

Relationship of petrographic and mineralogical characteristics with mechanical strength properties of granitic rocks: a case study from the Biga Peninsula, NW Turkey

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Abstract: This study was carried out on granitic rocks from the Biga Peninsula in order to investigate petrographic, and mineralogical properties in comparison with mechanical strength properties. This study was conducted in four different locations where granitic rocks outcrop from north to south in the Biga Peninsula: Lapseki (Şevketiye granite), Ezine (Kestanbol granite), Bayramiç (Yassıbağ granite), and Edremit (Eybek granite). Field observations and detailed petrographic studies of representative samples indicate that they are quartz monzodiorite (Şevketiye and Yassıbağ), quartz monzonite (Kestanbol), and granodiorite (Eybek) in composition. All the rocks have similar mineral composition, comprising mainly feldspar (plagioclase–alkali feldspar), quartz, mafic minerals (biotite and amphibole), accessory minerals (sphene, zircon, opaque minerals), and secondary minerals (sericite, epidote, chlorite) with differences in the percentage of modal mineralogy, textural details, and weathering. Physical and mechanical properties were also defined in this study, these include water absorption, porosity, uniaxial compressive strength (UCS), tensile strength (TS), Schmidt hardness tests (SHT), Los Angeles test (LA), and frost resistance test (FRT) with sodium sulfate (Na_2SO_4). The results of strength tests show that the Şevketiye granite had the lowest strength values with the highest values for Los Angeles abrasion, frost resistance, water absorption, and porosity. The Eybek granite exhibited the highest value for strength, with the lowest values for Los Angeles abrasion, frost resistance, water absorption, and porosity. A comparison of the petrographic properties of all studied rocks with their respective strengths show that modal mineralogy, degree of alteration, and texture influence the strength of the rocks. Additionally, an increasing propensity for UCS and TS values was found with increasing SHT values. The LA abrasion values and the FRT values were found to increase with decreasing Schmidt hardness test values for the tested samples. The found results of this study could help in the application of these rocks as row material.

Key words: Biga Peninsula, granites, mechanical properties, petrography, physical properties

1. Introduction

Biga Peninsula is located in the northwest of Turkey and the study area was the subject of many geological studies due to its geotectonic position (e.g., Kalafatçıoğlu, 1963; Bingöl, 1968; Bingöl et al., 1975; Gözler, 1986; Siyako et al., 1989; Okay et al., 1991; Ercan et al., 1995; Okay et al., 1996; Aldanmaz, 2000; Okay and Satır, 2000; Yılmaz et al., 2001; Yaltrak and Okay, 2004; Okay and Altın, 2004; Okay and Göncüoğlu, 2004; Duru et al., 2004; Beccalotto et al., 2007; Cavvaza et al., 2009; Tunç, 2014 etc.). In addition, since the most dominant lithology in the region is igneous rocks (plutonic-volcanic) hosting many metallic and raw materials of economic value, many studies about magmatic rocks are also available, especially those from the Cenozoic period (e.g., Bürküt, 1966; Öngen, 1978; Ercan, 1979; Birkle and Satır, 1992; Birkle and Satır, 1995; Karacık, 1995; Karacık and Yılmaz, 1998; Genç, 1998; Delaloye and

Bingöl, 2000; Yılmaz et al., 2001; Aysal, 2005; Karacık et al., 2008; Yılmaz Şahin et al., 2010; Erenoğlu, 2014).

Granites are known around the world for their use as structural engineering materials because of their high strength, resistance to weathering, abrasion resistance, structural and textural characteristics, and other environmental influences. Knowledge of the mechanical properties of rocks also has remarkable importance in engineering problems (e.g., slope stability analysis, underground construction, foundation design, and tunneling, etc.). The petrographic properties (e.g., mineralogical composition, grain size, shape of grains, fabric, etc.) influence the rock mechanical properties. For these reasons, investigations of the relationship between petrographic features and mechanical features of granites are the subject of numerous studies (e.g., İrfan and Derman, 1978; Onodera and Asoka Kumara, 1980;

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İrfan, 1996; Tuğrul and Zarif, 1999; Åkkeson et al., 2001; Begonha and Sequeira Braga, 2002; Tuğrul, 2004; Räisänen, 2004; Sajid et al., 2009; Güneş Yılmaz et al., 2011; Keikha and Keykha, 2013; Abuqubu et al., 2013; Arif et al., 2013; Sousa, 2013; Sajid and Arif 2014; Yadav and Anurag 2014; Arif et al, 2015; Sajid et. al., 2016; Cowie and Walton, 2018; Ajalloeian et al., 2020; Hemmati et al., 2020, etc.).

This study aimed to investigate the relationship between petrographic features and mechanical features of granite. With this aim, granitic rocks from the Biga Peninsula, NW Turkey, are the subject of the study. Although there are many studies about the geology of the granitic rocks covering large areas in the Biga Peninsula, there are few studies about the comparison of the geomechanical properties with the geological and petrographic properties of granitic rocks found in the region so far. Studies by Tuğrul and Zarif (1999), Göker and Tuğrul (2006) and Tunusluoğlu et al. (2012) are a few of these studies. Tuğrul and Zarif (1999) investigated various granitic rock specimens taken from different parts of Turkey including the province of Çanakkale (situated in the Biga Peninsula) and correlated their petrographical and textural characteristics with engineering properties. There was also a study about the quality of Kestanbol Pluton stone quarries in the Ezine district of Çanakkale province in terms of the production of dimension stone by Göker and Tuğrul (2006). Tunusluoğlu et al. (2012) investigated mineralogical-petrographic and uniaxial compressive strength of Kestanbol granites; they compared mineralogical-petrographic and uniaxial compression strength of Kestanbol granites with the results of surface degradation and chemical degradation indices. Therefore, little is known about these granites in terms of their geomechanical properties and the relationship between petrography and geomechanical properties in the region. The scope of this paper is to describe (1) the detailed petrography and mineralogy of representative granite samples from Lapseki-Şevketiye granite, Ezine-Kestanbol granite, Bayramiç-Yassıbağ granite, and Edremit-Eybek granite, (2) the physical properties of representative granite samples named in (1), (3) the mechanical properties of representative granite samples named in (1), (4) the relationship between petrography and geomechanical properties of these representative granite samples, and (5) the useable in the application of these rocks as raw material.

For the implementation of the study, granitic rock samples were gathered from the four locations mentioned above as the test samples. Thin sections of the samples were microscopically analyzed for the determination of modal composition and other textural characteristics. The physical properties (effective porosity, total porosity, and water absorption) of the samples were defined with a variety

of laboratory tests. Mechanical strength tests consisting of uniaxial compressive strength, tensile strength and Schmidt hardness tests, Los Angeles test, and frost resistance test with sodium sulfate (Na_2SO_4) were performed on the prepared samples. Firstly, uniaxial compressive strength, tensile strength, Los Angeles test, and frost resistance test with sodium sulfate (Na_2SO_4) were correlated with Schmidt hardness tests, then the determined values of strength parameters were correlated with the physical and petrographic variables by using regression models. Finally, the main results were interpreted and discussed.

2. Geology

The geological setting of the Biga Peninsula mainly consists of metamorphic and magmatic rocks from Eocene to Pliocene age, and Neogene sedimentary rocks. The Kazdag metamorphic units, containing different rock groups, comprise the basement rocks of the Biga Peninsula. They consist mainly of meta-granitic rocks and gneisses with marble and amphibolite intercalations in the core of the dome and are tectonically overlain by meta-ultramafic rocks enveloped in a marble-rich sequence at the base with amphibolite, metadiorite, and metapelitic rocks above. These are tectonically overlain by the Karakaya Complex consisting of Triassic low-grade metamorphic, magmatic, and sedimentary rocks, which include blocks of Permo-Carboniferous limestone olistoliths (Bingöl et al., 1975; Gözler, 1986; Okay et al., 1991, 1996).

Extensive magmatic activity occurred in Western Anatolia following the continental collision between the Sakarya continent and the Tauride-Anatolide platform during the Oligocene-Middle Miocene period (Genç, 1998, Yılmaz et al., 2001). This also affected the Biga Peninsula and propagated both intrusive and extrusive rocks in the Biga Peninsula. Upper Miocene-Pliocene sediments with lacustrine and fluvial facies, which form a common cover to the older rocks, overlie the magmatic rocks.

The Şevketiye granitic rocks belong to the oldest Cretaceous granitoid (71.9 ± 1.8 My, Delaloye and Bingöl, 2000) in the Biga Peninsula, and crop out over an area of approximately 22 km² southeast of Şevketiye village and northwest of Lapseki in the northern part of the Biga Peninsula (Figure 1). The Şevketiye granite was emplaced into the basement rocks, which are mainly composed of quartz schist, mica schist, amphibolite, and local marble bands (the Çamlıca metamorphics).

The Miocene Kestanbol granite (Birkle and Satır, 1992; Delaloye and Bingöl, 2000), outcrops south of Ezine in the southwestern part of the Biga Peninsula and was emplaced into Paleozoic metamorphic basement rocks (Figure 1). The unit outcrops in an area of approximately 200 km² (Yılmaz Şahin et al., 2010).

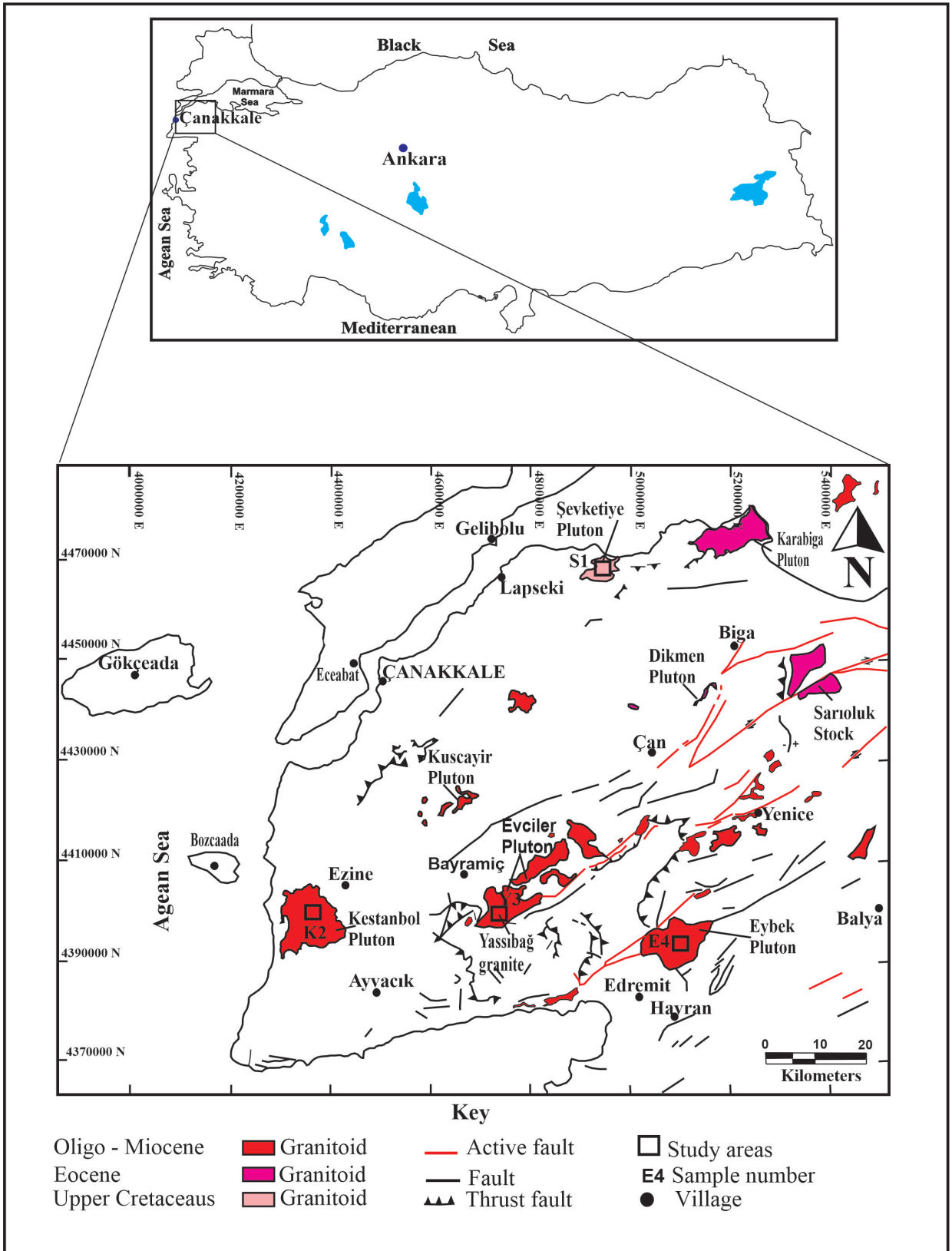


Figure 1. Geological map of plutonic rocks in the Biga Peninsula showing location of the study areas and sample locations (S1, K2, Y3, E4) (modified from MTA 2001).

The Yassibağ granite outcrops around Yassibağ village, south of Bayramiç region and belongs to the Evçiler pluton (Figure 1). The Evçiler pluton was dated to 25 ± 0.3 My with the Rb/Sr method (Birkle, 1992), and is an elliptical body with a long axis trending WSW–ENE, covering an area of approximately 180 km² (Genç, 1998). The plutonic rocks were emplaced into basement metamorphic rocks (Duru et al., 2007).

Finally, the Eybek granite crops out between Edremit and Kalkım districts with an area of approximately 90 km² in the southeastern part of the Biga Peninsula (Figure 1). The granitic unit was emplaced into Paleozoic basement metamorphic rocks composed of phyllite, schist, metaophiolite, marble, and serpentinite and the Triassic Karakaya formation (Duru et al., 2007a). The Eybek granite was dated by the K/Ar method to 20.3 ± 0.5 My– 35.9 ± 2.0 My (Oligocene - Eocene) (Murakami et al., 2005).

3. Materials and methods

Granitic rock samples were gathered from four locations of Lapseki, Ezine, Bayramiç, and Edremit in the Biga Peninsula (Figure 1) in this study. Mechanical strength and petrographic analyses were carried out on four previously described granites (Figure 1). To describe the investigated rocks, each one was analyzed to define its mechanical and petrographic characteristics.

Eighteen thin sections were made to determine detailed petrographic properties including mineral content, textural properties, and determination of modal mineralogical composition through visual estimation under a polarizing microscope. Thin sections of each granitic rock block and/or core sample from core drilling were made for petrographic study in the Mineralogy and Petrography Laboratory of the General Directorate of Mineral Research and Exploration (MTA)-Ankara. These studies were undertaken by the Department of Geological Engineering in Çanakkale Onsekiz Mart University.

Priority was placed on gathering fresh granitic block specimens and drill cores from locations to ensure that the samples were fresh granitic rock samples from the four selected locations. Since there is a high degree of alteration in granites at the Şevketiye and Yassibağ locations, core samples were taken with a drill rig from approximately 10–40 m depth and 15–45 m depth, respectively. The Kestanbol granite samples were taken from a granite quarry in Yahyaçavuş village and Eybek granite samples were taken as a granitic block from the outcrop.

Samples were prepared using a laboratory-drilling machine to obtain standard cylindrical samples required for geomechanical tests. Uniaxial compressive strength (UCS) and tensile strength tests were performed in accordance with the ISRM (2007) recommendations. Tensile strength (TS) was established by the Brazilian

test (BTS). Schmidt hardness tests (SHT) were carried out with L-type hammer with the hammer led vertically downwards and at right angles to the horizontal planes of core samples with respect to ISRM (2007). The results of these tests are given in Table 1.

The Los Angeles test is utilized to define the strength against abrasion of aggregate by utilizing the Los Angeles Machine. The Los Angeles (LA) test utilizes a steel drum enclosing a defined number of steel balls. When rotating with the sample, this implements a combination of attrition due to abrasion between rock particles and impacts from the charge of steel balls, which may be adequate to produce a whole-lump fracture (ASTM C 131, 2010). For this test, 15 kg samples passing a 1.6 mm sieve were organized from each granitic sample. Counts of fines (<1.60 mm) produced after 100 and 500 revolutions for rock samples were recorded. The Los Angeles value refers to the difference between the final weight and the original weight. The final weight of the sample is given as a percentage of the original weight of the test sample.

The frost resistance test with sodium sulfate (Na₂SO₄) was completed following ASTM (C 88) standards to determine the strength of aggregates used in natural stone or concrete applications and exposed to weather effects.

4. Results

4.1. Petrography

Based on the thin-section study and modal mineralogical analysis using Streckeisen's classification system (Streckeisen, 1974), the *Şevketiye granite* is classified as a monzodiorite with quartz. It is beige-grey colored in fresh samples but light brown color in altered samples. The granite is phanerocrystalline and has a holocrystalline–subhedral granular texture. Subhedral, polysynthetic twinned plagioclase is the predominant mineral, which is mostly altered to sericite, epidote, clay minerals, and locally minor saussurite in thin sections. Micro fissures are mainly found in plagioclase as crystal boundary cracks and intracrystalline cracks (Figure 2a), as well as in amphibole crystals. Anhedra, Carlsbad-twinning alkali feldspar (orthoclase), anhedra quartz, amphibole (hornblende), biotite, and pyroxene (clinopyroxene) are the other main rock-forming minerals. Small round zircon, euhedral to anhedra sphene, and euhedral to anhedra opaque minerals are accessories. Sericite, chlorite, and epidote are secondary minerals that occur due to alteration (Table 2).

The Kestanbol granite, which has a quartz monzonite composition based on thin-section study and modal mineralogical analyses, consists of a holocrystalline texture with coarse to fine-grained crystals (Table 2). It has pink-dark pink, greyish color, and porphyroid characteristics due to the presence of large alkali feldspars reaching 1–2 cm in size in hand samples. Quartz is the

Table 1. UCS, BTS, SHV LAT and FRT with sodium sulfate (Na_2SO_4) of the granitic rocks. S1-Şevketiye granite, K2-Kestanbol granite, Y3-Yassıbağ granite, E4-Eybek granite.

Sample No.	Uniaxial compressive strength (UCS) σ_c (MPa)			Brazilian Tensile Strength (BTS) (MPa)	Schmidt Hardnes Values (SHV) σ_c (MPa)	Los Angeles Abrasion (LA) (%)		Frost resistance Test (FRT) (%)
	Min	Max	Mean			100 Rotation	500 Rotation	
S1	10.4	95.5	47.1	4.4	23.5	12.1	49.8	4.50
K2	57.6	151.2	93.9	11.2	49.5	6.8	29.9	0.78
Y3	60.2	228.9	78.9	8.5	41.5	8.9	38.7	3.30
E4	91.1	191.3	137.4	11.4	61.5	4.1	18.7	0.71

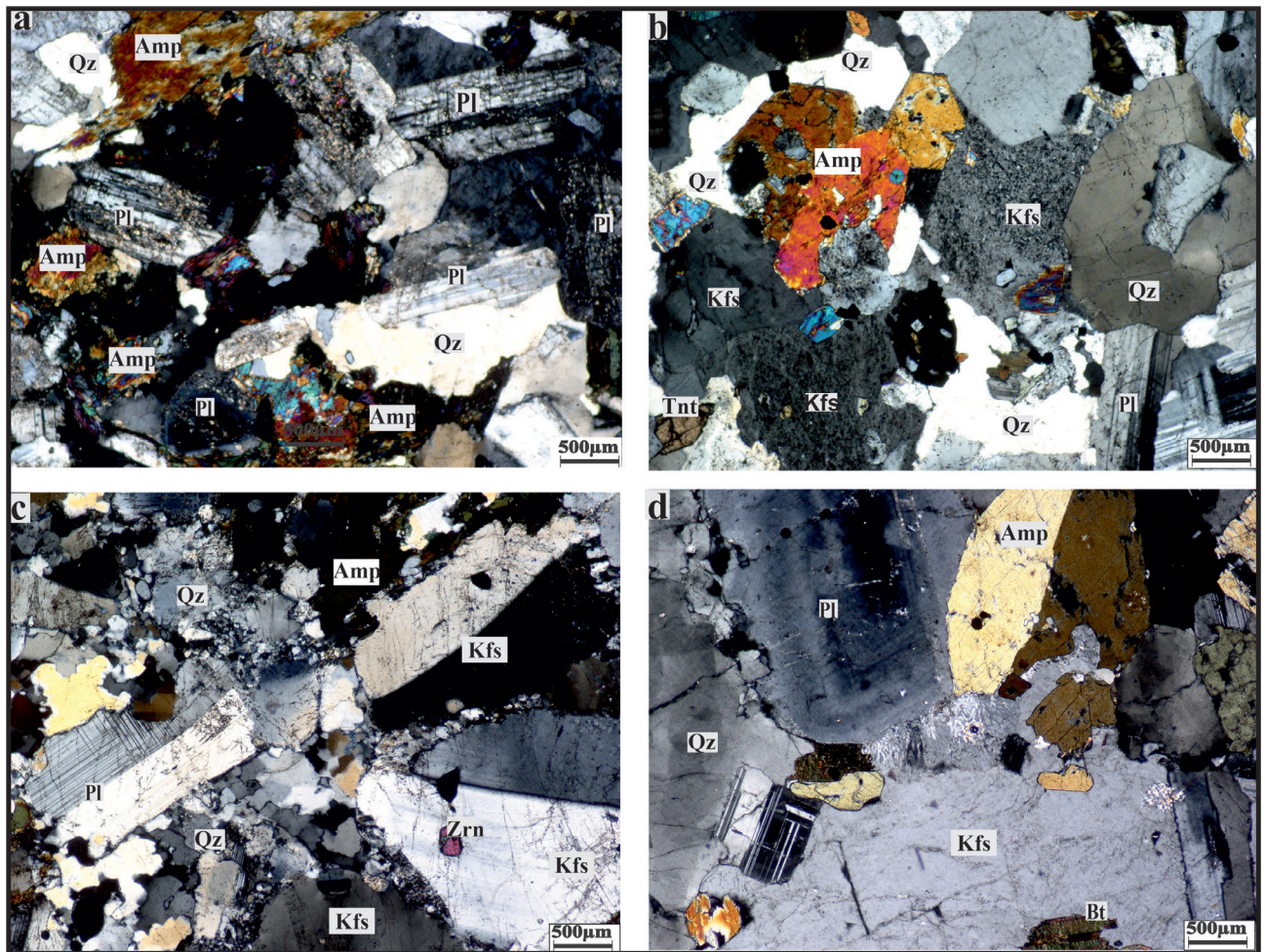


Figure 2. Photomicrograph of: (a) Şevketiye granite (quartz monzodiorite) composed of polysynthetic-twinned plagioclase crystals, anhedral amphibole (hornblende) crystals, and clear anhedral quartz crystals (S1), all of them showing some alteration processes. Plagioclase crystals are altered to sericite and epidote with intracrystalline fissures; (b) Kestanbol granite (quartz monzonite) composed of anhedral alkali feldspar, subhedral polysynthetic-twinned plagioclase, and subhedral, simple-twinned amphibole crystals, (K2); (c) Yassıbağ granite (quartz monzodiorite) has cataclastic texture in Carlsbad-twinned alkali feldspars with round shapes surrounded by fractured small grains. Polysynthetic twinned plagioclase has also deformation twins and fine-grained recrystallization in quartz is also seen. Rounded zircon is in the alkali feldspar (Y4); (d) Eybek granite (granodiorite). Alkali feldspar megacryst (light grey) has poikilitic texture with biotite amphibole and plagioclase. The quartz vermicules from alkali feldspar towards zoned plagioclase form myrmekite in the center of the image. Subhedral simple-twinned amphibole (hornblende) is replaced by alkali feldspar (E4). Kfs = alkali feldspar, Pl = plagioclase, Qz = quartz, Bt = biotite, Amp = amphibole, Zm = zircon. Mineral abbreviations after Whitney and Evans (2010).

Table 2. Mineral composition, grain size, and texture of the rocks tested.

Location Name/Rock Name	Modal Composition (%)	Mineral grain size (mm)	Texture
Şevketiye granite (S1) Quartz monzodiorite	58% Plagioclase	0.62–5.00	Medium to fine-grained holocrystalline subhedral granular
	20% Alkali Feldspar	0.41–1.11	
	5% Quartz	0.21–1.12	
	7% Amfibole	0.41–1.40	
	1% Pyroxene	0.80–1.20	
	6% Biotite	0.21–0.81	
	2% others-Zircon, sphene (titanite), opaque minerals, and seconder minerals (sericite, chlorite, and epidote)		
Kestanbol granite (K2) Quartz monzonite	29% Alkali Feldspar	0.55–21.00	Coarse to fine-grained holocrystalline subhedral porphyritic texture
	23% Plagioclase	0.54–8.00	
	36% Quartz	0.65–2.17	
	6% Amfibole	0.40–3.00	
	4% Biotite	0.21–1.03	
	2% others-Zircon, sphene (titanite), opaque minerals, and seconder minerals (chlorite and epidote)		
Yassibağ granite (Y3) Quartz monzodiorite	58% Plagioclase	0.27–6.00	Medium to fine-grained holocrystalline subhedral granular texture
	20% Alkali Feldspar	0.66–5.00	
	10% Quartz	0.15–0.56	
	9% Amfibol	0.66–5.00	
	3% Biotite	0.20–0.30	
	1% others-Zircon, sphene (titanite), opaque minerals, and seconder minerals (perthite, mrymekite, and chlorite)		
Eybek granite (E4) Granodiorite	37% Quartz	0.65–2.17	Medium to fine-grained holocrystalline subhedral granular texture
	32% Plagioclase	0.54–4.00	
	19% Alkali Feldspar	0.55–5.00	
	5% Amfibole	0.40–5.00	
	6% Biotite	0.21–1.03	
	1% others-Zircon, sphene (titanite), opaque minerals, and seconder minerals (perthite, mrymekite, and chlorite)		

predominant mineral (Figure 2b) and subhedral to mostly anhedral, perthitic alkali feldspar (orthoclase), subhedral, polysynthetic twinned plagioclase, amphibole (hornblende) (Figure 2b), and lath-shaped biotite are the main rock-forming minerals. Small, round zircon, euhedral to anhedral sphene, and opaque minerals are accessories. Epidote and chlorite are secondary minerals formed due to the alteration of feldspar and biotite. Euhedral to subhedral cleavaged amphibole crystals

show simple twinning (Figure 2b). Euhedral to subhedral opaque minerals occur as inclusions and around other minerals, especially hornblende.

The Yassibağ granite has light-gray color in fresh samples and is phanerocrystalline in hand samples. Based on the thin-section study and modal mineralogical analysis, the Yassibağ granite is a monzodiorite with quartz. The Yassibağ granite has medium to fine-grained texture and consists of quartz, poikilitic alkali feldspar,

plagioclase, biotite, and amphibole as principal minerals, while sphene, zircon, and opaque minerals are the accessory mineral phase. Sericite, perthite, myrmekite, and chlorite are secondary minerals. The cataclastic texture was recognized in the Yassıbağ granite. Carlsbad-twinning alkali feldspar crystals are fractured, and the edges of crystals are rounded and surrounded by fine grains (Figure 2c). Besides polysynthetic twinning, deformation twins occur in subhedral plagioclase due to deformation. Quartz grains are anhedral in shape and occur as clear crystals with a few tiny quartz grains resembling those that crystallize during ductile stress. Green hornblende crystals are fragmented and contain inclusions of alkali feldspar, plagioclase, and quartz. Biotite is seen as stretched mineral plates with light to dark brown colors that are strongly altered to chlorite.

The Eybek granite has light-gray color in rock hand samples and its crystals are medium- to fine-grained which can be distinguished by the naked eye. The Eybek Granite, which has a granodiorite composition according to modal mineralogical analyses, consists of holocrystalline medium- to fine-grained crystals (Table 2) in thin sections. Based on the thin-section study, anhedral quartz, poikilitic, subhedral to anhedral alkali feldspar (orthoclase) (Figure 2d), subhedral polysynthetic twinned plagioclase, green cleaved amphibole (hornblende), and biotite are the main rock-forming minerals. Euhedral to anhedral sphene (titanite), opaque minerals, and zircon are accessories. Sericite, perthite, myrmekite, and chlorite are secondary minerals.

4.2. Physical properties

The physical properties such as effective porosity, total porosity, and water absorption for the four different granites from Şevketiye, Kestanbol, Yassıbağ, and Eybek locations were defined with a variety of laboratory tests.

The determination of water absorption is important due to the entry of water into the rock creating an increase in the degree and rate of weathering. When a higher content of water is absorbed, the higher the loss in strength of the rock will be. The water absorption values for the studied

samples were determined by following the TS EN 13755 (2014) standard. Effective porosity and total porosity were tested following the TS EN 1936 (2010) standard. In the study, tests were done with 6 samples from each region, and the average values were calculated. The total and effective porosity and water absorption of the Şevketiye, Kestanbol, Yassıbağ, and Eybek granites are presented in Table 3.

4.3. Mechanical properties

The mechanical characteristics of the tested granitic rocks were defined by laboratory tests such as UCS, the BTS, the SHT, the LA test, and the FRT with sodium sulfate (Na_2SO_4). Table 1 sets out the obtained experimental results.

The UCS of the granitic samples was defined using a standard compression testing machine following the standards recommended by ISRM (2007) on prepared granitic core samples. The maximum load at failure was utilized to calculate the UCS of samples. Ten samples from each region (Şevketiye, Kestanbol, Yassıbağ and Eybek) were tested and average values were used. The average values of UCS for rock samples are presented in Table 1. The investigated rocks were also classified according to their UCS values as proposed in ISRM (1981) (Table 4). While the samples of Şevketiye granite fall into the medium strength category (UCS 20 – 60 MPa) of ISRM (1981) with 47.1 MPa, Kestanbol granite, Yassıbağ granite, and Eybek granite fall into the high strength category (UCS 60–200 MPa) of ISRM (1981). The tensile strength was determined by the Brazilian tensile test (BTS) according to the ISRM (2007) specification. The Eybek granite (granodiorite) exhibited the highest value for BTS (11.4 MPa), whereas the Şevketiye granite (quartz monzodiorite) exhibited the lowest BTS (4.4 MPa). SHT tests were performed according to ISRM (2007). Similarly, the Eybek granite samples exhibited the highest value for SHT (61.5 MPa), whereas the Şevketiye granite samples exhibited the lowest SHT (23.5 MPa).

The Los Angeles (LA) test is utilized to define the strength against abrasion of aggregate using the Los Angeles

Table 3. Water absorption, effective porosity, and total porosity of the studied granites. S1- Şevketiye granite, K2-Kestanbol granite, Y3-Yassıbağ granite, E4-Eybek granite.

Sample No	Water absorption W_s (%)			Effective porosity n_e (%)			Total porosity n_t (%)		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
S1	0.42	0.60	0.53	0.97	2.23	1.7	2.46	5.28	4.16
K2	0.26	0.37	0.30	0.87	0.99	0.93	2.91	3.99	3.39
Y3	0.23	0.46	0.35	0.56	2.85	1.58	0.36	3.18	1.59
E4	0.28	0.34	0.31	0.80	1.82	1.25	0.37	1.48	0.81

Table 4. Rock classification of the UCS values based on ISRM (1981) and UCS values of rock samples tested in the present study.

Rock Classes	UCS (MPa)		UCS (MPa)		
	ISRM (1981)	Şevketiye granite	Kestanbol granite	Yassıbağ granite	Eybek granite
Very weak strength	<6				
Weak strength	6–20				
Medium strength	20–60	47.1			
High strength	60–200		93.9	78.9	137.34
Very high strength	>200				

machine following the standards recommended by ASTM C 131 (2010). As shown in Table 1, the results for LA values ranged between 4.1%–11.4% for 100 rotations, and 18.7%–49.8% for 500 rotations. Frost resistance test with sodium sulfate (Na_2SO_4), performed by following ASTM (C 88) standards, determines the strength of aggregates used in natural stone or concrete applications and exposed to weather effects. The results for the FRT values also ranged between 0.71%–4.50%. The Eybek granite (granodiorite) samples exhibited the lowest values for LA (11.4%–18.7%) and FRT (0.71%), whereas the Şevketiye granite (quartz monzodiorite) samples exhibited the highest LA (12.1%–49.8%) and FRT (4.50%). The Eybek granite, as well as the Kestanbol granite, are clearly the most durable rocks, while Yassıbağ and Şevketiye granites have higher LA values and FRT values. Therefore, this result seems to indicate that the resistance of the tested granitic rocks to attrition and grinding is a linear function of their strength.

4.4. Relationship between UCS and BTS with SHT

Correlation analysis is performed to identify the degree of relationship between two variables, and regression analysis is utilized to supply the mathematical equation which best defines the way in which these two factors are related. Simple regression analysis was completed to learn the relationships between UCS and BTS with SHT (Figure 3) in this section. The correlations between uniaxial compressive strength and tensile strength with the Schmidt hardness test were researched in many studies (e.g., Ulusay et al., 1994; Yasar and Erdoğan, 2004; Karaman et al., 2015; Ajalloeian et al., 2020 etc.). In this study, simple regression analysis was also completed to examine the relationships between LA and FRT with SHT.

Figure 3a shows that there is a linear positive correlation between SHV and UCS with a correlation coefficient of 0.959. The equation for the correlation is;

$$\text{UCS} = 2.3048\text{SHV} - 12.062 \quad R^2 = 0.959$$

Figure 3b shows that there is also a positive linear strong correlation between BTS and SHT with the correlation coefficient of 0.918. The equation for the correlation is;

$$\text{BTS} = 0.1961\text{SHV} + 0.2451 \quad R^2 = 0.918$$

There is a linear but negative correlation between LA and SHV with a correlation coefficient of 0.983 and a linear correlation between FRT and SHV with a correlation coefficient of 0.861 (Figures 3c–3d).

4.5. Relationship between the physical and the mechanical properties

There were linear relationships between water absorption and UCS, SHT, BTS, and LA values for the tested samples. Water absorption values increased when the SHT, UCS, and BTS values decreased (Figures 4a–4b–4c). On one hand, LA values increased when water absorption increased (Figure 4d). Similarly, the total porosity increased while UCS and SHT values decrease for the tested samples (Figure 5a). On the other hand, the LA values increased when the water absorption increased (Figure 5b).

In this study, the tested samples were gathered from different locations of Şevketiye, Kestanbolu, Yassıbağ, and Eybek, as mentioned before. The presented values are the average values of ten samples tested for UCS, BTS, and SHT and the average values of six samples tested for total porosity and water absorption.

4.6. Relationship between the petrographic and mechanical properties

Petrographic properties such as grain size, the shape of grains, texture, and mineralogical composition are known to affect the mechanical properties of rocks. The mineral composition is one of the petrographic properties that influence mechanical characteristics. To define the relationship between mineralogical compositions and the mechanical properties (UCS, BTS, SHT, LA, and FRT), simple regression analyses were performed.

There was a significant relationship between the mechanical properties and the main mineral (plagioclase, quartz, and amphibole) content in this study (Figures 6 and 7). There was a positive linear correlation between quartz content, quartz-to-feldspar ratio, and uniaxial compressive strength (Figures 6a–6b). There was a similar

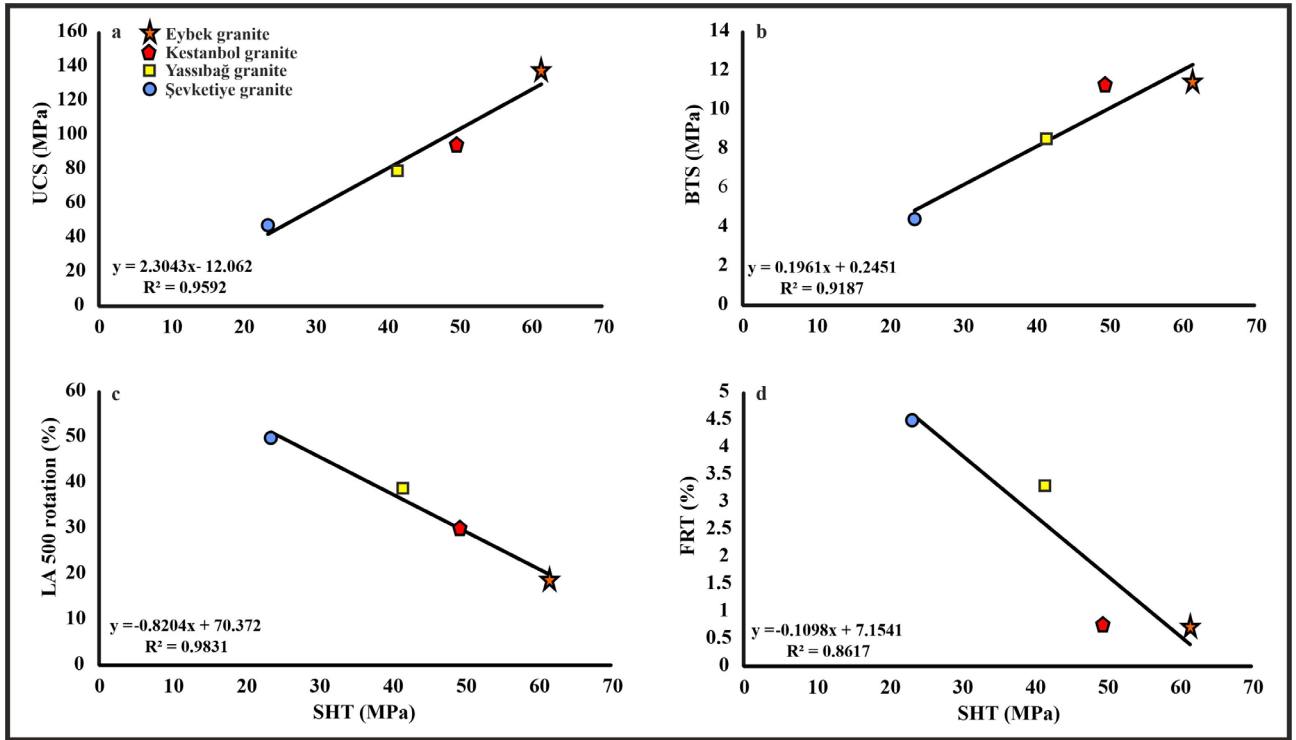


Figure 3. Relationships between Schmidt hardness test and: (a) Uniaxial compressive strength; (b) Brazilian tensile strength; (c) Los Angeles abrasion values; and (d) Frost resistance test and Schmidt hardness test.

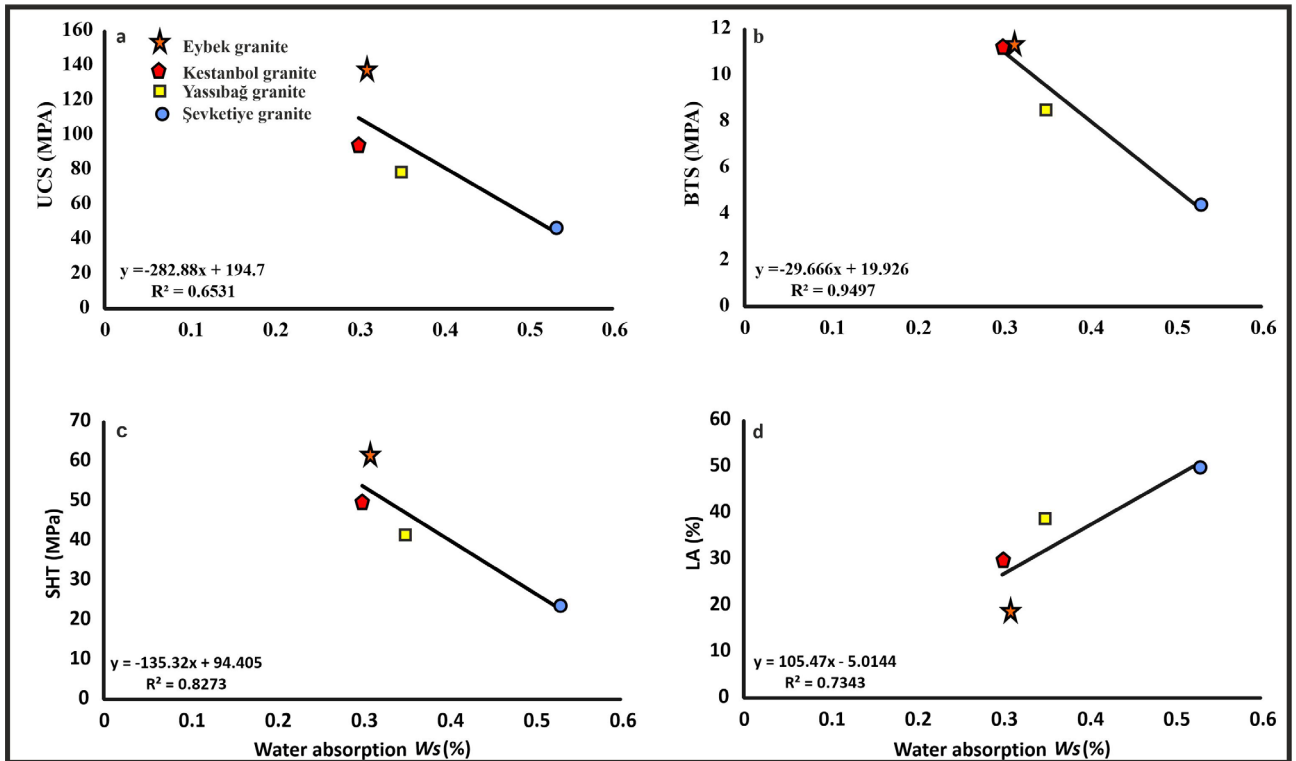


Figure 4. Relationships between a-Uniaxial compressive strength (UCS) versus water absorption, b-Schmidt hardness test (SHT) values versus water absorption, c-Brazilian tensile strength (BTS) versus water absorption, d-Los Angeles (LA) abrasion versus water absorption.

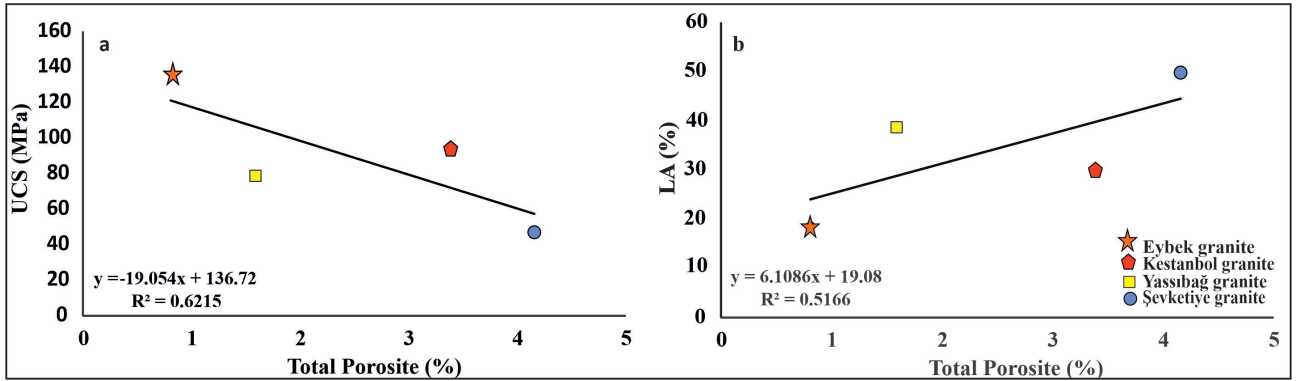


Figure 5. a-Relationship between Uniaxial compressive strength and the total porosity b-Relationship between Los Angeles abrasion test and the total porosity.

positive relationship between quartz content, quartz to feldspar ratio, and tensile strength (Figures 6c–6d) and Schmidt hardness tests (Figures 6e–6f). These results are consistent with the results of Tuğrul and Zarif (1999) who showed that the comparative ratio of quartz to feldspar might be correlated with the strength of granite. Quartz has no cleavage and is not susceptible to alteration to fine-grained minerals; therefore, as the quartz content increases, the strength increases. On the other hand, there was a negative linear relationship between percentage of quartz and Los Angeles (LA) test values (Figures 6g–6h) and the frost resistance test values (Figures 6i–6j).

The relationships between the percentage of the other main minerals (plagioclase and amphibole) and the mechanical properties of the tested rocks are shown in Figure 7. The regression analyses between these minerals and mechanical properties of tested samples show that there were negative linear correlations between these minerals (plagioclase and amphibole) with UCS, BTS, and SHT (Figures 7a–7b–7c–7d–7e–7f), while positive linear correlations existed between these minerals with LA and frost resistance test with sodium sulfate (Na_2SO_4) (Figures 7g–7h–7i–7j). The correlations between alkali feldspar and the mechanical properties of the tested samples were not statistically significant.

Previous works showed that the presence of micro-fissures and mineral cleavage in feldspar within intact specimens lowered the comprehensive strength (Ondera and Asoka Kumara, 1980; Tuğrul and Zarif, 1999). Besides this, the occurrence of alteration in plagioclase and amphibole crystals in the tested granite samples reduced the strength of the samples. Especially, plagioclase and amphiboles from Şevketiye granite, which had the lowest mechanical properties, were more altered than the other granitic samples.

LA values and FRT results tended to decrease with increasing quartz content (Figures 7 g–7h–7i–7j). This

result similarly showed that the quartz content provides strong resistance to attrition, grinding, and abrasion.

The previous studies showed that the grain size of rocks is also one of the main petrographic properties, which include the shape of grains, texture, and mineralogical composition, known to influence the mechanical properties of rocks (Ondera and Asoka Kumara, 1980; Akesson et al., 2001; Tuğrul and Zarif, 1999; Güneş Yılmaz et al., 2011). But, in this study, the correlations between grain size and mechanical characteristics of granites did not provide statistically significant results.

5. Discussion

Şevketiye, Kestanbol, Yassibağ, and Eybek locations, where granitic rocks outcrop in the Biga Peninsula, were chosen to research granitic rocks for relationships between petrographic properties and mechanical strength parameters. Correlation and regression analyses were performed.

Detailed petrographic investigations demonstrated that both Şevketiye granite and Yassibağ granite are quartz diorite and Kestanbol granite is quartz monzonite while Eybek granite is granodiorite in composition. All the rocks have a similar mineral composition of mainly feldspar (plagioclase–alkali feldspar), quartz, mafic minerals (biotite and amphibole), accessory minerals (sphene, zircon, opaque minerals), and secondary minerals (epidote, chlorite, sericite). Although there are similarities in mineral composition, there are some differences with respect to the percentage of modal mineralogy especially, texture details, and weathering. Plagioclase (58%) is the primary mineral, followed by alkali feldspar (20%), in both Şevketiye and Yassibağ granites. Quartz is the primary mineral (36%–37%), while feldspar has an equal portion to plagioclase (20%–32%)–alkali feldspar (19%–29%) in the Kestanbol granite and Eybek granite. They have equigranular texture, but Kestanbol granite also has

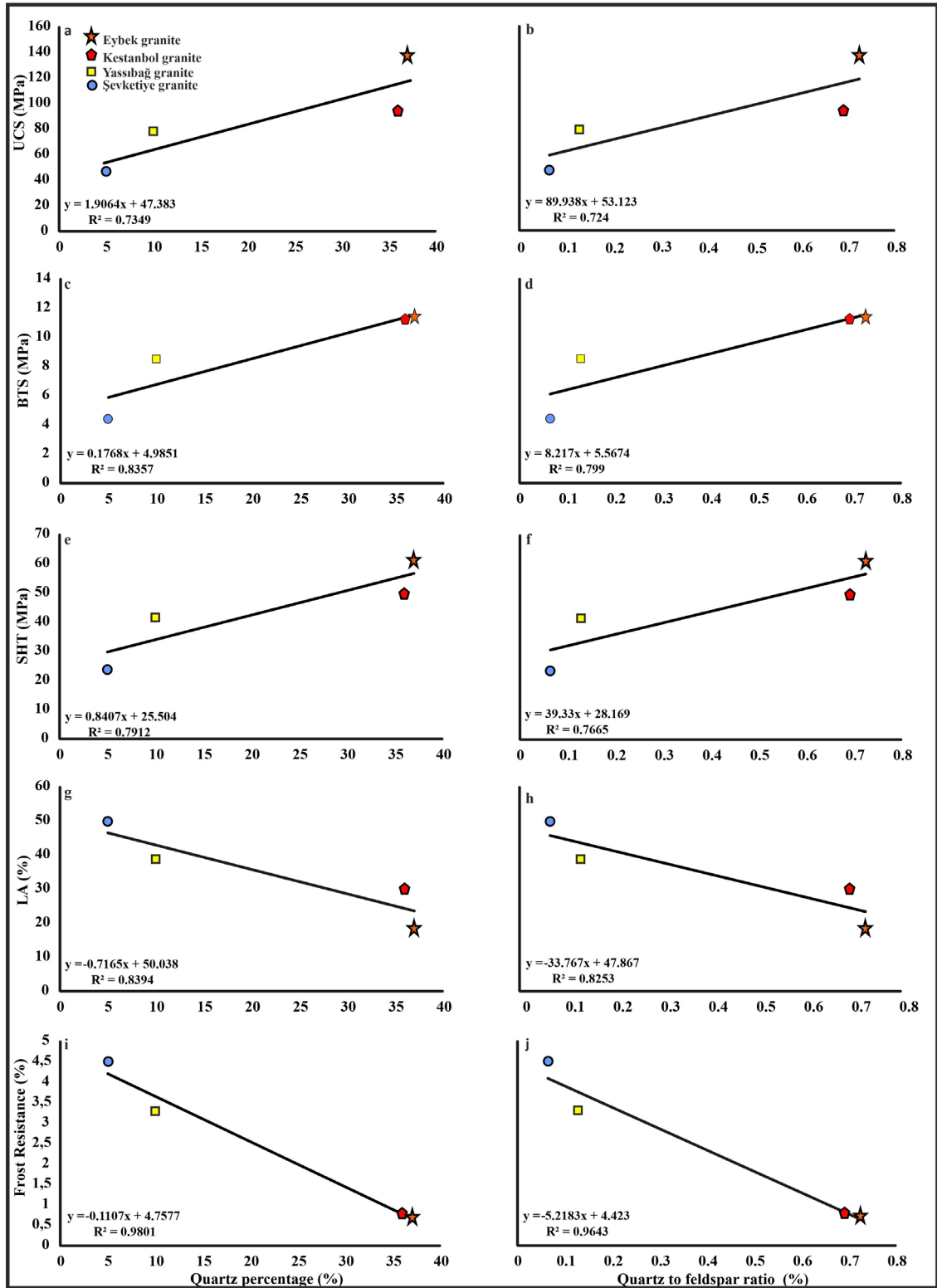


Figure 6. Relationships between (a) Uniaxial compressive strength and percentage of quartz, (b) Uniaxial compressive strength and quartz to feldspar ratio, (c) Brazilian tensile strength and percentage of quartz, (d) Brazilian tensile strength and quartz to feldspar ratio, (e) Schmidt hardness test and percentage of quartz, (f) Schmidt hardness test and quartz to feldspar ratio, (g) Los Angeles abrasion values and percentage of quartz, (h) Los Angeles abrasion values and the quartz to feldspar ratio, (i) Frost resistance test and percentage of quartz, (j) Frost resistance test and quartz to feldspar ratio.

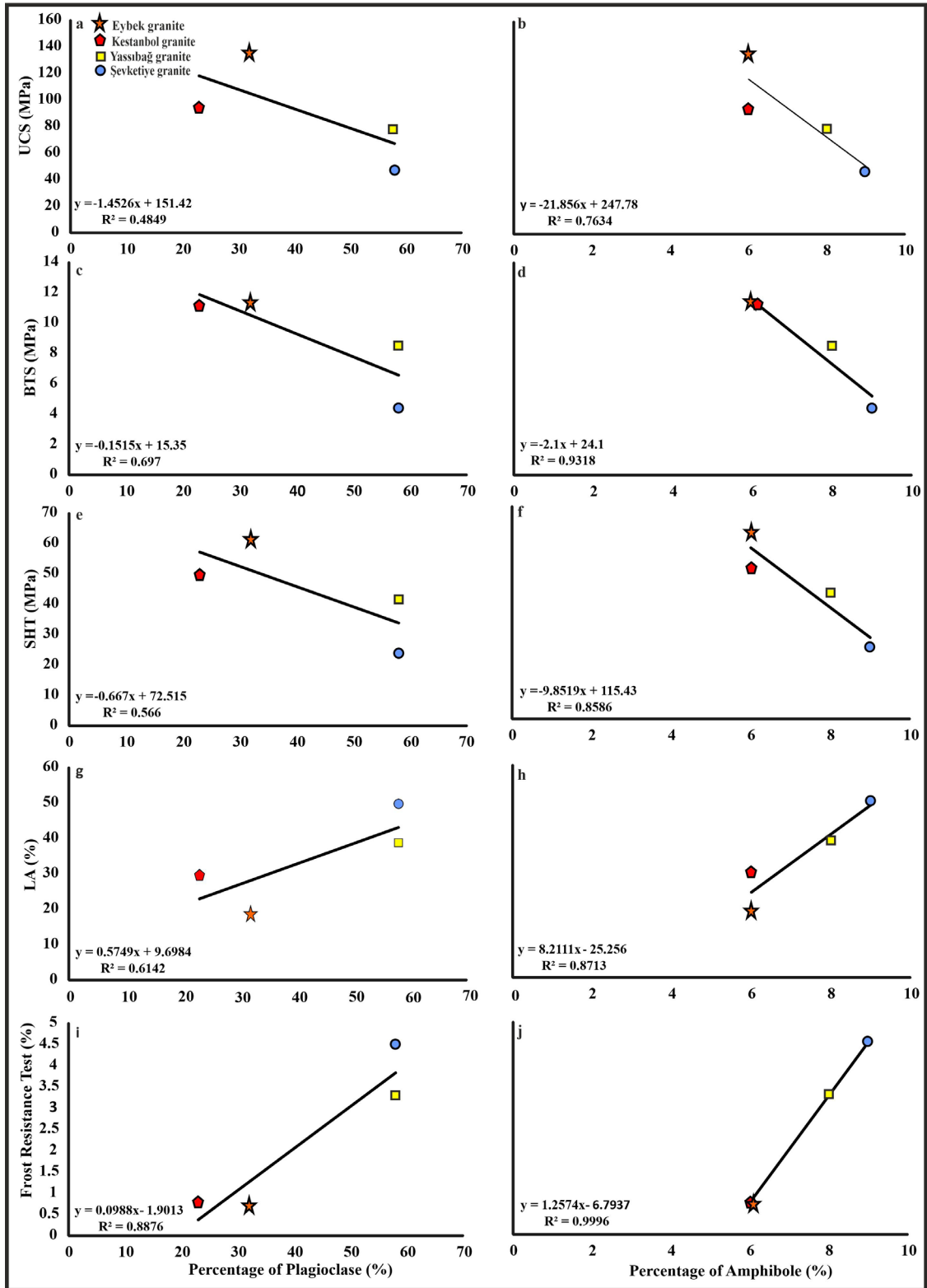


Figure 7. Relationships between (a) Uniaxial compressive strength and percentage of plagioclase, (b) Uniaxial compressive strength and percentage of amphibole, (c) Brazilian tensile strength and percentage of plagioclase, (d) Brazilian tensile strength and percentage of amphibole, (e) Schmidt hardness test and percentage of plagioclase, (f) Schmidt hardness test and percentage of amphibole, (g) Los Angeles abrasion values and percentage of plagioclase, (h) Los Angeles abrasion values and percentage of amphibole, (i) the Frost resistance test and percentage of plagioclase (j) the Frost resistance test and percentage of amphibole.

porphyroid characteristics due to the presence of large alkali feldspars reaching a centimeter size in hand samples. Additionally, the cataclastic texture is present in Yassıbağ granite. Both field studies and thin-section investigations show that Şevketiye and Yassıbağ granites are more altered than Kestanbol and Eybek granites. Subhedral plagioclase crystals have polysynthetic twinning, and are mostly altered to sericite, epidote, clay minerals, and locally minor saussurite in Şevketiye granite. Amphibole and biotite crystals are also altered to chlorite and opaque minerals. Moreover, micro fissures are mainly found in plagioclase as crystal boundary cracks and intracrystalline cracks, as well as in amphibole crystals. Yassıbağ granite has a cataclastic texture where Carlsbad-twinned alkali feldspar crystals are fractured, the edge of crystals are rounded and surrounded by fine grains, and in addition to polysynthetic twinning, deformation twins occur in subhedral plagioclase due to deformation.

When water accesses rock, it produces an increase in the degree and rate of weathering. When a high content of water is absorbed, the strength of the rock will be lost. Therefore, a low water absorption value indicates that the rock is highly resistant to weathering. These rocks have a very low degradation effect due to frost action and chemical weathering (Blyth and de Freitas, 1974). Water absorption values increased, while SHT, UCS, and BTS values decreased (Figures 4a–4b–4c) for the investigated samples. The LA values increased while the water absorption increased (Figure 4 d). A similar result was also seen in research by Arif et al. (2013) who found a negative correlation between uniaxial compressive strength and water absorption for granitic rocks they investigated. In a similar way, the total porosity increased while the UCS (Figure 5a) values decreased for the tested samples. The LA values increased, while the water absorption increased (Figure 5b). Therefore, this finding indicates that physical properties affect the strength of rocks. Tuğrul and Zarif (1999) found a negative linear trend between uniaxial compressive strength and porosity since porosity reduces the integrity of the material and a minor change in pore capacity could produce a significant mechanical effect (Tuğrul and Zarif, 1999).

Eybek granite had the highest value for UCS (137.34 MPa), whereas the samples from Şevketiye granite (quartz monzodiorite) exhibited the lowest UCS (4.4 MPa). The samples from the Şevketiye granite are classed in the medium strength category of ISRM (1981), with the UCS value of 47.1 MPa. The Kestanbol granite, Yassıbağ granite, and Eybek granite are classed in the high strength category. Similarly, the Eybek granite (granodiorite) exhibited the highest values for BTS (11.4 MPa) and the highest value for SHT, whereas the Şevketiye granite (quartz monzodiorite) exhibited the lowest BTS and SHT values. The Kestanbol

granite exhibited the second highest values for UCS (93.9 MPa), BTS (11.2 MPa), and SHT (30.4 MPa), whereas the Yassıbağ granite exhibited the second lowest UCS (78.9 MPa), BTS (8.5 MPa), and SHT (28.6 MPa) values after Şevketiye granite.

There was a tendency for UCS, BTS, and SHT to increase as quartz content and the quartz–feldspar ratio increases (Figures 6a–6b–6c–6d–6e–6f) for the studied granites. Quartz has no cleavage and is not susceptible to alteration to fine-grained minerals; therefore, as the quartz content increases, the strength increases. Contrarily, LA and FRT decreased when the quartz–feldspar ratio and the quartz content increased (Figures 6 i–6j) because it is the hardest mineral in the tested rocks providing strong resistance to attrition, grinding, and abrasion. Some works argued that there was an inverse relationship between quartz content and tensile strength (e.g., Merriam et al., 1970), or no considerable relationship (Prikrýl, 2006; Phillipson, 2008; Güneş Yılmaz et al., 2011; Sousa, 2013), while others argued there was a direct positive linear relationship with compressive strength or durability (Tuğrul and Zarif, 1999; Ghobadi and Momeni, 2011). In this study, quartz content influenced the strength of the tested granitic rocks.

There were negative linear correlations between other minerals (plagioclase and amphibole) and the UCS, and BTS and SHT (Figures 7a–7b–7c–7d–7e–7f), while positive linear correlations existed between these minerals with LA and frost resistance test with sodium sulfate (Na_2SO_4) (Figures 7g–7h–7i–7j). Cleavable minerals, especially feldspar, negatively affect the strength of rocks (Friedman et al., 1970; Sprunt and Brace 1974). Twinning planes, cleavages, and microfractures affect the strength of rock and could move as a plane of weakness, which directs the way in which failure develops (Willard and McWilliams, 1969). Therefore, the strength of a rock involves the presence of interruptions, where cracks might start at the time of failure (Lindqvist et al., 2007). Micro fissures were primarily found in plagioclase as intracrystalline and crystal boundary cracks, as well as in amphibole crystals in the samples tested in the present study. This result could explain why the strength properties of Şevketiye granite are the lowest among the other granites. Alteration in plagioclase and amphibole crystals in the tested Şevketiye granite sample reduced the strength of the samples. Moreover, Şevketiye granite had the lowest amount of quartz compared to the other tested rocks. Although Yassıbağ granite had similar amounts of plagioclase as Şevketiye granite, it had a higher amount of quartz, and its strength values were higher than Şevketiye granite. The findings in this study indicate positive and negative correlations between the strength of the tested granitic rocks and the content of quartz, plagioclase, and

amphibole (Figures 6–7), respectively, whereas the alkali feldspar content did not display a functional association with strength. These results are also compatible with the results of Yeşiloğlu–Gültekin et al., (2013).

There were also positive and negative linear correlations between the strength of the tested granitic rocks and resistance to abrasion and frost resistance in this study. The relationship between rock properties and resistance to abrasion (using the Los Angeles abrasion test) has been investigated by some researchers (Kazi and Al-Mansour, 1980; Ballivy and Dayre, 1984; Cargill and Shakoor, 1990; Kasim and Shakoor, 1996; Al-Harhi, 2001; Kahraman and Fener, 2007; Kahraman and Toraman, 2008; Özçelik 2011; Teymen, 2017). Some of the tests used by researchers for this purpose are uniaxial compressive strength, point load index, unit volume weight, and porosity tests. Unlike the previous studies, to define the relationship between mineralogical compositions and resistance to abrasion, simple regression analyses were performed in this study. Additionally, a frost resistance test was performed on the granitic rocks. As mentioned above LA and FRT decreased when the quartz-feldspar ratio and the quartz content increased. On the other hand, positive linear correlations existed between plagioclase and amphiboles with LA and frost resistance test with sodium sulfate (Na_2SO_4).

Correlations between the physical properties such as water absorption and porosity and mechanical properties of the investigated rocks showed that water absorption and porosity of rocks influenced their strength, attrition, and frost resistance in the present study. Tuğrul and Zarif (1999) reported that there was a significant negative relationship between uniaxial compressive strength and porosity. Arif et al., (2013) also indicated UCS and water absorption values had a negative correlation for the investigated granitic rocks. A low water absorption value gives the rock high resistance to weathering; therefore, water absorption influences the strength of rock.

Uniaxial compressive and tensile strengths of the rocks, defined directly by laboratory tests, are two significant geotechnical parameters for most engineering projects both for fieldwork and laboratory studies that are nondestructive. Performing both tests is expensive and time-consuming, particularly as granitic rocks can have high resistance, can be difficult to work with and high-quality core samples may not be taken appropriately. The Schmidt hammer test is performed in the field or laboratory and is nondestructive. Because of its easy application in field and laboratory conditions along with nondestructive nature and lower cost, the Schmidt hammer test is preferred for use in the prediction of uniaxial compressive and tensile strength. Therefore, the correlations between uniaxial compressive strength and tensile strength with the Schmidt hardness test were researched in many

studies (e.g., Ulusay et al., 1994; Yasar and Erdoğan, 2004; Karaman et al., 2015; Ajalloeian et al., 2020 etc.). The findings of previous studies show an increasing propensity for uniaxial compressive strength and tensile strength values with increasing Schmidt hardness test values. In this study, the correlations between UCS, BST with SHT were investigated and an increasing propensity for UCS and BST values was found with increasing SHT values. This result is coherent with the results of previous research. Additionally, unlike previous studies, the correlations between LA abrasion values and FRT values with SHT values were investigated in this study. An increasing propensity for the LA abrasion values and the FRT values was found with decreasing Schmidt hardness test values. This result also shows that the resistance of the tested granitic rocks to attrition, grinding, and frost resistance is a linear function of their strength.

6. Conclusion

Granitic rocks, one of the most dominant lithologies in the Biga Peninsula, were not previously studied regarding the relationship between petrographic and mechanical properties. With this aim, Şevketiye, Kestanbol, Yassıbağ, and Eybek granites were investigated to determine their petrographic and mechanical properties and the relationship between them. Field observations, modal mineralogic analysis, physical properties (porosity, water absorption), and strength tests (uniaxial compressive strength, tensile strength, Schmidt hardness test, Los Angeles test, and frost resistance test with sodium sulfate (Na_2SO_4)) results for the investigated granitic rocks provided data that led to the following conclusions.

Şevketiye granite and Yassıbağ granite are quartz diorite, while Kestanbol granite is quartz monzonite and Eybek granite is granodiorite in composition based on thin-section study and modal mineralogical analyses. All the rocks have a similar mineral composition comprising mainly feldspar (plagioclase–alkali feldspar), quartz, mafic minerals (amphibole and biotite), accessory minerals (zircon, sphene, opaque minerals), and secondary minerals (sericite, chlorite, epidote).

Eybek granite has the highest values for UCS, SHT, and BTS, whereas Şevketiye granite exhibits the lowest UCS, SHT, and BTS. Therefore, while the samples of Şevketiye granite fall into the medium strength category with a UCS value of 47.1 MPa, the Kestanbol granite, Yassıbağ granite, and Eybek granite fall into the high strength category of ISRM (1981). Contrarily Eybek granite exhibits the lowest value LA and FRT, whereas Şevketiye granite exhibits the highest LA and FRT. Eybek granite, as well as Kestanbol granite, are the most durable rocks, while Yassıbağ and Şevketiye granites have higher LA values and FRT values.

Therefore, this result indicates the resistance of the tested granitic rocks to attrition and grinding is a linear function of their strength.

The findings from the comparison of petrographic and mechanical properties indicate positive and negative correlations between the strength of the tested granitic rocks and the quartz, plagioclase, and amphibole contents, respectively. However, the alkali feldspar content did not display a functional association with strength. Relationships between the physical properties such as water absorption and porosity and mechanical properties of the tested rocks show that their physical properties also

influence their strength, attrition, and frost resistance in the present study.

The correlations between UCS and BST with SHT of the investigated rocks indicate an increasing tendency for UCS and BST values with increasing SHT values in the present study. Additionally, correlations between LA abrasion values and FRT values with SHT values show that an increasing tendency for LA abrasion values and FRT values with decreasing Schmidt hardness test values. This result also shows that the resistance of the tested granitic rocks to attrition, grinding, and frost resistance is a linear function of their strength.

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