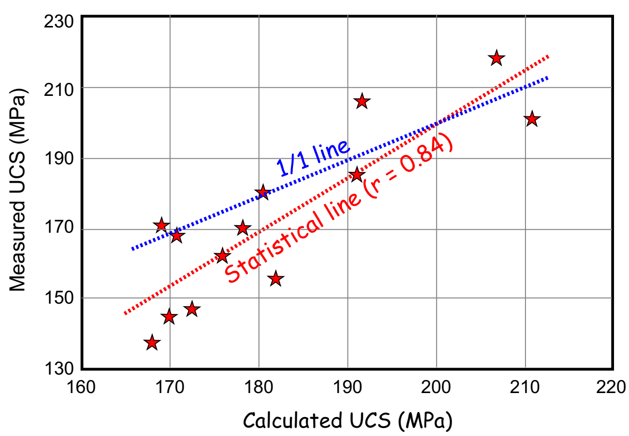

Fig. 9 Line-scatter plot diagrams for measured UCS (using experimental values) compared to calculated UCS (using proposed formula)

feldspar, plagioclase and quartz. Quartz and alkali feldspar content is not the only determining parameters on UCS values of these rocks. Although these minerals are physically competent minerals, increase in the quartz and alkali feldspar may partially increase rock strength.

The point to take into consideration is that contrary to general belief, the increase in the rate of quartz mineral will not equally increase rock strength. As is known, granitic rocks consist of minerals with different resistances and quartz is a rigid mineral with a high level of elasticity module. Quartz mineral, with a higher hardness, does not keep the rock structure together, but instead, it causes a rock fraction along the minerals by pressuring on the ones with lower resistances. This condition is clearly observed in the study.

Smaller granular sizes within basalt and gabbro rocks, which consist of only one type of mineral, are known to increase rock strength (Goodman 1989; Johnson and Degraff 1988). However, in granitic rocks which are the subject of this study, equal sizes of rock forming minerals decrease rock strength. The reason for this condition is that in rocks with equal size minerals with different hardness rates, the rock strength is controlled by minerals with lower strength. Particularly, when it is considered that the increase in the sizes of alkali feldspar minerals increases rock strength, under the conditions where the rock behavior is controlled by only one type of mineral, the rock strength is determined to be higher.

In this study, the uniaxial compressive strength (UCS) was predicted using the Quality Index (QI) values obtained from the mineral percent and P-wave velocity, and a correlation coefficient was determined as 0.84. However, the significant relationship between QI and UVR was investigated with the correlation coefficient of 0.77. Although both models have high correlation coefficient values, these models are very time-consuming because modal analysis is necessary to determine QI values. For this purpose, a new predictive model "ultrasonic velocity ratio" (UVR) was defined in the study for determination of the Quality Index of granitic rocks using the saturated and dry ultrasonic wave velocities, Furthermore, a new graphic was proposed in this study for the estimation of Quality Index values and thereby UCS values of rocks. The obtained correlation coefficient with 0.784 between UVR and UCS was tested using *t* test, and the significant relationship was obtained between QI and UVR.

References

Arslan M, Aslan Z (2006) Mineralogy, petrography and whole-rock geochemistry of the Tertiary granitic intrusions in the Eastern Pontide, Turkey. J Asian Earth Sci 27:177–193

Arslan M, Tuysuz N, Korkmaz S, Kurt H (1997) Geochemistry and petrogenesis of the eastern Pontide volcanic rocks, Northeast Turkey. Chemie der Erde 57:157–187

Arslan M, Temizel İ, Abdioğlu E, Kolaylı H, Yücel C, Boztuğ D, Şen C (2013) ^{40}Ar–^{39}Ar dating, whole-rock and Sr–Nd–Pb isotope geochemistry of post-collisional Eocene volcanic rocks in the southern part of the Eastern Pontides (NE Turkey): implications for magma evolution in extension-induced origin. Contrib Miner Petrol 166:113–142

ASTM C170–90 (1999) Standard test method for compressive strength of dimension stone. ASTM International, West Conshohocken

Babacan AE, Ersoy H, Gelisli K (2009) Determination of physical and mechanic properties of rocks with direct and indirect methods: A case study on the beige limestones in the Eastern Pontides. In: Proceedings of the 21st international mining congress and exhibition of Turkey, 123–130

Bektaş O, Yılmaz C, Taslı K, Akdağ K, Özgür S (1995) Cretaceous rifting of the eastern Pontide carbonate platform (NE Turkey): the formation of carbonates breccias and turbidites as evidences of a drowned platform. Geologia 57(1–2):233–244
Bell FG (2007) Engineering geology. Elsevier Press, Houston
Bieniawski ZT (1974) Estimating the strength of rock materials. J S Afr Inst Min Metall 74:312–320
Brown ET (1981) Rock characterization, testing and monitoring (ISRM suggested methods). Pergamon, Oxford, pp 171–183
Cargill JS, Shakoor A (1990) Evaluation of empirical methods for measuring the uniaxial compressive strength of rock. Int J Rock Mech Min Sci Geomech 27(6):495–503
Ceryan S, Tudes S, Ceryan N (2008) Influence of weathering on the engineering properties of Harsit granitic rocks (NE Turkey). Bull Eng Geol Environ 67:97–104
Chang C, Zoback MD, Khaksar A (2006) Empirical relations between rock strength and physical properties in sedimantary rocks. J Petrol Sci Eng 51:223–237
Çobanoglu İ, Celik SB (2008) Estimation of uniaxial compressive strength from point load strength, Schmidt hardness and P-wave velocity. Bull Eng Geol Environ 67:491–498
Coggan JS, Stead D, Howe JH, Faulks CI (2013) Mineralogical controls on the engineering behavior of hydrothermally altered granites under uniaxial compression. Eng Geol 160:89–102
Dehghan S, Sattari GH, Chelgani C, Aliabadi M (2010) Prediction of uniaxial compressive strength and modulus of elasticity for travertine samples using regression and artificial neural networks. Min Sci Technol 20:41–46
Ersoy H, Kanik D (2012) Multicriteria decision-making analysis based methodology for predicting carbonate rocks' uniaxial compressive strength. Earth Sci Res J 16(1):65–74
Ersoy H, Acar S, Sünnetçi MO, Yalçınalp B (2014) Granitlerin Fiziksel ve Mekanik Özelliklerin ve Bunlar Arasındaki İlişkilerin Araştırılması, 67. Türkiye Jeoloji Kurultayı Bildiri Özleri Kitabı, 616–617 (**in Turkish**)
Eyuboglu Y, Santosh M, Bektaş O, Ayhan S (2011) Arc magmatism as a window to plate kinematics and subduction polarity: example from the Eastern Pontides Belt, NE Turkey. Geosci Front 2(1):49–56
Fourmaintraux D (1976) Characterization of rocks; laboratory tests, Chapter IV in La Mecanique des roches appliquee aux ouvrages du genie civil by Marc Panet et al. Ecole Nationale des Ponts et Chaussees, Paris
Gaviglio P (1989) Longitudinal waves propagation in a limestone: the relationship between velocity and density. Rock Mech Rock Eng 22:299–306
Gokceoglu C (2002) A fuzzy triangular chart to predict the uniaxial compressive strength of the Ankara agglomerates from their petrographic composition". Eng Geol 66(1–2):39–51
Gokceoglu C, Zorlu K (2004) A fuzzy model to predict the uniaxial compressive strength and the modulus of elasticity of a problematic rock. Eng Appl Artif Intell 17:61–72
Goodman RE (ed) (1989) Introduction to rock mechanics, 2nd edn. Wiley, Hoboken
Grima MA, Babuska R (1999) Fuzzy model for the prediction of unconfined compressive strength of rock samples. Int J Rock Mech Min Sci 36(3):339–349
Heidari M, Momeni AA, Rafiei B, Khodabakhsh S, Torabi Kaveh M (2013) Relationship between petrographic characteristics and the engineering properties of jurassic sandstones, hamedan, Iran. Rock Mech Rock Eng 46(5):1091–1101
Iliev IG (1967) An attempt to estimate the degree of weathering of intrusive rocks from their physico-mechanical properties. Proc First Congr Int Soc Rock Mech Lisb 1:109–114
ISRM (2007) The complete ISRM suggested methods for rock characterization, testing and monitoring: 1974–2006. Suggested methods prepared by the commission on testing methods, ISRM. In: Ulusay R, Hudson JA (eds) Compilation arranged by the ISRM Turkish National Group, Ankara, Turkey
Johnson RB, Degraff JV (1988) Principles of engineering geology. Wiley, Hoboken
Kahraman S (2001) A correlation between P-wave velocity, number of joints and Schmidt Hammer rebound number. Int J Rock Mech Min Sci 38:729–733
Karakul H, Ulusay R (2013) Prediction of strength properties of rocks at different saturation conditions from P-wave velocity and sensitivity of P-wave velocity to physical properties. Yerbilimleri 33(3):239–268 **(in Turkish with English abstract)**
Karakuş M, Tütmez B (2006) Fuzzy and multiple regression modelling for evaluation of intact rock strength based on point load, Schmidt Hammer and sonic velocity. Rock Mech Rock Eng 39(1):45–57
Katz O, Reches Z, Roegiers JC (2000) Evaluation of mechanical rock properties using a Schmidt Hammer. Int J Rock Mech Min Sci 37:723–728
Koncagul CE, Santi PM (1999) Predicting the unconfined compressive strength of the Breathitt sahle using slake durability, Shore hardness and rock structural properties. Int J Rock Mech Min Sci 36:139–153
Mishra DA, Basu A (2013) Estimation of uniaxial compressive strength of rock materials by index test using regression analysis and fuzzy inference system. Eng Geol 160:54–68
Moradian ZA, Behnia M (2009) Predicting the uniaxial compressive strength and static young's modulus of ıntact sedimentary rocks using the ultrasonic test. Int J Geomech 9(1):14–19
Okay AI, Sahinturk O (1997) Geology of the eastern Pontides. In: Robinson AG (ed) Regional and petroleum geology of the black sea and surrounding region. American Association of Petroleum Geologist (AAPG) Memoir 68:291–311
Özçelik Y, Bayram F, Yasitli NE (2012) Prediction of engineering properties of rocks from microscopic data. Arab J Geosci 6(10):3651–3668
Özsayar T, Pelin S, Gedikoğlu A (1981) Cretaceous in the eastern Pontides. KTÜ Yer Bilimleri Dergisi 1(1):1–65 **(in Turkish with English abstract)**
Öztürk CA, Nasuf E (2013) Strength classification of rock material based on textural properties. Tunn Undergr Space Technol 37:45–54
Palchik V (1999) Influence of porosity and elastic modulus on uniaxial compressive strength in soft brittle porous sandstones. Rock Mech Rock Eng 32:303–309
Ramana YV, Venkatanarayana B (1973) Laboratory studies on Kolar rocks. Int J Rock Mech Min Sci 10:465–489
Sachpazis CI (1990) Correlating Schmidt hardness with compressive strength and young's modulus of carbonate rocks. Bull Int Assoc Eng Geol 42:75–83
Sarkar K, Vishal V, Singh TN (2012) An empirical correlation of index geomechanical parameters with the compressional wave velocity. Geotech Geol Eng 30(2):469–479
Singh B, Goel RK (2011) Engineering rock mass classification, tunnelling, foundations, and landslides. Elsevier, Amsterdam
Török A, Vasarhelyi B (2010) The influence of fabric and water content on selected rock mechanical parameters of travertine, examples from Hungary. Eng Geol 115:237–245
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
Ulusay R, Tureli K, Ider MH (1994) Prediction of engineering properties of a selected litharenite sandstone from its petrographic characteristics using correlation and multivariable statistical techniques. Eng Geol 37:135–157

Wong RHC, Chau KT, Wang P (1996) Microcracking and grain size ëect in Yuen Long marbles. Int J Rock Mech Min Sci 33(5):479–485

Yagiz S, Sezer EA, Gokceoglu C (2011) Artificial neural networks and nonlinear regression techniques to assess the influence of slake durability cycles on the prediction of uniaxial compressive strength and modulus of elasticity for carbonate rocks. Int J Numer Anal Meth Geomech 36(14):1636–1650

Yalçınalp B, Ersoy H, Fırat Ersoy A, Keke C (2008) Geological and geotechnical properties of the Bahçecik (Gümüşhane) travertine. Jeoloji Mühendisliği Dergisi 32(1):25–36 **(in Turkish with English abstract)**

Yasar E, Erdogan Y (2004) Estimation of rock physico-mechanical properties using hardness methods. Eng Geol 71:281–288

Yılmaz C, Kandemir R (2006) Sedimentary records of the extensional tectonic regime with temporal cessation: gümüşhane Mesozoic Basin (NE Turkey). Geol Carpath 57:3–13

Zorlu K, Gokceoglu C, Ocakoglu F, Nefeslioglu HA, Acikalin S (2008) Prediction of uniaxial compressive strength of sandstones using petrography-based models. Eng Geol 96:141–158